Regulatory Mechanisms in Biosystems

ISSN 2519-8521 (Print)
ISSN 2520-2588 (Online)
Regul. Mech. Biosyst.

Yield stability, ecological plasticity and spike productivity reveal adaptive strategies of winter wheat cultivars under hydrothermal variability

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Article info

Received 27.03.2026
Received in revised form 03.05.2026
Accepted 05.06.2026

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Havryliuk, I. V., Kovalyshyna, H. M., Makarchuk, O. S., Litvinov, D. V., Zhyla, R. S., Spriazhka, R. O., & Havryliuk, O. S. (2026). Yield stability, ecological plasticity and spike productivity reveal adaptive strategies of winter wheat cultivars under hydrothermal variability. Regulatory Mechanisms in Biosystems, 17(5), e26092. doi:10.15421/0226092

Climate variability increasingly affects winter wheat production by altering genotype × environment interactions and reducing the predictability of cultivar performance. Identifying cultivars that combine high yield, stability, ecological plasticity, and valuable spike productivity traits is therefore essential for sustainable wheat production under unstable hydrothermal conditions. This study evaluated grain yield, yield stability, ecological plasticity, homeostaticity, and main spike structure traits of 35 Ukrainian winter soft wheat (*Triticum aestivum* L.) cultivars grown in the Right-Bank Forest-Steppe of Ukraine during 2022–2024. Grain yield, coefficient of variation, ecological plasticity coefficient, homeostaticity index, spike rachis length, spike weight, number of spikelets per spike, number of grains per spike, and grain weight per spike were assessed using analysis of variance, correlation analysis, and cluster analysis. The study years differed markedly in hydrothermal conditions, providing a contrasting background for cultivar evaluation. Mean grain yield ranged from 508.4 to 661.7 g/m². The highest productivity was recorded for Tsarivna, Svitanok Myronivskyi, Vodohrai Bilotserkivskyi, Zorepad Bilotserkivska, Kraievyd, MIP Dniprianka, and Kvitka Poliv. Tsarivna and Vodohrai Bilotserkivskyi combined high yield with moderate interannual variability and a balanced ecological response, indicating broad adaptive value. Kesariia Poliska showed the highest homeostaticity and the lowest yield variability, while Romantyka combined stable yield expression with stable spike structure traits. Grain yield was mainly influenced by year and cultivar × year interaction. Correlation analysis revealed strong positive relationships among spike structure traits, particularly between grain number per spike and grain weight per spike, whereas their associations with mean yield were weaker. Cluster analysis distinguished cultivars with different adaptive strategies. The results demonstrate that winter wheat cultivar value cannot be reliably assessed by mean yield alone.

Keywords: winter wheat; *Triticum aestivum*; yield stability; ecological plasticity; genotype; homeostaticity; spike productivity; spike structure traits; adaptability.

Introduction

Wheat is one of the key crops for global food security, as it provides nearly one fifth of the calories and protein consumed worldwide. Its importance is increasing under the growing demand for food, limited natural resources, and the need for sustainable intensification of agricultural production. According to Shiferaw et al. (2013), further improvement in wheat productivity should rely not only on increasing yield potential, but also on developing cultivars adapted to warmer climates, water deficit, diseases, and reduced input use. Therefore, modern wheat breeding and cultivar evaluation should focus not only on maximizing productivity, but also on ensuring stable yield performance under variable environmental conditions.

In this context, cultivar adaptability should be considered one of the essential components of sustainable cereal production. The genetic capacity of a cultivar to maintain productivity under unstable hydrothermal conditions can be complemented by agronomic practices aimed at reducing environmental stress. In particular, Mazurenko et al., (2025) demonstrated that the combined use of biostimulants and intercropping can enhance biomass accumulation and grain yield under the climatic conditions of Ukraine. Although the present study focuses primarily on cultivar adaptability, these findings indicate that stabilizing cereal production under climate variability requires the integration of both genetic and agronomic approaches.

Climate variability increasingly complicates the evaluation and selection of wheat cultivars because it alters the nature of genotype × environment interaction. Xiong et al. (2021) showed that climate change increases the frequency of crossover interactions, leading to changes in genotype ranking for grain yield across environments. This means that cultivars showing high productivity in one environment or year may lose their advantage under different hydrothermal conditions. For winter wheat, weather conditions during autumn development, spring vegetation recovery, heading, flowering, and grain filling are particularly important, as these stages largely determine productive tillering, spike fertility, grain set, and final yield formation.

In rainfed winter wheat production regions, instability in temperature and precipitation patterns creates additional challenges for both breeding and cultivar selection for practical cultivation. Lopes et al. (2018) found that, under the conditions of Turkey and Iran, optimal phenology in winter wheat was closely associated with temperature and precipitation around the heading period. Later-maturing genotypes may be more strongly affected by elevated temperatures and water deficit during grain filling, which can limit yield realization. Similar challenges are also relevant to the Forest-Steppe zone of Ukraine, where recent years have been marked by increasing temperatures, uneven precipitation distribution, and a growing influence of stressful weather periods on winter wheat yield formation.

For the Ukrainian Forest-Steppe, previous studies have shown that modern winter wheat cultivars are capable of producing high yields; however, their adaptive potential is not always sufficient to ensure stable productivity under variable weather conditions. Shtakal et al. (2022) reported that, during 2010–2021, the mean daily air temperature from April to October increased in the Forest-Steppe zone, while total precipitation decreased compared with the long-term average. The authors also emphasized the dependence of yield on autumn precipitation and the negative response of most cultivars to higher temperatures during grain formation. These findings highlight the need for multi-year cultivar evaluation under specific soil and climatic conditions, as mean yield alone, without considering stability and the type of adaptive response, does not provide a comprehensive characterization of cultivar performance. One of the key methodological approaches to cultivar evaluation under variable conditions is the analysis of genotype × environment interaction, ecological plasticity, and yield stability. Multi-environment wheat studies have shown that environment is often the main source of yield variation, while genotype × environment interaction may exceed the direct genotypic effect (Mohammadi et al., 2009; Kucek et al., 2019). The use of AMMI, GGE biplot, cluster analysis, and other multivariate approaches makes it possible not only to identify high-yielding cultivars, but also to distinguish genotypes with broad or specific adaptation (Mohammadi et al., 2009; Mądry et al., 2012). For breeding and commercial production, cultivars that combine high yield with moderate variability, homeostaticity, and the ability to maintain productivity under contrasting conditions are of particular value.

Along with grain yield, spike structure traits are important indicators of the morphoproductive potential of wheat plants. Grain number per spike, grain weight per spike, spike weight, and spikelet fertility are key components involved in yield formation. Würschum et al. (2018) based on the analysis of 407 winter wheat cultivars, showed that long-term breeding progress in grain yield was largely associated with an increase in grain number per spike and spikelet fertility. Tsenov et al. (2020) also reported strong and significant relationships between grain yield and such traits as grain number per spike, grain weight per spike, and grain number per unit area. At the same time, these traits may vary considerably under environmental influence; therefore, they should be evaluated together with adaptive parameters.

Despite the considerable number of studies addressing yield, stability, and genotype × environment interaction, the integration of these approaches with a detailed analysis of main spike structure remains insufficiently explored under the conditions of the Right-Bank Forest-Steppe of Ukraine. An integrated evaluation of Ukrainian-bred cultivars based on mean yield, coefficient of variation, ecological plasticity, homeostaticity, morphoproductive spike traits, factor contribution, and cluster differentiation is therefore particularly relevant. Such an approach makes it possible not only to identify high-yielding cultivars, but also to distinguish genotypes with different adaptive strategies and breeding value.

The scientific novelty of this study lies in the integrated assessment of Ukrainian winter wheat cultivars through the combined analysis of grain yield, ecological plasticity, homeostaticity, main spike structure traits, factor contribution, and cluster grouping under the contrasting hydrothermal conditions of the Right-Bank Forest-Steppe of Ukraine. We hypothesized that cultivars with similar mean yield may differ substantially in stability, type of ecological response, and morphoproductive spike traits, reflecting different adaptive strategies of genotypes.

The aim of this study was to evaluate grain yield, ecological plasticity, homeostaticity, and main spike structure traits of Ukrainian winter wheat cultivars under the conditions of the Right-Bank Forest-Steppe of Ukraine, and to identify genotypes with different adaptive strategies based on an integrated statistical analysis.

Materials and methods

Study site and soil conditions. The study was conducted during 2022–2024 in the experimental fields of the Department of Genetics, Plant Breeding and Seed Production named after Prof. M. O. Zelenskyi, National University of Life and Environmental Sciences of Ukraine, at the Agronomic Research Station. The experimental site is located near Pshenycne village, Bila Tserkva district, Kyiv region, in the northern part of the Right-Bank Forest-Steppe of Ukraine. The geographical coordinates of the experimental site are 50.076803° N, 30.220293° E.

The study area belongs to the Forest-Steppe soil-climatic zone of Ukraine and is characterized by flat relief. The parent material of the experimental field is loess-like loam with signs of gleying and an increased content of calcium carbonates. The soil profile is characterized by a deep humus horizon of 90–95 cm. According to its particle-size distribution, the soil is coarse-dust light loam, while the upper arable layer has a granular-dusty structure, which provides favorable water-physical and aeration properties. The humus content in the upper arable layer is approximately 4.6%. The content of available phosphorus ranges from 3.3 to 3.4 mg per 100 g of soil, while exchangeable potassium ranges from 9.8 to 10.3 mg per 100 g of soil. The soil reaction is slightly alkaline, with pH values of 8.1–8.3. The soil supply of nitrogen and phosphorus is assessed as medium, whereas potassium availability is low. Groundwater occurs at a depth of 2.0–2.5 m, and the soil water regime is mainly determined by atmospheric precipitation and soil moisture accumulation.

Plant material. The plant material consisted of 35 winter soft wheat (*Triticum aestivum* L.) cultivars of Ukrainian breeding developed by leading breeding institutions of Ukraine. The studied set included cultivars originating from Bila Tserkva Experimental Breeding Station, the National Scientific Center "Institute of Agriculture of NAAS", and the V. M. Remeslo Myronivka Institute of Wheat of NAAS. Cultivars were selected according to their breeding origin, recommended growing zone, year of state registration, maturity group and grain quality category based on the State Register of Plant Varieties Suitable for Dissemination in Ukraine.

The cultivar set represented genotypes differing in breeding background, adaptive potential, productivity and spike structure traits. This made it possible to evaluate genotypic variation in grain yield, yield stability, ecological plasticity and individual spike productivity under the conditions of the Right-Bank Forest-Steppe of Ukraine.

