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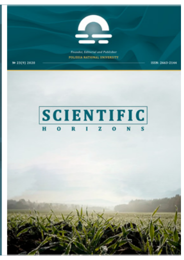

Variability and adaptability of winter soft wheat lines according to thousand-grain weight

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Abstract. The search for winter wheat genotypes with a high and stable expression level of valuable agronomic traits, including thousand-grain weight, is a relevant task for breeders under conditions of agricultural intensification. The aim of the study was to identify winter wheat lines with a high level of expression of thousand-grain weight and high adaptive indices for further use in breeding practice. Mathematical and statistical methods and regression analysis were used in the calculations. The adaptability of the lines was assessed by the integrated index of adaptability rating, using a set of stability and plasticity estimates. Contrasting weather conditions in 2019/20-2022/23 made it possible to identify adaptive lines for large grain size. It was found that the highest (47.9 g) mean thousand-grain weight was observed in the 2022/23 season, which was favourable in terms of weather conditions, and the minimum (41.3 g) in the dry 2019/20 season. A significant variability of trait expression was revealed depending on the conditions of the year (53.7%), genotype (27.3%) and

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the interaction (13.6%). Lines ER 60667, ER 60724 and LIUT 60680, which significantly exceeded the experiment mean, were identified. According to the regression coefficient, the lines were divided into three groups: highly plastic (b_i = 1.06-1.60), stable (b_i = 0.36-0.96) and medium-plastic (b_i = 0.97-1.04). From a practical point of view, the most valuable lines in terms of the trait were the most adaptive ones – highly plastic ER 60667, ER 60724 and the low-plastic LIUT 60680. An increased level of adaptability was noted for the medium-plastic lines LIUT 60430 and LIUT 60734 with an optimal response to improved growing conditions. The selected genotypes are valuable initial material in breeding for adaptability in terms of thousand-grain weight. Taking into account the yield level and the complex of traits, the obtained genotypes can be submitted as new winter wheat varieties for State varietal testing at the Ukrainian Institute for Plant Variety Examination (UIPVE)

Keywords: wheat; meteorological conditions; regression coefficient; phenotypic stability; homeostasis; breeding value

INTRODUCTION

Wheat (*Triticum aestivum* L.) is a vital crop that ensures food security worldwide and is a globally important source of nutrients. As noted by A. El Baouchi *et al.* (2024), wheat end-use products play an important role in human nutrition, providing up to 20% of daily protein intake and 21% of caloric intake. The authors also emphasise that the expected increase in the world's population to 9 billion people by 2050 will require an increase in global wheat production by about 70%. A. Ingver *et al. (*2024) underline that yield is the main breeding target, while quality traits that determine the nutritional value and technological properties of grain are also important. To meet the growing demand for wheat consumption, it is necessary to focus on breeding improvement strategies aimed at key parameters: yield, adaptability, grain size, and quality characteristics, including morphological traits of the caryopsis and protein content. Climate change poses a serious threat to crop production worldwide; therefore, varieties adapted to specific regions are needed. According to A.C. Kyratzis *et al.* (2022), new varieties must combine high stable yield with the necessary quality traits. This can be achieved only by using appropriate parental components in breeding programmes.

Genotype plays an important role in the formation of yield and grain quality. O.L. Ulich *et al.* (2022) state that productivity is determined by the plant's potential and its ability to realise this potential under specific growing conditions. The yield level of wheat is closely related to such complex traits as earliness, vernalisation period, photoperiod response, plant height and tolerance to abiotic stresses. However, the linear dimensions of the caryopsis, as shown by I. Al-Ashkar *et al.* (2023), also play an important role in raising yield and correlate with it due to the stability and influence on grain mass. According to V. Torianyk and V. Vasilenko (2023), thousand-grain weight is a species-specific indicator that largely depends on the variety and seed formation conditions. In cereals, it indirectly determines grain size and filling, the technological qualities of the variety and its productivity, and also indirectly characterises increased drought tolerance. Therefore, despite the low level of modification variability, evaluation of breeding material for adaptability in terms of grain size is necessary when creating new adaptive varieties under conditions of climate warming. B.M. Sewore and A. Abe (2024) demonstrated the importance of selecting genotypes that are stable under temperature stress.

In conformity with Yu.O. Chernobai and V.K. Riabchun (2022), despite different inheritance types of this trait depending on the parents' genotypes, selection for thousand-grain weight is effective in genera closely related to wheat. For example, in winter rye considerable success has been achieved in fixing the trait over many years. X. Hu *et al.* (2023) emphasise that phenotyping for thousand-seed weight in combination with modern genome sequencing technologies (GBS) makes it possible to predict inheritance of this trait in hybrids and thus increase breeding efficiency by forecasting and selecting only promising crossing combinations. In addition, J. Ma *et al.* (2025) state that significant progress has been made in identifying quantitative trait loci that can also be used for selection at the genetic level. Therefore, the aim of this work was to determine the degree of variability of the trait "thousand-grain weight" in winter wheat lines and to identify those lines most adaptive to changing environmental conditions.

