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Environmental plasticity and stability of medium-early maize (*Zea mays* L.) hybrids in different soil-climatic zones of Ukraine

Abstract. The purpose of the study was to determine the adaptive potential of modern medium-early maize hybrids in terms of yield, protein content, and starch content under different soil-climatic conditions of Ukraine. Field studies were conducted during 2024-2025 in the steppe, forest-steppe, and Polissia zones. The environmental plasticity of genotypes was assessed using the regression coefficient (b_i), trait expression stability using the stability variance (S^2_{di}) and coefficient of variation (V), and adaptive properties using the homeostaticity (H_{om}) and breeding value (S_c) indices. The hybrids under study were found to be characterised by high environmental

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plasticity for yield, with regression coefficient values ranging from 0.8 to 1.1. The hybrids RGT KELOXXS, EY3957, and MAGNITUDO were the most adaptive and stable in terms of yield (b_i = 1.0-1.1; S^2_{di} = 0.2-0.5). The hybrids Optix, PS 310, and KWS VELARO were characterised by increased breeding value (S_c = 1.8-2.0). The coefficient of variation for yield ranged from 36.4 to 46.1%, indicating a considerable dependence of this trait on growing conditions. For protein content, the regression coefficient varied between 0.8 and 1.4, while the most stable protein formation was observed in the hybrids Optix, PS 310, and KWS PETRARO (S^2_{di} = 0.2-0.3; V = 16.6-17.1%). The highest breeding value for this trait was recorded in the hybrid MAGNITUDO (S_c = 5.3). For starch content, the coefficient of variation was low, ranging from 1.9 to 3.4%, indicating high stability of the trait. The hybrid KWS PETRARO proved to be the most stable and adaptive (b_i = 0.7; V = 1.9%; H_{om} = 12.7; S_c = 68.2), being characterised by high homeostaticity and breeding value. Yield was found to be a more variable trait than starch content, whereas protein occupied an intermediate position in terms of variability. The hybrids RGT KELOXXS, EY3957, MAGNITUDO, Optix, and KWS PETRARO are the most promising for cultivation under different soil-climatic conditions of Ukraine, combining high productivity, stability, and adaptability. The practical value of the study lies in the possibility of using the obtained results by plant breeders, agronomists, and seed companies for the selection of highly productive and adaptive maize hybrids in different agroecological zones of Ukraine

Keywords: homeostaticity; adaptability; yield potential; protein content; starch content; environmental index

INTRODUCTION

Under current conditions of global climate change and the increasing frequency of extreme weather events, the issue of stable grain production of maize (*Zea mays* L.) has become particularly important. Ukraine is characterised by considerable spatial-temporal variability in hydrothermal conditions, which is especially evident in the climatic contrasts between the steppe, forest-steppe, and Polissia zones. Moisture deficit, high air temperatures during the formation of generative organs, uneven precipitation distribution, and changes in the duration of the growing season substantially affect the realisation of the genetic potential of modern maize hybrids. Under such conditions, the selection of genotypes capable of ensuring high productivity and stable expression of economically valuable traits regardless of environmental variability becomes increasingly important. For this reason, the assessment of environmental plasticity, stability, and adaptability of maize hybrids is one of the priority areas of contemporary plant breeding and agronomic science.

The problem of genotype-environment interaction has been actively researched in recent years by both Ukrainian and international scholars. Thus, R. Spriazhka & V. Zhemoida (2022), while examining experimental maize hybrids at different ecological locations in Ukraine, established a substantial dependence of yield formation on growing conditions and noted that high values of standard deviation indicate instability of productivity under contrasting weather conditions. According to the authors, the most valuable genotypes are those that combine a moderate response to improved agronomic conditions with a stable level of yield. A study by U. Grote *et al.* (2021) confirms that the phenotypic expression of traits in maize is formed under the combined influence of genetic characteristics and environmental factors. The authors emphasise that grain yield is among the most variable traits, as it largely depends on temperature conditions, moisture availability, and cultivation practices. Thereby, grain quality indicators, specifically starch content, are characterised by greater stability compared with yield. Similar conclusions were reached by C. Stratakis (2023), who noted that a substantial proportion of variability in economically valuable traits results from the interaction between heredity and environmental conditions. The author stresses that genotype responses to changes in growing conditions may differ considerably even at the same level of average productivity, which necessitates the use of quantitative parameters of environmental plasticity and stability for assessing the adaptive potential of crops.

O. Erenstein *et al.* (2021), analysing current trends in maize cultivation under conditions of climate change, noted that identical levels of yield may be achieved with fundamentally different levels of stability in trait expression. The researchers emphasise that highly productive genotypes are not always adaptive and that practical application requires consideration of both the absolute yield values and the genotype's ability to maintain them under variable environmental conditions. Important findings concerning the adaptability of parental maize components were obtained by L. Svinitskyi (2023). The author established that inbred lines with high values of the regression coefficient and standard deviation are characterised by increased sensitivity to changes in environmental conditions and insufficient yield stability. Such genotypes are capable of producing high levels of productivity only under favourable growing conditions and high-input agricultural systems. In contrast, lines with moderate regression coefficient values demonstrated greater stability and adaptability to extensive cultivation conditions. A similar position is held by E. Shahini *et al.* (2023), who indicate that excessive environmental sensitivity of genotypes may lead to yield instability and complicate productivity forecasting. The study concludes that one of the key objectives of contemporary plant breeding is the combination of high yield potential with adaptability and stability of trait expression across a wide range of environmental conditions.

