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RESEARCH ARTICLE

## Assessment of adaptability and yield formation in wheat winter under different nitrogen levels in the North-Eastern forest-steppe of Ukraine

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### Abstract

The aim of the research was to conduct a comparative evaluation of winter wheat varieties regarding their ability to consistently realize yield potential depending on the level of mineral nutrition and the mechanisms of formation of the main yield components. It was established that winter wheat yield was most closely related to productive tillering density and grain weight per spike, whereas the effect of thousand kernel weight was variety-specific. A two-factor regression model including productive tillering and grain weight per spike demonstrated high explanatory power ( $R^2=0.98-0.99$ ) for all studied varieties. However, the magnitude of residual variance differed significantly, indicating different yield formation mechanisms. The obtained results justify the feasibility of a differentiated approach to mineral fertilization of winter wheat considering varietal peculiarities of yield formation.

**Keywords:** Wheat winter, Variety, Yield, Productivity, Nutrition, Adaptation, Integral adaptability index

### Introduction

Yield formation of winter wheat is a complex integrative process determined by the interaction of genotype, environmental conditions, and agronomic factors. Modern studies indicate that the key yield structure components are productive tillering density, number of grains per spike, and thousand kernel weight, which collectively determine the realization level of the genetic potential of the crop (Fischer, 2011, Slafer, et al. 2014, Karpenko, et al. 2020).

Nitrogen nutrition is considered one of the most important regulators of wheat yield formation. Long-term field experiments show that optimization of nitrogen fertilizer rates increases both productive tillering density and grain weight per spike, while excessive rates do not always lead to proportional yield increases (Zörb, et al. 2018, Lollato, 2019). Nitrogen use efficiency significantly depends on genotype-specific traits of the variety (Jaenisch, 2022).

Several studies emphasize that the response of yield components to mineral nutrition intensification is variety-specific. Some genotypes increase yield mainly by increasing grain number, while others through increasing grain weight (Sadras and Lawson, 2011,

Zhemela, et al. 2020). This differentiation justifies the need for quantitative models to assess the contribution of individual components to yield formation.

A separate direction of modern research concerns the stability of yield components and their adaptability to variable weather conditions. The use of regression approaches and integral indices allows a more objective evaluation of varietal peculiarities in yield realization (Lisovyi and Tarariko, 2018). This aligns with current agronomic research trends combining morphostructural analysis with mathematical modeling.

Thus, the assessment of adaptability of winter wheat varieties remains one of the key issues in modern crop production. This is due to the need to ensure stable productivity under increasing climate variability and intensification of cultivation technologies.

Classical approaches to genotype  $\times$  environment interaction analysis are based on evaluating stability and plasticity. The Wricke model uses ecological stability index ( $W^2$ ), reflecting genotype contribution to total interaction variance (Gamayunova and Khonenko, 2020), while the Eberhart-Russell model applies regression analysis where the regression coefficient characterizes sensitivity to environmental changes and deviation variance indicates stability (Pysarenko, et al. 2019).

Further development of adaptability assessment approaches involves multifactor statistical models such as Additive Main Effects and Multiplicative Interaction (AMMI) and Genotype plus Genotype-by-Environment (GGE) biplot, which allow detailed analysis of genotype-environment interaction and identification of broadly or specifically adapted varieties (Yan and Kang, 2003).

Recently, increasing attention has been paid to integral adaptability indices combining stability indicators of morphological traits with yield realization levels. This approach provides a unified quantitative evaluation suitable for comparative varietal analysis and justification of variety-specific cultivation technologies. The relevance of this approach is confirmed by modern studies of adaptability and productivity stability of winter wheat varieties under different growing conditions (Alemu, et al. 2024).

Thus, the use of integral adaptability indices is considered a logical continuation of classical stability and plasticity analysis approaches and is of significant importance for both breeding research and agronomic practice.

## Materials and Methods

Field studies were conducted during 2022-2024 in the conditions of the North-Eastern forest-steppe of Ukraine. The soil of the experimental site was typical chernozem, medium loamy, with humus content in the arable layer of 3.8-4.2% and a soil solution reaction close to neutral. The climate of the research area is moderately continental with significant interannual variability in temperature regime and precipitation, typical for the North-Eastern forest-steppe zone of Ukraine.

The experiment was established according to a three-factor design: Factor A-winter wheat variety (Antonivka, Podolianka, Kubus); Factor B-mineral nutrition background: Control (without fertilizers),  $N_{40}P_{40}K_{40}$  ( $N_{20}P_{40}K_{40}$  before sowing+ $N_{20}$  as spring top-dressing),  $N_{60}P_{40}K_{40}$  ( $N_{20}P_{40}K_{40}$  before sowing+ $N_{40}$  as spring top-dressing); Factor C-growing year (2022, 2023, 2024). Crop cultivation practices corresponded to zonal recommendations and generally accepted winter wheat production technologies. Records and observations were carried out according to standard field research methodologies. (Pidoprigora and Pisarenko, 2003).