MATERIALS AND METHODS

The study was carried out in 2019/20-2022/23 in the fields of the breeding crop rotation of the Winter Wheat Breeding Laboratory at the V.M. Remeslo Myronivka Institute of Wheat of the National Academy of Agrarian Sciences of Ukraine (MIW). The material for the study comprised eighteen breeding lines of winter wheat under competitive testing, differing in vegetation period length, morphological characteristics and potential yield level compared with the reference variety Podolianka. Sowing was performed with an SN−10C drill after soybean as the preceding crop, in the first ten-day period of October, under less dry weather conditions. The seed sowing rate was 5.0 million viable seeds per hectare. The accounting plot area was 10 m^2, and the experiment was laid out in four replicates. The material was harvested with a Hege-125 combine. Records and observations were carried out in accordance with the method of State variety testing (Tkachyk, 2016). Thousand-grain weight was determined on RADWAG AS 220. R2 analytical scales (CAS MWP-300; max.: 300 g; min.: 0.2 g; e = d = 0.01 g).

To determine the influence of year conditions on trait formation, the following indices were used: "hydrothermal coefficient" (HTC), "environment index" (EI) and "relative environment index" (REI) (Vlasenko *et al.*, 2012).

$$REI = 100\% + (Pr - \bar{P})/\bar{P}100\%, \quad (1)$$

where Pr is the biometric indicator of the mean value of a specific trait for all lines in a particular year; $\bar{P}$ is the mean value of the trait for all lines over the entire study period.

The optimum value was taken as 100%. When the values fluctuate within 83-117% (favourable conditions according to HTC) the values are close to the norm; below 83% the values are significantly low, above 117% the values are significantly high; 58-83% and 117-133% indicate moderately unfavourable conditions; below 58% and above 133% indicate unsatisfactory conditions. Statistical analysis was performed using STATISTICA 8.0 software. The "Descriptive Statistics" function was used to calculate the main statistical parameters – mean ($\bar{X}$), minimum (x_{min}), maximum (x_{max}) and standard deviation (σ).

$$\bar{X} = \sum x_i / n, \quad (2)$$

where x_i is the trait value; *n* is the total number of variants (sample size).

Significant differences and the coefficient of variation (*V*) were calculated according to Dospekhov (1985):

$$V = (\sigma/\bar{x})*100, \quad (3)$$

where $\bar{x}$ is the genotype-averaged arithmetic mean; σ is the standard deviation.

Indices of stress tolerance ($x_{lim} - x_{opt}$) and genetic flexibility ($(x_{opt} + x_{lim})/2$) were determined according to the equations of Rosielle & Hamblin (1981), taking x_{lim} as the lowest value and xopt as the highest value. The indices of homeostasis (*Hom*) and breeding value (*Sc*) were calculated following Hangildin & Litvinenko (1981):

$$Hom = (\bar{x} \times \bar{x})/\sigma, \quad (4)$$

$$Sc = (\bar{x} \times (x_{lim}/x_{opt}), \quad (5)$$

where $\bar{x}$ is the genotype-averaged arithmetic mean; σ is the standard deviation.

Ecological plasticity (*bi*) and phenotypic stability (S^2di) were assessed according to Eberhart & Russell (1966). The regression coefficient (b_i) was calculated using the formula:

$$b_i = \sum_j Y_{ij} I_j / \sum_j I^2, \quad (6)$$

where b_i is the regression coefficient of thousand-grain weight for each *ith* genotype in the environment; *Yij* is the thousand-grain weight of the *ith* genotype under any *j* conditions; I_j is the environmental index, i.e. the difference between the mean value of thousand-grain weight for all genotypes under these conditions (year) and the overall mean for the experiment.

The variance of deviations from the regression line (S^2_{di}) was calculated as:

$$S^2_{di} = \sum(Y_{ij} - (\bar{x} + b_i I_{ij}))^2/(n-2), \quad (7)$$

where Y_{ij} is the actual thousand-grain weight (g) of the *ith* genotype under any *j* conditions; $\bar{x}$ is the genotype-averaged arithmetic mean; b_i is the regression coefficient (thousand-grain weight); I_i is the index of the *j-th* conditions.

Ranking of statistical indicators was carried out according to Snedecor (1961), with ranks denoted as Z. The mean trait value in the experiment, or the mean numerical value of a statistical indicator, was used as the baseline for comparison in the analysis. To assess the level of adaptability and differentiate it according to characteristics of different dimensions and units of measurement, an integrated parameter – the "variety adaptability rating" (VAR) – was calculated (Vlasenko *et al.*, 2012). To calculate the adaptability rating of breeding lines in terms of thousand-grain weight, it was necessary to normalise the arithmetic mean of thousand-grain weight by dividing it by the mean value of the sum of ranks, so that the contribution of high genetic potential would be decisive in this integrated parameter. In the rank assessment, higher positions were assigned to the following indicators: with higher numerical values – ($\bar{X}$), (x_{min}), (x_{max}), ($(x_{opt} + x_{lim})/2$), (*Hom*), (*Sc*), with lower values – ($x_{lim} - x_{opt}$), (*V*), (S^2_{di}). According to the regression coefficient, the highest rank was assigned to breeding lines with a plasticity value (bi) closest to 1.0. Ranks decreased with increasing deviation from unity in both directions – upward and downward.

Weather conditions during the study period differed from long-term averages in terms of moisture supply and temperature regime (Table 1). In 2019/20, 374 mm of precipitation fell during the vegetation period, in 2020/21 – 597 mm, in 2021/22 – 468 mm and in 2022/23 – 769 mm, with a long-term average of 615 mm. At the same time, an increased (+0.4°C to +2.0°C) mean air temperature was noted in different years relative to the norm, as well as dry conditions before sowing, at sowing and in spring after the resumption of vegetation.