Table 1
Winter soft wheat plant material used in the study

Cultivar	Recommended growing zone	Originator	Breeding method	Year of registration
Vidrada	SFP	BTES	SB	2010
Lybid	SFP	BTES	–	2006
Charodiika Bilotserkivska	FP	BTES	SB	2011
Legenda Bilotserkivska	SFP	BTES	SB	2017
Kvitka Poliv	SFP	BTES	SB	2018
Lisova Pisnia	FP	BTES	–	2008
Vodohrai Bilotserkivskyi	FP	BTES	SB	2014
Perlyna Lisostepu	FP	BTES	–	2001
Rozumnytsia	F	BTES	–	2019
Romantyka	FP	BTES	–	2009
Hratsiia Bilotserkivska	SFP	BTES	SB	2017
Tsarivna	FP	BTES	–	2008
Ros	FP	BTES	SB	2019
Zorepad Bilotserkivska	SFP	BTES	SB	2017
Hadzynka	SFP	BTES	SB	2020
Kraievyd	SFP	IA	SB	2013
Pamiati Hirka	SF	IA	SB	2017
Myroliubna	FP	IA	SB	2018
Vodohrai	SFP	IA	SB	2018
Spivanka Poliska	SFP	IA	SB	2018
Polisianka	FP	IA	SB	2018
Efektna	P	IA	SB	2020
Pyriatynka	F	IA	SB	2020
Liubito	SFP	IA	SB	2022
Fortetsia Poliska	SFP	IA	SB	2020
Namysto	FP	IA	SB	2018
Merezhka	F	IA	SB	2018
Kesariia Poliska	SF	IA	SB	2017
Poliska 90	FP	IA	–	1994
Berehynia Myronivska	S	MIW	SB	2016
Hospodynia Myronivska	SF	MIW	SB	2017
MIP Dniprianka	FP	MIW	SB	2018
MIP Kniazhna	SP	MIW	SB	2017
Oberih Myronivskyi	FP	MIW	SB	2014
Svitanok Myronivskyi	SP	MIW	SB	2014

Note: information is given according to the State Register of Plant Varieties Suitable for Dissemination in Ukraine; abbreviations used in the table: BTES – Bila Tserkva Experimental Breeding Station; IA – National Scientific Center "Institute of Agriculture of NAAS"; MIW – V. M. Remeslo Myronivka Institute of Wheat of NAAS; S – Steppe; F – Forest-Steppe; P – Polissia; SB – selection breeding; MR – medium-early; MM – medium-maturing; ER – early-maturing; SW – strong wheat; VW – valuable wheat; Filler – filler wheat.

Experimental design and crop management. Field experiments were conducted during 2022–2024 in three replications. The experimental variants were arranged randomly, which helped to reduce the influence of local soil and microclimatic heterogeneity on cultivar performance. The accounting plot area was 6 m². The seeding rate was 4.5 million viable seeds per hectare. Maize grown for grain was used as the preceding crop.

All cultivars were grown under uniform agronomic conditions within each year of the study. This allowed a reliable comparison of genotypic differences and cultivar responses to natural interannual variation in weather conditions. Since the study focused on cultivar-specific differences in grain yield, yield stability, ecological plasticity and spike structure traits, crop management practices were not considered as a separate experimental factor.

The field experiment was designed to evaluate the response of winter soft wheat cultivars to growing conditions in the northern part of the Right-Bank Forest-Steppe of Ukraine. This experimental design made it possible to determine not only the average yield level of the cultivars, but also the nature of their adaptive response under contrasting hydrothermal conditions during 2022–2024.

Grain yield and spike structure assessment. Grain yield of winter soft wheat cultivars was determined by harvesting grain from each accounting plot. The obtained values were expressed in g/m^2. For further analysis, grain yield data for 2022, 2023 and 2024 were used, together with the mean yield across the study years, standard deviation and coefficient of variation.

To characterize individual plant productivity, the structure of the main spike was analyzed. Measurements were performed on 20 plants from each experimental variant. The following traits were recorded: spike length, spike weight, number of spikelets per spike, number of grains per spike and grain weight per spike.

Spike structure traits were used to assess the morphoproductive potential of cultivars and to determine the relationship between individual productivity components and grain yield. Combining grain yield assessment with spike structure analysis made it possible to identify cultivars that achieved higher productivity through increased spike weight, higher number of grains per spike or greater grain weight per spike, as well as to evaluate the stability of these traits under contrasting conditions during the study years.

Weather conditions and hydrothermal indices. Weather conditions during the study years were characterized using mean monthly air temperature and total precipitation during the main growth and development periods of winter wheat. To assess the contrast between the study years, actual meteorological values were compared with long-term averages calculated for the most recent 30-year observation period.

Standardized anomalies, or z-scores, were calculated to quantify deviations of air temperature and precipitation from long-term mean values. This index makes it possible to compare deviations of different meteorological parameters on a dimensionless scale and to determine whether weather conditions in individual months and years were typical or atypical.

The standardized anomaly was calculated as follows:

$$\mathrm{Z} = \frac{Xi - \mu}{\sigma}$$

where Z is the standardized anomaly, Xi is the observed value of a meteorological parameter during a given period, μ is the mean value of the corresponding meteorological parameter for the most recent 30-year observation period, and σ is the standard deviation of this parameter over the same period.

Z-score values between –1 and +1 were considered to indicate conditions close to typical. Values from –1 to –2 or from +1 to +2 were interpreted as moderate deviations from the long-term mean. Values below –2 or above +2 indicated extreme or rare weather conditions.

To assess the balance between heat and moisture supply, the hydrothermal coefficient (1928) was used. It was calculated as the ratio of total precipitation during the period with mean daily air temperature above 5 °C to the sum of active temperatures over the same period divided by 10:

$$\mathrm{HTC} = \frac{\Sigma \mathrm{P} * 10}{\Sigma \mathrm{T}}$$

where HTC is the hydrothermal coefficient, ΣP is total precipitation for the corresponding period, mm, and ΣT is the sum of active temperatures during the period with mean daily air temperature above 5 °C.

The obtained HTC values were used to characterize moisture conditions during the study years and during individual periods of the winter wheat growing season. HTC values were interpreted according to the scale presented in Table 2.

Table 2
Interpretation scale for the hydrothermal coefficient

HTC value	Hydrothermal condition
< 0.4	Extremely dry conditions
0.4–0.5	Severely dry conditions
0.6–0.7	Moderately dry conditions
0.8–0.9	Slightly dry conditions
1.0–1.5	Adequate moisture conditions
> 1.5	Excessive moisture conditions

The combined use of z-scores and the hydrothermal coefficient provided an integrated assessment of weather conditions, made it possible to determine their deviation from the climatic norm for the most recent 30-year period, and allowed the relationship between hydrothermal conditions and grain yield formation in winter soft wheat cultivars to be evaluated.

Statistical analysis. Experimental data were processed using analysis of variance, correlation analysis and cluster analysis. For the primary characterization of trait variability, arithmetic mean, standard deviation and coefficient of variation were calculated. Grain yield and spike structure traits were analyzed separately by study year and as mean values for 2022–2024.

The coefficient of variation was calculated to assess variability in grain yield and spike structure traits:

$$\mathrm{CV} = \frac{SD}{\bar{x}} * 10$$

where CV is the coefficient of variation, %, SD is the standard deviation, and $\bar{x}$ is the mean value of the trait.

The effects of cultivar, year and their interaction on grain yield and spike structure traits were assessed using two-way analysis of variance. The statistical model included cultivar, year and cultivar × year interaction as sources of variation. Statistical significance was evaluated at $P \leq 0.05$. Mean comparisons among cultivars were performed using Tukey's HSD test at $P \leq 0.05$.

Homeostaticity of cultivars was assessed using the Hom index, which characterizes the ability of a genotype to maintain stable trait expression under variable environmental conditions:

$$Hom = \frac{\bar{x}^2}{S^2}$$

where Hom is the homeostaticity index, $\bar{x}$ is the mean value of the trait, and S^2 is the variance. Higher Hom values were interpreted as indicating a higher level of trait stability under contrasting conditions during the study years.

The environmental index Ij was calculated to characterize the favorability of each study year. It was defined as the deviation of the mean yield of all cultivars in a given year from the grand mean yield across all study years:

$$\mathrm{Ij} = \bar{x}j - \bar{x}$$

where Ij is the environmental index for the j-th year, $\bar{x}j$ is the mean yield of all cultivars in the j-th year, and $\bar{x}$ is the grand mean yield across all study years. Positive Ij values indicated more favorable conditions for yield formation, whereas negative values indicated less favorable conditions.

Ecological plasticity of cultivars was assessed using the regression coefficient bi, calculated from the response of cultivar yield to changes in the environmental index. Values of bi ≈ 1 indicated an average response to environmental variation; bi > 1 indicated an intensive response type with a greater ability to realize yield potential under favorable conditions; and bi < 1 indicated lower sensitivity to environmental changes and potentially higher stability under unfavorable conditions.

Correlation analysis was used to determine relationships between grain yield, spike structure traits and hydrothermal conditions. The strength and direction of relationships were assessed using Pearson's correlation coefficient. Statistical significance of correlations was evaluated at $P \leq 0.05$.

Cluster analysis was applied to group cultivars according to a complex of yield, stability, ecological plasticity and spike structure traits. Before clustering, all variables were standardized, which allowed traits expressed in different units to be compared on a common scale. The clustering matrix included mean grain yield, coefficient of variation for yield, homeostaticity index, ecological plasticity coefficient, spike weight, number of grains per spike and grain weight per spike. Variability indicators were interpreted considering that lower CV values correspond to greater cultivar stability.

The analysis of meteorological conditions during 2022–2024 revealed pronounced interannual variability in temperature regime and moisture supply during the winter wheat growing period (Table 3). The temperature regime was characterized mainly by positive deviations from the long-term average, indicating a general warming tendency. This trend was most clearly expressed in 2024, when the mean annual temperature reached 11.47 °C, exceeding the long-term norm by 2.64 °C. In this year, elevated temperatures were observed in most months, especially in April, June, July, August and September. The maximum temperature in July 2024 reached 36.0 °C, indicating increased summer heat stress during the vegetation period.

In 2022, temperature conditions were generally close to typical, although negative deviations were recorded in April and May. This could have slightly limited spring vegetation recovery and early formation of productive tillers. At the same time, June 2022 was characterized by a positive temperature anomaly (z-score = 1.03), coinciding with important stages of generative development.

In 2023, temperature deviations were predominantly positive. The most pronounced positive anomalies were observed in January, March, August, October, November and December. This indicates a general softening of the cold period and an elevated annual temperature background. During the vegetation period, most values remained within typical or moderately warmer-than-average conditions.

The strongest warming pattern was observed in 2024. Z-score values reached 1.24 in April, 1.41 in July and 1.12 in September. These values indicate moderately anomalous warm conditions during periods important for spring growth, grain filling and post-harvest soil moisture accumulation. Higher spring and summer temperatures may accelerate plant development but also increase the risk of heat stress, especially under limited moisture supply.

Precipitation during the study years was also unevenly distributed. In contrast to temperature, where positive anomalies predominated, precipitation was characterized by a more contrasting pattern, with some months showing moisture deficit and others excessive precipitation (Table 4).

