NARDI FUNDULEA, ROMANIA ROMANIAN AGRICULTURAL RESEARCH, NO. 43, 2026
www.incda-fundulea.ro; doi.org/10.59665/rar4371 First Online: June, 2026. DII 2067-5720 RAR 2026-210

Productivity and Stability of Various Commercial and Experimental Maize Hybrids across Six Regions of Romania

Daniela Horhocea[1*], Horia Iordan[1], Cătălin Lazăr[1], Alina Laura Agapie[2], Gergely-Andrei Smit[3], Mihai Tilihoi[4], Alin Ionel Ghiorghe[5], Emanuela Lungu[5], Claudia Ioana Dunăreanu[6]

[1]National Agricultural Research and Development Institute Fundulea, Călăraşi County, Romania
[2]Agricultural Research Development Station Lovrin, Timiş County, Romania
[3]Agricultural Research Development Station Livada, Satu Mare County, Romania
[4]Agricultural Research Development Station Valu lui Traian, Constanţa County, Romania
[5]Agricultural Research Development Station Brăila, Brăila County, Romania
[6]Agricultural Research Development Station Șimnic, Dolj County, Romania
[*]Corresponding author. E-mail: daniela_horhocea@yahoo.com

ABSTRACT

Understanding genotype × environment interactions (G×E) is essential for the development of maize hybrids with high and stable grain yield under increasingly variable climatic conditions. The identification of genotypes that combine superior productivity, drought tolerance and broad adaptation remains a major objective of maize breeding programs. The present study aimed to evaluate the yield performance and stability of maize hybrids developed at the National Agricultural Research and Development Institute (NARDI) Fundulea under contrasting environmental conditions and to identify genotypes with superior adaptability.

A set of 15 maize hybrids was evaluated during the 2021-2023 growing seasons in six locations representative of different pedoclimatic regions of Romania: Fundulea, Brăila, Șimnic, Valu lui Traian, Lovrin and Livada. The multi-environment trial generated 18 environment combinations, allowing a comprehensive assessment of hybrid performance under variable growing conditions. Grain yield stability was evaluated using several complementary approaches, including the Drought Resistance Index (DRIND), Drought Susceptibility Index (DSI), regression coefficient (b), coefficient of variation (CV), and Wricke's ecovalence (Wi).

Significant differences among hybrids were observed for grain yield and stability parameters, reflecting differential responses to environmental variation. Several hybrids, namely Felix, FDL Ovidiu, HSF1033-17, HSF1034-17, Miraj, Magnus and F423, exhibited high yield stability and favorable adaptation across environments. Among the tested genotypes, Felix achieved the highest mean grain yield (9.67 t ha^{-1}), combined with high drought tolerance (DRIND = 17.09; DSI = 0.86) and good stability (b = 0.87). The hybrid also showed a strong ability to maintain yield performance under both favorable and stress-prone conditions.

The combined use of drought tolerance and stability parameters enabled the identification of maize hybrids with broad adaptation and consistent performance across diverse environments. The results highlight Felix as a promising genotype for cultivation in different maize-growing regions of Romania and provide valuable information for future breeding and variety recommendation programs.

Keywords: *Zea mays* L., genotype × environment interaction, multi-environment trials, grain yield, yield stability, drought tolerance, adaptability.

INTRODUCTION

Maize (*Zea mays* L.) is one of the most important cereal crops worldwide, playing a fundamental role in food, feed, and industrial production. Due to its high productivity and wide adaptability, maize occupies a strategic position in global agriculture. However, increasing climate variability, characterized by more frequent droughts, heat waves, and irregular rainfall patterns, poses significant challenges to maize production and yield stability. Consequently, the development and identification of hybrids capable of maintaining high productivity under diverse environmental conditions has become a major objective of modern maize breeding programs (Cairns et al., 2013; Ray et al., 2015).

Grain yield is a complex quantitative trait determined by the interaction between the genetic potential of a genotype and

Received 17 June 2026; accepted 25 June 2026.

environmental conditions throughout the growing season. The performance of maize hybrids is strongly influenced by genotype × environment (G×E) interactions, which often result in differential responses of genotypes across locations and years. Yield stability, defined as the ability of a genotype to maintain consistent performance under varying environmental conditions, has therefore become a key criterion in hybrid evaluation and selection. Understanding and quantifying G×E interactions are essential for identifying hybrids with broad adaptation and reliable performance across diverse production environments (Ciocăzanu et al., 1996; Cooper et al., 2016; Smith et al., 2019).

Over the last decades, substantial genetic progress has been achieved in maize breeding through the development of hybrids with enhanced yield potential, improved resource-use efficiency, and increased tolerance to abiotic and biotic stresses. These improvements have contributed not only to higher productivity but also to greater yield stability under fluctuating environmental conditions (Duvick, 2005). As climate change continues to affect agricultural systems, breeding efforts increasingly focus on combining high yield potential with resilience to environmental stress factors, particularly drought and heat stress (Hammer et al., 2020).

The assessment of yield stability and adaptability is commonly performed through multi-environment trials, which provide valuable information on genotype performance under contrasting environmental conditions. Several statistical approaches have been developed to characterize genotype responses to environmental variation, including regression analysis, coefficients of variation, ecovalence statistics, drought tolerance indices, and multivariate methods such as the Additive Main Effects and Multiplicative Interaction (AMMI) model and Genotype plus Genotype-by-Environment (GGE) biplot analysis. These methods facilitate the identification of genotypes combining high productivity with stable performance across environments (Shojaei et al., 2021).

Recent studies have demonstrated that simultaneous selection for yield potential and stability significantly improves maize adaptation under climate change scenarios (Worku et al., 2020; Zhang et al., 2022). Research conducted in different maize-growing regions has shown that the integration of productivity, adaptability, and stability parameters provides a more comprehensive assessment of hybrid performance than yield evaluation alone.

Studies conducted in Romania have further highlighted the importance of multi-environment testing for maize improvement. Horhocea et al. (2024) evaluated Romanian maize hybrids across six testing locations and reported significant effects of genotype, environment, year, and their interactions on grain yield. The authors demonstrated that the combined use of regression parameters, drought susceptibility indices, and coefficients of variation effectively identifies hybrids with superior adaptability and stable performance across contrasting environments. Nišavić et al. (2025) emphasized the importance of G×E interactions in determining maize productivity and highlighted the value of stability analyses for identifying broadly adapted genotypes suitable for cultivation under increasingly variable climatic conditions.

Commercial maize hybrids are the result of extensive multi-year and multi-location testing programs and are generally characterized by high yield potential and stable performance across environments. In contrast, experimental hybrids represent important sources of genetic progress, offering opportunities to improve drought tolerance, heat tolerance, disease resistance, and water- and nutrient-use efficiency (Duvick, 2005; Hammer et al., 2020). The comparative evaluation of commercial and experimental hybrids is therefore essential for assessing breeding progress and identifying superior genotypes for future cultivar development and recommendation.

