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YIELD STABILITY AND PHYSIOLOGICAL ADAPTATION OF WINTER WHEAT (*TRITICUM AESTIVUM* L.) GENOTYPES UNDER DIVERSE AGROCLIMATIC CONDITIONS

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SUMMARY

This study sought to assess the yield performance, ecological stability, and physiological traits of 10 winter wheat (*Triticum aestivum* L.) genotypes grown for three years (2023–2025) under variable agroclimatic conditions of the Khorezm Region, Uzbekistan. Field trials conducted had a randomized complete block design with three replications. Yield stability evaluation used the coefficient of variation (CV), while physiological adaptation determination employed the chlorophyll content (soil plant analysis development, or SPAD). Significant genotypic differences observed were prevalent in yield and physiological responses, especially under early heat stress in 2025. The highest mean grain yields resulted in cultivars Sila (572.5 g m^{-2}) and Nikifor/Kroshka (543.0 g m^{-2}). Among these, the genotype Sila showed the lowest CV (0.84%), indicating the utmost ecological stability and broad adaptability. Both wheat genotypes also maintained the maximum SPAD values (> 58.5), reflecting robust photosynthetic tolerance in stress conditions. However, regression analysis revealed a weak relationship between chlorophyll content and grain yield, indicating high SPAD alone does not ensure yield superiority. Overall, the genotype Sila succeeded in its identification as an optimal genotype, combining high yield and stability, while the genotype Nikifor/Kroshka appeared suitable for favorable environments. The results support breeding strategies aimed at improving the yield stability under varied climatic conditions.

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Keywords: Wheat (*T. aestivum* L.), yield, ecological stability, coefficient of variation, stress, SPAD, genotype-environment interaction

Key findings: Wheat (*T. aestivum* L.) cultivars Sila (572.5 g m^{-2}) and Nikifor/Kroshka (543.0 g m^{-2}) recorded the highest average grain yield. The cultivar Sila showed the lowest coefficient of variation, confirming its better ecological stability. Both genotypes maintained the highest SPAD values in stress conditions, revealing robust photosynthetic tolerance.

INTRODUCTION

Wheat (*Triticum aestivum* L.) is the most widely cultivated grain crop in the world and serves as the primary food source for more than half of the global population (Shiferaw *et al*., 2013). Wheat is one of the most important cereal crops for global food security. However, increasing temperature and climatic variability significantly affect wheat productivity, particularly in arid regions such as Central Asia (Sharma and Sharma, 2025). The global population projection will reach 10.3 billion people by 2084 (Lam*,* 2025), surpassing expert forecasts made several years ago. Consequently, the level of food consumption continues to rise as well. Moreover, climate change negatively impacts crop production severely due to biotic and abiotic stresses. These include climate change itself (Meliev *et al.,* 2023), soil degradation (Campos-Avelar *et al.,* 2023), heat, drought, salinization, and yellow rust (Wang *et al.,* 2024; Awais *et al.,* 2025). The negative impact of climate change on wheat production poses a threat to global food security, and the global temperature rise will have an increasingly detrimental effect on sustainable wheat production (Tripathi *et al.,* 2016).

Each 1 °C increase in global temperature shows an association with an estimated 6.0% ± 2.9% reduction in wheat yield (Zhao *et al*., 2017). Elevated temperatures during the flowering stage can disrupt heading and reproductive development, thereby negatively affecting grain set. Heat stress occurring during the grain-filling period is commonly a terminal heat stress, whereas exposure to high temperatures during germination and early vegetative growth has the description of an early heat stress. Both forms of stress significantly constrain wheat growth, development, and final productivity.

The severity of heat stress experienced by a plant depends both on ambient temperature and agronomic management and genetic factors that influence its cooling capacity, particularly through transpiration efficiency (Braun *et al*., 2010). Previous research efforts have focused on enhancing heat tolerance in hexaploid wheat by incorporating resistant germplasm derived from wild relatives and ancestral species (Itam *et al*., 2021).

The plant's reproductive period is considerably the most vulnerable stage to high-temperature stress in cereal crops (Mondal *et al.,* 2021). Consequently, this affects the formation and development of grains in the ear due to an insufficient supply of assimilated substances, resulting in a substantial decrease in the number of spikelets/grains (Meliev *et al.,* 2021). If exposing wheat plants to temperatures reaching 30 °C during the pollination period, this significantly reduces grain formation and eventually grain yield. Conversely, the high temperature accelerates the development of anthers and pistils, which also shortens the duration of anther and pollen tube development (Heidari *et al.,* 2016).

