IRSTI 68.35.29 https://doi.org/10.26577/bb.2024.v100.i3.05

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YIELD STABILITY ANALYSIS OF BREAD WHEAT GENOTYPES IN KAZAKHSTAN

Bread wheat (*Triticum aestivum* L.) is a significant crop for human nutrition and global food security. Ensuring stable wheat yields is crucial, as fluctuations in production can have major effects on food availability and prices globally. We evaluated 82 bread wheat genotypes in two growing seasons using multi-environment trial analysis (eight environments) in Kazakhstan to identify superior genotypes using AMMI-based stability statistics. The analysis of variances (ANOVA) of AMMI showed that environmental effects largely explained yield variability (87.6 %), whereas the contribution of genotype (2.79 %) and genotype-environment interaction (8.19 %) had minimal influence. An estimated set of stability parameters showed positive correlations between each other, and these measurements can be utilized to choose stable genotypes. The mean yield of bread wheat genotypes ranged from 24.5 to 17.9 centners per ha. Genotypes 342/08 (G62), Line P-1413m (G8), Lyutescens 54 190/09 (G54), 233/10 (G58), Bajterek 15 (G25), and Lyutescens 57 4/09 (G52) were shown to be the most stable and productive based on AMMI-based stability scores for grain yield. Breeders and farmers could use these samples as stable and high-performing genotypes in a wide range of environments in Kazakhstan. Future studies could use more growth seasons to identify the most stable genotypes.

Key words: yield, AMMI, bread wheat, productivity, stability, multi-environment trials, genotype-environment interaction, superior genotypes.

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Қазақстандағы жұмсақ бидай генотиптері өнімділігінің тұрақтылығын талдау

Жұмсақ бидай (*Triticum aestivum* L.) адамның тамақтануы мен жаһандық азық-түлік қауіпсіздігі үшін маңызды дақыл болып табылады. Бидайдың тұрақты өнімділігін қамтамасыз ету өте маңызды, өйткені өндірістің ауытқуы бүкіл әлемде азық-түлік пен бағаға айтарлықтай әсер етуі мүмкін. Біз AMMI негізіндегі тұрақтылық статистикасын пайдалана отырып, ең жақсы генотиптерді анықтау үшін Қазақстанда әр түрлі сынақ талдауын қолданып (сегіз экологиялық жағдай), екі вегетациялық маусымда жұмсақ бидайдың 82 генотипін бағаладық. AMMI дисперсиялық талдауы (ANOVA) қоршаған ортаның әсері негізінен өнімділіктің өзгергіштігін (87,6%) түсіндіретінін көрсетті, ал генотиптің (2,79 %) және генотип-ортаның өзара әрекеттесуінің (8,19 %) үлесі ең аз әсер етті. Тұрақтылық параметрлерінің бағаланған жиынтығы өзара оң корреляцияны көрсетті және бұл өлшемдерді тұрақты генотиптерді таңдау үшін пайдалануға болады. Жұмсақ бидай генотиптерінің орташа өнімділігі 24,5-тен 17,9 ц/га-ға дейін болды. 342/08 (G62), P-1413m (G8), Лютесценс 54 190/09 (G54), 233/10 (G58), Байтерек 15 (G25) және Лютесценс 57 4/09 (G52) генотиптері AMMI негізіндегі дән өнімділігінің тұрақтылығын бағалау негізінде ең тұрақты және өнімді болды. Селекционерлер мен фермерлер бұл үлгілерді Қазақстанның кең ауқымында тұрақты және жоғары өнімді генотиптер ретінде пайдалана алады. Болашақ зерттеулер ең тұрақты генотиптерді анықтау үшін көбірек вегетациялық кезеңдерді қамтуы мүмкін.

Түйін сөздер: шығымдылық, AMMI, жұмсақ бидай, өнімділік, тұрақтылық, әртүрлі орталарда сынау, генотип-ортаның өзара әрекеттесуі, жоғары генотиптер.

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Анализ стабильности урожайности генотипов мягкой пшеницы в Казахстане

Мягкая пшеница (*Triticum aestivum* L.) является важной культурой для питания человека и глобальной продовольственной безопасности. Обеспечение стабильных урожаев пшеницы имеет решающее значение, поскольку колебания производства могут оказать серьезное влияние на доступность продовольствия и цены во всем мире. Мы оценивали 82 генотипа мягкой пшеницы в течение двух вегетационных периодов в Казахстане, используя мульти-средовый анализ (восемь сред), чтобы выявить лучшие генотипы с использованием статистики стабильности на основе AMMI. Дисперсионный анализ (ANOVA) AMMI показал, что влияние окружающей среды в значительной степени объясняет изменчивость урожайности (87,6 %), тогда как вклад генотипа (2,79 %) и взаимодействия генотип-среда (8,19 %) имели минимальное влияние. Анализируемые параметры стабильности показали положительную корреляцию между собой, и эти измерения можно использовать для выбора стабильных генотипов. Средняя урожайность генотипов мягкой пшеницы колебалась от 24,5 до 17,9 ц/га. Показано, что генотипы 342/08 (G62), линия P-1413m (G8), Лютесценс 54 190/09 (G54), 233/10 (G58), Байтерек 15 (G25) и G52 (Лютесценс 57 4/09) были наиболее стабильными и продуктивными на основе значений AMMI стабильности урожайности. Селекционеры и фермеры могут использовать эти образцы в качестве стабильных и высокопродуктивных генотипов в широком диапазоне сред Казахстана. Будущие исследования могут включать больше вегетационных сезонов для выявления наиболее стабильных генотипов.

Ключевые слова: урожайность, AMMI, мягкая пшеница, продуктивность, стабильность, мультисредовые испытания, взаимодействие генотипа и окружающей среды, лучшие генотипы.

Introduction

Triticum aestivum L., commonly known as common wheat or bread wheat, is one of the world's most widely cultivated cereal grains. Enriched with carbohydrates, proteins, dietary fiber, and an array of essential vitamins and minerals, including B vitamins, iron, zinc, and magnesium, bread wheat grains form an indispensable component of diets worldwide [1]. It is used in a variety of food products, such as bread, pasta, and cereals. Wheat is a cornerstone of Kazakhstan's economy, contributing significantly to the country's agricultural output and export earnings. Kazakhstan consistently ranks among the world's top wheat exporters, with a substantial portion of its agricultural land dedicated to wheat cultivation [2].