The National Agricultural Research and Development Institute (NARDI) Fundulea has played a major role in maize breeding in Romania through the development of hybrids adapted to the diverse pedoclimatic conditions of the country. Continuous breeding efforts have resulted in the release of numerous hybrids cultivated across different maize-growing regions, contributing significantly to national maize production.

Therefore, the objective of this study was to evaluate the grain yield, adaptability, and stability of 15 commercial and experimental maize hybrids developed at NARDI Fundulea under diverse environmental conditions across six representative locations in Romania during the 2021-2023 period. Hybrid performance was assessed using several complementary stability parameters, including drought tolerance and susceptibility indices, regression analysis, coefficient of variation, and ecovalence statistics, with the aim of identifying genotypes with superior productivity and broad adaptation for recommendation in specific maize-growing areas.

MATERIAL AND METHODS

Plant Material

The biological material used in this experiment consisted of 15 maize hybrids developed at INCDA Fundulea, belonging to the FAO 350-470 maturity groups (Table 1).

Table 1. The biological material- maize hybrids experienced during the period 2021-2023 in the six locations

No.	Hybrids	FAO groups	No.	Hybrids	FAO groups
1	F423	470	9	HSF1034-17	370
2	Felix	460	10	HSF3877-17	380
3	Magnus	350	11	HSF4075-17	390
4	Amurg	360	12	HSF1032-17	390
5	Miraj	390	13	HSF1214-17	350
6	FDL Ovidiu	400	14	HSF1089-17	390
7	HSF7395-18	400	15	HSF1142-17	400
8	HSF1033-17	350			

Field Trials

Maize hybrids were tested over three years (2021-2023) in experiments conducted across six locations with contrasting pedoclimatic conditions: NARDI Fundulea, ARDS Brăila, ARDS Şimnic, ARDS Valu lui Traian, ARDS Lovrin, and ARDS Livada (Figure 1).

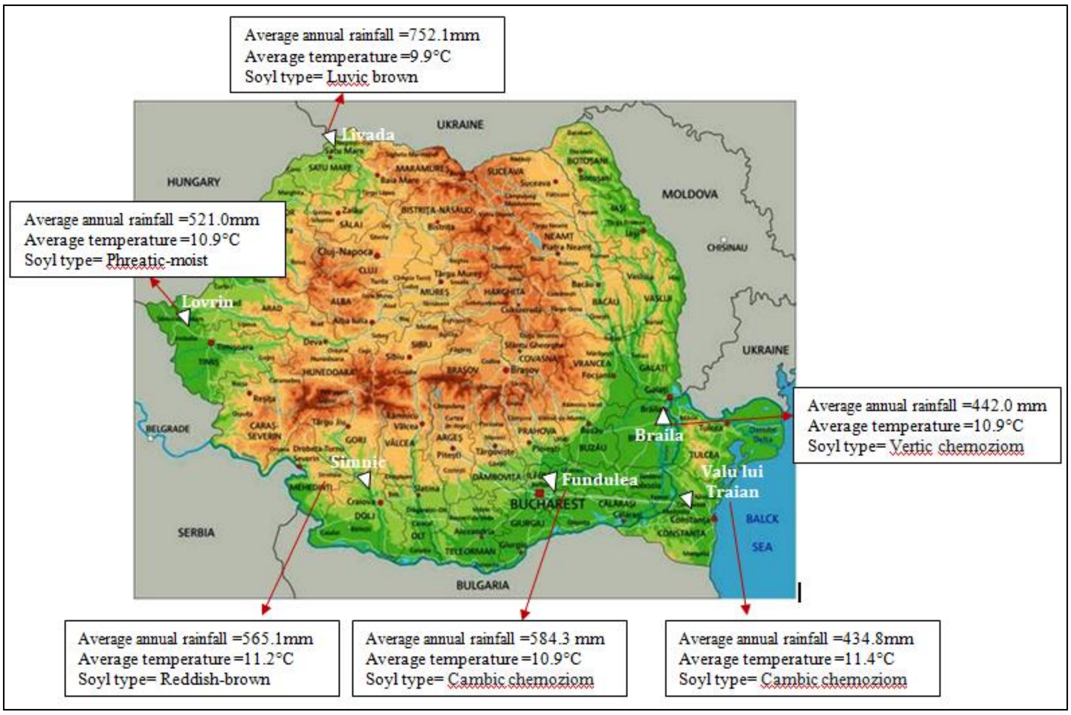


Figure 1. Locations where the researches were performed

The experimental design followed a randomized complete block design with three replications. Each plot consisted of four rows, 4.8 m in length, with 70 cm spacing between rows. To minimize border effects and intergenotypic competition, grain yield was determined from the two central rows only, corresponding to a harvestable area of 6.72 m². The final plant density at harvest was 65,000 plants ha⁻¹.

Based on the average grain yield recorded in each environment, the 18 environment combinations (six locations × three years) were classified into two water-stress categories (Table 2). The low water stress (LWS) environments were characterized by favorable moisture conditions, normal crop development, and high average grain yields exceeding 8 t ha⁻¹. In contrast, the high water stress (HWS) environments were characterized by drought conditions during the growing season, resulting in reduced crop performance and average grain yields below 6-7 t ha⁻¹.

This classification was used to assess hybrid responses to contrasting water availability conditions and to evaluate their adaptability and drought tolerance.

*Table 2.*Classification of the testing locations into hydric stress intensity breakouts, low water stress and high water stress, during 2021-2023

Locations		2021	2022	2023
NARDI Fundulea		LWS	LWS	HWS
ARDS Brăila		LWS	LWS	LWS
ARDS Șimnic		HWS	HWS	HWS
ARDS Valu lui Traian		LWS	HWS	HWS
ARDS Lovrin		LWS	HWS	LWS
ARDS Livada		LWS	LWS	LWS
TOTAL	**18**	**6**	**6**	**6**
LWS	11	5	3	3
HWS	**7**	1	3	3
LWS		Mean of yield/location >8 tonnes/hectare		
HWS		Mean of yield/location <6-7 tonnes/hectare		

LWS - low water stress; HWS - high water stress.

Statistical Analysis and Stability Parameters

Grain yield data were subjected to analysis of variance (ANOVA) to determine the effects of genotype, year, location, and their interactions. F-tests were performed using the MSTAT-C statistical software package (MSTAT-C, 1990).

Hybrid productivity and stability were evaluated using five complementary approaches: the Drought Resistance Index (DRIND), the Drought Susceptibility Index (DSI), regression analysis, coefficient of variation (CV), and Wricke's ecovalence (ω_i).

Drought Resistance Index (DRIND)

Drought tolerance was first assessed using the Drought Resistance Index (DRIND), according to the methodology described by Mandache (2013). The index was calculated based on grain yields obtained under contrasting water availability conditions, namely low water stress (LWS) and high water stress (HWS) environments. A dedicated software program was used to calculate the regression relationship between yields obtained under the two stress levels and to determine the position of each hybrid relative to the regression line. Confidence intervals (upper and lower limits) at the 5% probability level were estimated using graphical analysis in Microsoft Excel, following the procedure proposed by Mandache (2013). Higher DRIND values indicate greater drought tolerance and superior yield stability under water-limited conditions.