Table 3
Monthly standardized temperature anomalies in 2022–2024

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2022	0.75	0.79	0.09	-0.68	-0.90	1.03	-0.08	0.60	-0.33	0.68	0.60	0.54
2023	1.18	0.41	0.98	-0.09	0.65	0.23	0.13	0.97	0.79	0.96	1.27	1.04
2024	0.21	1.10	1.02	1.24	0.88	0.95	1.41	0.83	1.12	0.79	0.14	0.79

Note: Z-score values within ±1 indicate conditions close to typical; values between ±1 and ±2 indicate moderate deviations from the long-term average; values exceeding ±2 indicate extreme conditions.

Table 4
Monthly standardized precipitation anomalies in 2022–2024

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2022	-0.60	-1.30	-1.06	-0.02	-0.69	0.07	-0.02	1.10	0.60	0.13	0.70	0.20
2023	-0.16	-0.55	0.66	0.99	-0.90	0.08	1.40	-0.83	-0.97	0.99	1.22	1.23
2024	0.13	0.03	0.06	0.05	0.00	0.04	0.01	0.02	0.01	0.06	0.02	0.06

In 2022, precipitation deficit was typical for the winter–spring period, especially in February (z-score = -1.30) and March (z-score = -1.06). In May, a negative deviation was also recorded (-0.69), which could have affected vegetative growth and the formation of yield components. Increased precipitation was observed in August (z-score = 1.10); however, this period had limited influence on final grain yield formation. In 2023, precipitation distribution was the most contrasting. In April, precipitation was close to the upper limit of typical values (z-score = 0.99), whereas May was characterized by moisture deficit (–0.90). In July, excessive precipitation was recorded (z-score = 1.40), which may have partially compensated for previous moisture shortages. However, negative deviations in August and September indicate an unstable moisture regime during the year.

In 2024, standardized precipitation anomalies were close to zero in most months, indicating that monthly precipitation totals were generally close to the long-term average. However, this did not necessarily mean optimal water availability throughout the vegetation period, as the hydrothermal coefficient revealed strong monthly variation in the balance between heat and moisture (Table 5).

Table 5
Hydrothermal coefficient during the active vegetation period of winter wheat in 2022–2024

Year	Apr	May	Jun	Jul	Aug	Sep	Oct
2022	0.32	0.42	0.87	0.76	1.17	1.83	0.76
2023	0.66	0.18	0.98	2.46	0.24	0.27	1.15
2024	0.84	0.21	2.00	0.50	0.20	0.32	3.00

In 2022, the spring period was characterized by moisture deficit. HTC values were 0.32 in April, corresponding to extremely dry conditions, and 0.42 in May, corresponding to severely dry conditions. In June and July, conditions remained slightly to moderately dry. Adequate and excessive moisture conditions were observed only in August and September, but these later periods could not fully compensate for moisture deficit during the active formation of yield components. Thus, 2022 can be characterized as a year with spring and early-summer moisture deficiency. In 2023, May was the most critical month, with HTC reaching only 0.18, indicating extremely dry conditions. This could negatively affect productive tillering and the formation of spike productivity components. In contrast, HTC in July reached 2.46, indicating excessive moisture. Such a shift from extremely dry conditions in May to excessive moisture in July demonstrates a highly uneven hydrothermal regime. August and September were again very dry, which may have affected post-harvest soil moisture accumulation and preparation for the next vegetation cycle.

In 2024, hydrothermal conditions were particularly contrasting. In May, HTC was 0.21, corresponding to extremely dry conditions, whereas in June it reached 2.00, indicating excessive moisture. In July and August, moisture deficit was again observed, especially in August, when HTC decreased to 0.20. In October, HTC increased sharply to 3.00, indicating excessive moisture. Thus, 2024 combined an elevated temperature background with a highly uneven distribution of moisture during the vegetation period.

Statistical calculations were performed using Microsoft Excel and specialized statistical add-ins. Results were presented as mean values with corresponding variability parameters (Altman & Bland, 2005; Agbangba et al., 2024). Differences were considered statistically significant at $P \leq 0.05$.

Results

The contrasting hydrothermal conditions during 2022–2024 were clearly reflected in the mean grain yield of winter soft wheat cultivars.

Across the studied cultivars, the highest average yield was recorded in 2022 (683.53 g/m²), which exceeded the three-year mean by 97.24 g/m² (Table 6). The positive environmental index confirms that 2022 created the most favorable conditions for realizing cultivar productivity potential.

Table 6
Mean grain yield, environmental index and hydrothermal favorability of winter soft wheat cultivars in the Forest-Steppe soil-climatic zone of Ukraine during 2022–2024

Year	Mean grain yield, g/m²	Environmental index Ij	General assessment of conditions
2022	683.53	+97.24	The most favorable conditions for yield formation
2023	468.89	-117.39	The least favorable conditions, pronounced stress background
2024	606.44	+20.15	Moderately favorable but hydrothermally contrasting conditions

Note: positive environmental index values indicate more favorable conditions for grain yield formation compared with the three-year mean for 2022–2024, whereas negative values indicate less favorable conditions.

The lowest mean yield was obtained in 2023 – 468.89 g/m². The environmental index for this year was -117.39 g/m², indicating the least favorable background for grain yield formation. This is consistent with the hydrothermal analysis, as 2023 was characterized by highly uneven moisture supply: extremely dry conditions in May with HTC of 0.18, excessive moisture in July with HTC of 2.46.

In 2024, the mean yield was 606.44 g/m², and the environmental index was positive – +20.15 g/m². This indicates generally moderately favorable conditions for yield formation, although the year was characterized by strong hydrothermal contrast. In particular, the combination of elevated temperature background, extremely dry conditions in May, excessive moisture in June created heterogeneous effects on cultivar productivity realization.

Thus, the environmental index confirmed the contrast between the study years: 2022 was the most favorable year, 2023 was the most stressful, and 2024 occupied an intermediate position in terms of environmental favorability but showed pronounced hydrothermal unevenness. Such environmental contrast provides a valuable background for further assessment of ecological plasticity, stability and homeostaticity of winter soft wheat cultivars.

Yield performance, variability and adaptive parameters of winter soft wheat cultivars. The evaluation of winter soft wheat cultivars was based on a set of parameters characterizing the realization of productive potential, interannual yield variability, and the adaptive response of genotypes to changes in growing conditions. The analysis included mean grain yield, standard deviation, coefficient of variation, ecological plasticity coefficient (bi), and homeostaticity index (Hom) (Table 7).

Mean grain yield of the studied cultivars ranged from 508.4 to 661.7 g/m², indicating substantial genotypic differentiation in productivity. The highest mean yield values were recorded for Tsarivna (661.7 g/m²), Svitanok Myronivskyi (658.2 g/m²), Vodohrai Bilotserkivskyi (654.3 g/m²), Zorepad Bilotserkivska (639.4 g/m²), Kraievyd (633.5 g/m²), MIP Dniprianka (626.3 g/m²), and Kvitka Poliv (625.1 g/m²). According to the multiple comparison test, Tsarivna and Svitanok Myronivskyi belonged to the highest statistical group, confirming their high productivity under the conditions of the Right-Bank Forest-Steppe of Ukraine.

At the same time, cultivars with similar mean yield levels differed considerably in interannual variability. Tsarivna combined the highest mean yield with a moderate coefficient of variation (CV = 15.07%) and a bi value close to unity (bi = 0.92). This combination of parameters characterizes this cultivar as a highly productive genotype with a balanced response to changes in yearly conditions. A similar pattern of yield realization was observed for Vodohrai Bilotserkivskyi, which had a mean yield of 654.3 g/m², CV of 17.19%, and bi of 0.87.

Svitanok Myronivskyi was only slightly inferior to Tsarivna in mean grain yield; however, it showed substantially higher interannual variability (CV = 29.49%) and a higher ecological plasticity coefficient (bi = 1.68). This indicates a more intensive type of genotypic response, in which high productivity depends largely on the favorability of yearly conditions. A similar trend was observed for MIP Dniprianka: despite its high mean yield (626.3 g/m²), this cultivar had a CV of 28.97% and a bi value of 1.60.

Table 7
Grain yield, interannual variability and adaptive parameters of winter soft wheat cultivars during 2022–2024 (mean ± SD, n = 90)

Cultivar	Mean yield, g/m²	CV, %	bi	Hom
Tsarivna	661.7 ± 99.7[a]	15.1	0.92	44.1
Svitanok Myronivskyi	658.2 ± 194.1[a]	29.5	1.68	11.5
Vodohrai Bilotserkivskyi	654.3 ± 112.4[ab]	17.2	0.87	33.9
Zorepad Bilotserkivska	639.4 ± 102.4[bc]	16.0	0.56	39.0
Kraievyd	633.5 ± 130.0[cd]	20.5	1.15	23.7
MIP Dniprianka	626.3 ± 181.4[cde]	29.0	1.60	11.9
Kvitka Poliv	625.1 ± 113.6[cde]	18.2	-1.01	30.3
Hadzynka	621.9 ± 136.2[def]	21.9	0.73	20.8
Pyriatynka	620.8 ± 146.8[defg]	23.7	1.33	17.9
Ros	619.3 ± 114.2[defg]	18.4	0.21	29.4
Hospodynia Myronivska	614.1 ± 189.6[efgh]	30.9	1.59	10.5
Romantyka	608.0 ± 43.5[fgh]	7.2	0.40	195.1
Vodohrai	607.6 ± 159.5[fgh]	26.3	0.76	14.5
Lybid	606.5 ± 209.3[ghi]	34.5	1.86	8.4
Spivanka Poliska	603.8 ± 132.8[hij]	22.0	1.18	20.7
Namysto	600.0 ± 195.6[hij]	32.6	1.80	9.4
Rozumnytsia	592.1 ± 166.0[ijk]	28.0	1.45	12.7
Polisianka	590.2 ± 220.7[jk]	37.4	2.01	7.2
Kesariia Poliska	583.7 ± 11.5[kl]	2.0	-0.09	2598.8
Vidrada	583.4 ± 208.9[kl]	35.8	1.80	7.8
Oberih Myronivskyi	577.5 ± 193.7[kl]	33.6	1.74	8.9
Fortetsia Poliska	574.3 ± 150.1[l]	26.1	1.25	14.6
Perlyna Lisostepu	573.0 ± 153.9[l]	26.8	-0.06	13.9
Berehynia Myronivska	569.2 ± 171.8[lm]	30.2	1.57	11.0
Merezhka	556.7 ± 126.6[mn]	22.7	1.05	19.3
Liubito	554.9 ± 128.4[mn]	23.1	1.03	18.7
MIP Kniazhna	553.5 ± 230.4[mn]	41.6	2.04	5.8
Charodiika Bilotserkivska	550.5 ± 59.3[n]	10.8	0.46	86.1
Hratsiia Bilotserkivska	548.2 ± 82.0[n]	15.0	-0.50	44.7
Lisova Pisnia	532.4 ± 114.7[o]	21.5	0.16	21.6
Legenda Bilotserkivska	522.4 ± 346.0[op]	66.2	3.17	2.3
Pamiati Hirka	519.8 ± 103.2[op]	19.8	0.30	25.4
Poliska 90	518.3 ± 155.0[op]	29.9	1.40	11.2
Myroliubna	510.9 ± 95.4[p]	18.7	0.41	28.7
Efektna	508.4 ± 62.6[p]	12.3	0.21	66.0

Note: mean values followed by different letters differ significantly according to Tukey's HSD test at $P \leq 0.05$; SD – standard deviation; CV – coefficient of variation; bi – ecological plasticity coefficient; Hom – homeostaticity index.