Yet, the country's wheat yield, averaging 1.2-1.3 tons per hectare, experiences fluctuations attributed to various factors, encompassing climatic nuances and agrotechnical conditions. In 2023, wheat production was estimated at 12.1 million tons, below the five-year average [3]. In contrast, total wheat production, including winter and spring crops, was 16.4 million tons in 2022, above the five-year average [4]. These fluctuations indicate the dynamic nature of wheat yields in Kazakhstan, which is influenced by various internal and external factors.

Identifying high-performing wheat cultivars is crucial for improving wheat production and nutritional security, especially in regions heavily reliant on wheat. The highest grain yield in most cases was not the most stable. Stability, in this context, refers to the consistent performance of a variety despite fluctuations in environmental conditions [5]. As a complex trait, yield is largely determined by various agronomic characteristics, with environmental and genetic factors exerting significant influence [6].

Multi-environment trials (METs) are a crucial component of wheat breeding and agronomic research as they are designed to assess the performance of wheat genotypes (cultivars, lines, hybrids, etc.) across multiple locations (environments) and over multiple growing seasons. The primary goal of METs is to identify genotypes that exhibit consistent performance and adaptability across diverse environments, thereby facilitating the selection of superior genotypes for further breeding advancement or commercial release [7, 8, 9].

The degree of genotype-environment (G × E) interaction may be analyzed using various numerical and graphical stability methods, which can also be used to identify genotypes with high seed yields and stability under different environmental circumstances [10]. AMMI-based stability statistics refer to stability measures derived from the Additive Main Effects and Multiplicative Interaction (AMMI) model [11]. AMMI-based stability statistics aim to assess the stability of genotypes across different environments (such as varying growing conditions, locations, or years) by accounting for the main effects of genotypes and environments and their interactions. The AMMI offers advantages in capturing GEI patterns, improving yield estimates, providing meaningful interpretation, and identifying stable high-yielding genotypes through its analytical and graphical capabilities. This study aimed to identify superior genotypes of Kazakhstan breeding using METs and AMMI analysis to select genotypes with high yield and phenotypic stability.

Materials and methods

The seeds of 82 bread wheat genotypes used in this study were sourced from various breeding organizations in Kazakhstan (Table 1). The collection included 12 cultivars and lines from the Aktobe Agricultural Station, 13 from the Karaganda Agricultural Station, 31 from the Karabalyk Agricultural Station, 16 from the Barayev Research and Production Center for Grain Farming, and 10 from the North Kazakhstan Agricultural Station.

Table 1 – Origin of bread wheat genotypes field-tested in eight environments of Kazakhstan

Code	Genotype name	Origin	Code	Genotype name	Origin
G1	Aktyube 39	Aktobe AS	G42	Ajna	Karabalyk AS
G2	Stepnaya 2	Aktobe AS	G43	Fantaziya	Karabalyk AS
G3	Stepnaya 50	Aktobe AS	G44	5-14	Karabalyk AS
G4	Ekada 113	Aktobe AS	G45	3-26	Karabalyk AS
G5	Dinastiya	Aktobe AS	G46	14-12	Karabalyk AS
G6	Stepnaya 53	Aktobe AS	G47	15-14	Karabalyk AS
G7	Stepnaya 75	Aktobe AS	G48	17-19	Karabalyk AS
G8	Line P-1413m	Aktobe AS	G49	Lyutescens 47 55/00	Karabalyk AS
G9	Line P-1415m	Aktobe AS	G50	Lyutescens 3 67/02	Karabalyk AS
G10	Line 201 / 21g.	Aktobe AS	G51	Lyutescens 17 174/08	Karabalyk AS
G11	Line 205 / 21g.	Aktobe AS	G52	Lyutescens 57 4/09	Karabalyk AS
G12	Line 225 /21g.	Aktobe AS	G53	Lyutescens 32 12/09	Karabalyk AS
G13	Lyutescens 2261	Karaganda AS	G54	Lyutescens 54 190/09	Karabalyk AS
G14	Lyutescens 2262	Karaganda AS	G55	Lyutescens 20 161/08	Karabalyk AS
G15	Lyutescens 1519	Karaganda AS	G56	Lyutescens 11 95/10	Karabalyk AS
G16	Lyutescens 2202	Karaganda AS	G57	176/09	Barayev RPCGF
G17	Lyutescens 2203	Karaganda AS	G58	233/10	Barayev RPCGF
G18	Lyutescens 2205	Karaganda AS	G59	347/11	Barayev RPCGF
G19	Lyutescens 2207	Karaganda AS	G60	312/10	Barayev RPCGF

Continuation of the table

Code	Genotype name	Origin	Code	Genotype name	Origin
G20	Lyutescens 2210	Karaganda AS	G61	16/09	Barayev RPCGF
G21	Karagandinskaya 55	Karaganda AS	G62	342/08	Barayev RPCGF
G22	Lyutescens 2264	Karaganda AS	G63	248/10	Barayev RPCGF
G23	Lyutescens 2240	Karaganda AS	G64	55/08	Barayev RPCGF
G24	Lyutescens 2265	Karaganda AS	G65	21/11	Barayev RPCGF
G25	Bajterek 15	Karaganda AS	G66	330/12	Barayev RPCGF
G26	2-9	Karabalyk AS	G67	225/12	Barayev RPCGF
G27	3-9	Karabalyk AS	G68	66/10	Barayev RPCGF
G28	5-12	Karabalyk AS	G69	129/12	Barayev RPCGF
G29	8-13	Karabalyk AS	G70	25/13	Barayev RPCGF
G30	9-13	Karabalyk AS	G71	371/13	Barayev RPCGF
G31	10-13	Karabalyk AS	G72	238/09	Barayev RPCGF
G32	11-13	Karabalyk AS	G73	435/lyut2	North Kazakhstan AS
G33	12-13	Karabalyk AS	G74	659/12	North Kazakhstan AS
G34	13-13	Karabalyk AS	G75	486/lyut22	North Kazakhstan AS
G35	14-13	Karabalyk AS	G76	63/lyut37	North Kazakhstan AS
G36	15-14	Karabalyk AS	G77	23/07	North Kazakhstan AS
G37	16-14	Karabalyk AS	G78	218/10	North Kazakhstan AS
G38	20-16	Karabalyk AS	G79	Erit 42/12	North Kazakhstan AS
G39	21-16	Karabalyk AS	G80	Lyut 13/12	North Kazakhstan AS
G40	22-16	Karabalyk AS	G81	Shortandinskaya 95 uluchshennaya	North Kazakhstan AS
G41	25-16	Karabalyk AS	G82	Omskaya 36	North Kazakhstan AS
Note – AS – Agricultural Station, RPCGF – Research and Production Center for Grain Farming					

The studies were conducted in the 2022 and 2023 growing seasons under non-irrigated conditions at four locations in Kazakhstan (Table 2). These sites were chosen to represent different agroclimatic zones. The longitude, latitude, soil type, and precipitation of those ecological areas are shown in Table 2. The experiment was laid out in a randomized complete block design with two replications. A plot size of 5 m^2 was used for the grain yield evaluation.