Drought Susceptibility Index (DSI)

Drought susceptibility was also evaluated using the Drought Susceptibility Index (DSI), proposed by Fischer and Maurer (1978):

$$DSI = (1 - Ys/Yp) / (1 - S)$$

where:

$S = 1 - (\bar{Y}s/\bar{Y}p)$

Ys = grain yield of a given hybrid under stress conditions (HWS environments);

Yp = grain yield of the same hybrid under favorable conditions (LWS environments);

$\bar{Y}s$ = mean grain yield of all hybrids under stress conditions;

$\bar{Y}p$ = mean grain yield of all hybrids under favorable conditions.

Lower DSI values indicate lower yield reduction under drought stress and, consequently, greater drought tolerance.

Regression Analysis

Hybrid adaptability across environments was assessed using the linear regression model described by Brukner and Frohberg (1987). Grain yield of each hybrid was regressed against the environmental index calculated from the mean yield of all hybrids in each environment. The regression coefficient (b) and intercept (a) were used to characterize genotype responses to environmental variation across the 18 testing environments (six locations × three years).

According to Keim and Kronstad (1979) and Brukner and Frohberg (1987):

- $b < 1$ and $a > 0$ indicate adaptation to unfavorable environments;
- $b > 1$ and $a < 0$ indicate adaptation to favorable environments;
- $b > 1$ and $a > 0$ indicate broad adaptability and superior responsiveness to environmental improvement.

Genotypes with regression coefficients close to unity ($b \approx 1$) are generally considered stable across a wide range of environmental conditions.

Coefficient of Variation (CV)

Yield stability was further evaluated using the coefficient of variation (CV), calculated as:

$$CV (\%) = (\sigma/\bar{x}) \times 100$$

where:

σ = standard deviation of grain yield;

$\bar{x}$ = mean grain yield.

Lower CV values indicate greater yield stability across environments.

Wricke's Ecovalence

The contribution of each genotype to the genotype × environment interaction was quantified using Wricke's ecovalence (ω_i) (Wricke, 1965), according to the following equation:

$\omega_i = \Sigma(Y_{ij} - Y_{i\cdot} - Y_{\cdot j} + Y_{\cdot\cdot})^2$

where:

Y_{ij} = mean yield of genotype i in environment j;

$Y_{i\cdot}$ = mean yield of genotype i across all environments;

$Y_{\cdot j}$ = mean yield of all genotypes in environment j;

$Y_{\cdot\cdot}$ = grand mean across all genotypes and environments.

Ecovalence measures the contribution of individual genotypes to the total genotype × environment interaction. Genotypes with lower ω_i values contribute less to the interaction and are therefore considered more stable across environments (Căbulea, 2004).

Climatic Conditions During the Experimental Period

Climatic conditions varied considerably among years and locations during the 2021-2023 experimental period, significantly influencing maize hybrid performance across the six testing sites. Figure 2 illustrates the variation in precipitation (mm) during the maize growing season (April-August) for the years 2021-2023 across the six locations, compared with the multiannual average.

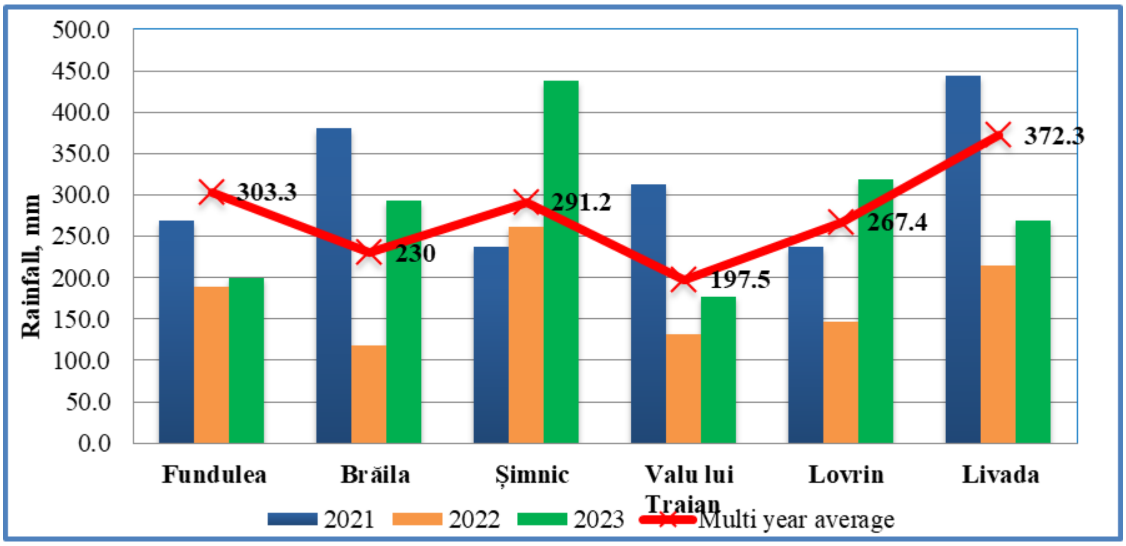
From a pluviometric perspective, a high degree of interannual climatic variability can be observed, with notable differences among locations.

The year 2021 was relatively wet in locations such as Brăila, Valu lui Traian, and Livada, where precipitation exceeded the multiannual average. In contrast, 2022 was predominantly dry, with precipitation levels below the average in all locations.

In 2023, a trend toward recovery to, or even exceeding, the climatological normal was observed in some locations, such as

Brăila, Şimnic, and Lovrin, where precipitation amounts surpassed the multiannual average.

Overall, the experimental period was characterized by pronounced climatic variability, both among years and across locations. These contrasting environmental conditions provided a suitable framework for evaluating genotype responses, drought tolerance, adaptability, and yield stability under diverse production environments (Figure 2).



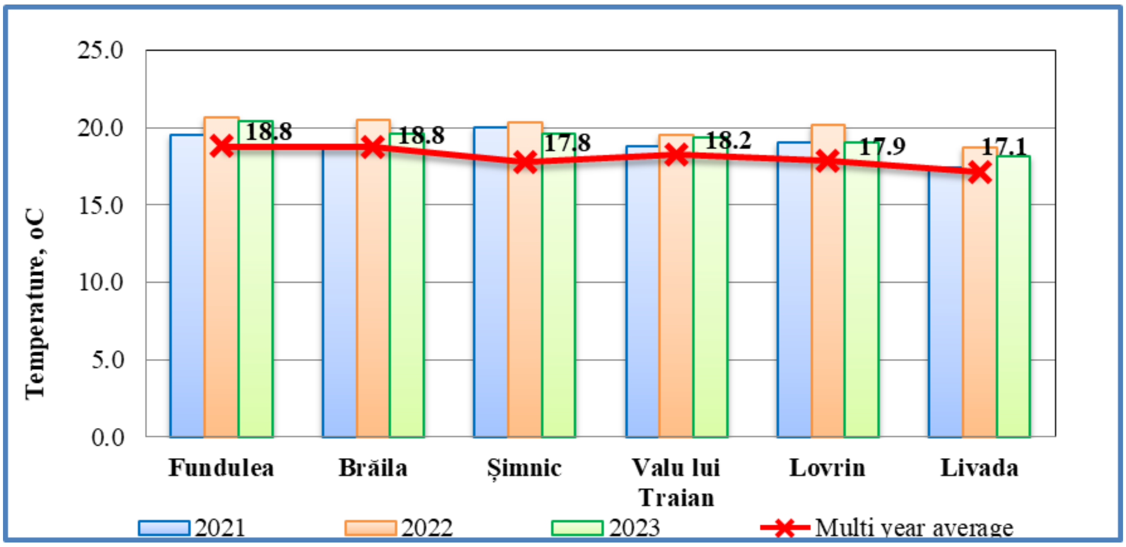
Source: meteorological stations of NARDI Fundulea, ARDS Brăila, ARDS Şimnic, ARDS Valu lui Traian, ARDS Lovrin, ARDS Livada.