Table 1. Meteorological indicators of the vegetation period of winter wheat in 2019/20–2022/23

Month	Amount of precipitation per month, mm					Average monthly air temperature, °C				
	2019/2020	2020/2021	2021/2022	2022/2023	Precipitation LTA, mm	2019/2020	2020/2021	2021/2022	2022/2023	Temperature LTA, °C
VIII	10	8	88	84	53.9	20.4	21.1	20.5	21.6	20.4
IX	12	21	19	118	56.6	15.8	18.5	13.2	12.9	14.5
X	7	22	18	30	40.3	11.0	13.2	7.6	8.2	8.7
XI	17	28	26	81	40.1	4.8	3.8	4.8	3.8	2.1
XII	36	38	63	43	42.3	2.8	-0.3	-1.1	0.2	-1.6
I	20	57	23	11	36.9	0.8	-2.3	-1.2	-0.1	-3.4
II	40	49	9	28	31.8	2.4	-4.7	1.7	-0.5	-2.2
III	15	28	10	46	34.2	6.6	2.3	2.3	5.2	2.3
IV	48	47	86	85	44.9	9.5	7.7	8.4	9.3	9.8
V	92	87	29	21	51.4	12.8	14.5	14.6	15.5	15.7
VI	57	100	42	39	84.8	21.7	20.1	20.7	19.7	19.3
VII	21	111	55	184	71.7	21.7	23.3	20.4	20.9	21.1
X	31	50	39	64	49.1	10.9	9.8	9.3	9.7	8.9
Total for the vegetation period	374	597	468	769	588.9					
HTC for the vegetation period	0.6	1.03	0.8	1.52						
HTC for IV–VI	0.80	2.5	0.80	0.90						

Note: *LTA – long-term average; VP – vegetation period; HTC – hydrothermal coefficient*
Source: *compiled by the authors based on data from the Myronivka Agrometeorological Station*

The 2019/20 period was characterised by drought conditions (HTC = 0.6) under elevated temperature regimes, which had a significant negative impact on winter wheat yield formation. Early spring vegetation recovery (2 March) took place under severe drought: in March, the moisture deficit was 24 mm with an air temperature increase of +4.2°C above the norm. In April, the average monthly indicators were within the norm – 48 mm of precipitation and 9.5°C respectively. May had sufficient precipitation (92 mm) but a lower temperature regime (-2.9°C below the norm), which led to a prolonged ear formation period (18-28 May). In June, 57 mm of precipitation fell, with a moisture deficit of 30 mm and an average air temperature of 21.7°C (+2.4°C above the norm). A prolonged June drought during the grain formation and filling stages, combined with high daytime temperatures (26.8°C, absolute maximum – 33.7°C), caused a reduction in grain size and fullness.

In 2020/21, a slightly elevated temperature regime (+0.9°C above the norm) and sufficient precipitation (597 mm; HTC = 1.03) improved plant moisture supply and contributed to the formation of an adequate productivity level. Spring vegetation began on 26 March. March was cold, with a large number (15 days) of frosts, ranging from -2.2°C to -7.8°C. In April, a temperature drop was observed, with night frosts reaching -0.2°C to -2.1°C (first decade). May was marked by reduced temperatures and significant daily fluctuations, with differences reaching 18.5°C, resulting in a delay in the onset of heading (25-30 May) and uneven flowering. In June and July, adverse weather conditions such as local heavy rains and squalls led to partial lodging of winter wheat crops.

The 2021/22 period was defined as a year of mild drought (HTC = 0.9) with a precipitation deficit of 121 mm and an annual mean air temperature close to the norm. Vegetation resumed on 21 March under adequate moisture supply and average air temperatures. In April and May, the air temperature was 1.4°C and 1.0°C below the long-term average respectively, while in June it exceeded the norm by 1.5°C. April showed excessive moisture, with precipitation exceeding the norm by 41.0 mm. However, from May to July a precipitation deficit of 82 mm was recorded (compared with the long-term average of 208 mm). The beginning of heading was noted between 21 and 26 May. Overall, insufficient moisture was observed during the spring–summer vegetation period (HTC = 0.8).

The 2022/23 period was excessively wet (HTC = 1.52). Early spring vegetation recovery (8 March) under gradually rising temperatures (1.9°C above the norm) promoted good root development and the formation of a strong vegetative mass. During the spring-summer period, a moisture deficit was observed (30-45 mm for May-June). April precipitation (198% of the norm) under near-average air temperature, evenly distributed across the first two decades, had a positive effect on grain yield levels. Climatic summer began in mid-May. The start of heading was recorded between 20 and 25 May. Adverse weather conditions were observed in July, with record high air temperatures (32.1°C) and excessive moisture (260% of the norm; HTC = 2.8), accompanied by thunderstorms and squalls. Favourable hydrothermal conditions during the winter wheat vegetation period significantly contributed to the formation of a high productivity potential. The authors adhered to the standards of the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1979).