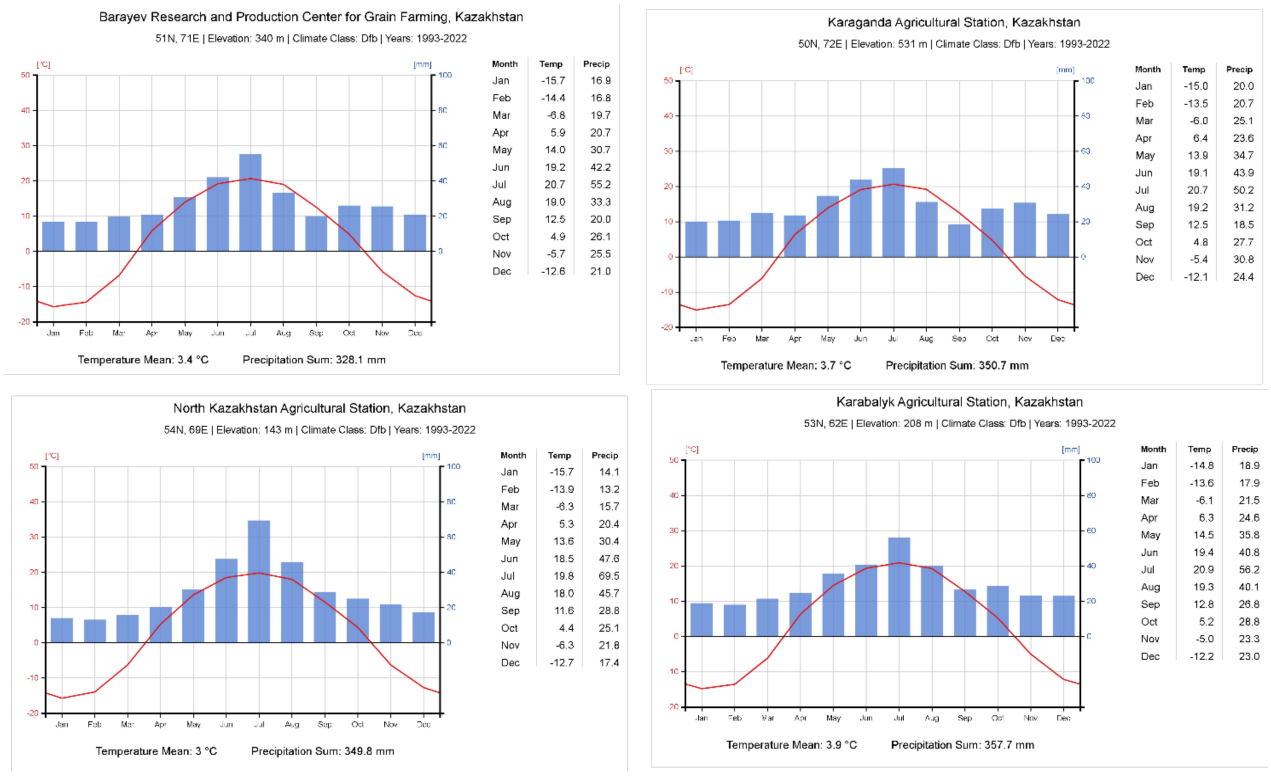
The locations where the experiment was conducted were different regarding seasonal rainfall and temperature (Table 3, Fig. 1). Therefore, combinations of years (2022 and 2023) and four locations were considered eight different environments.

Table 2 – Characteristics of environmental conditions at experimental research stations

Environment	Altitude (m)	Latitude	Longitude	Soil type
Barayev Research and Production Center for Grain Farming	340	51°37’58»	71°02’28»	southern carbonate chernozem
Karaganda Agricultural Station	531	50°10′42″	72°44′20″	dark chestnut
North Kazakhstan Agricultural Station	143	54°10′42″	69°31′31″	ordinary chernozem
Karabalyk Agricultural Station	208	53°51′06″	62°06′14″	ordinary chernozem

Table 3 – Weather characteristics at the experimental research stations in 2022 and 2023 growing seasons

Environment	Parameter	April	May	June	July	August	September	October
Barayev RPCGF	T 2022 (°C)	8.3	15.7	20.2	21.1	17.2	13.2	3.4
	R 2022 (mm)	3.0	16.9	22.2	52.9	25.2	8.0	14.9
	T 2023 (°C)	3.2	15.3	20.0	24.4	19.0	11.8	6.6
	R 2023 (mm)	4.1	2.5	13.2	10.6	12.7	33.2	19.7
Karaganda AS	T 2022 (°C)	7.9	15.1	24.9	20.2	17.0	13.5	3.9
	R 2022 (mm)	6.8	15.3	12.0	55.9	10.2	4.5	24.4
	T 2023 (°C)	5.2	13.7	14.9	22.5	19.1	12	6
	R 2023 (mm)	3.5	16.6	40.3	40.1	29.2	31.5	34.2
North Kazakhstan AS	T 2022 (°C)	8.6	14.8	18.7	21.2	18.0	13.3	4.4
	R 2022 (mm)	18.2	7.6	52.7	83.6	35.3	14.0	23.4
	T 2023 (°C)	6.9	14.1	19.1	24.1	18.4	13.4	6.0
	R 2023 (mm)	2.2	22.3	41.1	22.7	59.3	34.3	48.6
Karabalyk AS	T 2022 (°C)	9.8	13.5	18.9	23.4	22.2	14.7	4.8
	R 2022 (mm)	13.4	40.6	20.9	17.7	10.5	17.0	22.0
	T 2023 (°C)	8.2	16.9	19.9	25.2	18.8	14.0	5.9
	R 2023 (mm)	2.3	10.3	39.3	23.2	117.4	54.4	58.2
Note – T – Temperature, R – Rainfall								