Weather conditions during the study years were contrasting in terms of temperature regime and precipitation, creating different conditions for realization of varietal productivity potential: 2022-was characterized by moisture deficit during spring vegetation; 2023-2024-had more favorable hydrothermal conditions.

## Results and Discussion

The lowest yields were formed under the control treatment (without fertilizers). Mineral fertilization significantly increased crop productivity. Transition from control to  $N_{40}P_{40}K_{40}$  increased yield in all studied varieties, though the magnitude of increase differed, indicating different varietal responses to initial nitrogen levels. Increasing nitrogen to  $N_{60}P_{40}K_{40}$  generally led to further yield increases; however, response intensity strongly depended on varietal genetic traits and year conditions (Tab. 1).

**Table 1.** Yield of wheat winter depending on variety and mineral nutrition background (average for 2022-2024), t/ha.

Variety	Control	$N_{40}P_{40}K_{40}$	$N_{60}P_{40}K_{40}$	$\pm$ vs. Control $N_{40}P_{40}K_{40}$	$\pm$ vs. Control $N_{60}P_{40}K_{40}$
Antonivka	4.57	5.35	7.49	+0.78	+2.92
Podolianka	4.56	4.87	7.49	+0.31	+2.93
Kubus	5.46	5.59	7.65	+0.13	+2.19

Varietal differences were manifested not only in the absolute yield level but also in the pattern of its stability under different fertilization backgrounds. Some varieties ensured relatively uniform yield formation across all fertilizer treatments, while others were characterized by a more pronounced response to nitrogen intensification. This indicates different mechanisms of yield potential realization and necessitates a detailed analysis of the role of individual yield structure components and their interaction with mineral nutrition levels.

Thus, the results indicate a clearly expressed variety-specific response of winter wheat to mineral nutrition levels. The varieties Antonivka and Podolianka were characterized by a more intensive response to increased nitrogen doses, whereas the Kubus variety demonstrated yield stability and lower dependence on intensification of the input background. This determines the feasibility of a differentiated fertilization approach considering varietal characteristics.

To clarify the role of individual yield structure elements in winter wheat yield formation, a correlation analysis of the main morphological and productivity indicators was conducted. The obtained results confirmed that the nature and strength of relationships between yield and its components were clearly variety-specific and depended on mineral nutrition levels (Tab. 2).

**Table 2. Correlation coefficients between biological yield of wheat winter and yield components.**

Parameters	Variety		
	Antonivka	Podolianka	Kubus
Plant height, cm	0.798	0.836	0.633
Number of productive stems, pcs/m <sup>2</sup>	0.742	0.857	0.437
Spike length, cm	0.676	0.661	0.417
Number of spikelets per spike, pcs	0.709	0.685	0.309
Number of grains per spike, pcs	0.411	0.723	0.028
Grain weight per spike, g	0.677	0.868	0.750
Thousand kernel weight, g	-0.190	-0.348	-0.191

The parameter that showed the strongest correlation with yield was productive tillering density. The values of the correlation coefficients between the number of productive stems and yield were high and positive, indicating the decisive role of this indicator in forming the quantitative basis of yield. This confirms that optimization of productive tillering density is one of the key factors in realizing the yield potential of winter wheat, especially under increased nitrogen levels.

High positive correlations were also found between yield and grain weight per spike. This indicator integrates the number of grains per spike and their individual weight, which determines its significance as a generalized characteristic of spike productivity. At the same time, grain weight per spike demonstrated a stronger relationship with yield than individual spike elements, indicating the expediency of using this parameter in further regression analysis.

The relationship between yield and thousand kernel weight was moderate and differed among varieties. This suggests that this indicator plays a secondary role in yield formation and more strongly determines grain quality characteristics rather than total yield level. At the same time, close correlations were observed between individual components of spike productivity, particularly between the number of grains per spike and grain weight per spike, indicating the presence of multicollinearity between these indicators.

The obtained results of the correlation analysis justify the use of integral yield structure indicators in quantitative assessment of yield formation mechanisms. Considering the identified relationships, a two-factor regression model including productive tillering density and grain weight per spike as the most informative and methodologically correct variables was selected for further analysis. The results of the regression analysis showed high adequacy of the model for all studied winter wheat varieties (Tab. 3). The values of the coefficient of determination ranged from 0.980 to 0.988, indicating the model's ability to explain the main portion of yield variation through two key components—the number of productive stems and spike productivity. At the same time, the magnitude of residual variance differed significantly among varieties, indicating different mechanisms of yield potential realization.