Wheat leaves have become one of the main morphological features that influence grain yield, with the three uppermost leaves (flag leaf, second leaf, and third leaf) positively distinguishing themselves by their contribution to the harvest (Lou *et al.,* 2021). Among these, the flag leaf plays the most significant role compared with the other leaves, intercepting 30% of light (Liu *et al.,* 2018). The flag leaf is also the main organ exerting a positive influence on grain yield, contributing up to

50% (Ba *et al.,* 2020). The leaves' positive effect on grain yield proved to have an association with chloroplasts in the leaves. Chloroplasts (chlorophylls) are responsible for carbon fixation and the formation of vegetative organs during the growth period (photosynthesis), as well as for the response to environmental stresses, including heat stress (Allahverdiyev*,* 2015).

Chloroplasts, being one of the intercellular energy-producing organelles in cells, carry out key metabolic processes, chlorophyll synthesis, regulation of reactive oxygen species (ROS) types, metabolic changes in protein turnover, and carbon assimilation in response to heat stress. Past studies revealed even genetically similar genotypes differ in their chlorophyll content depending on the environment and growing conditions, as well as in their response to environmental influences (Dadoboeva *et al.,* 2018). The high chlorophyll content can serve as a criterion for wheat's resistance to high temperatures (Munjal and Dhanda*,* 2016). Chlorophyll acts as a weak photo-inhibitor at high temperatures, leading to increased heat resistance (Choudhary *et al.,* 2020).

Research has demonstrated that chloroplasts play an influential role in activating cellular stimulator signaling during heat stress (Yuan *et al.,* 2015). Chlorophylls are the pigments involved in the accumulation of light energy and the regulation of electron exchange in primary processes of photosynthesis. Physiological traits serve as a protective mechanism against stress, with photosynthesis, water use efficiency (WUE), and other physiological processes determining wheat's resistance to abiotic stresses such as drought and heat. Improvement in these traits is crucial for developing climate-resilient and high-yielding wheat cultivars. Therefore, the concerned study sought to evaluate yield stability and physiological adaptation of winter wheat genotypes under contrasting agroclimatic conditions of the Khorezm Region using yield stability indices and SPAD-based physiological assessment.

MATERIALS AND METHODS

Plant materials and procedure

The presented research on wheat (*T. aestivum* L.) took place for three years (2023–2025), with the experiments conducted at the Khorezm Scientific Experimental Station, Research Institute of Selection, Seed Production, and Agrotechnology of Cotton Growing, Khorezm Region, Uzbekistan (41°19'60.00"N, 61°00'0.00"E). The study utilized 10 cultivars of winter wheat with various genetic origins. These cultivars came from Uzbekistan, Kyrgyzstan, Mexico, Russia, Kazakhstan, and Tajikistan (Durdona, Vostorg, Starshina, Kamol, Sila, Ayvina, Nikifor/Kroshka, Kasiet, Adyr, and Vlada). These wheat cultivars, adapted to diverse soil and climatic conditions, had their genetic diversity providing extensive opportunities for studying genotype-environment interaction effects and identifying promising genotypes suitable for local conditions.

Trait's measurement

The study analyzes the dependence of wheat's physiological, morphological, and productive traits on environmental factors, as well as their adaptability to local climatic conditions. The experiment proceeded using a randomized complete block design with three replications. Each plot measured 2 m², with the statistical significance evaluated at $P \leq 0.05$. Chlorophyll content measurement used the SPAD 500 device, while leaf area determination utilized a LI-COR 3100C instrument. By assessing grain yield, the traits, such as spike weight, spike length, the number of spikelets per spike, grain count, grain weight, and 1000-grain weight, also received analysis.

Data analysis

All the recorded data entailed analysis using Microsoft Excel and Statgraphics Centurion 34 software. Statistical analysis sought to compare the wheat genotypes for these characteristics. The quantitative indicators determining grain yield obtained calculations based on the formula developed by the International Maize and Wheat Improvement Center (CIMMYT) scientists (Ken *et al*., 1997).