RESULTS AND DISCUSSION

Phenotypic plasticity is the ability of a genotype to show phenotypic variability under different environmental conditions (Saieed *et al.*, 2024), which is inherent in a limited number of economically valuable traits (Han *et al.*, 2025). It is an important property that is extremely necessary as a component of the varietal profile under conditions of intensification of agriculture. That is, it is the ability to respond positively to the optimisation of important agrometeorological or agrotechnical measures. At the same time, the results of individual studies indicate that genomic regions associated with yield do not fully overlap with regions associated with its phenotypic plasticity (Giordano *et al.*, 2025). This makes it possible to assume that, at least partially, selection for high plasticity may be effective. As a rule, the greatest attention of researchers is directed towards the analysis of the interaction of the yield trait and environmental factors, to which a significant number of publications are devoted. However, the general patterns of this interaction may differ considerably if the variability of each trait is considered separately. The most plastic components of the yield structure in wheat are the traits "number of ears per plant" and "number of spikelets per ear", as well as "thousand grain weight" (Saieed *et al.*, 2024). Therefore, the study of the patterns of the inheritance may be important for understanding yield formation under diverse conditions. In this process, various statistical approaches to the analysis of the adaptive potential of the studied trait may be effective.

In the present study, weather conditions had different effects on the formation of grain size in winter wheat lines. Over the years of the study, thousand grain weight varied within quite a wide range (36.7-52.1 g), with a mean value of 44.4 g. It was established that the lowest mean value (41.3 g) was observed in the dry 2019/20 season with an environmental index EI = -3.15 g, and a slightly higher one (42.3 g, EI = -2.15 g) in 2020/21 (Table 2).

***Table 2**. Degree of expression and variation of thousand grain weight (g) in winter wheat lines, 2019/20-2022/23*

Line name	Weight of 1000 grains, g				$\bar{X}$
	Year				
	2020	2021	2022	2023	
Podolyanka, standard	40.8	43.0	46.3	48.2	44.6
ER 60667	44.1	45.3	50.8	52.1	48.1
ER 60724	43.0	46.7	50.2	50.6	47.6
LIUT 60734	45.5	42.9	51.2	49.5	47.3
ER 60793	40.2	46.8	47.8	50.1	46.2
LIUT 60815	40.7	41.2	48.4	50.5	45.2
LIUT 60355	41.7	43.1	48.1	47.0	45.0
LIUT 60680	41.9	44.2	45.1	48.3	44.9
LIUT 60430	42.5	41.8	46.3	48.7	44.8
LIUT 60608	42.0	42.3	45.6	49.2	44.8
LIUT 60816	37.1	42.4	47.4	48.7	43.9
LIUT 60510	40.9	41.9	45.2	47.7	43.9
LIUT 60766	38.9	41.6	46.6	48.6	43.9
LIUT 60763	42.5	41.9	42.9	48.2	43.9
LIUT 60412	40.9	39.7	45.1	46.3	43.0
LIUT 60181	42.4	40.7	43.1	44.8	42.8
LIUT 60492	40.2	39.7	43.7	44.9	42.1
LIUT 60729	41.8	39.0	41.5	43.4	41.4
LIUT 60702	36.7	39.9	44.3	42.9	41.0
$\bar{X}$	41.3	42.3	46.3	47.9	44.4
max	45.5	46.8	51.2	52.1	48.1
min	36.7	39.0	41.5	42.9	41.0
CV	5.2	5.2	5.8	5.2	4.4
EI	- 3.18	-2.12	1.86	3.44	
REI	93	95	104	108	
HIP_{05}			2.52		

***Note:** $\bar{X}$, max, min – mean, maximum and minimum value of the indicator, g; CV, % – coefficient of variation (Dospekhov, 1985); EI – environmental index, g; REI – relative environmental index, % (Vlasenko et al., 2012)*
***Source:** compiled by the authors*

Significantly higher values (46.3 g, EI = 1.86 g) were recorded in 2021/22, and the maximum ones (47.9 g, EI = 3.44 g) – in the meteorologically favourable 2022/23 season, which indicated the potential for grain size in this set of lines. Over the study period, under the conditions of 2019/2020 and 2020/2021, a small proportion of lines formed a 1000 grain mass of less than 40 g – 16.7% and 22.2% respectively. The largest range of variation in 1000 grain mass was in 2021/22 (41.5-51.2 g) and 2022/23 (42.9-52.1 g), and the smallest – in 2020/21 (39.0-46.8 g). At the same time, the level of variability of the trait was low (CV, % = 5.3-6.0%) and depended on the hydrothermal conditions of the year. The REI value, calculated for the trait, indicates that the conditions of the growing seasons for grain formation and filling were within the normal range – 93%, 95%, 104% and 108%. According to the REI value (53%, 107%, 99% and 140%), the nature of the factor's effect on yield level was clearer – 3.39 t/ha, 6.82 t/ha, 6.29 t/ha and 8.89 t/ha respectively. The results of analysis of variance reliably confirmed the considerable influence of the year (53.7%) and genotype (27.3%) and of the interaction (13.6%) on the formation of 1000 grain mass in the winter wheat lines. The high contribution of the first factor to the level of variability of the trait was confirmed by the significant difference in the mean value for the trial in years with contrasting weather conditions (the dry 2019/20 and the favourable 2022/23 seasons). Similar studies carried out on common wheat cultivars in the Canadian prairies under different moisture regimes also confirmed the large contribution of the year and, in particular, of the water regime to the expression of thousand grain mass and other traits related to yield (Sangha *et al.*, 2025).