**Table 3. Results of regression analysis.**

Variety	R <sup>2</sup>	Standard error	Residual variance, $\sigma^2_e$
Antonivka	0.980	23.07	532.18
Podolianka	0.988	19.89	395.60
Kubus	0.983	17.49	305.97

The highest explanatory power of the model was observed in the Podolianka variety ( $R^2=0.988$ ), which indicates a balanced pattern of yield formation, where quantitative and qualitative yield structure components consistently respond to changes in mineral nutrition levels. This type of response ensures high yield predictability and effective realization of yield potential under intensified input conditions.

For the Antonivka variety, the coefficient of determination was also high ( $R^2=0.980$ ), but the residual variance was greater, indicating a higher influence of additional factors on yield formation. This may be associated with stronger dependence of this variety on annual growing conditions and compensatory processes within spike structure that are not fully accounted for in the two-factor model. The Kubus variety was characterized by high model adequacy ( $R^2=0.983$ ) and the lowest residual variance among the studied varieties. This indicates a stable yield formation mechanism, in which the main portion of yield variation is determined by productive

tillering density and grain weight per spike, while the influence of other factors is limited. This feature is consistent with the lower sensitivity of the variety to nitrogen intensification and its ability to ensure a relatively stable yield level under different input conditions.

Thus, the application of the two-factor regression model allowed not only quantitative assessment of the contribution of major yield structure components but also identification of variety-specific mechanisms of winter wheat yield realization, which is important for substantiating differentiated agronomic decisions. The generalization of the correlation and regression analyses results allowed for the identification of dominant yield structure components that determined the pattern of winter wheat productivity formation depending on varietal characteristics (Tab. 4). It was established that the studied varieties realized their yield potential through different mechanisms, resulting in distinct responses to mineral nutrition levels.

**Table 4.** Dominant yield structure components of winter wheat depending on varietal biological characteristics.

Variety	Dominant component	Type of yield formation
Antonivka	Spike productivity	Compensatory, spike-oriented
Podolianka	Tillering density+spike	Balanced, intensive
Kubus	Tillering density	Stabilizing, moderately intensive

Thus, the identified varietal differences in dominance of individual yield structure components confirm the necessity of a differentiated approach to fertilization systems and variety selection, taking into account yield formation mechanisms. For a generalized assessment of the ability of winter wheat varieties to stably realize yield potential under different levels of mineral nutrition, the Integral Adaptability Index (IAy) was applied. This index allows combining yield level with the nature of varietal response to changes in the input background. Application of this indicator enabled comparison of varieties not only by absolute yield values but also by efficiency and stability of yield formation under nitrogen intensification. Calculation of the IAy index revealed clear varietal differences in adaptive response patterns. The Podolianka variety demonstrated the highest IAy values under increased mineral nutrition levels, indicating high adaptability to intensified input conditions and the ability to effectively realize yield potential under increasing nitrogen supply. This response pattern corresponds to regression analysis results that revealed a balanced yield formation mechanism in this variety. The Antonivka variety showed moderate values of the integral adaptability index, indicating selective response to increased nitrogen levels. In this variety, input intensification was accompanied by significant yield increases; however, yield realization stability was lower, corresponding to a compensatory type of yield formation with dominance of spike productivity.

The Kubus variety was characterized by relatively high IAy values under control and moderate input levels; however, further nitrogen increase did not result in proportional index growth. This indicates orientation of the variety toward stable yield realization under limited mineral nutrition and limited sensitivity to nitrogen intensification. This finding is consistent with the minimal residual variance observed in regression model M2. Thus, the integral adaptability index confirmed the existence of different strategies of winter wheat yield formation depending on varietal characteristics. The combination of yield analysis, yield structure evaluation, regression modeling, and IAy values allows substantiated recommendation of a differentiated approach to mineral fertilizer application considering genetic potential and adaptive properties of varieties.

## Conclusion

Winter wheat yield formation under the experimental conditions was determined by the combination of productive tillering density and spike productivity; however, the contribution of these components had a clearly expressed variety-specific character. This is confirmed by the high explanatory power of the two-factor regression model ( $R^2=0.98-0.99$ ) and differences in residual variance among varieties. The Podolianka variety was characterized by the most balanced mechanism of yield potential realization, in which yield was effectively explained by both quantitative and qualitative yield structure components. This corresponds to the maximum values of the Integral Adaptability index (IAy) under increased nitrogen rates. The Antonivka and Kubus varieties realized yield potential through different adaptation models: Antonivka was characterized by dominance of spike productivity and increased residual variability, whereas Kubus showed high yield stability and lower sensitivity to nitrogen intensification. This confirms the feasibility of a differentiated fertilization approach depending on varietal characteristics.

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