Barayev Research and Production Center for Grain Farming, Kazakhstan

51N, 71E | Elevation: 340 m | Climate Class: Dfb | Years: 1993-2022

Month	Temp	Precip
Jan	-15.7	16.9
Feb	-14.4	16.8
Mar	-6.8	19.7
Apr	5.9	20.7
May	14.0	30.7
Jun	19.2	42.2
Jul	20.7	55.2
Aug	19.0	33.3
Sep	12.5	20.0
Oct	4.9	26.1
Nov	-5.7	25.5
Dec	-12.6	21.0

Temperature Mean: 3.4 °C Precipitation Sum: 328.1 mm

Karaganda Agricultural Station, Kazakhstan

50N, 72E | Elevation: 531 m | Climate Class: Dfb | Years: 1993-2022

Month	Temp	Precip
Jan	-15.0	20.0
Feb	-13.5	20.7
Mar	-6.0	25.1
Apr	6.4	23.6
May	13.9	34.7
Jun	19.1	43.9
Jul	20.7	50.2
Aug	19.2	31.2
Sep	12.5	18.5
Oct	4.8	27.7
Nov	-5.4	30.8
Dec	-12.1	24.4

Temperature Mean: 3.7 °C Precipitation Sum: 350.7 mm

North Kazakhstan Agricultural Station, Kazakhstan

54N, 69E | Elevation: 143 m | Climate Class: Dfb | Years: 1993-2022

Month	Temp	Precip
Jan	-15.7	14.1
Feb	-13.9	13.2
Mar	-6.3	15.7
Apr	5.3	20.4
May	13.6	30.4
Jun	18.5	47.6
Jul	19.8	69.5
Aug	18.0	45.7
Sep	11.6	28.8
Oct	4.4	25.1
Nov	-6.3	21.8
Dec	-12.7	17.4

Temperature Mean: 3 °C Precipitation Sum: 349.8 mm

Karabalyk Agricultural Station, Kazakhstan

53N, 62E | Elevation: 208 m | Climate Class: Dfb | Years: 1993-2022

Month	Temp	Precip
Jan	-14.8	18.9
Feb	-13.6	17.9
Mar	-6.1	21.5
Apr	6.3	24.6
May	14.5	35.8
Jun	19.4	40.8
Jul	20.9	56.2
Aug	19.3	40.1
Sep	12.8	26.8
Oct	5.2	28.8
Nov	-5.0	23.3
Dec	-12.2	23.0

Temperature Mean: 3.9 °C Precipitation Sum: 357.7 mm

line – temperature (°C), bars – precipitation (mm)

Figure 1 – Long-term meteorological data in 4 experimental locations in Kazakhstan [12]

All of the statistical analyses presented in this study were performed with R statistical software (version 4.1.3), using the package "METAN" for stability analysis of multi-environment trial data [13]. Table 4 represents different statistics and indices analyzed to evaluate yield stability in this study.

Table 4 – Stability statistics and indices used in this study

Stability statistics	Symbol	Pattern of Selection	Type of Method	References
Averages of the squared eigenvector values	*E*v	Minimum value	Parametric	[14]
Sums of the absolute value of the IPC scores	*SIPC*	Minimum value	Parametric	[15]
Distance of IPCAs point with origin in space	*D*A	Minimum value	Parametric	[16, 17]
Zhang's D Parameter	*DZ*	Minimum value	Non-Parametric	[17]
Stability measure based on fitted AMMI model	*FA*	Minimum value	Parametric	[18, 19]
AMMI stability value	*ASV*	Minimum value	Parametric	[20]
Modified AMMI stability value	*MASV*	Minimum value	Parametric	[19]
The absolute value of the relative contribution of IPCAs	*Za*	Minimum value	Parametric	[19]
The sum across environments of the absolute value of GEI modeled by AMMI	*AV(AMGE)*	Minimum value	Parametric	[19]
AMMI stability index	*ASI*	Minimum value	Parametric	[21]
Modified AMMI stability index	*MAS*I	Minimum value	Parametric	[22]
Weighted average of absolute scores	*WAA*S	Minimum value	Parametric	[13]

Results and discussion

Eighty-two bread wheat genotypes sourced from Kazakhstan's germplasm were evaluated for grain yield performance. The yearly temperature and water supply fluctuations throughout the two growing seasons created diverse environmental conditions for assessing bread wheat yield stability. The mean grain yield varied across all environments, ranging from 6.8 (Karaganda AS) to 30.7 (Karabalyk AS) centners per hectare. The descriptive statistics for yield, including mean, maximum, and minimum, standard error of the mean, and standard deviation across all environments, are detailed in Table 5. The highest mean grain yield among the genotypes was observed at the Karabalyk Agricultural Station. At the same time, the lowest was recorded at the Karaganda Agricultural Station, highlighting significant differences in yield between these locations. Specific genotypes demonstrating superior performance under distinct environmental conditions were identified, offering valuable insights for breeding programs to develop more resilient and high-yielding crop varieties.

Table 5 – Bread Wheat Yield Values (centners per hectare) by Location and Year

Environment	Year	min	max	Mean	SE	SD	Winner genotype
Barayev RPCGF	2022	7.7	20.6	15.5	0.3	2.9	15-14 (G36)
	2023	9.8	20.8	15.6	0.3	2.3	342/08 (G62)
	average	8.8	20.7	15.6	0.3	2.6	Fantaziya (G43)
Karabalyk AS	2022	24.1	39.8	33.0	0.4	3.4	Dinastiya (G5)
	2023	17.9	35.7	28.4	0.4	3.6	486/lyut 22 (G75)
	average	21.0	37.8	30.7	0.4	3.5	Lyutescens 32 12/09 (G53)