RESULTS

Grain yield and physiological traits

Grain yield is the leading criterion for evaluating wheat (*T. aestivum* L.) cultivars, as it reflects the cumulative effects of the genotype's genetic potential, environmental conditions, and physiological and morphological processes throughout the growing season. During the three years of experiments (2023–2025), significant differences were evident among the studied winter wheat cultivars for grain yield. These differences indicated a main association with the genotype's genetic background, winter hardiness, and the genotype's ability to adapt to fluctuating agroclimatic conditions.

Based on the three-year average of grain yield, the winter wheat cultivars reached categorization into three distinct productivity groups. The high-yielding group comprised cultivars Sila (572.5 ± 5.5 g m^{-2}) and Nikifor/Kroshka (543.0 ± 6.0 g m^{-2}), which consistently outperformed the remaining genotypes across the study period (Table 1). These cultivars demonstrated superior productivity under both favorable and stress-prone climatic conditions.

The medium-yielding group included cultivars Vostorg (441.0 ± 8.0 g m^{-2}), Adyr (421.0 ± 3.0 g m^{-2}), and Kamol (420.0 ± 26.0 g m^{-2}), which exhibited a moderate yield performance with varying levels of stability.

In contrast, cultivars Starshina (265.0 ± 4.0 g m^{-2}) and Vlada (335.0 ± 6.0 g m^{-2}) gained the classification as low-yielding genotypes, producing significantly lower grain yields than the other evaluated cultivars.

For assessing yield stability and resistance to environmental fluctuations, the study calculated the coefficient of variation (CV) for each cultivar. The CV values clearly reflected the degree of yield stability under contrasting environmental conditions. According to the coefficient of variation, the most stable wheat cultivars were the Sila (CV: 0.84%), Ayvina (CV: 2.69%), Adyr (CV: 2.90%), and Vlada (CV: 1.65%). These genotypes exhibited minimal yield variability across the three-year experiments and maintained their stable productivity under favorable conditions in 2024 and stress conditions in 2025. Such low variability

Table 1. Grain yield of winter wheat cultivars under the agroclimatic conditions of the Khorezm Region during 2023–2025.

No.	Cultivars	Years			Average crop yield, ±S (g/m^2)
		2023	2024	2025	
1	Durdona	384	395	389.6	389.5±5.50
2	Vostorg	433	449	442	441.0±8.0
3	Starshina	261	269	266	265.0±4.0
4	Kamol	394	446	421	420.0±26.0
5	Sila	567	578	572	572.5±5.5
6	Ayvina	366	374	369.9	370.0±4.0
7	Nikifor/Kroshka	549	537	543	543.0±6.0
8	Kasiet	297	401	334	349.0±52.0
9	Adyr	418	424	421	421.0±3.0
10	Vlada	329	341	335	335.0±6.0
Mean value		399.8	421.4	409.3	410.5±6.5
Standard deviation (S.D.)		104.6	94.8	97.6	
Standard error (S.E.)		33.2	30	30.8	4.88
Coefficient of variation (CV %)		26.2	22.5	23.8	
$LSD_{0.05}$					

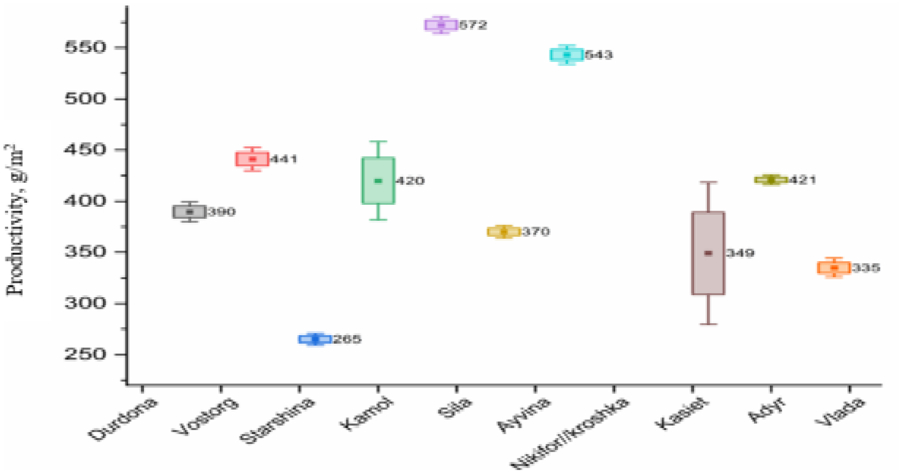

Figure 1. Grain yield distribution and stability of winter wheat cultivars under agroclimatic conditions of the Khorezm Region during 2023–2025.

suggested the highest level of ecological stability and stress tolerance traits, particularly vital for wheat breeding programs targeting climate resilience.