O. Erenstein *et al.* (2021), analysing current trends in maize cultivation under conditions of climate change, stated that identical levels of yield may be achieved with fundamentally different levels of stability in trait expression. The researchers draw attention to the fact that highly productive genotypes are not always adaptive and that practical application requires consideration not only of absolute yield values but also of the genotype's ability to maintain them under variable environmental conditions. Important findings concerning the adaptability of parental maize components were obtained by L. Svinitskyi (2023). The author established that inbred lines with high values of the regression coefficient and standard deviation are characterised by increased sensitivity to changes in environmental conditions and insufficient yield stability. Such genotypes are capable of producing high levels of productivity only under favourable growing conditions and high-input agricultural systems. In contrast, lines with moderate regression coefficient values demonstrated greater stability and adaptability to extensive cultivation conditions. A similar position is held by E. Shahini *et al.* (2023), who indicate that excessive environmental sensitivity of genotypes may lead to yield instability and complicate productivity forecasting. It is underlined that one of the key objectives of contemporary plant breeding is the combination of high yield potential with adaptability and stability of trait expression across a wide range of environmental conditions.

Studies by D. Chuiko & R. Kryvoruchenko (2023) and O. Prysiazhniuk & O. Kopytov (2025) demonstrated the effectiveness of using stability variance, coefficient of variation, and phenotypic stability index indicators for the adaptive assessment of crop cultivation technologies. According to the authors, the application of such parameters allows assessing the level of realisation of a genotype's productive potential and determining the limits of technological influence within which maximum stability of economically valuable traits is ensured. In turn, F. Ozair *et al.* (2025), analysing multifactorial field studies of maize, established that accounting for genotype × environment interaction significantly improves the accuracy of predicting hybrid productivity under different ecological conditions. The authors demonstrated that the use of environmental regression models and reaction norm parameters constitutes an effective tool for assessing the adaptability of modern maize genotypes.

Consequently, the results of contemporary studies indicate the importance of a comprehensive assessment of the environmental plasticity, stability, and adaptability of maize hybrids under contrasting hydrothermal regimes. Despite the considerable number of publications available, the features of yield formation and grain quality indicators of medium-early maize hybrids in different soil-climatic zones of Ukraine remain insufficiently explored. The study aimed to determine the environmental plasticity, stability, and adaptability of modern medium-early maize hybrids in terms of yield, protein content, and starch content under different soil-climatic conditions of Ukraine.

LITERATURE REVIEW

The issue of ecological plasticity and stability in maize (*Zea mays* L.) remains one of the key areas of modern plant breeding and agroecology, as it is the genotype's ability to maintain a stable level of productivity under changing environmental conditions that determines the effectiveness of its practical application. In light of climate change, uneven rainfall distribution, and rising temperatures in many regions of the world, studies on genotype × environment interactions are becoming particularly relevant, as they provide for the assessment of the adaptive potential of modern maize hybrids. Multifactorial field trials under various ecological conditions are regarded as the basis for identifying stable and high-yielding genotypes suitable for widespread commercial use. In the work of J. Di Salvo *et al.* (2021), it is shown that modern multifactorial field studies allow for a more accurate prediction of the response of maize genotypes to changes in environmental conditions. The authors emphasise that the assessment of adaptability should be based not only on average yield figures but also on stability parameters, which characterise the degree of trait variability under different environmental conditions. Regression methods proposed by K. Finlay & G. Wilkinson (1963) and S. Eberhart & W. Russell (1966) remain the basis for assessing ecological plasticity and are widely used in contemporary research. Building on these approaches, N. Săulescu *et al.* (2025) determined that the regression coefficient does not always fully characterise yield stability. Therefore, it is advisable to combine it with indicators of minimum predicted yield and the coefficient of variation. The authors demonstrated that genotypes with moderate regression coefficients and low coefficients of variation possess the highest adaptive value under contrasting growing conditions.

Further development of methods for assessing stability involves the use of multidimensional statistical models. H. Gauch (2013) noted the high effectiveness of the AMMI (Additive Main effects and Multiplicative Interaction) model for analysing genotype × environment interactions, as it allows for the simultaneous assessment of the additive effects of genotypes and the environment, along with their multiplicative interaction. According to the author, the use of such models greatly improves the accuracy of interpreting the adaptive properties of genotypes in multi-location trials. A similar view is held by W. Yan & N. Tinker (2006), who emphasise the effectiveness of GGE biplot analysis for visualising the stability and productivity of maize hybrids. The authors indicate that this approach allows not only the identification of the highest-yielding genotypes but also the determination of their specific adaptation to particular ecological zones. Of particular importance is the fact that the GGE biplot enables the assessment of the stability of trait expression in conjunction with yield levels, which is of practical significance for breeding and production.

M. Tollenaar & E. Lee (2002) confirm that modern high-yielding maize hybrids can combine high yields with stable yield formation. The authors attribute this to improvements in the genetic mechanisms of resistance to stress factors, enhanced water use efficiency, and optimisation of plant architecture. In their opinion, modern breeding is aimed not only at increasing potential productivity but also at ensuring stable yield realisation under conditions of variable moisture supply. The influence of climatic factors on maize adaptability was investigated by C. Messina *et al.* (2019), who found that hydrothermal fluctuations significantly alter the response of genotypes to growing conditions. The authors underscore that drought tolerance and water-use efficiency are key components of yield stability under climate change. They also highlight the importance of integrating physiological and statistical approaches to predict the productivity of modern hybrids.

Important findings regarding the adaptability of modern maize hybrids were presented by F. Ozair *et al.* (2025), who determined that accounting for the reaction norms of genotypes and ecological indices allows for a significant improvement in the accuracy of genomic yield prediction across different environments. The authors demonstrated that combining ecological plasticity parameters with genomic models enables effective prediction of hybrid behaviour under contrasting growing conditions.