During the study period, the more large-grained lines belonged to the erythrospermum variety type. Lines that differed significantly from the trial mean and from the standard Podolianka were: with higher values – ER 60667 (48.1 g), ER 60724 (47.6 g), LIUT 60734 (47.3 g); with lower values – LIUT 60729 (41.4 g) and LIUT 60702 (41.0 g). The other eleven lines formed grain of a size comparable with the standard and with the trial mean. The considerable influence of genotype on expression of the trait in the above-mentioned lines was confirmed by the ranking (first to third place each year). Among these lines, ER 60667 was distinguished by the maximum 1000 grain mass in the favourable 2023 season and in the trial overall – 52.1 g and 48.1 g respectively. This line belongs to the group with a short vegetation period: every year it headed first among the studied assortment, three days after the local early-ripening control cultivar (Myronivska rannostyhla). In the other lines, the heading stage occurred five to six days later, almost simultaneously with the standard Podolianka. The maximum value in the trial was obtained in the line LIUT 60734 under the dry conditions of the 2019/2020 growing season as a whole and in April-June 2022 – 45.5 g and 51.2 g respectively, which indicates its tolerance to moisture deficit and its ability to respond adequately to stress.

Analysis of adaptability parameters made it possible to identify winter wheat lines that combined a high 1000 grain mass, as an important indicator of productivity, with resistance to changing environmental conditions. The maximum level (x_{max}) of the trait (43.4-52.1 g) in the vast majority (83%) of lines was observed in the favourable 2022/23 season (Tables 2, 3). Nine lines exceeded the standard Podolianka, of which the best were ER 60667 (52.1 g), ER 60724 (50.6 g) and ER 60793 (50.1 g). One of the important indicators of adaptability is the genotype's resistance to stress, which is characterised by the level of minimum values under unfavourable conditions (x_{min}). Under the difficult (drought) weather conditions of 2019/20, eight lines together with the standard formed a minimum 1000 grain mass of 36.7-40.9 g. A smaller response (41.7-42.5 g), which indirectly characterises increased drought tolerance, was observed in the remaining lines. The highest lower threshold of the studied trait (x_{min}) was recorded in LIUT 60734 (45.5 g), ER 60667 (44.1 g) and ER 60724 (43.0 g) (Table 3). In 2020/21, under late heading in over-moistened conditions in May-June against a background of reduced temperature regime and partial lodging (5-7 points) of the stands, a 1000 grain mass of less than 40 g was observed in the tall lines LIUT 60412, LIUT 60492, LIUT 60702 and LIUT 60729.

***Table 3**. Parameters and adaptability rating for 1000 grain mass in winter wheat lines, 2019/20-2022/23*

Line name	Statistical parameters										
	$\bar{X}$ - Z	x_{max} - Z	x_{min} - Z	$(x_{max}+x_{min})/2)$ - Z	x_{min} - x_{max} - Z	CV - Z	Hom - Z	Sc - Z	b_i - Z	S^2_{di} - Z	∑Z - Z	VAR
Podolianka, st.	44.6-9	48.2-10	40.8-9	44.5-10	-7.4-11	7.4-10	600-9	37.7-10	1.04-4	0.33-3	8.5	5.244-9
ER 60667	48.1-1	52.1-1	44.1-1	48.1-1	-8.0-13	7.3-9	583-11	40.7-1	1.25-10	0.13-1	4.9	9.811-1
ER 60724	47.6-2	50.6-3	43.0-2	46.8-3	-7.6-12	7.8-12	640-6	40.5-2	1.06-5	2.06-13	6.0	7.938-2
LIUT 60680	44.9 -7	48.3 -9	41.9-5	45.1-7	- 6.4 -6	4.2-1	760-3	38.9-5	0.77-9	1.62 -11	6.3	7.123 -3
LIUT 60430	44.8 -8	48.7 -7	41.8-6	45.3-5	- 6.9-9	6.6-5	618-8	38.5-7	1.00-1	0.95 -7	6.3	7.115 -4

Table 3. Continued

Line name	Statistical parameters											
	$\bar{X}$ - Z	x_{max} - Z	x_{min} - Z	$(x_{max} + x_{min})/2)$ - Z	x_{min} - x_{max} - Z	CV - Z	Hom - Z	Sc - Z	b_i - Z	S^2_{di} - Z	∑Z - Z	VAR
LIUT 60734	47.3 -3	51.2 -2	42.9-3	47.1-2	- 8.3-14	8.9-14	593-10	39.6-3	1.00-1	6.42 -18	7.0	6.754 -5
LIUT 60355	45.0 -6	48.1 -12	41.7-7	44.9-9	- 6.4-5	7.1-7	661-5	39.0-4	0.91-6	1.71 -12	7.3	6.161 -6
LIUT 60608	44.8 -8	49.2 -6	42.0-4	45.6-4	- 7.2-10	6.7-6	595-18	38.2-8	1.03-3	1.15 -8	7.5	5,970 -7
LIUT 60510	43.9 -10	47.7 -13	40.9-8	44.3-11	- 6.8-8	7.7-11	619-7	37.7-10	0.98-2	0.24 -2	8.2	5.357 -8
LIUT 60181	42.8 -13	44.8 -16	40.7-10	42.8-15	- 4.1-1	5.0-2	1076-1	38.8-6	0.44-13	1.43 -10	8.7	4.914 -10
LIUT 60763	43.9 -11	48.2 -11	41.9-5	45.1-8	- 6.3-4	7.3-9	661-5	38.1-9	0.72-11	4.90 -17	9.0	4.875 -11
LIUT 60492	42.1 -14	44.9 -15	39.7-12	42.3-16	- 5.2-3	5.9-3	691-4	37.2-11	0.79-8	0.47 -6	9.2	4.579 -12
ER 60793	46.2 -4	50.1 -5	40.2-11	45.2-6	- 9.9-17	8.0-13	503-13	37.1-2	1.14-7	7.48 -19	10.7	4.320 -13
LIUT 60815	45.2 -5	50.5 -4	40.7-10	45.6-4	- 9.8-16	12.6-17	410-16	36.4-14	1.57-14	0.40 -5	10.5	4.305 -14
LIUT 60412	43.0 -12	46.3 -14	39.7-12	43.0-13	- 6.6-7	7.2-8	579-12	36.9-13	0.97-3	1.31 -9	10.3	4.175 -15
LIUT 60729	41.4 -15	43.4 -18	39.0-13	41.2-17	- 4.4-2	5.0-2	943-2	37.2-11	0.36-16	2.99 -14	11.0	3.766 -16
LIUT 60766	43.9 -10	48.6 -8	38.9-14	43.8-12	- 9.7-15	10.4-15	433-15	35.2-15	1.40-12	0.38 -4	12.0	3,660 -17
LIUT 60702	41.0 -16	44.3 -17	36.7-16	40.5-18	- 7.6-12	6.5-4	497-14	33.9-16	0.96-4	3.34 -15	13.2	3.102 -18
LIUT 60816	43.9 -11	48.7 -7	37.1-15	42.9-14	-11.6-18	12.2-16	365-17	33.4-17	1.60-16	3.62 -16	14.6	3.007 -19
$\bar{X}$	44.4	48.1	40.7	44.4	7.4	7.6	622.4	37.6	1.0 0	2.15	8.5	