In contrast, cultivars Kasiet (CV: 5.50%), Nikifor/Kroshka (CV: 6.18%), Durdona (CV: 11.60%), and Vostorg (CV: 6.55%) exhibited the highest yield variability, revealing greater sensitivity to varied environmental conditions. Among these, the genotype Kasiet showed the most pronounced response to climatic variations. Under favorable conditions in 2024, the cultivar Kasiet produced a relatively high yield (401 g m^{-2}), whereas under unfavorable conditions in 2025, its yield declined sharply to 334 g m^{-2}. This yield reduction can be due to the inability of the plants to fully develop grains despite the formation of a large vegetative biomass, highlighting the importance of efficient assimilate partitioning in stress conditions.

Overall, the genotypes' grain yield acquired influences from both climatic factors and morphological and physiological trait variations. For example, the low yield potential of the cultivar Starshina can refer to its relatively low winter hardiness (72.4%), which substantially limited its productivity. Similarly, although cultivar Nikifor/Kroshka displayed the topmost grain yield, its winter hardiness remained low (72.6%). Nevertheless, the cultivar Nikifor/Kroshka was able to achieve the higher yield by sowing at optimal plant density, suggesting the appropriate agronomic management practices can partially compensate for reduced winter survival.

The cultivars' differences for grain yield have a clear illustration in Figure 1. The highest-yielding cultivars, Sila (572 g m^{-2}) and Nikifor/Kroshka (543 g m^{-2}), have the tallest bars representing these, visually confirming their yield superiority. In contrast, the cultivar Starshina with the lowest yield (265 g m^{-2}) has the shortest bar representation. Vertical error bars revealed the standard error (±) of the mean and reflect yield stability across years. Cultivars, such as Sila and Adyr, as shown in relatively short error bars, demonstrated highly stable yields, proving their average values as reliable. Conversely, the cultivar Kasiet exhibited the longest error bars, enunciating substantial yield fluctuations across the three years of experimentation (312 g m^{-2} in 2023, 401 g m^{-2} in 2024, and 334 g m^{-2} in 2025). This observation was consistent with its highest CV value, confirming its sensitivity to environmental variations.

Overall, the graphical results support the conclusions drawn from the statistical analysis. Wheat cultivars Sila and

Table 2. Chlorophyll content (SPAD), leaf area, and grain yield of winter wheat cultivars evaluated during 2023–2025.

No.	Cultivars	Years			Mean values	Leaf area (cm)	Grain yield (g/m²)
		2023	2024	2025			
1	Durdona	54.1±1.29	55.2±0.68	54.8±1.75	54.7±0.35	378.7±62.6	389.5±5.50
2	Vostorg	56.6±0.93	57.0±1.55	55.9±0.86	56.5±0.32	345.2±88.7	441.0±8.0
3	Starshina	53.3±1.18	54.2±0.90	54.2±1.58	53.9±0.30	211.2±35.1	265.0±4.0
4	Kamol	57.2±0.80	59.7±0.77	56.6±0.94	57.8±0.95	292.9±18.6	420.0±26.0
5	Sila	57.7±0.96	60.3±1.36	57.4±1.86	58.5±0.92	267.5±29.1	572.5±5.5
6	Ayvina	53.8±1.53	54.3±1.61	54.6±1.77	54.2±0.23	323.8±34.6	370.0±4.0
7	Nikifor/Kroshka	57.9±1.28	61.8±0.65	60.0±1.78	59.9±1.13	309.8±51.0	543.0±6.0
8	Kasiet	54.8±1.41	55.7±1.38	55.1±2.14	55.2±0.26	373.8±49.6	349.0±52.0
9	Adyr	55.0±1.14	55.9±1.65	55.5±1.36	55.5±0.26	224.8±23.7	421.0±3.0
10	Vlada	55.4±0.52	56.9±0.71	55.9±0.39	56.1±0.44	224.4±13.4	335.0±6.0
Mean values		55.2±1.10	57.1±1.10	56.0±1.44	56.2±0.51	295.2±40.6	410.5±3.46

Nikifor/Kroshka were distinct with the highest grain yield potential, while genotypes Sila and Adyr demonstrated superior yield stability. Although the cultivar Kasiet showed the highest productivity under favorable conditions, its robust sensitivity to climatic stress conditions limited its reliability across the years.