Continuation of the table

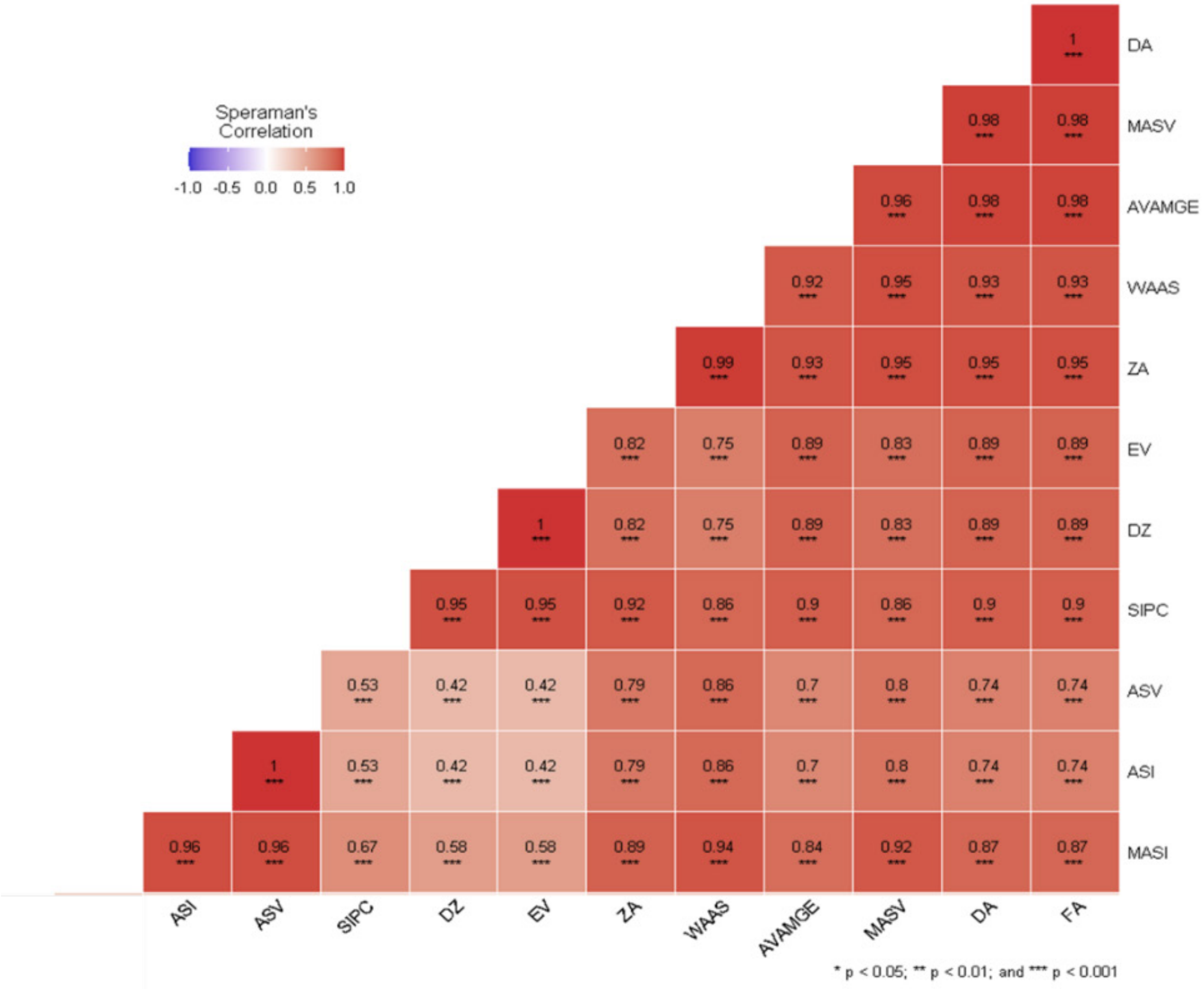
Environment	Year	min	max	Mean	SE	SD	Winner genotype
North Kazakhstan AS	2022	26.9	42.4	34.6	0.4	3.5	248/10 (G63)
	2023	11.6	23.4	17.6	0.3	2.6	16/09 (G61)
	average	19.3	32.9	26.1	0.3	3.0	Line P-1413m (G8)
Karaganda AS	2022	5.4	18.5	11.2	0.3	2.5	Bajterek 15 (G25)
	2023	8.1	23.5	18.4	0.3	2.7	248/10 (G63)
	average	6.8	21.0	14.8	0.3	2.6	Bajterek 15 (G25)
Note – c/ha – centners per hectare, SE- standard error of the mean, SD- standard deviation							

The AMMI ANOVA was introduced in the current investigation concerning the yield performance of 82 bread wheat genotypes evaluated in eight environments. This statistical method partitioned the total variance of squared yield into components attributed to genotype, environment, and their interaction (Table 6). The main effects of environment, replication, genotypes, and interaction were all highly significant at P < 0.01. The environment contributed the most to yield variability (87.6 %), with a significantly smaller contribution from the genotype (2.79 %) and genotype-environment interaction (8.19 %). The Principal Component Analysis (PCA) further revealed that PCA1 and PCA2 explained 34.1 % and 18 % of the total GE variance (51.1 %) in AMMI analysis for grain yield, respectively. Previous findings confirmed that employing the first two PCAs may explain the greatest GEI in the majority of cases [23].

Table 6 – AMMI PCA analysis under multi-location trials during 2022-23 growing seasons

Source of variation	df	Sum Sq	Mean Sq	F value	Pr(>F)	Contribution to variability, %	
						Yield	Interaction
Environment	7	90578	12939.77	70.61	1,46E-06	87.6	
Replication	8	1466	183.27	32.68	2,89E-43	1.42	
Genotype	81	2881	35.57	6.34	1,04E-43	2.79	
Interaction	567	8467	14.93	2.66	3,93E-33	8.19	
PC1	87	2886	33.17	5.91	0.00e+00		34.1
PC2	85	1524	17.92	3.20	0.00e+00		18
PC3	83	1215	14.64	2.61	0.00e+00		14.3
PC4	81	897	11.07	1.97	0.00e+00		10.6
PC5	79	751	9.51	1.70	3.00e-04		8.9
PC6	77	632	8.21	1.46	8.80e-03		7.5
PC7	75	562	7.50	1.34	3.54e-02		6.6
Residuals	648	3634	5.61				
Total	1878	115495	61.5				