Ukrainian researchers also devote considerable attention to assessing the ecological plasticity and stability of maize hybrids. Similar conclusions were reached by Ye. Adamshchyk & V. Zakharchenko (2026). The hydrothermal regime is stated to be one of the determining factors in the formation of maize yield and grain quality indicators. They stress that, in the Ukrainian context, multi-year and multi-zone evaluation of hybrids is of particular importance, as it allows for an objective assessment of their adaptability and stability. In particular, significant differentiation has been observed among medium-early hybrids in terms of their adaptive properties, depending on the soil-climatic growing conditions. Genotypes of the intensive type, characterised by a high response to improvements in agronomic conditions, have been identified, as well as stable genotypes suitable for cultivation under high-risk farming conditions.

A study by L. Svinitskyi (2023) showed that maize parental lines with high values for the regression coefficient and standard deviation are characterised by increased sensitivity to changes in environmental conditions and lower yield stability. Genotypes with moderate regression coefficient values proved to be more adaptable to unstable growing conditions and provided a more stable level of productivity. The findings of E. Shahini *et al.* (2023) confirm that excessive sensitivity of genotypes to environmental factors may limit the stability of yield formation. The authors emphasise that one of the key areas of modern breeding is the development of hybrids capable of combining high potential productivity with broad ecological adaptability. Thus, current scientific research indicates a shift from the use of solely classical one-dimensional stability indicators towards comprehensive, multi-factor models for assessing the adaptability of genotypes. Despite a significant number of publications, the issues of ecological plasticity and stability of medium-early maize hybrids under the contrasting soil-climatic conditions of Ukraine remain insufficiently examined, which highlights the need for further research in this area.

MATERIALS AND METHODS

Ten medium-early new maize hybrids were examined, namely: DKC3557, PS 310, RGT KELOXXS, RGT PETERXXON, Optix, EY3957, MIDLAND, MAGNITUDO, KWS PETRARO, and KWS VELARO, which were entered in the State Register of Plant Varieties Suitable for Dissemination in Ukraine in 2025 (n.d.). Field trials were conducted during 2024-2025 at the experimental fields of the branches of the Ukrainian Institute for Plant Variety Testing (UIPVT) in three soil and climate zones: the steppe (Dnipropetrovsk and Kirovohrad branches); forest-steppe (Vinnytsia branch and the Karlivka division of the Poltava branch); Polissia (Transcarpathian, Lviv and Rivne branches) in accordance with the Methodology for examination of cereal… (2016). Yields, adjusted to standard moisture content, were determined according to the Methodology for conducting qualification examination… (2023). The soils of the experimental plots are characteristic of the respective growing zones (steppe, forest-steppe, Polissia). The plot area was 25 m^2, the plot arrangement was randomised, and the experiment was replicated four times.

During the growing season of common maize, the average daily temperature and precipitation were recorded at each site, and the mean values were calculated for the soil-climatic zone. According to preliminary data, the average annual air temperature in 2024 and 2025 in the steppe, forest-steppe, and Polissia regions of Ukraine was higher than the long-term averages by 3.4-4.5, 3.6-4.6, and 2.3-3.6°C, respectively, and averaged +11.9…+13.0, +10.2…+11.3, and +9.5…+10.7°C, respectively. Annual precipitation in 2024 and 2025 averaged 414 and 351 mm in the steppe, 577 and 609 mm in the forest-steppe, and 687 and 613 mm in the Polissia region, which represented, respectively, 98 and 83% of the annual norm in the steppe zone, 106 and 112% in the forest-steppe, and 115 and 102% in the Polissia region.

Laboratory studies were conducted in accordance with the Methodology for conducting qualification examination... (2023). The conditional environment index (*Ij*), ecological plasticity (b_i) and stability (S^2_{di}) were calculated and analysed using the method of S. Eberhart & W. Russel (1966). Based on the results of calculations of the plasticity (b_i) and stability (S^2_{di}) parameters for maize hybrids, the following categories were identified: $b_i < 1$, $S^2_{di} > 0$ – perform better under unfavourable conditions, unstable; $b_i < 1$, $S^2_{di} = 0$ – perform better under unfavourable conditions, stable; $b_i = 1$, $S^2_{di} = 0$ – respond well to improved conditions, stable; $b_i = 1$, $S^2_{di} > 0$ – respond well to improved conditions, unstable; $b_i > 1$, $S^2_{di} = 0$ – perform better under favourable conditions, stable; $b_i > 1$, $S^2_{di} > 0$ – perform better under favourable conditions, unstable. During the research period, weather conditions were contrasting, which allowed for assessing the new maize varieties in terms of plasticity and stability and identifying the best among them.

The overall homeostasis (H_{om}) and breeding value (S_c) of the variety were determined according to L. Burdeniuk-Tarasevych *et al.* (2012). Statistical parameters: the arithmetic mean (), minimum (*min*) and maximum (*max*) values, range of variation (*V*), coefficient of variation (*r*), standard deviation (*σ*), and the Least Significant Difference (LSD) were calculated according to O. Vasylenko & I. Sencha (2011) and V. Bakhrushyn (2011) using Excel 2016 software. The study was conducted in accordance with the ethical standards of the Convention on Biological Diversity (1992) and the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973).

RESULTS AND DISCUSSION

The results obtained confirm that hydrothermal conditions are one of the key factors determining the extent to which the genetic potential of maize hybrids is realised and shaping their adaptive responses in various soil-climatic zones of Ukraine. Spatio-temporal variability in moisture and temperature significantly influenced yield and the biochemical characteristics of the grain, which is consistent with the findings of many recent studies. According to Iu. Lavrynenko *et al.* (2020), a retrospective analysis of cereal crop yields in the arid steppe zone over a 130-year period, showed that maize exhibited the highest rates of yield growth. The authors established that the use of modern hybrids, combined with improved cultivation techniques and irrigation, led to an increase in yield from 6.59 to 82.3 ts/ha. Of particular importance is the researchers' conclusion regarding the need to select hybrids with a genetically programmed response to optimal moisture conditions. The results obtained in the study confirm these findings, as the most adaptable hybrids, RGT KELOXXS, EY3957 and MAGNITUDO were characterised by high regression coefficients (b_i=1.0-1.1) and low stability variance (S^2_{di}=0.2-0.5), indicating their ability to effectively realise their productive potential under improved growing conditions. The significant variability in yield (*V*=36.4-46.1%) confirms the high sensitivity of this trait to changes in hydrothermal conditions.