Figure 2. Evolution of rainfall during the maize growing season, April-August (2021-2023)

The graph in Figure 3 shows the variation in mean annual temperature recorded during the maize growing season for the period 2021-2023 across the six locations, compared with the multiannual average.

Regarding temperature, it can be observed that in all experimental years and at all locations, mean values during the maize growing season exceeded the multiannual average.

In 2021, the highest mean temperatures were recorded at Şimnic, while in 2022 and 2023, the highest values were observed at Fundulea, Brăila, Şimnic, and Lovrin.



Source: meteorological stations of NARDI Fundulea, ARDS Brăila, ARDS Şimnic, ARDS Valu lui Traian, ARDS Lovrin, ARDS Livada.

Figure 3. Evolution of average temperatures during the maize growing season, April-August (2021-2023)

RESULTS AND DISCUSSION

Table 3 presents the average grain yields (t ha^{-1}), adjusted to the standard moisture content of 15.5%, for the 15 maize hybrids tested at INCDA Fundulea and at the Agricultural Research and Development Stations in Brăila, Șimnic, Valu lui Traian, Lovrin, and Livada.

Across all environments, mean grain yield ranged from 7.53 t ha^{-1} (HSF 1214-17) to 9.67 t ha^{-1} (Felix), with an overall experimental mean of 8.58 t ha^{-1}. Among the tested genotypes, Felix recorded the highest average yield (9.67 t ha^{-1}), corresponding to a 13% increase over the overall mean. It was followed by F423, Magnus, Amurg, HSF 1034-17, and FDL Ovidiu, which exhibited yield advantages ranging from 3% to 9% above the experiment mean.

A pronounced genotype × environment interaction was observed, as reflected by differences in hybrid performance across locations. The highest grain yields for Felix were recorded at ARDS Livada (12.74 t ha^{-1}) and ARDS Brăila (10.92 t ha^{-1}), indicating strong responsiveness to favorable environmental conditions. Similarly, F423 exhibited maximum yields at ARDS Livada (12.59 t ha^{-1}) and ARDS Brăila (10.38 t ha^{-1}), confirming its high productivity potential under optimal growing conditions.

Table 3. Grain yield (t ha^{-1}, 15.5% grain moisture) of maize hybrids tested across six locations during 2021-2023

No.	Hybrids	Average grain yield (to/ha) with 15.5% moisture						Average	
		NARDI Fundulea	ARDS Brăila	ARDS Șimnic	ARDS Valu lui Traian	ARDS Lovrin	ARDS Livada	t/ha	%
1	F423	9.12	10.38	6.74	8.41	8.78	12.59	9.33	109
2	Felix	9.31	10.92	6.86	8.87	9.31	12.74	9.67	113
3	Magnus	9.44	10.48	6.70	8.27	8.99	10.51	9.07	106
4	Amurg	8.47	10.84	5.23	8.50	9.40	11.62	9.01	105
5	Miraj	8.55	10.04	5.16	8.07	9.22	10.98	8.67	101
6	FDL Ovidiu	8.84	10.90	5.46	7.87	9.11	10.64	8.80	103
7	HSF7395-18	8.02	9.49	4.61	7.83	8.38	11.19	8.25	96
8	HSF1033-17	9.08	9.87	5.71	7.81	9.25	10.72	8.74	102
9	HSF1034-17	9.55	9.86	5.59	8.22	9.16	10.90	8.88	104
10	HSF3877-17	8.25	9.13	4.73	8.35	8.54	10.24	8.21	96
11	HSF4075-17	8.22	10.26	5.41	8.42	8.25	10.67	8.54	100
12	HSF1032-17	7.66	8.82	4.28	8.01	7.67	9.91	7.73	90
13	HSF1214-17	7.45	9.25	4.18	7.16	7.46	9.69	7.53	88
14	HSF1089-17	8.49	10.53	4.27	7.80	7.96	10.59	8.28	97
15	HSF1142-17	8.53	10.28	4.71	7.02	7.82	9.68	8.01	93
	Average	**8.60**	**10.07**	**5.31**	**8.04**	**8.62**	**10.84**	**8.58**	**100**

The analysis of variance (ANOVA) for grain yield (Table 4) highlights the effects of genetic and environmental factors, as well as their interactions.

The hybrid effect (H) had a highly significant effect on grain yield, indicating clear differences among hybrids and confirming that hybrid selection strongly influences productivity.

The year factor (Y) was also highly significant, demonstrating that interannual climatic variability and growing conditions have a major impact on yield.

The H × Y interaction was not significant, suggesting that the relative performance of hybrids remained stable across years.

The locality factor (L) showed the strongest effect, indicating that the growing environment (soil characteristics, local climate, and management conditions) is the primary determinant of yield variation.

The H × L interaction was significant, indicating that certain hybrids respond differently depending on the location, reflecting specific adaptation to environmental conditions.

The Y × L interaction was also highly significant, suggesting that the effect of yearly climatic variation differs among locations; thus, a drought year does not affect all environments in the same way.

Overall, grain yield was mainly influenced by location and year, followed by genotype effects. The observed interactions suggest that hybrid selection should take into account the specific location, as hybrid performance is not consistent across all environments. However, yield stability across years appears relatively good, as the H × Y interaction was not significant.

Table 4. ANOVA- Analysis of variance for grain yield of maize hybrids tested in the six locations during 2021-2023

Analysed trait	Source of variation	Degrees of Freedom	Sum of Squares	Mean Square	F Value
Grain yield	Hybrid	14	86.43	6.174	18.4973***
	Year	2	46.237	23.19	69.2672***
	H x Y	28	9.179	0.328	0.9823
	Location	5	824.89	165	494.308***
	H x L	70	44.165	0.631	1.8904***
	Y x L	10	168.99	16.9	50.6324***
	H x Y x L	140	46.726	0.334	0.0000
	Total	269	1226.6		

Figure 4 illustrates the relationship between mean grain yield under low water stress (LWS; 11 environments, X-axis) and high water stress (HWS; 7 environments, Y-axis) for the 15 maize hybrids evaluated during the 2021-2023 period.