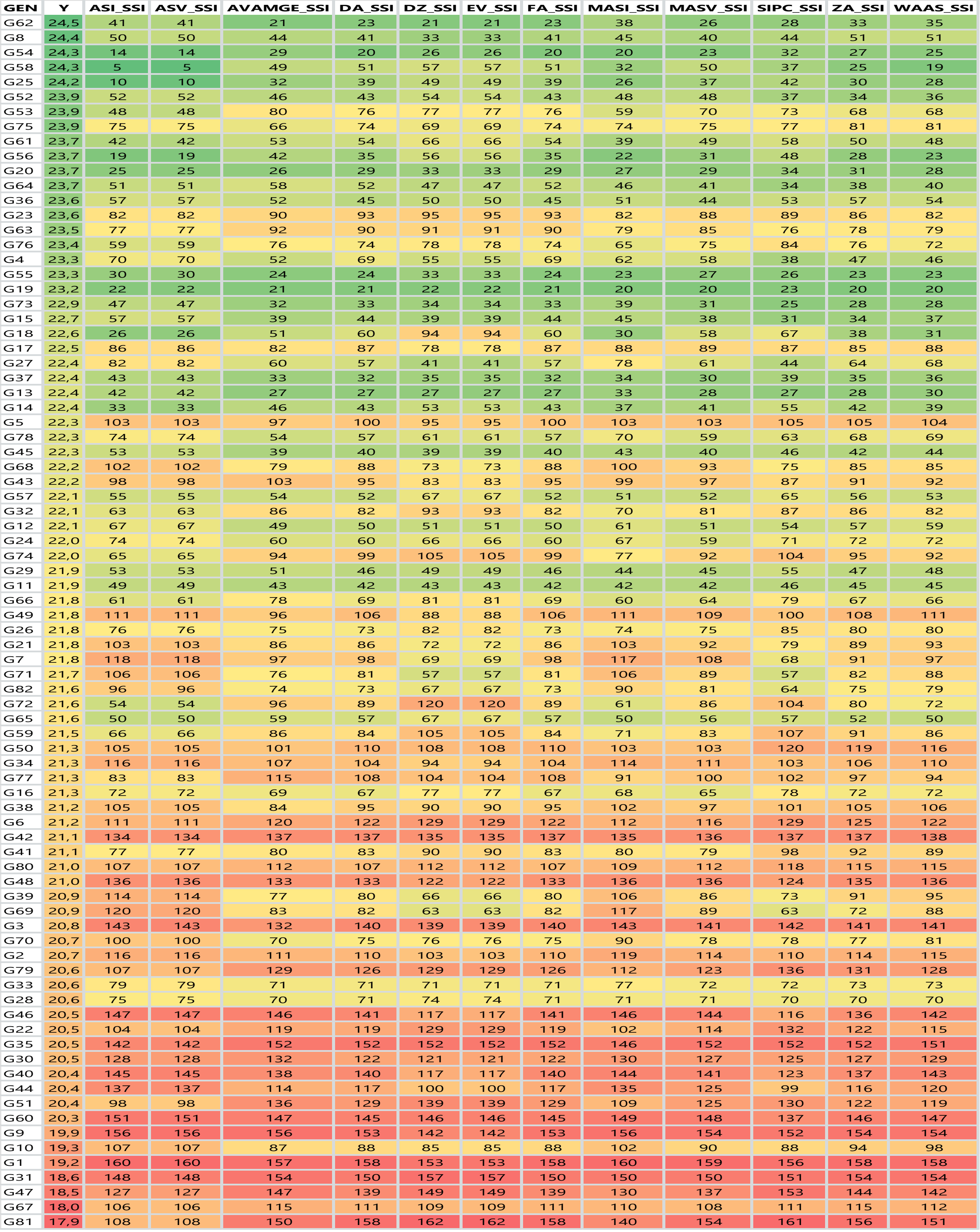
Twelve stability metrics derived from the AMMI model were assessed for each genotype's mean yield across all environments. All these indices correlated positively (Fig. 2). It was found that stable genotypes did not necessarily exhibit high yields; thus, stability alone proved inadequate as a selection criterion [24, 25]. To address this, the Stability Selection Index (SSI), the summing of the rankings of the stability index and mean yields, also known as GSI or YSI, was employed [26]. The 82 genotypes were ordered according to SSI for each of the twelve stability indices from the AMMI model, with the highest ranking going to the genotype with the highest yield and stability and the lowest ranking going to the genotype with the lowest yield and instability (Fig. 3). Genotypes 342/08 (G62), Line P-1413m (G8), Lyutescens 54 190/09 (G54), 233/10 (G58), Bajterek 15 (G25), and G52 (Lyutescens 57 4/09) were shown to be the most stable and high-yielding in the current study, while genotype G81 (Shortandinskaya 95 uluchshennaya) displayed the lowest stability and poor yield performance according to SSI calculations using all stability metrics.



	ASI	ASV	SIPC	DZ	EV	ZA	WAAS	AVAMGE	MASV	DA	FA
DA											1***
MASV										0.98***	0.98***
AVAMGE									0.96***	0.98***	0.98***
WAAS								0.92***	0.95***	0.93***	0.93***
ZA							0.99***	0.93***	0.95***	0.95***	0.95***
EV						0.82***	0.75***	0.89***	0.83***	0.89***	0.89***
DZ					1***	0.82***	0.75***	0.89***	0.83***	0.89***	0.89***
SIPC				0.95***	0.95***	0.92***	0.86***	0.9***	0.86***	0.9***	0.9***
ASV			0.53***	0.42***	0.42***	0.79***	0.86***	0.7***	0.8***	0.74***	0.74***
ASI		1***	0.53***	0.42***	0.42***	0.79***	0.86***	0.7***	0.8***	0.74***	0.74***
MASI	0.96***	0.96***	0.67***	0.58***	0.58***	0.89***	0.94***	0.84***	0.92***	0.87***	0.87***

DA – Distance of IPCAs point with origin in space; *MASV* – Modified AMMI stability value;
AVAMGE – The sum across environments of the absolute value of GEI modeled by AMMI;
WAAS – Weighted average of absolute scores; *ZA* – The absolute value of the relative contribution of IPCAs;
EV- Averages of the squared eigenvector values; *DZ* – Zhang's D Parameter;
SIPC – Sums of the absolute value of the IPC scores; *ASV* – AMMI stability value; *ASI* – AMMI stability index;
MASI – Modified AMMI stability index; *FA* – Stability measure based on fitted AMMI model; *Y* – grain yield.
*, **, and *** Significant at 0.05, 0.01, and 0.001 probability levels, respectively