Note: *$\bar{X}$ – mean value of thousand grain weight, g; Z – rank; xmax, xmin – maximum and minimum thousand grain weight, g; ((xmax + xmin) / 2) – compensatory capacity; (xmin - xmax) – stress tolerance, g; CV – coefficient of variation, %; Hom – homeostasis; Sc – selection value of the genotype; bi – coefficient of linear regression; S2di – mean-square deviation; ∑ Z – sum of ranks; VAR – variety adaptability rating; LIUT – Lutescens; ER – Erythrospermum*
Source: *compiled by the authors*

The level of resistance of the lines to stressful growing conditions is an important indicator, which shows the difference between the minimum and maximum value of the trait with a negative sign. The smaller it is, the higher the stress tolerance, or stability, and the wider the range of adaptive possibilities of the genotype (Rosielle & Hamblin, 1981). The indicator (x_{min} – x_{max}) ranged from -4.1 g to -11.6 g. The highest resistance and stability were manifested by the lines with a low level of xmax – LIUT 60181 (-4.1 g), LIUT 60729 (-4.4 g), LIUT 60492 (-5.1 g). These lines were also characterised by low variability of this trait according to the coefficient of variation (CV) as a relative indicator of variability (5.0-5.9%). In the vast majority of lines, the level of thousand grain weight varied slightly (CV = 4.1-10.4%), except for LIUT 60816 and LIUT 60815, with medium variability (12.2% and 12.6% respectively) and with the highest value of stress tolerance – -11.6 g and -9.8 g respectively. The mean coefficient of variation in the experiment, 7.6%, confirmed the low variability of the trait. The characterisation of the lines in terms of stress tolerance is complemented by the index of genetic flexibility ((x_{lim} + x_{opt})/2), which reflects the average yield of genotypes in contrasting (optimal and limiting) conditions and characterises the compensatory capacity, and indicates the degree of correspondence between the genotype and the environment. The highest index of genetic flexibility in contrasting conditions was found in lines ER 60667 (48.1 g), ER 60724 (47.0 g) and LIUT 60734 (46.7 g), which had the highest minimum and maximum values of the trait. When studying and analysing the ecological stability and adaptability to different environments of winter wheat varieties, other researchers selected varieties with maximum productivity and yield stability, which indicates the relative effectiveness of this method (Konovalova *et al.*, 2024).

The term homeostasis (Hom) is understood as the ability of plants to maintain internal balance and realise the genetic potential of a variety under changing environmental conditions (Hangildin & Litvinenko, 1981). It is known that genotypes with high homeostasis (Hom) respond less to the deterioration of conditions and respond well to the improvement. Hom is calculated as the ratio of the genotype-averaged arithmetic mean to the mean square deviation. The analysis of variability in terms of homeostasis and resistance to unfavourable external environmental factors for thousand grain weight showed that its highest value was in winter wheat lines LIUT 60181 (Hom = 1076), LIUT 60729 (Hom = 943) and LIUT 60680 (Hom = 760). That is, the realisation of the genetic potential took place under different growing conditions, which is important in the period of global climate change. With the help of the breeding value indicator (Sc), it is possible to identify genotypes that combine a high or medium thousand grain weight with its stable realisation under variable growing conditions. The assessment according to this indicator showed a range of variation within 33.4-40.7.

The lines with the best breeding value were ER 60667 (Sc = 40.7); ER 60724 (Sc = 40.5); LIUT 60734 (Sc = 39.6).