A separate group consisted of cultivars with high or medium yield levels but lower interannual variability. The most pronounced example was Kesariia Poliska, for which the coefficient of variation was only 1.96%, while the homeostaticity index reached 2598.8. Although its mean yield (583.7 g/m²) was not among the highest, this cultivar showed the most uniform yield expression across the study years. A high level of homeostaticity was also recorded for Romantyka (Hom = 195.1; CV = 7.16%), Charodiika Bilotserkivska (Hom = 86.1; CV = 10.77%), and Efektna (Hom = 66.0; CV = 12.31%).

Among the cultivars with moderate or low yield variability, Zorepad Bilotserkivska, Hratsiia Bilotserkivska, and Ros should also be noted. In particular, Zorepad Bilotserkivska combined high mean yield (639.4 g/m²) with a relatively moderate coefficient of variation (16.02%) and a sufficiently high homeostaticity index (39.0). Hratsiia Bilotserkivska had a lower mean yield (548.2 g/m²), but its CV was 14.96% and Hom reached 44.7, indicating more stable yield expression compared with genotypes of the intensive response type. The highest interannual yield variability was recorded for Legenda Bilotserkivska, with a CV of 66.22%, SD of 346.0, and a homeostaticity index of only 2.3. The high bi value (3.17) indicates a strongly pronounced response of this genotype to changes in environmental conditions. Increased yield variability was also characteristic of MIP Kniazhna (CV = 41.63%; bi = 2.04), Polisianka (CV = 37.39%; bi = 2.01), Vidrada (CV = 35.81%; bi = 1.80), Lybid (CV = 34.49%; bi = 1.86), and Oberih Myronivskyi (CV = 33.55%; bi = 1.74). These cultivars showed greater sensitivity to yearly conditions and a wider amplitude of yield fluctuations. The values of the ecological plasticity coefficient made it possible to differentiate the cultivars according to the type of adaptive response. Genotypes with bi > 1, including Legenda Bilotserkivska, MIP Kniazhna, Polisianka, Lybid, Namysto, Vidrada, Oberih Myronivskyi, Svitanok Myronivskyi, and MIP Dniprianka, were characterized by an increased response to changes in environmental conditions. These cultivars may realize their productive potential more effectively under favorable conditions; however, under stress conditions, their yield declined more markedly.

Cultivars with bi values close to unity, such as Tsarivna (0.92), Vodohrai Bilotserkivskyi (0.87), Liubito (1.03), Merezhka (1.05), and Kraievyd (1.15), showed a more balanced response to changes in yearly conditions. These genotypes were characterized by a combination of adequate productivity and moderate ecological responsiveness.

Negative or near-zero bi values were recorded for Kvitka Poliv (-1.01), Hratsiia Bilotserkivska (-0.50), Kesariia Poliska (-0.09), and Perlyna Lisostepu (-0.06). This type of response differed from the general pattern of yield change across years and may be associated with a specific genotypic response to particular combinations of temperature regime and moisture supply.

Spike structure traits of winter soft wheat cultivars. The analysis of main spike structure made it possible to characterize in greater detail the morphoproductive features of cultivars that differed in yield level and adaptive response. The assessment included spike rachis length, spike weight, number of spikelets per spike, number of grains per spike, and grain weight per spike. These traits reflect the potential of individual plant productivity and make it possible to determine which spike components contributed to yield realization in individual genotypes. Spike rachis length ranged from 5.2 cm in Vodohrai to 9.1 cm in Legenda Bilotserkivska. The longest spike rachis was recorded in Legenda Bilotserkivska and Spivanka Poliska, with values of 9.1 and 8.5 cm, respectively; these cultivars formed the highest statistical groups for this trait. High values were also observed in Hadzynka (7.8 cm), Kvitka Poliv (7.7 cm), Myroliubna (7.6 cm), Vodohrai Bilotserkivskyi (7.4 cm), and Tsarivna, Romantyka, Lisova Pisnia, and Pamiati Hirka, each with 7.3 cm. The shortest spike rachis was formed by Vodohrai and MIP Dniprianka, with values of 5.2 and 5.3 cm, respectively. The lowest variability for this trait was recorded in Myroliubna (CV = 3.6%), Berehynia Myronivska (CV = 5.7%), Romantyka (CV = 6.3%), and Svitanok Myronivskyi (CV = 6.3%), indicating more uniform expression of spike length across the study years.

Table 8
Mean ± SD values and coefficients of variation for five main spike structure traits of winter soft wheat cultivars during 2022–2024 (n = 90)

Cultivar	Spike rachis length, cm	CV of spike rachis length, %	Spike weight, g	CV of spike weight, %	Spikelets per spike, pcs.	CV of spikelets per spike, %	Grains per spike, pcs.	CV of grains per spike, %	Grain weight per spike, g	CV of grain weight per spike, %
Vidrada	6.4 ± 0.6^{hij}	9.4	2.0 ± 0.5^{hi}	23.8	15.4 ± 1.3^{op}	8.7	31.0 ± 5.6^{ij}	18.2	1.7 ± 0.6^{f}	36.3
Lybid	6.9 ± 0.8^{fg}	12.3	2.0 ± 0.4^{hi}	20.6	16.3 ± 0.9^{lm}	5.6	33.1 ± 6.6^{fgh}	20.0	1.5 ± 0.4^{h}	28.1
Charodiika Bilotserkivska	6.2 ± 1.2^{ijk}	19.0	1.9 ± 0.6^{ij}	29.6	22.1 ± 15.9^{b}	71.9	25.6 ± 3.8^{mn}	14.9	1.4 ± 0.3^{i}	21.8
Legenda Bilotserkivska	9.1 ± 0.6^{a}	6.6	2.6 ± 0.3^{c}	12.9	28.0 ± 13.8^{a}	49.4	46.4 ± 5.1^{a}	11.0	2.1 ± 0.2^{b}	8.6
Kvitka Poliv	7.7 ± 1.5^{b}	19.6	2.2 ± 0.8^{fg}	36.9	14.9 ± 2.6^{pq}	17.6	36.9 ± 12.7^{d}	34.5	1.8 ± 0.7^{e}	37.0
Lisova Pisnia	7.3 ± 1.1^{cde}	15.1	2.3 ± 0.5^{ef}	21.8	17.9 ± 0.6^{efg}	3.1	36.0 ± 4.0^{de}	11.0	1.8 ± 0.3^{e}	17.4
Vodohrai Bilotserkivskyi	7.4 ± 1.1^{cd}	15.1	2.8 ± 0.8^{b}	26.8	15.5 ± 0.8^{o}	4.9	36.5 ± 7.0^{de}	19.2	1.7 ± 0.5^{f}	27.5
Perlyna Lisostepu	7.2 ± 1.9^{def}	26.5	2.4 ± 0.8^{de}	33.2	16.2 ± 1.9^{mn}	11.4	38.9 ± 12.8^{c}	32.9	2.0 ± 0.7^{c}	35.2
Rozumnytsia	6.5 ± 1.2^{hi}	18.5	2.1 ± 0.9^{gh}	42.3	15.5 ± 1.5^{op}	9.4	32.8 ± 9.4^{gh}	28.6	1.8 ± 0.8^{e}	43.1
Romantyka	7.3 ± 0.5^{cde}	6.3	2.2 ± 0.1^{fg}	5.7	16.4 ± 0.9^{lm}	5.5	36.5 ± 2.7^{de}	7.5	1.8 ± 0.1^{e}	6.3
Hratsiia Bilotserkivska	6.5 ± 0.9^{hi}	14.4	2.5 ± 0.5^{cd}	21.5	16.5 ± 0.5^{lm}	2.8	37.4 ± 4.0^{cd}	10.7	1.8 ± 0.3^{e}	14.3
Tsarivna	7.3 ± 0.5^{cde}	7.4	2.6 ± 0.5^{c}	20.5	17.5 ± 1.8^{ghi}	10.4	40.3 ± 8.7^{b}	21.7	2.1 ± 0.4^{b}	20.7
Ros	7.2 ± 1.5^{def}	21.4	2.5 ± 0.6^{cd}	23.8	17.2 ± 1.4^{hijk}	8.2	38.9 ± 11.6^{c}	29.7	1.8 ± 0.8^{e}	43.6
Zorepad Bilotserkivska	6.9 ± 1.0^{fg}	14.4	2.4 ± 1.0^{de}	42.7	16.9 ± 2.1^{ijkl}	12.5	41.3 ± 14.9^{b}	36.0	1.9 ± 0.8^{d}	42.1
Hadzynka	7.8 ± 1.5^{b}	19.1	2.0 ± 0.8^{hi}	41.3	18.5 ± 1.2^{e}	6.2	33.2 ± 9.1^{fgh}	27.4	1.5 ± 0.7^{h}	48.0
Kraievyd	6.6 ± 1.2^{gh}	17.7	2.1 ± 0.9^{gh}	45.4	16.6 ± 4.9^{klm}	29.5	31.8 ± 14.0^{hi}	43.9	1.5 ± 0.6^{h}	40.8
Pamiati Hirka	7.3 ± 2.2^{cde}	30.3	2.0 ± 1.0^{hi}	50.6	17.2 ± 5.1^{hijk}	29.8	34.1 ± 14.0^{fg}	41.2	1.5 ± 0.8^{h}	51.8
Myroliubna	7.6 ± 0.3^{bc}	3.6	2.0 ± 0.4^{hi}	21.6	17.3 ±2.1^{ghhij}	11.9	37.4 ± 6.8^{cd}	18.1	1.6 ± 0.4^{g}	24.9
Vodohrai	5.2 ± 0.9^{m}	16.9	1.6 ± 0.5^{lm}	29.6	14.6 ± 1.5^{qr}	10.5	26.1 ± 7.1^{lmn}	27.2	1.2 ± 0.4^{k}	36.4
Spivanka Poliska	8.5 ± 1.6^{a}	18.3	2.9 ± 0.8^{b}	27.7	18.0 ± 0.8^{efg}	4.4	45.8 ± 11.2^{a}	24.4	2.2 ± 0.5^{a}	24.9
Polisianka	6.0 ± 0.6^{kl}	9.4	1.6 ± 0.9^{lm}	55.4	14.2 ± 2.6^{r}	18.1	30.3 ± 16.0^{ij}	52.7	1.2 ± 0.6^{k}	48.4
Efektna	6.1 ± 1.1^{jkl}	17.6	1.9 ± 0.3^{ij}	18.1	18.3 ± 2.7^{ef}	14.6	33.2 ± 6.2^{fgh}	18.8	1.4 ± 0.2^{i}	15.7
Pyriatynka	6.9 ± 0.8^{fg}	12.3	2.0 ± 0.2^{hi}	8.2	16.8 ± 2.1^{jklm}	12.3	33.2 ± 2.4^{fgh}	7.3	1.6 ± 0.1^{g}	8.4
Liubito	6.9 ± 1.3^{fg}	18.6	1.7 ± 0.6^{kl}	39.2	17.8 ± 2.2^{fgh}	12.5	29.8 ± 11.3^{j}	37.8	1.2 ± 0.4^{k}	34.9
Fortetsia Poliska	5.8 ± 1.6^{l}	27.2	1.3 ± 0.5^{n}	40.5	19.9 ± 6.5^{d}	32.5	25.7 ± 9.4^{mn}	36.6	1.0 ± 0.4^{l}	40.8
Namysto	7.0 ± 1.0^{ef}	14.8	2.2 ± 0.4^{fg}	18.7	17.8 ± 1.5^{fgh}	8.3	36.4 ± 7.8^{de}	21.4	1.7 ± 0.5^{f}	27.8
Merezhka	6.2 ± 1.4^{ijk}	21.8	1.8 ± 0.8^{jk}	45.0	15.6 ± 2.5^{no}	16.1	30.8 ± 13.0^{ij}	42.3	1.3 ± 0.7^{j}	50.8
Kesariia Poliska	7.0 ± 0.9^{ef}	12.7	2.0 ± 1.2^{hi}	59.0	20.3 ± 5.9^{c}	29.0	29.4 ± 12.3^{jk}	41.7	1.8 ± 0.7^{e}	39.3
Poliska 90	5.8 ± 0.7^{l}	12.6	1.6 ± 0.6^{lm}	35.7	14.9 ± 2.8^{pq}	18.9	26.1 ± 7.6^{lmn}	29.1	1.3 ± 0.5^{j}	37.5
Berehynia Myronivska	6.9 ± 0.4^{fg}	5.7	2.3 ± 0.3^{ef}	12.0	16.9 ± 1.1^{ijkl}	6.5	34.8 ± 6.1^{ef}	17.5	1.5 ± 0.2^{h}	14.2
Hospodynia Myronivska	6.4 ± 1.1^{hij}	16.3	2.1 ± 0.7^{gh}	35.4	16.4 ± 0.5^{lm}	3.0	31.0 ± 8.5^{ij}	27.4	1.5 ± 0.4^{h}	27.5
MIP Dniprianka	5.3 ± 0.5^{m}	9.5	1.4 ± 0.2^{n}	17.2	13.4 ± 2.1^{s}	15.4	25.1 ± 3.1^{n}	12.5	1.2 ± 0.2^{k}	14.8
MIP Kniazhna	6.2 ± 0.5^{ijk}	7.2	1.8 ± 0.1^{jk}	6.2	15.3 ± 1.1^{op}	7.0	27.7 ± 6.8^{kl}	24.6	1.3 ± 0.2^{j}	16.2
Oberih Myronivskyi	5.8 ± 0.5^{l}	8.6	1.9 ± 0.4^{ij}	19.8	14.0 ± 0.4^{rs}	3.1	27.0 ± 1.8^{lm}	6.5	1.3 ± 0.1^{j}	9.0
Svitanok Myronivskyi	6.9 ± 0.4^{fg}	6.3	3.4 ± 1.9^{a}	56.1	16.8 ± 0.6^{jklm}	3.4	36.8 ± 3.2^{d}	8.6	1.8 ± 0.3^{e}	16.7