V. Kozechko & O. Leukhin (2024) emphasise the importance of selecting hybrid maturity groups in accordance with the climatic conditions of the region. According to the authors, the use of hybrids that are not sufficiently early-maturing in cooler zones often leads to a reduction in yield. The results obtained confirm the validity of this approach, as the medium-early hybrids under study in the Polissia and forest-steppe regions demonstrated varying levels of adaptability depending on their response to changes in environmental conditions. This highlights the need for a differentiated selection of hybrids, not only based on yield potential but also on indicators of ecological plasticity and stability. The findings of L. Svinitskyi (2023) regarding the evaluation of parental components of maize hybrids confirm the significant role of weather conditions in determining yield. The author found that the coefficient of variation in yield for self-pollinated lines ranged from 3.3 to 10.0%, and the most valuable genotypes were characterised by high ecological plasticity and stability. Similar patterns were observed in the present study, where hybrids with high breeding value (Optix, PS 310, KWS VELARO) combined adaptability with relative stability of economically valuable traits. The higher values of the coefficient of variation in this study are explained by the more contrasting soil-climatic conditions between the steppe, forest-steppe, and Polissia zones.

An important aspect of the present paper is the refinement of methodological approaches to assessing adaptability. For instance, N. Săulescu *et al.* (2025) demonstrated that assessing plasticity solely on the basis of the regression coefficient is insufficient, and that yield stability should be analysed in conjunction with the minimum predicted yield and the coefficient of variation. In the present study, the comprehensive use of the indicators b_i, S^2_{di}, V, H_{om}, and S_c enabled a more complete assessment of the hybrids' response to changing environmental conditions and the identification of genotypes combining high productivity and stability. This approach is supported by F. Ozair *et al.* (2025), who emphasise the need to account for genotype × environment (G×E) interactions and to use multifactorial models for predicting maize productivity. The authors established that the integration of ecological indices and genomic prediction substantially improves the accuracy of assessing genotype adaptability. The study also confirmed that yield is characterised by significantly higher variability compared with starch content, whilst protein occupies an intermediate position in terms of variability. This indicates differing levels of genetic and environmental determination of individual traits and the need for a comprehensive approach to assessing the adaptive potential of hybrids.

Given the significant influence of hydrothermal conditions on the realisation of the genetic potential of maize hybrids, in addition to the results of recent studies on genotype × environment interactions, a comprehensive assessment of the ecological plasticity, stability, and adaptability of modern hybrids in various agro-ecological zones of Ukraine is of particular relevance. A review of the literature indicates that maize yield and grain quality parameters depend significantly on weather conditions, moisture levels, soil cover characteristics, and the genetic characteristics of the hybrids. Nevertheless, the comparative assessment of the adaptive potential of medium-early hybrids across a range of economically valuable traits under the contrasting soil-climatic conditions of Ukraine remains insufficiently researched. In this regard, a study was conducted to determine the characteristics of yield formation, as protein and starch content in the grain of medium-early maize hybrids, and to assess their ecological plasticity, stability, and adaptability under the conditions of the steppe, forest-steppe, and Polissia regions of Ukraine.

The Selianinov hydrothermal coefficient (HTC) as interpreted by J. Chmist-Sikorska *et al.* (2022) was used to quantitatively assess moisture supply conditions, which combines the ratio of atmospheric precipitation to thermal resources during the growing season. The use of this indicator allows for an objective characterisation of the level of environmental moisture and the assessment of its impact on the ecological plasticity and stability of medium-early maize hybrids in the steppe, forest-steppe and Polissia regions of Ukraine. Overall, in 2024-2025, the hydrothermal conditions in the steppe zone were characterised as arid (HTC = 0.4-0.5), whereas in the forest-steppe they were close to optimal or sufficiently moist (HTC = 1.0-1.4), and in the Polissia zone – predominantly excessively moist (HTC = 1.2-1.3) (Fig. 1). It was established that the hydrothermal coefficient (months IV-X) varied significantly both between years and within individual maize growth stages. During the sowing and seed germination period (April), very dry conditions were observed in the steppe zone (HTC 0.1-0.2), whilst in the forest-steppe in 2024, moisture levels were sufficient (1.1) and in 2025 – they were insufficient (0.5). In the Polissia region, this period was characterised by conditions close to optimal (0.8-0.9). During seedling emergence and early plant growth (May), significant fluctuations were noted in the steppe: ranging from severe drought in 2024 (0.3) to optimal moisture levels in 2025 (1.1). In the forest-steppe during this period in 2025, excessive moisture was observed (2.5), whilst in the Polissia region, moisture levels were elevated (1.9). During the phase of intensive vegetative growth (June), a moisture deficit persisted in the steppe (0.2-0.6), while in the forest-steppe, conditions in 2024 were close to optimal (1.0) and in 2025 – slightly dry (0.6). In the Polissia region during this period, moisture levels were sufficient or excessive (1.3-1.9). During the flowering period (July), the drought persisted in the steppe (0.3), and in the forest-steppe in 2025 there was a significant excess of the norm (2.0), whilst in the Polissia region – excessive moisture (1.4-2.1).