A strong and positive correlation was observed between the two stress conditions (r = 0.846***), indicating that hybrids with high yield potential under favorable conditions generally also exhibit superior performance under drought stress. The fitted regression model ($Y = 1.183X - 5.527$) suggests a slightly greater yield response under high water stress conditions, indicating that certain genotypes are able to maintain or even relatively improve their performance under limited water availability.

The dashed lines represent the 95% confidence intervals of the regression, while the horizontal and vertical reference lines correspond to the mean yields under LWS and HWS conditions, respectively. These lines divide the graph into four quadrants used for classification of genotypes based on their adaptability and stability.

The upper-right quadrant includes high-yielding and broadly adapted genotypes, characterized by above-average performance under both stress conditions. The lower-left quadrant contains low-performing genotypes under both environments, indicating poor adaptability. The lower-right quadrant includes genotypes with superior performance under favorable conditions but reduced performance under stress, while the upper-left quadrant contains genotypes showing relatively better performance under stress conditions but lower productivity under optimal environments.

Hybrids Felix and F423 were positioned in the upper-right quadrant, exhibiting consistently high performance under both stress levels and indicating strong productivity and stability. Hybrid Magnus was located above the regression line, suggesting superior performance under high water stress conditions relative to its performance under favorable conditions.

Hybrids such as HSF1033-17, HSF1034-17, Miraj, and FDL Ovidiu were located near the mean values, indicating intermediate performance and moderate stability across contrasting environments. The hybrid Amurg also fell within the upper-right quadrant but slightly below the regression line, reflecting above-average productivity combined with relatively stable performance across water regimes.

In contrast, genotypes HSF1214-17 and HSF1032-17, positioned in the lower-left quadrant, exhibited consistently low performance under both stress conditions, indicating limited adaptability. Finally, genotypes located below the regression line and characterized by below-average performance under stress conditions (e.g., HSF4075-17 and HSF1089-17) were more sensitive to drought, performing better only under favorable environmental conditions.

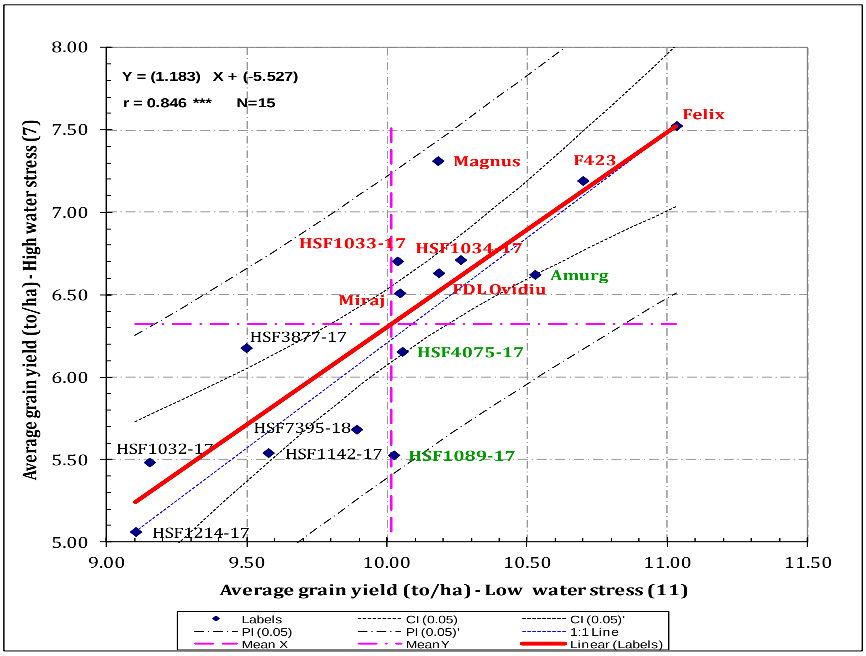


Figure 4. Relationship between average yields from low water stress locations and high water stress locations, for maize hybrids, tested in the six locations during 2021-2023

The high performance and stability of the hybrids Felix, F423, Magnus, HSF1033-17, and HSF1034-17 are also confirmed by the stability indices, with values ranging from 16.04 to 17.09, respectively, as well as by the drought susceptibility index (ISS), with values between 0.75 and 0.95 (Table 5).

These results suggest that the mentioned hybrids are able to maintain high yield levels even under water-deficit conditions, making them suitable for cultivation in areas characterized by pronounced climatic variability.

Table 5. Average yields and selection index DRIND and DSI

Hybrids	Average grain yield, to/ha, LWS	Average grain yield, to/ha, HWS	Drought tolerance index-DRIND (Mandache, 2013)	Drought susceptibility index-DSI (Fischer and Mauer, 1978)
F423	**10.70**	**7.19**	**16.66**	**0.89**
Felix	**11.03**	**7.53**	**17.09**	**0.86**
Magnus	**10.18**	**7.31**	**16.89**	**0.75**
Amurg	10.53	6.62	15.88	1.00
Miraj	10.04	6.51	**15.78**	**0.95**
FDL Ovidiu	10.18	6.63	**15.93**	**0.94**
HSF7395-18	9.89	5.68	14.63	1.15
HSF1033-17	10.04	6.70	**16.05**	**0.90**
HSF1034-17	10.26	6.71	**16.04**	**0.94**
HSF3877-17	9.50	6.18	15.37	0.95
HSF4075-17	10.05	6.16	15.28	1.05
HSF1032-17	9.15	5.48	14.44	1.09
HSF1214-17	9.10	5.06	13.85	1.20
HSF1089-17	10.02	5.53	14.40	1.22
HSF1142-17	9.58	5.54	14.47	1.14

Table 6 presents the performance of the 15 maize hybrids evaluated over three agricultural years (2021-2023) in terms of grain yield, stability, and adaptability, using regression analysis (parameters *b* and *a*) and coefficient of variation (CV%).

Overall, the mean grain yield was 8.58 t ha^{-1}, with annual values decreasing from 9.13 t ha^{-1} in 2021 to 8.13 t ha^{-1} in 2022, followed by a slight increase to 8.48 t ha^{-1} in 2023. This trend highlights the strong influence of climatic conditions on yield performance, with 2022 representing the least favorable year.

Among the hybrids, Felix recorded the highest mean yield (9.67 t ha^{-1}), followed by F423 (9.33 t ha^{-1}) and Magnus (9.07 t ha^{-1}), indicating superior productive potential. These hybrids also exhibited sub-unit regression coefficients (*b* = 0.74–0.87) and positive intercept values (*a* = 1.80–2.95), suggesting good adaptation to unfavorable environmental conditions and greater stability.

In contrast, the hybrids Amurg (*b* = 1.29), HSF1032-17 (*b* = 1.29), and HSF1089-17 (*b* = 1.71) showed supra-unit regression coefficients, indicating higher responsiveness to favorable environments but lower stability under stress conditions. Conversely, hybrids such as FDL Ovidiu (*b* = 0.53) and Miraj (*b* = 0.67) exhibited sub-unit values, suggesting greater stability and better performance under limiting environmental conditions.