Note: values are presented as mean ± SD; CV – coefficient of variation.

Spike weight was highest in Svitanok Myronivskyi (3.4 g), which statistically distinguished this cultivar from most other genotypes. High values were also recorded for Spivanka Poliska (2.9 g), Vodohrai Bilotserkivskyi (2.8 g), Legenda Bilotserkivska and Tsarivna (2.6 g each), and Hratsiia Bilotserkivska and Ros (2.5 g each). The lowest spike weight was observed in Fortetsia Poliska (1.3 g) and MIP Dniprianka (1.4 g). According to the coefficient of variation, the most stable formation of spike weight was recorded in Romantyka (CV = 5.7%), MIP Kniazhna (CV = 6.2%), and Pyriatynka (CV = 8.2%). In contrast, Kesariia Poliska, Svitanok Myronivskyi, Polisianka, and Pamiati Hirka had CV values exceeding 50%, indicating substantial interannual variability in this trait.

The number of spikelets per spike ranged from 13.4 in MIP Dniprianka to 28.0 in Legenda Bilotserkivska. For this trait, Legenda Bilotserkivska occupied the highest statistical position. High values were also characteristic of Charodiika Bilotserkivska (22.1 spikelets), Kesariia Poliska (20.3), Fortetsia Poliska (19.9), Hadzynka (18.5), Efektna (18.3), and Spivanka Poliska (18.0). The lowest number of spikelets was recorded in MIP Dniprianka, Oberih Myronivskyi, Polisianka, Vodohrai, Kvitka Poliv, and Poliska 90. The lowest variability in the number of spikelets per spike was observed in Hratsiia Bilotserkivska (CV = 2.8%), Hospodynia Myronivska (CV = 3.0%), Lisova Pisnia and Oberih Myronivskyi (CV = 3.1%), and Svitanok Myronivskyi (CV = 3.4%), indicating more stable expression of this structural trait.

The number of grains per spike was one of the most differentiated traits. The highest values were recorded in Legenda Bilotserkivska (46.4 grains) and Spivanka Poliska (45.8 grains), which formed the highest statistical group. High values were also observed in Zorepad Bilotserkivska (41.3 grains), Tsarivna (40.3 grains), Perlyna Lisostepu and Ros (38.9 grains each), and Hratsiia Bilotserkivska and Myroliubna (37.4 grains each). The lowest number of grains per spike was recorded in MIP Dniprianka (25.1 grains), Charodiika Bilotserkivska (25.6 grains), Fortetsia Poliska (25.7 grains), and Vodohrai and Poliska 90 (26.1 grains each). The lowest CV values for grain number per spike were found in Oberih Myronivskyi (CV = 6.5%), Pyriatynka (CV = 7.3%), Romantyka (CV = 7.5%), and Svitanok Myronivskyi (CV = 8.6%), indicating more stable formation of spike grain productivity in these cultivars.

Grain weight per spike ranged from 1.0 g in Fortetsia Poliska to 2.2 g in Spivanka Poliska. The highest values for this trait were recorded in Spivanka Poliska (2.2 g), Legenda Bilotserkivska and Tsarivna (2.1 g each), Perlyna Lisostepu (2.0 g), and Zorepad Bilotserkivska (1.9 g). The group of cultivars with a value of 1.8 g included Kvitka Poliv, Lisova Pisnia, Rozumnytsia, Romantyka, Hratsiia Bilotserkivska, Ros, Kesariia Poliska, and Svitanok Myronivskyi. The lowest grain weight per spike was observed in Fortetsia Poliska, Vodohrai, Polisianka, Liubito, and MIP Dniprianka. In terms of stability for this trait, the best values were recorded in Romantyka (CV = 6.3%), Pyriatynka (CV = 8.4%), Legenda Bilotserkivska (CV = 8.6%), and Oberih Myronivskyi (CV = 9.0%).

Comparison of main spike structure with the previously obtained yield data showed that a high level of mean yield did not always directly coincide with the maximum values of individual spike components. For example, Legenda Bilotserkivska had the highest or among the highest values for spike length, number of spikelets, number of grains, and grain weight per spike; however, it was not among the leading cultivars in terms of mean yield because of substantial interannual variability in productivity. In contrast, Tsarivna combined high yield with high values of spike weight, number of grains per spike, and grain weight per spike. Spivanka Poliska was characterized by the highest grain weight per spike and a high number of grains, emphasizing its strong morphoproductive potential.

Among the cultivars with the most balanced expression of spike structure traits, Romantyka should be highlighted. This cultivar had moderately high values for most traits and, at the same time, the lowest variability in spike weight, number of grains per spike, and grain weight per spike. A similarly stable expression of individual structural traits was observed in Pyriatynka, Oberih Myronivskyi, Berehynia Myronivska, and Hratsiia Bilotserkivska, although their absolute levels of spike productivity differed.

The obtained results demonstrate substantial cultivar differentiation in the components of main spike structure. Spike weight, number of grains per spike, and grain weight per spike are of particular importance for further analysis, as these traits most closely reflect the individual grain productivity of plants. Further correlation analysis will clarify which spike structure components are most closely associated with grain yield and adaptive parameters of the cultivars.

Relationships between grain yield, adaptive parameters and spike structure traits. To determine the relationships among mean grain yield, adaptive parameters, and main spike structure components, correlation analysis was performed using the mean values of winter soft wheat cultivars. The analysis included mean grain yield, coefficient of variation for yield, ecological plasticity coefficient (bi), homeostaticity index (Hom), and morphoproductive spike traits: spike rachis length, spike weight, number of spikelets per spike, number of grains per spike, and grain weight per spike.

Table 9

Correlation matrix among grain yield, adaptive parameters, and main spike structure traits of winter soft wheat cultivars (mean ± SD, n = 3150)

Parameter	Mean yield	CV (yield)	bi	Hom	Spike rachis length	Spike weight	Spikelets per spike	Grains per spike	Grain weight per spike
Mean yield	1.000	–	–	–	–	–	–	–	–
CV (yield)	–0.161	1.000	–	–	–	–	–	–	–
Bi	0.035	0.818**	1.000	–	–	–	–	–	–
Hom	–0.008	–0.393*	–0.259	1.000	–	–	–	–	–
Spike rachis length	0.035	0.063	–0.083	0.053	1.000	–	–	–	–
Spike weight	0.364*	–0.062	–0.090	–0.038	0.641**	1.000	–	–	–
Spikelets per spike	–0.311	0.171	0.138	0.220	0.544**	0.204	1.000	–	–
Grains per spike	0.139	0.052	–0.102	–0.127	0.848**	0.789**	0.364*	1.000	–
Grain weight per spike	0.247	–0.105	–0.211	0.161	0.778**	0.840**	0.332	0.876**	1.000

Note: * – P ≤ 0.05; ** – P ≤ 0.001; CV – coefficient of variation; bi – ecological plasticity coefficient; Hom – homeostaticity index; correlation analysis was performed using the mean values of 35 cultivars for 2022–2024.

The correlation analysis showed that mean grain yield had weak to moderate relationships with most main spike structure traits. The strongest correlation among these traits was found between mean grain yield and spike weight (r = 0.364; P ≤ 0.05), indicating a certain contribution of spike weight to the overall productivity level of the cultivars. At the same time, the relationships between mean grain yield and the number of grains per spike (r = 0.139) and grain weight per spike (r = 0.247) were positive but statistically non-significant. Therefore, in the studied set of cultivars, grain yield was not determined solely by main spike productivity, but was formed through a broader complex of traits, including productive stand density, productive tillering, and genotype response to yearly conditions.