Figure 2 – Correlation among AMMI-based stability parameters with yield data of 82 bread wheat genotypes evaluated under eight test environments



GEN	Y	ASI_SSI	ASV_SSI	AVAMGE_SSI	DA_SSI	DZ_SSI	EV_SSI	FA_SSI	MASI_SSI	MASV_SSI	SIPC_SSI	ZA_SSI	WAAS_SSI
G62	24,5	41	41	21	23	21	21	23	38	26	28	33	35
G8	24,4	50	50	44	41	33	33	41	45	40	44	51	51
G54	24,3	14	14	29	20	26	26	20	20	23	32	27	25
G58	24,3	5	5	49	51	57	57	51	32	50	37	25	19
G25	24,2	10	10	32	39	49	49	39	26	37	42	30	28
G52	23,9	52	52	46	43	54	54	43	48	48	37	34	36
G53	23,9	48	48	80	76	77	77	76	59	70	73	68	68
G75	23,9	75	75	66	74	69	69	74	74	75	77	81	81
G61	23,7	42	42	53	54	66	66	54	39	49	58	50	48
G56	23,7	19	19	42	35	56	56	35	22	31	48	28	23
G20	23,7	25	25	26	29	33	33	29	27	29	34	31	28
G64	23,7	51	51	58	52	47	47	52	46	41	34	38	40
G36	23,6	57	57	52	45	50	50	45	51	44	53	57	54
G23	23,6	82	82	90	93	95	95	93	82	88	89	86	82
G63	23,5	77	77	92	90	91	91	90	79	85	76	78	79
G76	23,4	59	59	76	74	78	78	74	65	75	84	76	72
G4	23,3	70	70	52	69	55	55	69	62	58	38	47	46
G55	23,3	30	30	24	24	33	33	24	23	27	26	23	23
G19	23,2	22	22	21	21	22	22	21	20	20	23	20	20
G73	22,9	47	47	32	33	34	34	33	39	31	25	28	28
G15	22,7	57	57	39	44	39	39	44	45	38	31	34	37
G18	22,6	26	26	51	60	94	94	60	30	58	67	38	31
G17	22,5	86	86	82	87	78	78	87	88	89	87	85	88
G27	22,4	82	82	60	57	41	41	57	78	61	44	64	68
G37	22,4	43	43	33	32	35	35	32	34	30	39	35	36
G13	22,4	42	42	27	27	27	27	27	33	28	27	28	30
G14	22,4	33	33	46	43	53	53	43	37	41	55	42	39
G5	22,3	103	103	97	100	95	95	100	103	103	105	105	104
G78	22,3	74	74	54	57	61	61	57	70	59	63	68	69
G45	22,3	53	53	39	40	39	39	40	43	40	46	42	44
G68	22,2	102	102	79	88	73	73	88	100	93	75	85	85
G43	22,2	98	98	103	95	83	83	95	99	97	87	91	92
G57	22,1	55	55	54	52	67	67	52	51	52	65	56	53
G32	22,1	63	63	86	82	93	93	82	70	81	87	86	82
G12	22,1	67	67	49	50	51	51	50	61	51	54	57	59
G24	22,0	74	74	60	60	66	66	60	67	59	71	72	72
G74	22,0	65	65	94	99	105	105	99	77	92	104	95	92
G29	21,9	53	53	51	46	49	49	46	44	45	55	47	48
G11	21,9	49	49	43	42	43	43	42	42	42	46	45	45
G66	21,8	61	61	78	69	81	81	69	60	64	79	67	66
G49	21,8	111	111	96	106	88	88	106	111	109	100	108	111
G26	21,8	76	76	75	73	82	82	73	74	75	85	80	80
G21	21,8	103	103	86	86	72	72	86	103	92	79	89	93
G7	21,8	118	118	97	98	69	69	98	117	108	68	91	97
G71	21,7	106	106	76	81	57	57	81	106	89	57	82	88
G82	21,6	96	96	74	73	67	67	73	90	81	64	75	79
G72	21,6	54	54	96	89	120	120	89	61	86	104	80	72
G65	21,6	50	50	59	57	67	67	57	50	56	57	52	50
G59	21,5	66	66	86	84	105	105	84	71	83	107	91	86
G50	21,3	105	105	101	110	108	108	110	103	103	120	119	116
G34	21,3	116	116	107	104	94	94	104	114	111	103	106	110
G77	21,3	83	83	115	108	104	104	108	91	100	102	97	94
G16	21,3	72	72	69	67	77	77	67	68	65	78	72	72
G38	21,2	105	105	84	95	90	90	95	102	97	101	105	106
G6	21,2	111	111	120	122	129	129	122	112	116	129	125	122
G42	21,1	134	134	137	137	135	135	137	135	136	137	137	138
G41	21,1	77	77	80	83	90	90	83	80	79	98	92	89
G80	21,0	107	107	112	107	112	112	107	109	112	118	115	115
G48	21,0	136	136	133	133	122	122	133	136	136	124	135	136
G39	20,9	114	114	77	80	66	66	80	106	86	73	91	95
G69	20,9	120	120	83	82	63	63	82	117	89	63	72	88
G3	20,8	143	143	132	140	139	139	140	143	141	142	141	141
G70	20,7	100	100	70	75	76	76	75	90	78	78	77	81
G2	20,7	116	116	111	110	103	103	110	119	114	110	114	115
G79	20,6	107	107	129	126	129	129	126	112	123	136	131	128
G33	20,6	79	79	71	71	71	71	71	77	72	72	73	73
G28	20,6	75	75	70	71	74	74	71	71	71	70	70	70
G46	20,5	147	147	146	141	117	117	141	146	144	116	136	142
G22	20,5	104	104	119	119	129	129	119	102	114	132	122	115
G35	20,5	142	142	152	152	152	152	152	146	152	152	152	151
G30	20,5	128	128	132	122	121	121	122	130	127	125	127	129
G40	20,4	145	145	138	140	117	117	140	144	141	123	137	143
G44	20,4	137	137	114	117	100	100	117	135	125	99	116	120
G51	20,4	98	98	136	129	139	139	129	109	125	130	122	119
G60	20,3	151	151	147	145	146	146	145	149	148	137	146	147
G9	19,9	156	156	156	153	142	142	153	156	154	152	154	154
G10	19,3	107	107	87	88	85	85	88	102	90	88	94	98
G1	19,2	160	160	157	158	153	153	158	160	159	156	158	158
G31	18,6	148	148	154	150	157	157	150	150	150	151	154	154
G47	18,5	127	127	147	139	149	149	139	130	137	153	144	142
G67	18,0	106	106	115	111	109	109	111	110	108	111	115	112
G81	17,9	108	108	150	158	162	162	158	140	154	161	156	151

