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The starting material is the basis of heterotic wheat breeding

A. Rakov[1,*], Y. Dmytrenko[1], R. Spriazhka[1] and Y. Zaika[1,2]

[1]National University of Life and Environmental Sciences of Ukraine, 15 Heroyiv Oborony Str., UA03041 Kyiv, Ukraine
[2]The V.M. Remeslo Myronivka Institute of Wheat of National Academy of Agrarian Sciences of Ukraine, 68 Tsentralna Str., village Central, Myronivskyi district, UA08853 Kyiv region, Ukraine
[*]Correspondence: a.rakov@nubip.edu.ua

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Abstract. This study addresses key aspects of developing initial breeding material for heterosis breeding in bread winter wheat (*Triticum aestivum L.*). In the context of climate change and threats to food security, particularly in Ukraine, the creation of new high-yielding hybrids resistant to biotic and abiotic stresses is of paramount importance. The research involved a comprehensive assessment of 78 winter wheat varieties from the Ukrainian National Gene Bank. Field trials were conducted during 2022–2024 at the Agronomic Research Station (Forest-Steppe zone of Ukraine) using a randomized complete block design with three replications.

The study focused on morphological and physiological traits influencing cross-pollination efficiency, including anther extrusion (VAEX-method scored on a 1–9 scale), plant height (cm), flowering synchrony (days from January 1 to heading), spike characteristics, grain yield (t ha^{-1}), and resistance to pathogens (septoria, powdery mildew; % leaf area affected) and winter hardiness (1–9 score).

Cluster analysis revealed three distinct groups with specific breeding potential. Group 1 (Achim, Mescal, Yuvileyna Patona) demonstrated the highest spike productivity (61.2–63.6 grains/spike; grain mass 2.8–3.4 g) and yield (6.1–6.2 t ha^{-1}). Female components (Group 2: Altigo, Soborna, Taira) exhibited short plant height (71.4–78.2 cm) and early heading time (140.3–144.0 days). Male components (Group 3: Zoreslava, Metelytsya Kharkivska, Urbanus, Liryka Bilotserkivska, and Kyivska 17, etc.) were characterized by tall plant height (80.3–89.8 cm) and high anther extrusion (6.3–7.5 score).

A topcross mating design is proposed for further evaluation of combining ability and heterosis effects. The results provide a foundation for the development of hybrid wheat breeding programs under Ukrainian conditions, with an emphasis on parental lines with complementary flowering biology and agronomic performance.

Key words: bread wheat, hybrid breeding, heterosis, parental selection, anther extrusion, *Triticum aestivum* L.

INTRODUCTION

Wheat (*Triticum aestivum L.)* is the most important cereal crop for global food security, supplying carbohydrates to nearly 40% of the world's population. In the context of climate change and increasing biotic and abiotic stresses, the development of high-yielding and resilient hybrids has become a strategic goal of modern breeding programs (Zemoida et al., 2019; Kovalyshyna et al., 2020a; Polishchuk et al., 2024).

Therefore, obtaining consistently high wheat grain yields by selectively increasing the yield potential of varieties and hybrids is extremely relevant for agricultural production in Ukraine. To create high-yielding hybrids of bread winter wheat, it is necessary to have homozygous lines that meet the basic requirements of breeders - increased individual productivity, high donor properties, genetic protection from bio- and abiotic factors, increased biochemical indicators and baking properties, adaptability to soil and climatic conditions, and different ecological, geographical and genetic origins as breeding starting material (Domaratsky et al., 2018; Kyrylenko et al., 2021).

Hybrids have several significant advantages over varieties due to heterosis which is an effect that occurs as a result of crossing two genetically promising parental forms (Longin et al., 2014; Gupta et al., 2019). The main manifestation of heterosis is increased yield and stability of productivity, especially under adverse growing conditions (Whitford et al., 2013; Longin et al., 2014; Ferreira et al., 2024).

In addition to increased yield, hybrids demonstrate significantly better agronomic characteristics compared to traditional varieties. They have improved grain quality Gupta et al., 2019, drought tolerance, more efficient use of nutrients, and are characterized by a more developed root system. In addition, hybrids exhibit higher resistance to biotic and abiotic stress factors, which makes them more adaptable to climate change and adverse environmental conditions (Singh et al., 2010; Prysiazhniuk et al., 2023).

To successfully create wheat hybrids, both male and female parent plants must have morphological and biological characteristics that facilitate effective cross-pollination. However, the requirements for male and female flower characteristics differ significantly (Betul et al., 2022).

Flowering in spikelets occurs gradually, and the entire flowering period lasts from one to three days, depending on the genotype and environmental conditions (Whitford et al., 2013). One of the key factors is the presence of open flowers in the spike, which provides maximum exposure of the reproductive organs. Ideal characteristics for this are large lodicules and floral scale, as well as widely spaced flowers on long spikes (Murai et al., 2002). One of the important morphological features is the long, well-developed stigmas, which completely emerge from the flower and remain receptive to pollen for a long time. This structure allows the flowers to open fully, creating optimal conditions for pollen to reach the stigmas. In addition, according to literature data the extended period of receptiveness of the stigmas of more than 5 days contributes to increased pollination efficiency even under conditions of low pollen concentrations in the air (Longin et al., 2012; Whitford et al., 2013).