Mean grain yield was almost unrelated to the ecological plasticity coefficient bi (r = 0.035) and the homeostaticity index Hom (r = –0.008). This indicates that a high level of mean productivity was not necessarily associated with high ecological plasticity or homeostaticity. The weak negative relationship between mean grain yield and yield CV (r = -0.161) also suggests that the highest-yielding cultivars did not necessarily have greater interannual variability. Among the adaptive parameters, the strongest relationship was found between the coefficient of variation for yield and the ecological plasticity coefficient bi (r = 0.818; P ≤ 0.001). This level of correlation is expected, as cultivars with higher bi values responded more strongly to changes in environmental conditions, which was accompanied by a wider amplitude of yield fluctuations across years. At the same time, Hom was negatively correlated with yield CV (r = -0.393; P ≤ 0.05), confirming the methodological consistency of these parameters: as homeostaticity increased, interannual yield variability decreased. The relationship between bi and Hom was negative but statistically non-significant (r = –0.259). This indicates that cultivars with a stronger response to changes in yearly conditions generally tended to have lower homeostaticity; however, this trend was not strong enough to be statistically confirmed. This result highlights the need to use several adaptive parameters simultaneously, as each of them reflects a different aspect of genotype response to the environment.

The strongest and most consistent relationships were observed among main spike structure traits. Spike rachis length was strongly correlated with the number of grains per spike (r = 0.848; P ≤ 0.001), grain weight per spike (r = 0.778; P ≤ 0.001), and spike weight (r = 0.641; P ≤ 0.001). This demonstrates the important role of spike morphological size in the formation of its grain productivity. An increase in spike rachis length was accompanied by an increase in grain number and grain weight per spike; therefore, this trait may be considered an informative morphological marker of main spike productivity.

Spike weight showed a very strong positive relationship with grain weight per spike ($r = 0.840$; $P \leq 0.001$) and the number of grains per spike ($r = 0.789$; $P \leq 0.001$). This pattern indicates that spike weight integrates several components of individual plant productivity. From a practical perspective, this trait may be useful for the preliminary selection of genotypes with increased potential for spike grain productivity.

The strongest relationship among the structural traits was found between the number of grains per spike and grain weight per spike ($r = 0.876$; $P \leq 0.001$). This association is biologically expected, as an increase in grain number directly increases the potential grain weight of an individual spike. At the same time, grain weight per spike was also strongly associated with spike weight ($r = 0.840$; $P \leq 0.001$) and spike rachis length ($r = 0.778$; $P \leq 0.001$), confirming the complex nature of this trait formation.

The number of spikelets per spike showed a moderate positive relationship with spike rachis length ($r = 0.544$; $P \leq 0.001$) and the number of grains per spike ($r = 0.364$; $P \leq 0.05$). However, its relationship with grain weight per spike was weaker and statistically non-significant ($r = 0.332$). This indicates that an increase in the number of spikelets was not always accompanied by a proportional increase in grain weight per spike. Therefore, high spike grain productivity depended not only on the number of spikelets, but also on grain set and the efficiency of grain filling.

The relationships between adaptive parameters and spike structure traits were generally weak. The ecological plasticity coefficient bi showed weak or negative relationships with spike rachis length, spike weight, number of grains per spike, and grain weight per spike. A similar tendency was observed for Hom, whose relationships with structural traits were weak and non-significant. This indicates that the adaptive response of cultivars in terms of grain yield was not determined by individual components of main spike structure alone, but resulted from a more complex interaction between genotype and yearly conditions.

Overall, the results of the correlation analysis make it possible to distinguish two relatively independent groups of traits. The first group includes main spike structure components–spike rachis length, spike weight, number of grains per spike, and grain weight per spike–which showed strong positive relationships with one another. The second group consists of adaptive yield parameters, including yield CV, bi, and Hom, which characterize interannual variability and the type of cultivar response to environmental conditions. The relatively weak relationships between these two groups indicate that high individual spike productivity and yield stability across years are not always expressed simultaneously in the same genotype.

Contribution of genotype, year and their interaction to yield and spike structure traits. To provide a more detailed assessment of the sources of variability in grain yield and main spike structure traits, the contribution of the main factors–cultivar, study year, and their interaction was determined. This approach made it possible to identify which traits were mainly controlled by the genotypic characteristics of cultivars and which were more strongly influenced by yearly conditions or by the specific response of a cultivar to environmental changes.

The analysis showed that the contribution of cultivar was highest for spike rachis length, accounting for 37.45%. This indicates that this trait was the most strongly genotype-dependent among the studied spike structure parameters. A relatively high contribution of the cultivar factor was also observed for the number of spikelets per spike (32.77%), grain weight per spike (26.04%), and number of grains per spike (26.00%). Thus, the morphological and morphoproductive components of the spike were largely determined by cultivar-specific characteristics.

Table 10
Contribution of cultivar, year and cultivar × year interaction to yield and spike structure traits of winter soft wheat, %

Source of variation	Spike rachis length	Spike weight	Spikelets per spike	Grains per spike	Grain weight per spike	Grain yield
Cultivar	37.45	18.65	32.77	26.00	26.04	10.05
Year	19.78	5.99	0.90	20.82	24.07	43.32
Cultivar × year	29.08	27.31	59.57	35.65	30.82	29.51
Error	13.69	48.06	6.76	17.52	19.07	17.13

Note: the contribution of each source of variation was calculated as the ratio of the corresponding sum of squares to the total sum of squares, expressed as a percentage.

In contrast to the structural traits, grain yield was predominantly influenced by the year, which accounted for 43.32% of the total variation. This indicates a high dependence of overall cultivar productivity on the hydrothermal conditions of a particular year. A substantial contribution of the year factor was also observed for grain weight per spike (24.07%), number of grains per spike (20.82%), and spike rachis length (19.78%). At the same time, the contribution of year to the number of spikelets per spike was minimal, only 0.90%, indicating that this trait was relatively less dependent on interannual changes in growing conditions.

The cultivar × year interaction was also an important source of variability. Its contribution was highest for the number of spikelets per spike, reaching 59.57%, which indicates a pronounced specificity of cultivar responses for this trait across the study years. A high contribution of this interaction was also found for the number of grains per spike (35.65%), grain weight per spike (30.82%), grain yield (29.51%), and spike rachis length (29.08%). This means that the expression of most traits depended not only on cultivar or year separately, but also on their combined effect.

For spike weight, the largest share was attributed to residual variability, which accounted for 48.06%. This may be associated with high individual variability in this trait, the influence of microenvironmental conditions during plant development, or specific features of spike formation within replications. At the same time, the contribution of the cultivar × year interaction to spike weight was also notable (27.31%), whereas the contribution of year was among the lowest for the studied traits (5.99%).

Grain yield showed the lowest direct contribution of the cultivar factor, accounting for only 10.05%, whereas the combined contribution of year and cultivar × year interaction exceeded 72%. This distribution emphasizes that winter soft wheat productivity under the conditions of this study was largely determined by the weather characteristics of a particular year and the specific adaptive response of genotypes. This is consistent with the results of the ecological plasticity, CV, and homeostaticity analyses, which revealed substantial cultivar differentiation in the type of response to changing growing conditions.

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Cluster differentiation of winter soft wheat cultivars based on productivity, spike structure and adaptive traits. Cluster analysis was used as a summarizing stage in the evaluation of winter soft wheat cultivars based on a set of productivity, morphoproductive, and adaptive parameters. The clustering included standardized values of spike rachis length, spike weight, number of spikelets per spike, number of grains per spike, grain weight per spike, mean grain yield, coefficient of variation for yield, ecological plasticity coefficient (bi), and homeostaticity index (Hom). This approach made it possible to group cultivars not by a single trait, but by their overall profile of productivity realization and adaptive response.

According to the results of cluster analysis, the studied cultivars were divided into three groups that differed in productivity level, development of spike structure components, yield stability, and response to yearly conditions (Table 11).

Table 11
Cluster grouping of winter soft wheat cultivars based on standardized productivity, spike structure and adaptive traits

Cluster	General profile	Number of cultivars	Cultivars
Cluster I	High-yielding and morphoproductive cultivars with balanced or specific adaptive responses	15	Kvitka Poliv; Lisova Pisnia; Vodohrai Bilotserkivskyi; Perlyna Lisostepu; Romantyka; Hratsiia Bilotserkivska; Tsarivna; Ros; Zorepad Bilotserkivska; Hadzynka; Pamiati Hirka; Myroliubna; Spivanka Poliska; Kesariia Poliska; Svitanok Myronivskyi
Cluster II	Moderately productive cultivars with lower or variable spike productivity and higher environmental responsiveness	19	Vidrada; Lybid; Charodiika Bilotserkivska; Rozumnytsia; Kraievyd; Vodohrai; Polisianka; Efektna; Pyriatynka; Liubito; Fortetsia Poliska; Namysto; Merezhka; Poliska 90; Berehynia Myronivska; Hospodynia Myronivska; MIP Dniprianka; MIP Kniazhna; Oberih Myronivskyi
Cluster III	Specific high-variability genotype with high spike potential but unstable yield realization	1	Legenda Bilotserkivska

Note: clustering was performed using standardized values of mean yield, yield CV, ecological plasticity coefficient, homeostaticity index and spike structure traits.

The first cluster included 15 cultivars characterized by a more favorable combination of grain yield and selected main spike structure traits. This group comprised cultivars with the highest or medium-high mean yield values, including Tsarivna, Svitanok Myronivskyi, Vodohrai Bilotserkivskyi, Zorepad Bilotserkivska, Kvitka Poliv, Ros, and Spivanka Poliska. This cluster was characterized by increased or balanced values of spike weight, number of grains per spike, and grain weight per spike. At the same time, different types of adaptive response were represented within the cluster, ranging from highly stable cultivars such as Romantyka and Kesariia Poliska to cultivars with higher productive potential and moderate or increased variability, such as Svitanok Myronivskyi and Spivanka Poliska.

Particular value within the first cluster was shown by Tsarivna, Vodohrai Bilotserkivskyi, and Zorepad Bilotserkivska, which combined high mean yield with well-developed spike structure components. Spivanka Poliska was distinguished by high grain weight per spike and a high number of grains per spike, characterizing it as a genotype with strong morphoproductive potential. Romantyka and Kesariia Poliska formed a stable component within this cluster: they did not always reach the maximum yield values, but were characterized by low interannual variability, while Kesariia Poliska showed the highest level of homeostaticity.

The second cluster was the largest and included 19 cultivars. It consisted of genotypes with moderate productivity, lower or unstable spike structure parameters, and generally higher responsiveness to yearly conditions. This group included both cultivars with relatively high yield but increased variability, such as Lybid, Namysto, Hospodynia Myronivska, and MIP Dniprianka, and cultivars with lower values for individual structural traits, including MIP Dniprianka, Oberih Myronivskyi, Vodohrai, Poliska 90, and Fortetsia Poliska.