Chlorophyll content and physiological performance

The analysis of wheat genotypes for chlorophyll content, expressed as SPAD values, revealed apparent genetic differences. In 2023, the overall mean SPAD value across the cultivars was 55.2 ± 1.10. The recorded above-average chlorophyll content resulted in the cultivars Vostorg, Kamol, Sila, and Nikifor/Kroshka (Table 2). High SPAD values disclosed sufficient chlorophyll concentration in plant leaves, enabling efficient light absorption and energy conversion during photosynthesis. A decline in SPAD values often reflects nitrogen deficiency, which may occur before the appearance of chlorosis symptoms, proving SPAD as a useful early indicator of plant physiological status.

During the crop season of 2024, the average chlorophyll content enhanced to 57.1 ± 1.10, showing an association with relatively cooler and more humid weather conditions. Enhanced photosynthetic activity under these favorable conditions led to an increased chlorophyll accumulation, particularly in the wheat cultivars Nikifor/Kroshka and Sila, which emerged with the highest SPAD values. In contrast, the genotypes Starshina and Ayvina exhibited the lowest SPAD values.

In the varietal evaluation during 2025, the mean SPAD value slightly declined to 56.0 ± 1.44, which may be ascribable to early heat stress during the flowering and heading stages. Despite these abiotic stress conditions, cultivars Nikifor/Kroshka and Sila maintained relatively high chlorophyll content, demonstrating robust physiological resilience.

Regression analysis gave a weak positive relationship between chlorophyll content and grain yield ($y = 0.018x - 48.8$; $R^2 = 0.17$; $P > 0.05$), indicating that chlorophyll content alone was not a strong predictor of productivity (Figure 2). Although higher SPAD values contributed to improved photosynthetic performance and stress tolerance, grain yield formation gained primary influence from multiple yield components, including grain number per unit area and a thousand-grain weight. Therefore, effective selection strategies should integrate both physiological and agronomic parameters.

DISCUSSION

Grain yield is the leading criteria for evaluating wheat (*T. aestivum* L.) cultivars, as it reflects the cumulative effects of the genotype's

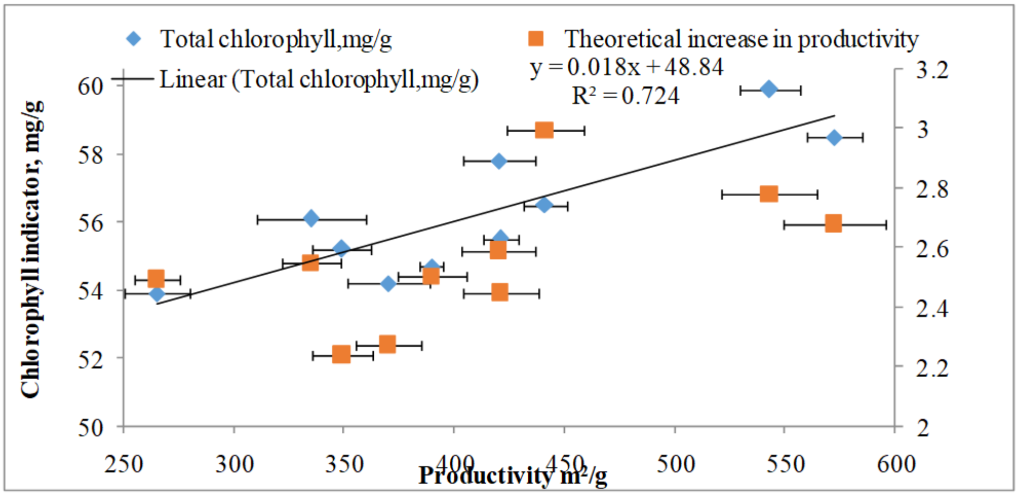

Figure 2. Relationship between total chlorophyll content and grain yield of winter wheat cultivars based on the regression analysis.

genetic potential, environmental conditions, and physiological and morphological processes throughout the growing seasons. The promising study enunciated that the grain yield performance of winter wheat (*T. aestivum* L.) genotypes under agroclimatic conditions of the Khorezm Region had considerable effects from the genotypes' genetic makeup and existing diverse environmental conditions. The three-year evaluation revealed substantial genotype-dependent differences in productivity and physiological responses, confirming that grain yield stability remains a key component of wheat adaptation under climate change scenarios.