The intercept (*a*) further supports this interpretation. Positive values (e.g., FDL Ovidiu, *a* = 4.26; Miraj, *a* = 2.90) indicate good yield potential under unfavorable conditions, whereas negative values (e.g., HSF1089-17, *a* = −6.37; HSF1214-17, *a* = −4.30) reflect lower adaptability in such environments.

The coefficient of variation (CV%) ranged from 3.16% (FDL Ovidiu) to 10.80% (HSF1089-17), indicating substantial differences in yield stability among hybrids. Hybrids with low CV values (<5%), such as FDL Ovidiu, Miraj, Felix, HSF1034-17, HSF1033-17, Magnus, and F423, are characterized by high yield stability. In contrast, HSF1089-17, HSF1214-17, and HSF1032-17 showed higher variability, indicating less consistent performance across environments.

In conclusion, hybrids Felix, F423, and Magnus combine high yield potential with good stability and adaptability, making them suitable for a wide range of environmental conditions. Hybrids FDL Ovidiu and Miraj are characterized by greater stability and better adaptation to less favorable environments, whereas hybrids with a stronger environmental response (Amurg, HSF1089-17) are more suitable for optimal conditions where their yield potential can be fully expressed.

Table 6. Parameters regarding the response of maize hybrids to the variation of environmental conditions in the 6 locations during 2021-2023

No.	Hybrids	Average grain yield (tonnes/ha)			Average (to/ha)	a regression constant, intercept	b regression slope	CV, %
		2021	2022	2023				
1	F423	9.83	9.17	9.00	**9.33**	**2.95**	**0.74**	**4.71**
2	Felix	10.18	9.35	9.48	**9.67**	**2.22**	**0.87**	**4.61**
3	Magnus	9.52	8.68	9.00	**9.07**	**1.80**	**0.85**	**4.70**
4	Amurg	9.67	8.35	9.00	**9.01**	**-2.09**	**1.29**	**7.32**
5	Miraj	9.08	8.45	8.48	**8.67**	**2.90**	**0.67**	**4.10**
6	FDL Ovidiu	9.12	8.63	8.66	**8.80**	**4.26**	**0.53**	**3.16**
7	HSF7395-18	9.00	7.90	7.87	**8.25**	**-1.95**	**1.19**	**7.79**
8	HSF1033-17	9.18	8.43	8.61	**8.74**	**2.09**	**0.78**	**4.50**
9	HSF1034-17	9.28	8.49	8.87	**8.88**	**2.21**	**0.78**	**4.45**
10	HSF3877-17	8.60	7.66	8.36	**8.21**	**0.63**	**0.88**	**5.99**
11	HSF4075-17	9.04	8.21	8.36	**8.54**	**1.16**	**0.86**	**5.15**
12	HSF1032-17	8.39	7.07	7.72	**7.73**	**-3.36**	**1.29**	**8.51**
13	HSF1214-17	8.35	7.04	7.20	**7.53**	**-4.30**	**1.38**	**9.49**
14	HSF1089-17	9.11	7.33	8.39	**8.28**	**-6.37**	**1.71**	**10.80**
15	HSF1142-17	8.53	7.25	8.24	**8.01**	**-2.15**	**1.18**	**8.37**
	Average	9.13	8.13	8.48	**8.58**	**x**	**x**	**x**

Figure 4 presents a dispersion analysis between mean grain yield (t ha^{-1}) and the coefficient of variation (CV%) for the tested maize hybrids. The two reference axes (red lines) represent the mean values of the two indicators and allow the classification of hybrids according to productivity and yield stability.

From an agronomic perspective, the most favorable quadrant is the lower-right quadrant, which includes hybrids characterized by above-average yield and low variability. These genotypes are considered the most valuable in terms of yield stability under variable environmental conditions. This group includes F423, Magnus, Felix, and FDL Ovidiu, which combine high yields (8.80-9.67 t ha^{-1}) with low coefficients of variation (3.16-4.71%), indicating good stability.

The hybrid Amurg, although exhibiting high yield potential, shows greater variability, suggesting lower stability across different growing conditions.

In contrast, the upper-left quadrant includes hybrids such as HSF1089-17, HSF1214-17, HSF1032-17, HSF1142-17, and HSF7395-18, which are characterized by high variability and less stable performance, indicating greater sensitivity to environmental factors.

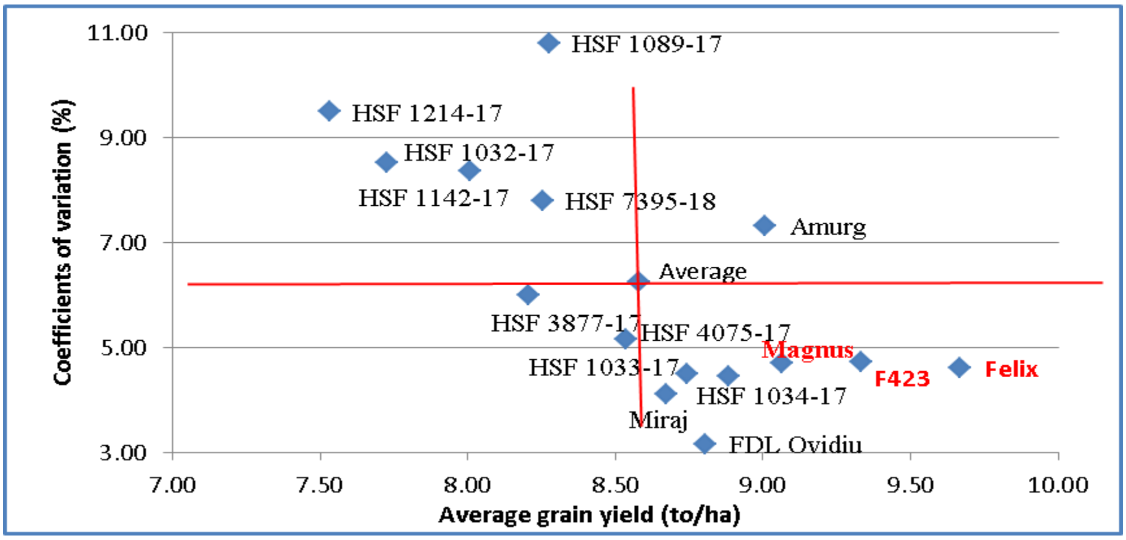


Figure 4. Average yields and coeficients of variation for the maize hybrids tested in 18 environmental conditions

Table 7 presents the estimated stability of the hybrids across the six test locations, expressed through the individual values of the ecovalence parameter (ω_i) and their sum ($\Sigma\omega_i$). The interpretation of these results highlights both the specific behavior of genotypes under different environmental conditions and their overall stability and adaptability.