The second cluster was characterized by greater heterogeneity in adaptive parameters. Some cultivars had increased bi values and higher yield CV, indicating a more intensive type of response to changes in yearly conditions. These genotypes included Vidrada, Lybid, Polisianka, Namysto, MIP Kniazhna, Oberih Myronivskyi, and MIP Dniprianka. At the same time, this cluster also included cultivars with lower yield but relatively more stable expression of certain structural traits, such as Efektna, Pyriatynka, and Oberih Myronivskyi. This indicates that Cluster II should not be interpreted as a homogeneous group of low-yielding cultivars, but rather as a group of genotypes with a less balanced combination of yield, spike structure, and adaptive response.

The third cluster was represented by only one cultivar, Legenda Bilotserkivska. Its separation into an independent group is methodologically justified because this cultivar had a sharply distinct trait profile. On the one hand, Legenda Bilotserkivska was characterized by the highest or among the highest values of spike rachis length, number of spikelets per spike, number of grains per spike, and grain weight per spike. On the other hand, it showed very high interannual yield variability, the highest value of the ecological plasticity coefficient bi, and a low homeostaticity index. This profile indicates considerable potential for individual spike productivity, but unstable realization of this potential at the grain yield level.

Discussion

Hydrothermal variability as a driver of winter wheat yield formation. Interannual variability in hydrothermal conditions is one of the key factors determining the realization of the productive potential of winter soft wheat. In the present study, the contrast between years was reflected not only in changes in mean grain yield, but also in differences in the adaptive response of cultivars. This confirms that cultivar evaluation based only on mean yield is insufficient, especially in regions characterized by unstable combinations of temperature regime and moisture supply.

The obtained results are consistent with the findings of Morgounov et al. (2013), who showed that, at winter wheat breeding sites in Eastern Europe, Central Asia, and the United States, climate change after 1991 was most clearly expressed through increased spring temperatures, particularly in May and June. The authors emphasized that spring warming may accelerate plant development, shift heading dates, and shorten the period of productive organ formation. Elevated temperatures in June are especially critical, as this period coincides with grain filling and therefore directly affects final productivity. In this context, our results confirm the relevance of selecting cultivars capable of maintaining productivity under the combined effects of elevated temperature background and uneven moisture supply. Similar trends for the Forest-Steppe of Ukraine were described by Butenko et al., (2020). The authors found that, during 2004–2016, a considerable proportion of years differed substantially from long-term average values for temperature and precipitation, while the conditions of some years approached extreme levels. They also showed that the effect of weather conditions on cereal crop yield in the Forest-Steppe may reach 60–70%. This is in good agreement with our findings regarding the significant role of year and cultivar × year interaction in grain yield formation. Therefore, under the conditions of the Right-Bank Forest-Steppe of Ukraine, cultivar productivity should not be interpreted as a fixed genotypic characteristic, but rather as the result of genotype interaction with the specific hydrothermal conditions of a given year.

In addition to hydrothermal variability, the agroecological background of the experimental site should also be considered when interpreting cultivar productivity. Forest-Steppe soils are sensitive both to moisture regime and to changes in nutrient availability associated with fertilization and chemical plant protection systems. Litvinova et al. (2023a, 2023b) showed that the application of fertilizers and pesticides on dark gray podzolic soils affected the accumulation of surface-active substances and was associated with changes in the content of mobile nutrient forms within the soil profile. Although soil chemical contamination was not the subject of the present study, these data indicate that cultivar responses under field conditions are formed against a complex soil, climatic, and agronomic background. Therefore, the use of uniform agronomic management for all cultivars in our experiment was important for the correct identification of genotypic effects and cultivar × year interaction (Pavlichenko et al., 2023; Dehodiuk et al., 2024; Bulygin et al., 2025).

Importantly, the unfavorability of a particular year is not always determined by precipitation deficit or elevated temperature alone. Their combined effect during specific plant developmental stages is often more critical. Beillouin et al. (2020), based on the analysis of more than 82,000 regional yield records from 17 European countries, showed that negative yield anomalies were most often associated with the combined effects of extreme temperatures and precipitation deficit. Particularly severe yield losses in Northern and Eastern Europe in 2018 were caused by the simultaneous occurrence of high temperatures and very low precipitation from March to August. This supports the relevance of using not only separate analyses of temperature and precipitation in the present study, but also the hydrothermal coefficient and environmental index, which provide a more comprehensive characterization of yield-forming conditions.

Long-term variety trials also confirm that yield stability is no less important than mean yield. Based on long-term data from winter wheat and winter rye variety trials, Hadasch et al. (2020) showed that evaluation based only on mean productivity does not provide a complete assessment of genotype value, because climatic factors affect not only the average yield level but also its variance. The authors emphasized the need to analyze yield stability while considering climatic covariates during specific developmental stages. This methodologically supports the approach used in the present study, where mean yield was combined with the coefficient of variation, ecological plasticity, homeostaticity, and cluster differentiation of cultivars.

A specific feature of our results is that the cultivars responded differently to the same hydrothermal background. Some genotypes realized their productive potential more effectively in favorable years but showed higher interannual variability, whereas others maintained a more stable level of productivity under contrasting conditions. This differentiation confirms the need to distinguish between intensive-type cultivars, stable cultivars, and genotypes with a balanced adaptive response. From a practical perspective, this is important for cultivar selection depending on the production strategy: maximizing yield under favorable conditions requires one type of genotype, whereas cultivation under an increased risk of hydrothermal stress requires another.

Thus, comparison of our results with the findings of other researchers shows that the productivity of winter soft wheat under the conditions of the Right-Bank Forest-Steppe of Ukraine is formed under the combined influence of climatic factors and genotype-specific cultivar responses. The scientific value of the obtained results lies in the integrated approach to cultivar evaluation: in addition to mean yield, stability, ecological plasticity, homeostaticity, and spike structure traits were considered. This approach makes it possible to more reliably identify cultivars suitable not only for high productivity, but also for more stable yield realization under unstable hydrothermal conditions.

Yield stability, ecological plasticity and genotype × environment interaction. Evaluation of winter soft wheat cultivars based only on mean grain yield does not provide a complete characterization of their adaptive value, especially under increasing climate variability. In the present study, the cultivars differed substantially not only in productivity level, but also in coefficient of variation, ecological plasticity, and homeostaticity. This confirms the need for a comprehensive approach to genotype selection, in which high yield is assessed together with the stability of its realization across years differing in environmental favorability.

The interpretation of the ecological plasticity coefficient in our study is consistent with the approach of Dimitrov et al., (2022), who considered the regression coefficient as an indicator of cultivar sensitivity to changes in environmental conditions. The authors noted that coefficient values close to unity characterize genotypes with broad adaptation, whereas deviations from this level indicate a more specific response to growing conditions. In the present study, cultivars with bi values close to 1, particularly Tsarivna and Vodohrai Bilotserkivskyi, combined high yield with moderate variability, which allows them to be considered genotypes with a balanced adaptive response.

At the same time, cultivars with increased bi and CV values were characterized by a more pronounced dependence of yield on yearly conditions. This type of response corresponds to the interpretation proposed by Gupta et al. (2022), who, using the Eberhart and Russell model, showed that genotypes with high mean yield and bi > 1 realize their potential more effectively in favorable environments, whereas genotypes with bi < 1 may be more valuable under less favorable conditions. This is important for the practical interpretation of our results: intensive-type cultivars should not be regarded as less valuable, but they are more appropriate for environments where growing conditions allow a fuller realization of productive potential.

Similar patterns were reported for winter wheat cultivars under climate variability in the Right-Bank Forest-Steppe of Ukraine. Holyk et al. (2026) showed that the main sources of yield variability were environmental conditions and genotype × environment interaction, whereas the direct genotypic effect was less pronounced. The authors also demonstrated the practical value of combining ecological plasticity and homeostaticity to distinguish cultivars with different adaptive strategies, including intensive-type genotypes and more stable genotypes for stressful conditions. This agrees with our results, where year conditions and cultivar × year interaction made the largest contribution to yield variability, while cultivars differed substantially in the balance between productivity, response to yearly conditions, and stability. The consistency of these findings confirms that, in the Right-Bank Forest-Steppe of Ukraine, cultivar evaluation should be based not only on mean yield, but also on the type of adaptive response under contrasting hydrothermal conditions.

The obtained results also confirm that high yield and high stability are not always combined within the same cultivar. A similar pattern was reported by Dimitrov et al. (2022), who, among 56 winter soft wheat cultivars, identified separate genotypes with high yield, others with high stability, and only a limited group of cultivars combining both characteristics. In the present study, Svitanok Myronivskyi and MIP Dniprianka were characterized by high mean yield but greater interannual variability. In contrast, Kesariia Poliska and Romantyka showed more stable yield expression, although they were not always among the most productive genotypes.

The strong role of year and cultivar × year interaction in yield formation is consistent with the findings of Gupta et al. (2022), who demonstrated a significant effect of genotype, environment, and their interaction on wheat yield. In their study, the major share of variation was attributed to the environment, emphasizing the leading role of growing conditions in productivity realization. A similar tendency was observed in our study: grain yield was largely determined by yearly conditions and the specific response of cultivars to these conditions. This supports the need for multi-year cultivar testing in regions with an unstable hydrothermal regime.

The results of Havryliuk & Kovalyshyna (2024) also support the relevance of combining yield evaluation with the analysis of structural traits and adaptability in Ukrainian-bred cultivars. The authors showed that the expression of productivity components in winter soft wheat depends on genotype, environmental conditions, and their interaction. In the present study, this approach was expanded by the simultaneous use of grain yield, CV, bi, Hom, spike structure traits, factor contribution, and cluster analysis. Such an integrated assessment makes it possible not only to identify high-yielding cultivars, but also to differentiate genotypes according to their adaptive strategy: stable, intensive, or balanced.

Spike structure traits and their contribution to yield formation. Main spike structure traits are important morphoproductive characteristics that reflect the potential of individual plant productivity; however, their relationship with plot-level yield is not always direct. In the present study, the strongest correlations were found among spike structure components, particularly between the number of grains per spike, spike weight, and grain weight per spike. At the same time, mean grain yield showed only a moderate relationship with spike weight and weaker relationships with the number of grains per spike and grain weight per spike. This confirms that wheat yield is formed not only through main spike productivity, but also through the interaction of several components, including the number of productive stems, grain set, grain weight, and the ability of a genotype to realize these traits under specific yearly conditions.

The obtained results are consistent with the findings of Philipp et al. (2018), who showed that breeding progress in winter wheat yield is largely associated with an increase in grain number and spike grain productivity. The authors found that elite cultivars had higher yield than genetic resources mainly due to increased grain number and spike yield, whereas thousand-grain weight increased to a lesser extent. This provides a good explanation for the strong relationships observed in the present study between the number of grains per spike and grain weight per spike. At the same time, Philipp et al. (2018) noted that the number of spikelets per spike is not always positively associated with most productivity traits, which is also consistent with our results, where the number of spikelets showed a weaker relationship with grain weight per spike compared with the number of grains.