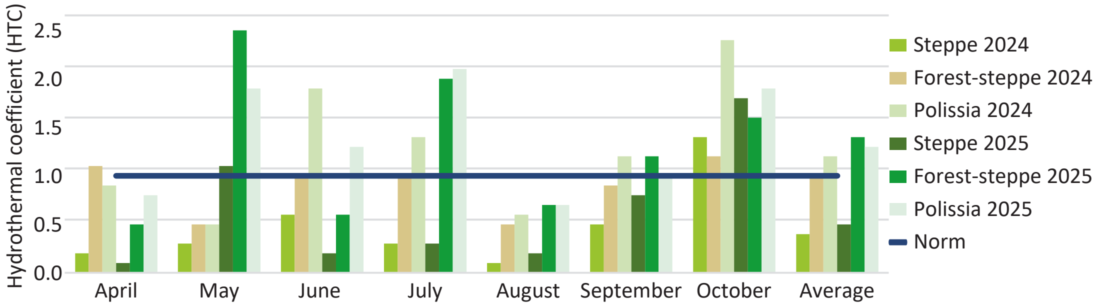

Figure 1. Hydrothermal index based on average daily data for the 2024-2025 study period
Source: compiled by the authors based on data from the Ukrainian Hydrometeorological Center (n.d.)

During the grain-filling stage (August), conditions in the steppe remained dry (0.1-0.2). In the forest-steppe and the Polissia region, they were close to insufficient or moderate moisture levels (0.5-0.7). During the ripening period (September), the steppe continued to experience a moisture deficit (0.5-0.8), while conditions in the forest-steppe and Polissia were close to optimal (1.0-1.2). At full maturity and during harvest (October), sufficient or above-average moisture levels (1.2-2.4) were observed in all zones. Overall, the most favourable hydrothermal conditions for the growth and development of maize (*Zea mays* L.) were identified in the forest-steppe zone, particularly in 2025, whereas in the steppe, arid conditions prevailed throughout most of the growing season. In the Polissia zone, excessive moisture during certain stages of development may have limited the realisation of yield potential. Thus, the contrasting hydrothermal conditions of 2024-2025 substantially influenced the formation of yield and the adaptive properties of maize hybrids, depending on the growing zone. The yield of common maize (*Zea mays* L.) hybrids in 2024-2025 varied significantly depending on soil-climatic conditions and genotype, ranging from 4.58-11.16 t/ha. The highest average yields were achieved by the hybrids RGT PETERXXON (8.4 t/ha), EY3957 (8.3 t/ha), and Optix (8.2 t/ha), while PS 310 (7.4 t/ha) and DKC3557 (7.3 t/ha) showed slightly lower yields (Table 1).

Table 1. Yield parameters and performance indicators of maize hybrids (2024-2025)

Hybrids	Steppe		Forest-steppe		Polissia		min	max	S$\bar{x}$	HIP$_{05}$
	2024	2025	2024	2025	2024	2025				
Yield, t/ha										
DKC3557	5.75	4.71	6.05	6.06	8.30	10.60	1.6	16.1	7.3	2.6
PS 310	5.28	4.84	6.02	6.99	9.12	10.06	3.6	14.6	7.4	2.3
RGT KELOXXS	6.31	4.77	7.53	6.20	9.06	11.14	1.6	16.5	7.9	2.8
RGT PETERXXON	8.23	5.33	8.97	6.59	8.88	11.03	3.1	15.8	**8.4**	2.6
Optix	7.41	4.98	5.84	8.76	9.55	10.65	3.8	15.5	**8.2**	2.3
EY3957	6.89	4.86	9.14	6.63	9.17	**11.16**	1.5	15.3	**8.3**	2.5
MIDLAND	6.34	**4.58**	7.74	4.99	8.66	10.60	1.5	16.2	7.5	2.7
MAGNITUDO	7.15	5.02	7.92	5.81	8.85	10.79	2.1	15.4	7.9	2.6
KWS PETRARO	5.61	4.81	8.33	5.55	8.86	10.70	2.0	15.3	7.7	2.6
KWS VELARO	5.11	5.02	8.49	6.12	9.32	10.43	3.2	14.2	7.8	2.2
LSD$_{05}$	0.9	0.2	1.1	0.9	0.3	0.7				

Table 1, Continued

Hybrids	Steppe		Forest-steppe		Polissia		min	max	$S\bar{x}$	HIP_{05}
	2024	2025	2024	2025	2024	2025				
Protein content, %										
DKC3557	8.0	10.5	10.0	10.8	8.9	8.1	6.4	13.2	9.2	1.4
PS 310	9.2	9.7	9.7	9.7	8.9	7.7	7.1	12.2	9.0	1.2
RGT KELOXXS	9.0	10.4	10.5	11.0	9.4	8.8	7.4	14.6	**9.7**	1.5
RGT PETERXXON	8.9	11.6	10.0	11.3	9.3	8.9	6.3	15.0	**9.9**	1.8
Optix	8.2	10.1	9.1	10.5	9.1	8.5	7.3	12.8	9.2	1.2
EY3957	7.8	10.1	9.0	9.8	7.9	8.1	7.0	12.1	8.7	1.2
MIDLAND	9.8	12.7	11.1	8.9	9.1	9.0	6.1	15.9	**9.9**	1.8
MAGNITUDO	9.3	11.3	10.0	10.9	9.2	8.4	7.6	13.8	**9.7**	1.4
KWS PETRARO	8.2	10.6	9.1	9.4	8.7	8.1	7.0	12.4	8.9	1.2
KWS VELARO	8.2	10.2	9.2	10.3	8.9	8.7	7.0	13.1	9.2	1.3
LSD_{05}	0.6	0.8	0.6	0.7	0.4	0.4				
Starch content, %										
DKC3557	73.7	71.6	73.3	70.4	73.6	74.5	67.6	75.9	**73.0**	1.6
PS 310	73.9	73.0	72.5	70.3	73.3	73.5	69.2	74.3	**72.8**	1.2
RGT KELOXXS	72.5	69.7	71.9	68.8	72.1	71.9	66.9	73.2	71.3	1.5
RGT PETERXXON	73.4	70.7	73.0	69.0	73.2	72.3	67.2	74.2	72.0	1.6
Optix	72.6	71.0	71.8	69.7	72.7	72.9	68.3	73.3	71.9	1.3
EY3957	73.0	71.2	72.8	69.6	73.6	72.8	68.0	74.5	72.3	1.5
MIDLAND	72.1	68.9	71.1	68.3	73.6	73.0	66.2	74.6	71.4	1.9
MAGNITUDO	73.9	71.6	73.2	69.7	73.6	73.2	66.8	74.6	**72.7**	1.5
KWS PETRARO	72.4	71.5	73.1	70.6	73.1	72.6	69.9	74.1	72.3	1.1
KWS VELARO	73.0	71.9	72.6	68.1	72.3	73.2	67.8	74.7	72.0	1.5
LSD_{05}	0.6	1.1	0.7	0.8	0.5	0.6				