Important characteristics of the adaptability of genotypes to environmental conditions are the ecological plasticity and stability (Hangildin & Litvinenko, 1981). Plasticity is assessed by the regression coefficient (b_i), which is a criterion for assessing the level of ecological plasticity and indicates the reaction of the genotype to changes in growing conditions. According to this indicator, the lines were divided into three groups: intensive type ($b_i > 1$); stable ($b_i < 1$) and adapted to different conditions ($b_i = 1$). The higher the value of b_i, the more sensitive the genotype is to changes in growing conditions, for example, to the level of agronomic practices, mineral nutrition, etc. Genotypes with $b_i > 1$ and its variation from 1.06 to 1.60 can be considered intensive for this trait, which respond strongly to changes in environmental conditions. With $b_i < 1$, which is close to zero, the genotype reacts less to changes in environmental conditions than the average of the studied assortment. Lines with low b_i values (0.36-0.96) showed only a weak response to improved growing conditions, which determines the value in terms of stability, because under minimal inputs such lines can still achieve maximum productivity. Lines with a regression coefficient within 0.97-1.04, together with the standard Podolianka, were more adapted to various environmental conditions and optimally (adequately) responded to the changes. The highest rank for this parameter was held by lines with bi closest to one. In the study by N. Săulescu *et al.* (2025), nine semi-dwarf winter wheat varieties were evaluated in 63 multifactor field trials conducted in different regions of Romania during 2021-2024. Yield data were analysed using analysis of variance (ANOVA) to assess the effects of environment, genotype, and the interaction. Phenotypic plasticity and stability were determined by such indicators as the coefficient of variation, Wricke's ecovalence, Finlay-Wilkinson regression coefficients and rank dispersion. In addition, regression and correlation analyses were used to assess the response of varieties to environmental conditions and to identify relationships between stability and plasticity indicators. The results showed considerable variation between varieties, with some combining high yields with increased stability under different growing conditions.

In the study by C. Adams *et al.* (2025), yield, plasticity, and stability of 45 winter wheat varieties were analysed based on the results of many years of field trials in the north-western USA. Using Finlay-Wilkinson regression analysis, the authors revealed significant differences between varieties in the response to environmental conditions and established that the main share of yield variation (over 80%) was due precisely to the influence of the environment. On the basis of regression coefficients, an integrated performance indicator was developed, which makes it possible to effectively rank varieties by a combination of high yield, plasticity, and stability. Similar results on yield variation were obtained in the present study.

The variance of trait stability (S^2_{di}), defined as the mean-square deviation from the regression line, reveals the degree of variability of the studied genotypes and the degree of stability of the response to environmental conditions. The closer the S^2_{di} indicator is to zero, the less the empirical values of the trait differ from the theoretical ones located on the regression line. The range of variation in the differences in thousand grain weight according to the stability parameter was 0.13-7.48. Genotypes with the lowest S^2_{di} values for the trait can be considered more stable under different environmental conditions. According to the combination of the two above-mentioned indicators, the lines with higher stability, compared with the mean ($S^2_{di} = 2.15$) value in the experiment, were: intensive – ER 60667 ($b_i = 1.25$, $S^2_{di} = 0.13$), LIUT 60815 ($b_i = 1.57$, $S^2_{di} = 0.40$), LIUT 60766 ($b_i = 1.40$, $S^2_{di} = 0.38$); stable (low-plastic) LIUT 60492 ($b_i = 0.79$, $S^2_{di} = 0.47$); medium-plastic – LIUT 60510 ($b_i = 0.98$, $S^2_{di} = 0.24$), LIUT 60430 ($b_i = 1.00$, $S^2_{di} = 0.95$), LIUT 60412 ($b_i = 0.97$, $S^2_{di} = 1.31$). Low stability coefficients were recorded in ER 60793 ($b_i = 1.14$, $S^2_{di} = 7.48$), LIUT 60734 ($b_i = 1.00$, $S^2_{di} = 6.42$), LIUT 60763 ($b_i = 0.72$, $S^2_{di} = 4.90$), LIUT 60702 ($b_i = 0.96$, $S^2_{di} = 3.34$), LIUT 60816 ($b_i = 1.60$, $S^2_{di} = 3.62$), LIUT 60729 ($b_i = 0.36$, $S^2_{di} = 2.99$). Thus, not all lines that were characterised by lower plasticity indicators ($b_i = 0.36$-0.96), which may indicate the stability, also had low stability coefficients (S^2_{di}), stress tolerance (x_{min} - x_{max}) and coefficient of variation (CV). Therefore, to select the best genotypes, it is necessary to take into account all adaptive statistical parameters.

For a comprehensive assessment of the level of adaptability of winter wheat lines according to parameters that characterise its various features, non-parametric statistical methods and the generalised indicator "variety adaptability rating" – VAR (Demydov *et al.*, 2023) were used. Lines that had the best ratio of thousand grain weight and statistical parameters of adaptability occupied higher positions in the variety adaptability rating. Determining the position of lines in the VAR (taking into account the genetic potential of this trait) showed that the most adaptable were the intensive ER 60667 and ER 60724, which were distinguished by the highest mean, maximum and minimum values of the trait. The class with the highest overall adaptive capacity also included the lines: homeostatic, low-plastic LIUT 60680 and medium-plastic LIUT 60430 and LIUT 60734 with an optimal response to improved growing conditions. All of these lines occupied higher positions in the VAR ranking (1st-5th). The next group with medium overall adaptive capacity for this trait included the lines that occupied 6th to 11th positions in the ranking, among which LIUT 60181 and LIUT 60492 were distinguished by increased stability according to the indicators (x_{min} - x_{max}), CV, S^2_{di}. The remaining lines belonged to the class with low overall adaptive capacity (12th-19th positions). These lines in the experiment had poorer values of statistical parameters, both in terms of the individual values and in terms of the mean rank in the ranking. Within this group, the highly plastic genotypes LIUT 60815, LIUT 60766 had increased stability of the trait, whereas ER 60793, LIUT 60816 had low stability. The obtained data demonstrate some differences in the ranking of genotypes according to the sum of the mean rank values of the calculated statistical parameters and the combined indicator "variety adaptability rating", which confirms the significant contribution of the genotype to the formation of the trait "thousand grain weight".