The role of a large spike as a potential source of yield improvement was discussed in detail by Gaju et al. (2009). The authors showed that genotypes with a large-spike phenotype may have greater spike length and a higher number of spikelets and grains per spike; however, this does not always result in higher yield at the crop stand level because of a possible reduction in the number of spikes per unit area. This conclusion is important for interpreting our data. For example, some cultivars with high main spike productivity traits were not necessarily among the highest-yielding cultivars in terms of mean productivity. This indicates that the breeding value of spike traits should be evaluated together with the overall architecture of the plant stand and the ability of a cultivar to form sufficient productive stem density.

An important aspect of yield formation is the relationship between grain number and individual grain weight. Xie & Sparkes (2021) emphasized that wheat yield is determined by the product of grain number per unit area and individual grain weight, while grain number itself depends on the number of spikes per unit area and the number of grains per spike. The authors also demonstrated the existence of a genetic and phenotypic trade-off between grain number and grain weight. A similar approach was developed by Vicentin et al. (2024), who showed that the trade-off between grain weight and grain number is related to the partial overlap of the critical periods determining these yield components. In the context of our results, this explains why high values of individual spike structure components do not automatically ensure maximum yield: an increase in grain number may be accompanied by changes in grain filling, and the final result depends on the balance between grain set and grain weight.

Studies of Ukrainian winter soft wheat cultivars also confirm the importance of a comprehensive analysis of structural traits. Havryliuk & Kovalyshyna (2024) showed that cultivars differed significantly in spike rachis length, spike weight, number of spikelets, number of grains per spike, grain weight per spike, and thousand-grain weight, while the expression of these traits depended on genotype, environmental conditions, and their interaction. In the present study, similar cultivar differentiation was supplemented by the assessment of ecological plasticity, homeostaticity, correlation relationships, and cluster grouping, which made it possible not only to identify cultivars with high structural trait values, but also to evaluate their adaptive value.

Additional confirmation of the breeding value of spike structure traits is provided by the results of Havryliuk & Kovalyshyna (2025), who studied F1 hybrids of winter soft wheat for the main morphological and productive spike traits. The authors found substantial variability among hybrid combinations in spike rachis length, spike weight, number of spikelets and grains per spike, and grain weight per spike. Cultivars with high general combining ability as maternal or paternal components were of particular value, including Svitanok Myronivskyi, which in the present study was also distinguished by high spike weight and high mean grain yield. This emphasizes that spike structure traits may have not only diagnostic value for assessing cultivar productivity, but also practical importance for predicting the efficiency of their use in hybridization.

Cultivars that combine valuable spike productivity traits with other breeding-relevant characteristics are of particular interest. Demydov et al. (2024), studying F1 hybrids of winter soft wheat for resistance to *Fusarium graminearum* and spike productivity components, emphasized the importance of combining disease resistance with high morphoproductive traits in the breeding of adaptive cultivars. This provides an important addition to the interpretation of our results, as cultivars with high spike productivity but unstable yield realization may be valuable not so much as ready-to-use commercial cultivars, but rather as sources of specific breeding traits.

Thus, main spike structure traits have high diagnostic value for characterizing the morphoproductive potential of winter soft wheat cultivars. However, they should not be used in isolation, but rather in combination with the assessment of grain yield, stability, ecological plasticity, and response to hydrothermal conditions. This approach makes it possible to distinguish genotypes with high potential for individual spike productivity from cultivars capable of stably realizing this potential at the grain yield level in a specific agroecological environment.

Cluster differentiation and breeding value of winter wheat cultivars. In the present study, cluster analysis served as a summarizing step because it enabled the integration of grain yield, ecological plasticity, homeostaticity, and main spike structure traits into a single cultivar evaluation system. Unlike simple ranking based on mean yield, this approach makes it possible to differentiate genotypes according to the type of adaptive strategy: high-yielding cultivars with moderate variability, stable cultivars with higher homeostaticity, intensive genotypes with an increased response to favorable conditions, and specific genotypes with high potential for individual traits.

The relevance of multivariate approaches for assessing wheat stability and adaptability is supported by the findings of Mohammadi et al. (2023), who compared different parametric, non-parametric, and multifactorial stability methods for durum wheat genotypes. The authors showed that combining mean yield with stability parameters, particularly through AMMI, GGE biplot, WAASB, and cluster analysis, is effective for identifying genotypes with both high productivity and stability across environments. In the present study, a similar role was performed by cluster analysis based on standardized productivity, structural, and adaptive traits, which made it possible to distinguish cultivar groups not only by yield level, but also by the pattern of its realization under contrasting hydrothermal conditions.

A similar approach was applied by Mădry et al. (2011), who combined AMMI and cluster analysis to evaluate the adaptive response of winter wheat cultivars across 20 environments in Poland. The authors showed that clustering based on adaptive responses makes it possible to distinguish cultivars with broad adaptation, specific adaptation, and weaker suitability for particular growing regions. This is directly consistent with our results, where the identified clusters differed not only in productivity, but also in the balance between stability, plasticity, and the morphoproductive potential of the spike.

Importantly, recent studies on multi-environment wheat evaluation confirm the need to account for genotype × environment interaction when selecting promising genotypes. Naheed et al. (2026), using AMMI and PCA to analyze agronomic traits of bread wheat lines across different environments, found a significant influence of environment and GEI on grain yield and individual productivity components. The authors showed that different traits may have different proportions of genotypic, environmental, and interaction control. This agrees with our results: grain yield was more strongly dependent on yearly conditions and cultivar × year interaction, whereas some spike structure traits showed a more pronounced cultivar-specific determination.

In this context, the practical importance lies not only in identifying the highest-yielding cultivars, but also in determining their adaptive role. Al-Ashkar et al. (2023) showed that the combination of stability, productivity, and multi-trait selection indices, particularly MGIDI, WAASB, and WAASBY, enables more effective identification of genotypes tolerant to water deficit and heat stress. In the present study, a similar analytical function was performed by the combined use of CV, bi, Hom, correlation analysis, factor contribution analysis, and clustering. This made it possible to characterize cultivars not only by their absolute yield level, but also by their ability to maintain or modify productivity depending on yearly conditions.

The separation of Legenda Bilotserkivska into an individual cluster has important methodological and breeding significance. This cultivar combined high values of main spike productivity traits with unstable yield realization, confirming the need for a comprehensive approach to genotype evaluation. Based only on structural traits, this cultivar could be considered highly promising; however, the inclusion of CV, bi, and Hom made it possible to refine its adaptive profile. This corresponds to the general logic of multivariate selection, in which genotypes are evaluated not by a single advantage, but by a combination of productive and stabilizing characteristics.

Thus, the cluster analysis confirmed that the studied winter soft wheat cultivars had different adaptive strategies. For commercial cultivation under the conditions of the Right-Bank Forest-Steppe, the most valuable cultivars are those that combine high yield with moderate variability and a balanced ecological response. Stable and homeostatic genotypes may be useful under stressful or unstable conditions, whereas cultivars with high spike productivity potential but greater variability should be considered as sources of specific breeding traits. This differentiation has practical importance for developing cultivar recommendations and selecting initial material for breeding programs aimed at improving wheat adaptability to climate instability.

Overall, the results of the study show that the adaptive value of winter soft wheat cultivars cannot be fully assessed based only on mean grain yield. Under contrasting hydrothermal conditions, cultivar productivity was determined by the combined effects of yearly conditions, genotype-specific response, yield stability, and the ability to form productive spike components. The integration of grain yield, ecological plasticity, homeostaticity, spike structure traits, factor contribution, and cluster analysis made it possible to distinguish cultivars with different adaptive strategies. This approach is particularly relevant for the Right-Bank Forest-Steppe of Ukraine, where increasing hydrothermal instability requires the selection of cultivars capable of combining productivity with stable yield realization.

Conclusion

This study demonstrated substantial cultivar differentiation in grain yield, yield stability, ecological plasticity, homeostaticity, and main spike structure traits among 35 Ukrainian winter soft wheat cultivars evaluated under contrasting hydrothermal conditions in the Right-Bank Forest-Steppe of Ukraine. The three-year assessment confirmed that cultivar performance was strongly influenced by yearly conditions, while the cultivar × year interaction played an important role in determining both yield realization and the expression of several spike productivity traits.

Mean grain yield ranged from 508.4 to 661.7 g/m², indicating a wide range of productivity among the studied cultivars. The highest-yielding cultivars were Tsarivna, Svitanok Myronivskyi, Vodohrai Bilotserkivskyi, Zorepad Bilotserkivska, Kraievyd, MIP Dniprianka, and Kvitka Poliv. Among them, Tsarivna and Vodohrai Bilotserkivskyi showed the most favorable combination of high yield, moderate interannual variability, and balanced ecological response, which makes them promising for cultivation under variable hydrothermal conditions. Svitanok Myronivskyi and MIP Dniprianka had high productive potential, but their higher CV and bi values indicated stronger dependence on favorable yearly conditions.

The highest homeostaticity and the lowest yield variability were recorded for Kesariia Poliska, indicating its value as a source of yield stability under contrasting environmental conditions. Romantyka also showed stable yield expression and balanced spike structure traits. These cultivars may be useful for breeding programs aimed at improving yield stability and stress resilience, even if their mean yield does not always reach the level of the most productive genotypes.

Spike structure traits provided important additional information on the morphoproductive potential of the cultivars. Strong positive correlations were found among spike rachis length, spike weight, number of grains per spike, and grain weight per spike. However, their relationships with mean grain yield were weaker, confirming that plot-level yield is determined not only by main spike productivity, but also by the interaction of several traits, including productive tillering, stand density, grain set, grain filling, and genotype-specific response to yearly conditions.

The analysis of factor contribution showed that grain yield was mainly determined by year and cultivar × year interaction, whereas spike rachis length and number of spikelets per spike were more strongly influenced by cultivar-specific characteristics. This confirms the need for multi-year evaluation of winter wheat cultivars, especially in regions with unstable temperature and moisture supply. Cluster analysis further differentiated the cultivars into groups with distinct adaptive strategies, including high-yielding and morphoproductive cultivars, stable and homeostatic genotypes, environmentally responsive intensive-type cultivars, and genotypes with high spike productivity potential but unstable yield realization.

Overall, the results show that the adaptive value of winter soft wheat cultivars cannot be adequately assessed by mean grain yield alone. The integrated use of yield stability, ecological plasticity, homeostaticity, spike structure traits, factor contribution analysis, and cluster grouping provides a more informative approach for identifying cultivars adapted to climate-related hydrothermal instability. The obtained results may be used for cultivar recommendation in the Right-Bank Forest-Steppe of Ukraine and as a basis for selecting breeding material aimed at combining high productivity with stable yield realization under variable environmental conditions.

The authors declare no conflict of interests.

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