Source: compiled by the authors

An analysis of yield by growing zone showed that in the steppe region in 2024, the hybrids produced yields of 5.11-8.23 t/ha, while in 2025, due to dry conditions, this figure fell to 4.58-5.33 t/ha. The difference between the years for most hybrids exceeded the LSD_{05} value (0.2-0.9 t/ha), indicating a significant influence of weather conditions. In the forest-steppe zone, yields were consistently higher, at 5.84-9.14 t/ha in 2024 and 4.99-8.76 g/ha in 2025, with variation within hybrids also exceeding the LSD_{05} value (0.9-1.1 t/ha) in a number of cases, confirming the statistical significance of the differences between genotypes. The highest productivity figures were recorded in the Polissia region – 8.30-9.55 t/ha in 2024 and 10.06-11.16 t/ha in 2025; the increase in yield in 2025 was statistically significant for most hybrids (LSD_{05} = 0.3-0.7 t/ha)

The protein content in the grain of the hybrids ranged from 6.1-15.9%. The highest average values were recorded for the RGT PETERXXON and MIDLAND hybrids (9.9% each), as well as for the RGT KELOXXS and MAGNITUDO hybrids (9.7% each). The difference between the extreme values exceeded the LSD05 (0.4-0.8%), indicating statistically significant differences between the hybrids. It was found that the increase in protein content under steppe conditions, compared with other zones, was also significant in most cases, which is associated with the arid growing conditions. The starch content in the grains of the hybrids varied within the range of 66.2-75.9%. The highest mean values were recorded for the hybrids DKC3557 (73.0%) PS 310 (72.8%), and MAGNITUDO (72.7%), whilst the lowest – for RGT KELOXXS (71.3%) and MIDLAND (71.4%). Differences between individual hybrids and growing zones in most cases exceeded the LSD_{05} (0.5-1.1%), confirming their statistical significance. In the Polissia zone, a trend towards higher starch content was observed, which in some cases was statistically significant compared with other zones. Variation (*V*, %) and homeostasis (H_{om}) characterise the variability of a trait and the genotype's ability to compensate for the effects of stress factors, whilst the selection value index (S_c) integrates the levels of productivity and stability.

The results of the study indicate that weather conditions and soil-climatic zones have a considerable impact on the formation of maize grain yield and biochemical composition. The most favourable conditions for realising the productive potential of the hybrids were observed in the Polissia zone, where the increase in yield was statistically significant. In the steppe, a statistically reliable decrease in yield was observed due to a moisture deficit, but there was a trend towards an increase in protein content. The forest-steppe was characterised by relative stability of indicators, as confirmed by smaller deviations within the LSD_{05} range. Overall, the RGT PETERXXON, EY3957, and Optix hybrids demonstrated high productivity and relative stability of performance indicators, as confirmed by statistically significant differences. This indicates their potential for cultivation under various soil-climate conditions in Ukraine.

An assessment of maize (*Zea mays* L.) hybrids under contrasting conditions in 2024-2025 allowed establishing the characteristics of their response to changes in environmental conditions and determining their level of ecological plasticity, stability, and adaptability (Table 2). The regression coefficient (b_i) characterises a genotype's response to changes in growing conditions: when $b_i \approx 1$, the hybrids are considered plastic; when $b_i > 1$ – more sensitive to improved conditions (intensive type); and when $b_i < 1$ – relatively stable under unfavourable conditions. The stability variance (S^2_{di}) reflects the deviation of observed values from the regression line, with lower values indicating higher stability (D. Chuiko & R. Kryvoruchenko, 2023). The coefficient of variation (V, %) and homeostasis (H_{om}) characterise the variability of a trait and the genotype's ability to compensate for the effects of stress factors, and the selection value index (S_c) integrates the levels of productivity and stability.

In terms of yield, the regression coefficient (b_i) for the hybrids under study ranged within 0.8-1.1, indicating sufficient ecological plasticity in most genotypes. The intensive type, characterised by a heightened response to improved conditions, included RGT KELOXXS, MIDLAND, and KWS PETRARO (b_i = 1.1). Meanwhile, the Optix (b_i = 0.8), PS 310, and KWS VELARO (b_i = 0.9) hybrids were characterised by relatively better adaptation to unfavourable conditions. The most stable yield performance (low values of S^2_{di} = 0.2-0.5) was observed in RGT KELOXXS, MIDLAND, EY3957, and MAGNITUDO, whereas Optix (S^2_{di} = 2.9) exhibited increased trait variability. The coefficient of variation for yield was 36.4-46.1%, indicating a considerable influence of weather conditions during the study years. Optix (36.4%) and KWS VELARO (37.3%) were characterised by the lowest variability. No significant differences between the hybrids were detected in terms of homeostasis (H_{om} = 0.1-0.2); however, in terms of breeding value (S_c), Optix (2.0), PS 310, and KWS VELARO (both 1.8) excelled, indicating their high adaptive potential (Table 2).