Comparative analysis of the total values ($\Sigma\omega_i$) reveals considerable variability among hybrids in terms of stability. The lowest values of the parameter were recorded for HSF1214-17 (0.120), Miraj (0.362), and HSF4075-17 (0.498), indicating a high degree of ecological stability. These hybrids exhibited relatively consistent performance across all experimental locations, suggesting good adaptability to environmental variation.

An intermediate level of stability was observed for HSF7395-18 (0.737), HSF1033-17 (0.747), FDL Ovidiu (0.788), HSF1034-17 (0.816), and HSF1032-17 (0.889). These genotypes showed some sensitivity to environmental variation, but without extreme fluctuations, and can therefore be considered moderately stable.

High values of the ω_i parameter indicate low stability. In this category fall Amurg (0.924), F423 (2.195), Magnus (1.711), HSF1142-17 (1.473), Felix (1.301), and HSF1089-17 (1.306). In particular, F423 showed the highest ecovalence value, suggesting pronounced variability in performance depending on environmental conditions and, consequently, lower adaptability and greater environmental sensitivity.

Analysis of the distribution of values across locations shows that certain genotypes exhibit high ω_i values in specific environments (e.g., Magnus at ARDS Şimnic or HSF1032-17 at ARDS Valu lui Traian), indicating a strong genotype × environment interaction. In contrast, stable genotypes maintain consistently low values across all locations.

In conclusion, hybrids with the lowest ω_i values can be considered the most stable and therefore the most suitable for cultivation under variable environmental conditions.

Table 7. Estimation of the stability parameter Ecovalence - ω_i, obtained by the method of Wricke (1965)

Hybrids	NARDI Fundulea	ARDS Brăila	ARDS Şimnic	ARDS Valu lui Traian	ARDS Lovrin	ARDS Livada	Σ (ω_i)
F423	0.055	0.199	0.458	0.152	0.355	0.977	**2.195**
Felix	0.145	0.057	0.214	0.067	0.158	0.660	**1.301**
Magnus	0.128	0.006	0.825	0.067	0.012	0.672	**1.711**
Amurg	0.310	0.114	0.258	0.001	0.123	0.118	**0.924**
Miraj	0.019	0.015	0.059	0.003	0.263	0.002	**0.362***
FDL Ovidiu	0.000	0.375	0.005	0.152	0.070	0.185	**0.788**
HSF7395-18	0.063	0.062	0.141	0.013	0.008	0.450	**0.737**
HSF1033-17	0.104	0.133	0.059	0.151	0.220	0.080	**0.747**
HSF1034-17	0.424	0.257	0.000	0.015	0.059	0.061	**0.816**
HSF3877-17	0.001	0.322	0.044	0.471	0.087	0.053	**0.977**
HSF4075-17	0.115	0.054	0.022	0.180	0.109	0.018	**0.498***
HSF1032-17	0.007	0.152	0.032	0.682	0.009	0.006	**0.889**
HSF1214-17	0.009	0.053	0.006	0.027	0.013	0.011	**0.120***
HSF1089-17	0.039	0.592	0.545	0.004	0.123	0.003	**1.306**
HSF1142-17	0.258	0.612	0.001	0.200	0.051	0.351	**1.473**

The comparative analysis of the 15 hybrids highlights significant differences in terms of productivity, stability, and drought tolerance, evaluated through several parameters: mean yield, regression coefficient (*b*), intercept (*a*), coefficient of variation (CV%), drought tolerance index (DRIND), drought susceptibility index (DSI), and ecovalence (ω_i). The final ranking was obtained by summing the positions achieved for each criterion (Table 8).

The hybrid Felix ranked first due to its highest mean yield (9.67 t ha^{-1}), combined with good stability (*b* = 0.87) and high drought tolerance (low DSI and high DRIND values). These results indicate broad adaptability and a strong capacity to maintain performance under variable environmental conditions.

In second place, FDL Ovidiu was characterized by high stability (CV = 3.16%) and a sub-unit regression coefficient (*b* = 0.53), indicating excellent adaptation to unfavorable conditions, particularly water stress. This hybrid is therefore recommended for areas with high climatic variability.

The hybrids HSF1033-17 and HSF1034-17 showed a good balance between productivity and stability, with moderate regression coefficients (*b* ≈ 0.78) and low CV values (4.45-4.50%), indicating suitable adaptability across diverse environments.

The hybrid Miraj was characterized by high stability and favorable performance under stress conditions, despite slightly lower yield potential, making it suitable for environments where yield consistency is a priority.

The group of hybrids with intermediate performance includes Magnus, which exhibited high drought tolerance (minimum DSI = 0.75) but slightly lower overall yield performance, and F423, characterized by high yield potential but moderate stability.

The hybrid Amurg showed a supra-unit regression coefficient (*b* = 1.29), indicating a strong ability to exploit favorable conditions; however, its lower stability (higher CV = 7.32%) limits its suitability under stress environments.

The lowest-ranked hybrids (HSF3877-17, HSF7395-18, HSF1032-17, HSF1214-17, HSF1142-17, and HSF1089-17) were characterized by low yield, high variability, and increased drought susceptibility, making them less suitable for cultivation under variable conditions.

Overall, the results emphasize the importance of integrating productivity, stability, and drought tolerance criteria in hybrid selection. The superiority of Felix is clearly demonstrated, alongside the strong adaptive potential of FDL Ovidiu and Miraj under water-stress conditions.

Table 8. Ranking of the 15 hybrids based on the value of the stability parameters

No.	Hybrids	Average (to/ha)	Rank 1	a regression constant, intercept	b regression slope	Rank 2	CV, %	Rank 3	Drought tolerance index-DRIND (Mandache, 2013)	Rank 4	Drought susceptibility index-DSI (Fischer and Mauer, 1978)	Rank 5	(ω_i)	Rank 6	Rank (1+2+3+4+5+6)	Rank final
1	F423 STABLE	**9.33**	2	**2.95**	**0.74**	7	**4.71**	7	16.66	3	**0.89**	3	**2.195**	15	37	**7**
2	Felix STABLE	**9.67**	1	**2.22**	**0.87**	5	**4.61**	5	17.09	1	**0.86**	2	**1.301**	11	25	**1**
3	Magnus STABLE	**9.07**	3	**1.80**	**0.85**	6	**4.70**	6	16.89	2	**0.75**	1	**1.711**	14	32	**6**
4	Amurg	**9.01**	4	**-2.09**	**1.29**	10	7.32	10	15.88	7	1.00	9	**0.924**	9	49	**9**
5	Miraj STABLE	**8.67**	8	**2.90**	**0.67**	2	**4.10**	2	15.78	8	**0.95**	8	**0.362**	2	30	**5**
6	FDL Ovidiu STABLE	**8.80**	6	**4.26**	**0.53**	1	**3.16**	1	15.93	6	**0.94**	6	**0.788**	6	26	**2**
7	HSF7395-18	**8.25**	11	**-1.95**	**1.19**	11	7.79	11	14.63	11	1.15	13	**0.737**	4	61	**11**
8	HSF1033-17 STABLE	**8.74**	7	**2.09**	**0.78**	4	**4.50**	4	16.05	4	**0.90**	4	**0.747**	5	28	**3**
9	HSF1034-17 STABLE	**8.88**	5	**2.21**	**0.78**	3	**4.45**	3	16.04	5	**0.94**	5	**0.816**	7	28	**4**
10	HSF3877-17	**8.21**	12	**0.63**	**0.88**	9	5.99	9	**15.37**	9	**0.95**	7	**0.977**	10	56	**10**
11	HSF4075-17	**8.54**	9	**1.16**	**0.86**	8	**5.15**	8	15.28	10	1.05	10	**0.498**	3	48	**8**
12	HSF1032-17	**7.73**	14	**-3.36**	**1.29**	13	8.51	13	14.44	13	1.09	11	**0.889**	8	72	**12**
13	HSF1214-17	**7.53**	15	**-4.30**	**1.38**	14	9.49	14	13.85	15	1.20	14	**0.120**	1	73	**13**
14	HSF1089-17	**8.28**	10	**-6.37**	**1.71**	15	10.80	15	14.40	14	1.22	15	**1.306**	12	81	**15**
15	HSF1142-17	**8.01**	13	**-2.15**	**1.18**	12	8.37	12	14.47	12	1.14	12	**1.473**	13	74	**14**