The color intensity of the heatmap from green (high rank) to red (low rank)
Y – grain yield; *ASI* – AMMI stability index; *ASV* – AMMI stability value;
AVAMGE – The sum across environments of the absolute value of GEI modeled by AMMI;
DA – Distance of IPCAs point with origin in space; *DZ* – Zhang's D Parameter;
EV – Averages of the squared eigenvector values; *FA* – Stability measure based on fitted AMMI model*;*
MASI – Modified AMMI stability index; *MASV* – Modified AMMI stability value;
SIPC – Sums of the absolute value of the IPC scores; *ZA* – The absolute value of the relative contribution of IPCAs;
WAAS – Weighted average of absolute scores.

Figure 3 – Ranking of genotypes based on simultaneous selection index (SSI) considering stability and yield for 82 bread wheat genotypes tested in four locations

Conclusion

The importance of wheat extends beyond its role as a staple food; it is crucial for global food security and economic development. Wheat production in Kazakhstan contributes significantly to both local consumption and international markets. Kazakhstan faces challenges due to adverse climate conditions such as short growing seasons, low precipitation, and temperature extremes, which can limit yields. Certain genotypes may thrive in specific environments but perform poorly in others, highlighting the importance of selecting suitable genotypes for target environments. Selecting genotypes with broad or particular adaptation involves conducting multi-environment trials to identify which genotypes perform best across different conditions. This ensures that farmers can choose cultivars that maximize yield and minimize risks associated with environmental variability.

This study assessed 82 bread wheat genotypes of Kazakhstan breeding for grain yield and examined eight environmental conditions. The eight environments (Location + Year) varied in temperature and precipitation during the 2022–2023 growing seasons.

Yields in Barayev RPCGF were 15.5 and 15.6 c/ha in 2022 and 2023, respectively, which farmers consider a good result, even though 2023 was characterized by insufficient rainfall in June and July. Despite insufficient rainfall in June and July of 2023, grain yields at Barayev RPCGF reached 15.5 and 15.6 c/ha in 2022 and 2023, respectively, which farmers deemed satisfactory. Among the tested genotypes, lines 15-14 (G36), 342/08 (G62), and Fantaziya (G43) demonstrated notable performance in terms of yield. Specifically, lines 15-14 (G36) and 342/08 (G62) displayed consistently high yields across all experimental locations, whereas Fantaziya (G43) exhibited lower yield stability indices.

The lowest yield of 14.8 c/ha was observed in Karaganda AS. Over two years, the cultivar Bajterek 15 (G25) consistently performed well, achieving an average yield of 24.2 c/ha. This cultivar demonstrated notable stability across all tested environments.

In Karabalyk AS, despite two consecutive dry years, the highest average yield was recorded – 30.7 c/ha. Among the tested cultivars, Dinastiya (G5), 486/lyut 22 (G75), and Lyutescens 32 12/09 (G53) exhibited the highest maximum yields. However, only 486/lyut 22 (G75) and Lyutescens 32 12/09 (G53) demonstrated moderate yield stability across all eight environmental conditions.

Despite challenging conditions in the 2023 growing season in North Kazakhstan AS, the average yield reached 26.1 c/ha. Among the evaluated cultivars, 248/10 (G63), 16/09 (G61), and Line P-1413m (G8) demonstrated the highest yields. Particularly noteworthy, Line P-1413m (G8) exhibited exceptional yield stability across all research regions.

The average yield varied significantly across different regions: Karabalyk AS recorded the highest yield (30.7 c/ha), whereas Karaganda AS and Barayev RPCGF reported the lowest yields at 14.8 c/ha and 15.6 c/ha, respectively. Recent studies on wheat yield have indicated a strong correlation with precipitation levels, particularly in June and July [19]. Furthermore, soil types varied among these regions, with North Kazakhstan and Karabalyk Agricultural stations having ordinary chernozem soil and Barayev RPCGF and Karaganda AS featuring southern carbonate chernozem and dark chestnut soils, respectively. These soil differences underscore the significant impact of soil type on crop productivity, particularly in challenging environmental conditions.

The AMMI analysis of variance highlighted that environmental factors exerted the most significant influence on the variability in grain yield. This finding underscores the crucial role of environmental conditions, including temperature, precipitation, soil quality, and agricultural practices, in shaping wheat productivity. The study identified substantial variations in grain yield across different environments, genotypes, and their interactions (GEI), with statistical significance observed at 0.1% ($p < 0.001$) based on the combined ANOVA mean squares. Additionally, the analysis indicated that the first two principal components effectively explained the genotype-environment interactions (GEI).

The research utilized twelve stability metrics derived from the AMMI model to assess the mean yield of each genotype across diverse environmental conditions. The positive correlation among these stability indices suggests their suitability for selecting desirable genotypes. Based on the Stability Selection Index (SSI), the study ranked 82 genotypes, emphasizing those with optimal yield and stability. Genotypes such as 342/08 (G62), Line P-1413m (G8), Lyutescens 54 190/09 (G54), 233/10 (G58), Bajterek 15 (G25), and G52 (Lyutescens 57 4/09) emerged as the top performers, exhibiting superior stability and high yield across eight environments.

The analysis provided valuable insights into identifying wheat cultivars and lines that can consistently yield well across various environments in Kazakhstan. These results indicate which genotypes perform optimally and consistently across eight different environments. Future work could seek to include additional growing seasons to pinpoint the most stable and high-performing genotypes.

Acknowledgments

This study was carried out within the framework of funding by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan (IRN AP14871383 «Development of KASP markers to facilitate construction of competitive bread wheat, durum wheat, and barley cultivars in Kazakhstan»).

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Received May 7, 2024
Re-uploaded July 5, 2024
Accepted August 20, 2024