Thus, stability is one of the basic traits that is evolutionarily necessary for survival in interaction with a changing external environment. Some researchers point to an analogy of such a process in the creation of varietal mixtures, because in nature pure populations are rarely found, whereas mixtures of genotypes and even species predominate. Under artificial mixtures, the spike density changed the most, which had a positive effect on the plasticity of thousand seed weight, yield and biomass, and a negative effect on protein content. In practice, it is quite realistic to increase thousand seed weight by means of long-term repeated selection, but it should be borne in mind that the constant increase of this trait must be analysed in combination with other traits of yield structure.

CONCLUSIONS

Based on the results of the conducted study, it can be stated that assessment of adaptability according to grain size can be an important component of the breeding process in creating new adaptive winter wheat varieties under climate change conditions. A significant range of variation in thousand grain weight of winter wheat lines was revealed, depending on the weather conditions of the year and genotype. Reliable differences in genotype response to changes in year conditions were established. The maximum mean value over the study period was recorded in the favourable 2022/23 season. A significant influence of year (53.7%), genotype (27.3%) and the interaction (13.6%) on the formation of large grain was confirmed. Lines ER 60667 (48.1 g), ER 60724 (47.6 g), LIUT 60734 (47.3 g) differed significantly from the mean experimental value in the direction of increasing the trait. For the studied set of genotypes grown in the Forest-Steppe zone under certain agrometeorological conditions, it was determined that high values of adaptability parameters, namely the mean value for the experiment, maximum and minimum values, compensatory ability, stability of realisation and response to growing conditions, made it possible to identify winter wheat lines that combined high thousand grain weight with resistance to environmental changes. The best according to the integrated assessment based on the variety adaptability rating (VAR) were the intensive lines ER 60667 (early-ripening, stable), ER 60724 and LIUT 60680 (homeostatic). The class with the highest overall adaptive ability also included the medium-plastic lines LIUT 60734 and LIUT 60430, adapted to different growing conditions. The selected lines are valuable initial material in breeding for adaptability according to thousand grain weight. In the course of the study, the best winter wheat samples in terms of plasticity, ER 60667 and ER 60724, were selected; these samples can be submitted for state variety testing at the UIPVE (Ukrainian Institute for Plant Variety Examination) in 2026. Given the importance and objectivity of evaluating genotypes according to adaptability parameters in different environments, it is planned to continue studying the initial material created for a complex of valuable traits at the final stages of the breeding process. The use of selection by thousand grain weight at the early stages of the breeding process makes it possible to select genotypes with high yield potential and production value, which has been confirmed by the example of the Myronivka breeding centre.

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CONFLICT OF INTEREST

All authors declare no conflict of interest in writing the article.

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Мінливість і адаптивність ліній пшениці м’якої озимої за масою 1000 зерен

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Анотація. Пошук генотипів пшениці озимої, які мають високий і стабільний рівень прояву цінних господарських ознак, в тому числі маси 1000 зерен, є актуальним завданням для селекціонерів в умовах інтенсифікації сільського господарства. Мета роботи передбачала виділення ліній пшениці озимої із значним рівнем прояву маси 1000 зерен та високими адаптивними показниками для подальшого використання в селекційній практиці. У обрахунках використовували математично-статистичні методи, регресійний аналіз. Оцінку адаптивності ліній проводили за інтегрованим показником рейтингу адаптивності, використовуючи сукупність оцінок стабільності та пластичності. Контрастні погодні умови 2019/20–2022/23 рр. дали можливість виділити адаптивні лінії за крупнозерністю. Досліджено, що найвищу (47,9 г) середню масу 1000 зерен спостерігали в сприятливому за погодними умовами 2022/23 р. а мінімальну (41,3 г) – у посушливому 2019/20 рр. Виявлено значну варіабельність прояву ознаки залежно від умов року (53,7 %), генотипу (27,3 %) та їх взаємодії (13,6 %). Визначено лінії ЕР 60667, ЕР 60724 і ЛЮТ 60680, які суттєво перевищували середній показник по досліду. За коефіцієнтом регресії лінії розподілили на три групи: високопластичні (b_i = 1,06–1,60), стабільні (b_i = 0,36–0,96) і середньопластичні (b_i = 0,97–1,04). Практичну цінність за ознакою мають найбільш адаптивні лінії – високо пластичні ЕР 60667, ЕР 60724 та низькопластична ЛЮТ 60680. Підвищений рівень адаптивності відмітили для середньопластичних ліній ЛЮТ 60430 і ЛЮТ 60734 з оптимальною реакцією на покращення умов вирощування. Виділені генотипи є цінним вихідним матеріалом у селекції на адаптивність за масою 1000 зерен. З урахуванням рівня їх урожайності та комплексу ознак отримані генотипи можуть бути передані як нові сорти пшениці озимої на державну кваліфікаційну експертизу в Український інститут експертизи сортів рослин (УІЕСР)

Ключові слова: пшениця; метеорологічні умови; коефіцієнт регресії; фенотипічна стабільність; гомеостатичність; селекційна цінність