These findings are consistent with previous studies reporting that low-CV genotypes are more suitable for breeding programs targeting yield stability under climate variability. However, as emphasized by Liu *et al*. (2017), the highest productivity must complement stability across varied environments to ensure practical value. In this present study, the cultivar Sila integrates the highest grain yield with the lowest coefficient of variation, revealing broad ecological adaptability. These results were greatly analogous to the findings of Moghadam *et al*. (2024), who reported that low-CV genotypes represent an ideal base for breeding in stress-prone regions.

The marked yield reduction observed in the cultivar Kasiet under unfavorable conditions further confirms that high-yield potential under optimal environments does not necessarily guarantee resilience in stress. Heat stress during reproductive stages likely reduced grain formation and assimilate partitioning efficiency, thereby limiting yield stability. Similar conclusions occurred from a study by Lekhana *et al*. (2025), who reported the terminal heat stress significantly affects stay-green traits and senescence processes, ultimately influencing grain yield and quality. Mondal *et al*. (2021) and Bunta (2020) also emphasized the vulnerability of reproductive stages to high-temperature stress and its direct impact on grain set. Collectively, these studies reinforce that considering yield stability should be a central selection criterion alongside productivity.

Winter hardiness was another important determinant of yield performance. The relatively low productivity of the cultivar Starshina can be because of reduced winter survival, which affected plant density and yield component formation. This observation is consistent with Itam *et al*. (2021), who demonstrated the stress-related adaptive traits significantly influence yield outcomes under variable environmental conditions.

Physiological assessment based on chlorophyll content provided additional insight into genotype performance. Cultivars Sila and Nikifor/Kroshka consistently maintained high SPAD values across seasons, reflecting robust photosynthetic capacity and stress tolerance. Previous studies (Choudhary *et al*., 2020; Jin *et al*., 2025) have linked chlorophyll retention with the stay-green trait and enhanced heat tolerance. However, the weak relationship observed between chlorophyll content and grain yield in the presented study indicates that chlorophyll concentration alone is insufficient to predict yield performance. Grain productivity is a complex trait governed by multiple interacting components, including spike fertility, grain number, and a thousand-kernel weight, rather than a single physiological parameter.

Year-to-year variation in chlorophyll content further reflects genotype × environment interactions. The increase in SPAD values under favorable conditions in 2024 and their decline under early heat stress in 2025 demonstrate the sensitivity of physiological processes to climatic variation. Similar environmental responsiveness of photosynthetic traits was in reports by Ba *et al*. (2020) and Lou *et al*. (2021).

Overall, the findings highlight that effective wheat improvement under climate variability requires the integration of yield potential, ecological stability, and physiological adaptation traits. The cultivar Sila emerged as an outstanding genotype due to its combination of high productivity and minimal variability across environments. Genotypes, such as Adyr and Ayvina, although moderately productive, may serve as valuable sources of stability traits in breeding programs. Meanwhile, the cultivar Nikifor/Kroshka appears particularly suitable for favorable environments, where its high-yield potential can be fully exploited.

The present results are consistent with modern wheat breeding strategies that emphasize resilience to climatic stress (Braun *et al*., 2010; Shiferaw *et al*., 2013). Future research integrating physiological screening with molecular and genomic approaches could facilitate the identification of loci associated with yield stability and stress tolerance, thereby enhancing selection efficiency in climate-resilient wheat breeding programs.

CONCLUSIONS

The study demonstrated that winter wheat yield stability under the agroclimatic conditions of the Khorezm Region gained strong influences from genotype adaptability and environmental variability. Among the evaluated genotypes, the cultivar Sila exhibited the optimal combination of high grain yield, minimal variability, and strong physiological performance, making it a promising candidate for climate-resilient breeding programs. The cultivar Nikifor/Kroshka showed high productivity under favorable conditions and may serve as a valuable parental line in targeted breeding strategies. These findings highlight the importance of integrating yield performance, ecological stability, and physiological traits in wheat improvement programs aimed at enhancing resilience to climate change.

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