Table 2. Parameters of ecological plasticity, stability, and adaptability of maize hybrids in terms of yield and quality indicators (2024-2025)

Hybrids	Parameters of ecological plasticity / stability		Parameters of adaptability		
	b_i	S^2_{di}	V, %	H_{om}	Sc
Yield, t/ha					
DKC3557	1.0	0.9	46.0	0.1	0.7
PS 310	0.9	1.1	39.4	0.2	1.8
RGT KELOXXS	1.1	0.2	45.3	0.1	0.8
RGT PETERXXON	1.0	1.1	39.1	0.2	1.7
Optix	0.8	2.9	36.4	0.2	2.0
EY3957	1.0	0.5	38.8	0.2	0.8
MIDLAND	1.1	0.3	46.1	0.1	0.7
MAGNITUDO	1.0	0.5	41.6	0.2	1.1
KWS PETRARO	1.1	1.0	44.1	0.2	1.0
KWS VELARO	0.9	1.0	37.3	0.2	1.8

Table 2, Continued

Hybrids	Parameters of ecological plasticity / stability		Parameters of adaptability		
	b_i	S^2_{di}	V, %	H_{om}	Sc
Protein content, %					
DKC3557	1.1	0.3	20.0	0.7	4.5
PS 310	0.8	0.4	16.6	1.2	5.2
RGT KELOXXS	1.1	0.7	19.9	0.7	4.9
RGT PETERXXON	1.4	0.3	24.2	0.5	4.1
Optix	0.9	0.2	16.8	1.1	5.2
EY3957	0.9	0.4	18.6	1.1	5.0
MIDLAND	1.1	2.4	23.4	0.4	3.8
MAGNITUDO	1.0	0.3	18.6	0.9	5.3
KWS PETRARO	0.9	0.3	17.1	1.1	5.0
KWS VELARO	1.0	0.2	18.4	0.9	4.9
Starch content, %					
DKC3557	1.1	0.7	2.9	4.2	65.0
PS 310	0.8	0.6	2.1	9.5	67.8
RGT KELOXXS	1.1	0.2	2.7	5.9	65.1
RGT PETERXXON	1.1	0.9	2.8	5.1	65.2
Optix	0.9	0.5	2.3	8.8	67.0
EY3957	1.1	0.4	2.6	5.8	66.0
MIDLAND	1.3	1.1	3.4	3.5	63.4
MAGNITUDO	1.1	0.6	2.7	4.7	65.1
KWS PETRARO	0.7	0.6	1.9	12.7	68.2
KWS VELARO	0.9	1.2	2.7	5.4	65.3

Source: compiled by the authors

The regression coefficient for protein content varied between 0.8 and 1.4. The RGT PETERXXON hybrid proved to be the most sensitive to changes in environmental conditions (b_i=1.4), whilst PS 310 (b_i = 0.8) was characterised by greater stability under various growing conditions. The lowest values for the stability variance (S^2_{di} = 0.2-0.4) were observed in Optix, KWS VELARO, DKC3557, and KWS PETRARO, indicating stable protein content. Meanwhile, MIDLAND (S^2_{di} = 2.4) exhibited significant variability in this trait. The coefficient of variation ranged from 16.6-24.2%, which generally indicates moderate variability in this trait. The highest homeostasis was observed in PS 310 (H_{om} = 1.2), Optix, EY3957, and KWS PETRARO (H_{om} = 1.1), confirming their ability to maintain a stable protein level. In terms of breeding value (S_c = 3.8-5.3), MAGNITUDO (5.3), PS 310, and Optix (both 5.2) were the most prominent.

Starch content showed the lowest variability among the traits examined: the coefficient of variation was only 1.9-3.4%, which indicates that the trait is genetically determined. The values of the regression coefficient (b_i = 0.7-1.3) point to different responses of the hybrids to growing conditions: MIDLAND (b_i = 1.3) showed high sensitivity to improved conditions, while KWS PETRARO (b_i = 0.7) – increased stability. The lowest values of the stability variance (S^2_{di} = 0.2-0.6) were observed in most hybrids, indicating the stability of the trait's expression. High values of homeostasis were observed in KWS PETRARO (12.7), PS 310 (9.5), and Optix (8.8), confirming their ability to maintain a stable starch content. The KWS PETRARO hybrid had the highest breeding value for this trait (S_c = 68.2).

Correlation analysis showed a weak positive correlation (r = 0.28) between yield and the regression coefficient (b_i), indicating a tendency towards increased productivity in more plastic genotypes. A moderate negative correlation (r = -0.38) was identified between yield and the variance of stability (S^2_{di}), confirming a decline in productivity as trait instability increases (Table 3). The strongest correlation was established between yield and the coefficient of variation (V) (r = -0.57), indicating a significant influence of environmental variability on yield formation. A positive correlation between S^2_{di} and V ($r = 0.46$) suggests that as the variability of the trait increases, so does its instability.

Table 3. Correlations between yield and parameters of ecological plasticity and stability in maize hybrids (2024-2025)

Indicator	Yield	b_i	S^2_{di}	V, %
Yield	1.00	0.28	-0.38	-0.57
b_i	0.28	1.00	0.12	0.20
S^2_{di}	-0.38	0.12	1.00	0.46
V, %	-0.57	0.20	0.46	1.00

Source: compiled by the authors

The results obtained show that the maize hybrids under investigation exhibit varying responses to changes in hydrothermal conditions. RGT KELOXXS, EY3957, and MAGNITUDO were distinguished by their combination of high plasticity and yield stability, whilst Optix, PS 310, and KWS VELARO – in terms of adaptability. Optix and KWS PETRARO demonstrated high stability in protein content, while KWS PETRARO and PS 310 showed high stability in starch content. The contrasting weather conditions during the study years provided an opportunity to effectively differentiate the hybrids by their level of adaptability and to identify the most promising genotypes for cultivation in various soil-climatic zones of Ukraine.