CONCLUSIONS

Multi-year and multi-location testing is essential for the selection of superior maize genotypes with high productivity and stability, either broadly adapted to diverse environmental conditions or specifically adapted to particular environments.

The assessment of yield stability was performed by integrating multiple parameters, including mean yield, drought resistance index (DRIND), drought susceptibility index (DSI), regression coefficient (*b*), intercept (*a*), coefficient of variation (CV%), and Wricke's ecovalence (ω_i), in order to better characterize genotype performance under variable environmental conditions.

The results demonstrated significant variability among maize hybrids for both yield potential and stability parameters across environments, confirming the strong influence of genotype × environment interaction.

The integrated analysis indicates that the hybrid Felix exhibits the most favorable combination of high productivity and stability, followed by Magnus and F423. Under more restrictive environmental conditions, the hybrids FDL Ovidiu, Miraj, HSF1033-17 and HSF1034-17 showed better adaptation and higher stability, making them suitable for cultivation in stress-prone environments. In contrast, hybrids hybrids HSF1032-17 and HSF1214-17 exhibited high variability and limited adaptability, and are therefore not recommended for cultivation under highly variable environmental conditions.

ACKNOWLEDGEMENTS

This research was supported by Ministry of Agriculture and Rural Development through project ADER 113/22.09.2019 - "Creating high-yielding maize hybrids tolerant to drought, heat, diseases, and pests in order to reduce the impact of global warming on agroecosystems in Romania".

The project was implemented by a consortium coordinated by the National Agricultural Research and Development Institute (NARDI) Fundulea (CP), with the following partners: Agricultural Research and Development Station (ARDS) Livada (P1), ARDS Lovrin (P2), ARDS Șimnic (P3), and ARDS Valu lui Traian (P4). The Agricultural Research and Development Station Brăila participated as a collaborating institution.

REFERENCES

Brukner, P.L., and Frohberg, R.C., 1987. *Stress tolerance and adaptation in spring wheat*. Crop Science, 27: 31-36.

Căbulea, I., 2004. *Maize genetics*. Maize - monographic study, Ed. Academiei Române, București: 207-296.

Cairns, J.E., Hellin, J., Sonder, K., Araus, J.L., MacRobert, J.F., Thierfelder, C., Prasanna, B.M., 2013. *Adapting maize production to climate change in sub-Saharan Africa*. Agronomy Journal, 105(3): 713-725.

Ciocăzanu, I., Terbea, M., Micut, G., Lazăr, C., 1996. *Inheritance of physiological parameters implied in maize drought resistance*. Romanian Agricultural Research, 5-6: 57-66.

Cooper, M., Technow, F., Messina, C., Gho, C., Totir, L.R., 2016. *Use of crop growth models with whole-genome prediction: Application to a maize multienvironment trial*. Crop Science, 56(5): 2141-2156.

Duvick, D.N., 2005. *The contribution of breeding to yield advances in maize (Zea mays L.)*. Advances in Agronomy, 86: 83-145.

Fischer, R.A., and Maurer, R., 1978. *Drought resistance in spring wheat cultivars. I. Grain yield response*. Aust. J. Agric. Res., 29: 897-907.

Hammer, G.L., Messina, C., Wu, A., Cooper, M., 2020. *Biological reality and parsimony in crop models - Implications for crop improvement*. Field Crops Research, 248, 107700.

Horhocea, D., Petcu, E., Iordan, H., Ciontu, C., 2024. *Evaluation of New Maize Genotypes for Seed Yield Potential and Stability*. Romanian Agricultural Research, 41: 489-496. https://doi.org/10.59665/rar4147

Keim, D.L., and Kronstad, W.E., 1979. *Drougt resistance and dryland adaptation in winter wheat*. Crop Science, 19(5): 574-576.

Mandache, V., 2013. *Aspects of Maize Breeding for Drought Tolerance; contributions on drought tolerance testing and estimation in maize*. Doctoral Thesis, University of Agronomic Sciences and Veterinary Medicine Bucharest.

MSTAT-C, 1990. *Users Guide to MSTAT-C. A software program for the design, management and analysis of agronomic research experiments*. In Department of Crop and Soil Sciences, USA: Michigan State University, East Lansing, MI.

Nišavić, N., Čamdžija, Z., Živanović, T., Božinović, S., Grčić, N., Radinović, I., Božović, D., 2025. *Impact of Genotype × Environment Interactions on the Yield and Stability of Maize Hybrids in Serbia*. Romanian Agricultural Research, 42: 233-245. https://doi.org/10.59665/rar4221

Ray, D.K., Gerber, J.S., MacDonald, G.K., West, P.C., 2015. *Climate variation explains a significant fraction of global crop yield variability*. Nature Climate Change, 5: 123-126.

Shojaei, S.H., Mostafavi, K., Omrani, A., Omrani, S., Mousavi, S.M N., Illés, Á., Bojtor, C., Nagy, J., 2021. *Yield stability analysis of maize (Zea mays L.) hybrids using AMMI and parametric methods*. Scientifica, 2021, 5576691.

Smith, S., Cooper, M., Gogerty, J., Löffler, C., Borcherding, D., 2019. *Maize hybrid performance and stability across diverse environments*. Field Crops Research, 230: 1-10.

Worku, M., Bänziger, M., Erley, G.S.A., Friesen, D., Diallo, A.O., Horst, W.J., 2020. *Performance and yield stability of maize hybrids across stress-prone environments*. The Crop Journal, 8(1): 107-118.

Wricke, G., 1965. *Zur berechning der okovalenz bei sommerweizen und hafer*. Zeitschrift fur Pflanzenzuchtung, 52: 127-138.

Zhang, X., Chen, S., Sun, H., Wang, Y., Shao, L., 2022. *Yield and stability of maize under climatic variability and management practices*. Field Crops Research, 285, 108589.