CONCLUSIONS

The assessment of parameters of ecological plasticity, stability, and adaptability is an effective approach for identifying promising maize (*Zea mays* L.) hybrids suitable for cultivation in various soil-climatic conditions across Ukraine. The results obtained confirmed the substantial influence of environmental conditions and the hydrothermal regime on the formation of yield and the biochemical parameters of the grain, which highlights the need for multi-year and multi-location studies of modern maize hybrids. In terms of yield, the hybrids RGT KELOXXS, EY3957, and MAGNITUDO ($b_i = 1.0$-1.1; $S^2_{di} = 0.2$-0.5) were distinguished, characterised by high ecological plasticity and stability of yield formation under variable environmental conditions. It was established that these hybrids are capable of effectively realising their genetic potential across a wide range of growing conditions, which attests to their high adaptability. In turn, the Optix, PS 310, and KWS VELARO hybrids ($S_c = 1.8$-2.0) demonstrated high breeding value and can be recommended for use in breeding programmes and grain production under conditions of unstable moisture supply.

By protein content, the Optix, KWS PETRARO, and PS 310 hybrids were highlighted ($b_i = 0.8$-0.9; $S^2_{di} = 0.2$-0.3; $V = 16.6$-17.1%; $H_{om} = 1.1$-1.2; $S_c = 5.0$-5.2), which were characterised by stable expression of the trait and high adaptability under various growing conditions. The highest breeding value for this trait was recorded in the MAGNITUDO hybrid ($S_c = 5.3$), confirming its potential for use as breeding material for selection for higher protein content. In relation to starch content, the KWS PETRARO hybrid ($b_i = 0.7$; $S^2_{di} = 0.6$; $V = 1.9\%$; $H_{om} = 12.7$; $S_c = 68.2$) stood above the rest, characterised by high stability, homeostasis, and breeding value. The PS 310 and Optix hybrids also displayed high stability indices ($H_{om} = 8.8$-9.5; $S_c = 67.0$-67.8), reflecting their ability to maintain a stable biochemical composition of the grain under changing environmental conditions. The results obtained indicate that the maize hybrids under study differ significantly in their response to changes in hydrothermal conditions, which allows them to be effectively differentiated in terms of adaptability and breeding value. The most promising hybrids for cultivation across a wide range of soil-climatic conditions in Ukraine are RGT KELOXXS, EY3957, MAGNITUDO, Optix, and KWS PETRARO, which combine high yield potential, ecological plasticity, stability, and adaptability of economically valuable traits. Prospects for further research lie in expanding multi-year and multi-location trials of maize hybrids in the context of intensifying climate change and instability in hydrothermal conditions. It is advisable to apply modern multidimensional statistical methods, in particular, AMMI and GGE biplot analyses, for an in-depth examination of the genotype × environment interaction. Special attention should be paid to investigating the physiological and biochemical mechanisms underlying the hybrids' resistance to drought and temperature stress, and to determining the relationship between adaptability, grain quality indicators, and the economic efficiency of growing the hybrids in various agro-ecological zones of Ukraine.

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CONFLICT OF INTEREST

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Екологічна пластичність і стабільність середньоранніх гібридів кукурудзи звичайної (*Zea mays* L.) в різних ґрунтово-кліматичних зонах України

Анотація. Метою дослідження було визначити адаптивний потенціал сучасних середньоранніх гібридів кукурудзи за показниками врожайності, вмістом білку та крохмалю в різних ґрунтово-кліматичних умовах України. Польові дослідження проводили упродовж 2024-2025 років у зонах степу, лісостепу та полісся. Екологічну пластичність генотипів оцінювали за коефіцієнтом регресії (b_i), стабільність прояву ознак – за варіансою стабільності (S^2_{di}) та коефіцієнтом варіації (V), адаптивні властивості – за показниками гомеостатичності (Hom) й селекційної цінності (S_c). Встановлено, що досліджувані гібриди характеризувалися високою екологічною пластичністю за показниками урожайності, де значення коефіцієнта регресії становило 0,8-1,1. Найбільш адаптивними та стабільними за врожайністю були гібриди RGT KELOXXS, EY3957 та MAGNITUDO (b_i = 1,0-1,1; S^2_{di} = 0,2-0,5). Гібриди Оптікс, ПС 310 та KWS VELARO характеризувалися підвищеною селекційною цінністю (S_c = 1,8-2,0). Коефіцієнт варіації врожайності становив 36,4-46,1 %, що свідчить про значну залежність ознаки від умов вирощування. За вмістом білку коефіцієнт регресії варіював у межах 0,8-1,4, найбільш стабільним формуванням білку характеризувалися гібриди Оптікс, ПС 310 та KWS PETRARO (S^2_{di} = 0,2-0,3; V = 16,6-17,1 %). Найвищу селекційну цінність за цією ознакою встановлено у гібрида MAGNITUDO (S_c = 5,3). За вмістом крохмалю коефіцієнт варіації був низьким і становив 1,9-3,4 %, що свідчить про високу стабільність ознаки. Найбільш стабільним та адаптивним виявився гібрид KWS PETRARO (b_i = 0,7; V = 1,9 %; H_{om} = 12,7; S_c = 68,2), який характеризувався високими показниками гомеостатичності та селекційної цінності. Встановлено, що врожайність є більш варіабельною ознакою порівняно з вмістом крохмалю, тоді як білок займає проміжне положення за рівнем мінливості. Найбільш перспективними для вирощування в різних ґрунтово-кліматичних умовах України є гібриди RGT KELOXXS, EY3957, MAGNITUDO, Оптікс та KWS PETRARO, які поєднують високу продуктивність, стабільність і адаптивність. Практична цінність роботи полягає у можливості використання отриманих результатів селекціонерами, агрономами та насінницькими компаніями для добору високопродуктивних і адаптивних гібридів кукурудзи в різних агроекологічних зонах України

Ключові слова: гомеостатичність; адаптивність; потенціал врожаю; вміст білку; вміст крохмалю; індекс умовного середовища