Plant height is important from a heterosis perspective, as it was the first trait on which dominance was observed and described in first-generation hybrids in wheat as early as 1919 (Singh et al., 2010). To successfully maintain cmS-sterile female parents, it is important to identify semi-dwarf lines that combine optimal height and high pollination ability (Garst et al., 2023).

Important characteristics of male plants that facilitate cross-pollination and efficient seed production include the ability to actively disperse pollen using long, well-extruded anthers that contain large amounts of viable pollen with high fertility duration (Whitford et al., 2013; Longin et al., 2014; Langer et al., 2014; Hanafi et al., 2022). Studies have shown that this trait has a medium-high heritability (0.62–0.87), indicating the possibility of its improvement through selection (Langer et al., 2014; Boeven et al., 2016; Sade et al., 2022). High pollination productivity increases the likelihood of successful fertilization of female plants even under difficult weather conditions. Another key factor in hybrid wheat breeding is the synchronization of male and female flowering to maximize pollination (Whitford et al., 2013; Longin et al., 2014; Langer et al., 2014; Hanafi et al., 2022). The ideal time for female plants to flower is 1–2 days earlier than male plants, coinciding with the peak of pollen release (Garst et al., 2023. The anthers remain receptive to pollen for 4–13 days, and a prolonged pollination period promotes more efficient seed formation. One way to prolong pollination in male plants is to stimulate tillering by adjusting the crop density (Schmidt et al., 2024).

Therefore, a detailed understanding of wheat flowering mechanisms is critical for successful hybrid seed production. This knowledge allows for effective breeding strategies development, aimed at improving the hybrid's yield and stability.

Despite the potential of heterosis, commercial success of hybrid wheat in Ukraine and Europe remains limited due to insufficient adaptation of available hybrids to local environments. The efficiency of hybrid breeding strongly depends on the selection of parental components with complementary flowering biology, pollination traits, and agronomic performance. (Basnet et al., 2022).

MATERIALS AND METHODS

Germplasm collection. The research material consisted of 78 varieties of bread winter wheat obtained from the National Center for Plant Genetic Resources of Ukraine, The Institute of Plant Physiology and Genetics of the NAAS of Ukraine, the V.M. Remeslo Myronivka Institute of Wheat of the NAAS of Ukraine, the National Scientific Center ‘Institute of Agriculture of the National Academy of Sciences of Ukraine’, the Institute of Irrigated Farming NAAS, the Yuriev Plant Production Institute NAAS of Ukraine, the Plant Breeding and Genetics Institute - National Center of Seed and Cultivar Investigation, the Bilotserkivska Experimental Breeding Station of the Institute of Bioenergy Crops and Sugar Beet of the NAAS of Ukraine, and other breeding centers.

Experimental design. The purpose of this study was to comprehensively evaluate 78 varieties of bread winter wheat and to select promising parental forms for hybrid breeding programs in Ukraine. The evaluation of the breeding material was carried out during 2022–2024 in the experimental fields of the Department of Genetics, Breeding and Seed Production named after Professor M.O. Zelensky in the Separate Unit of the National University of Life and Environmental Sciences of Ukraine ‘Agronomic Research Station’. The agricultural technology of the experiments corresponded to the generally accepted technology of growing bread winter wheat in the Forest-Steppe of Ukraine and was aimed at optimizing the growth and development of plants. The experiment in the collection nursery was established on randomized single-row plots using a manual seeder, with three replications. Each plot was 1.2 m in length with a row spacing of 20 cm, and the sowing density was 1.5 million seeds per hectare. All other agronomic practices were applied according to the standard regional recommendations.

Morphological data recording. Determination of plant height, winter hardiness, productive tillering coefficient, and weight of a thousand seeds was carried out by the Methodology for conducting the examination of plant varieties of the cereal and legume groups for suitability for distribution in Ukraine, approved by the Ukrainian Institute for the Examination of Plant Varieties (UIEPV) (Korzun, 2016). Earing calculated as the difference between the date of full earing of the plot and January 1 of the calendar year.

In the study, the International Classifier of the genus *Triticum L.* (1987) was used to determine the group of varieties by plant height, according to which wheat varieties are divided into dwarfs of the first group (< 36 cm), dwarfs of the second group (36–50 cm), short-growing of the first group (51–65 cm), short-growing of the second group (66–80 cm), medium-growing of the first group (81–95 cm), medium-growing of the second group (96–110 cm), tall-growing of the first group (111–125 cm), tall-growing of the second group (126–140 cm), and extremely tall-growing (> 140 cm) (Dorofeev et al., 1987; Samoilyk et al., 2024).

The anther extrusion was assessed according to the score of visual anther extrusion - VAEX method (Langer et al., 2014). Three days after the Zadoks 61, the number of anthers that protruded beyond the flowers was measured in five randomly selected plants from each plot or row, with the subsequent calculation of the proportion of such spikelets. The upper and lower two spikelets were not taken into account (Langer et al., 2014; Betul et al., 2022). The obtained results are presented in the form of a 9–point scale, according to which at 9 points, almost all anthers are extruded from the flowers of the spikelet (Whitford et al., 2013).

After the plants reached full maturity, 20 typical plants were selected from each recording plot for biometric analysis, which included determining the spike length, the number of spikes, the number of grains in the spike, and the mass of grains per spike.

Disease scoring. The assessment of the intensity of the lesion was carried out visually, analyzing 10 plants, and the degree of damage to the flag and subflagellar leaves was assessed using scales (Trybel et al., 2010) and the integral resistance scale (Petrenkova et al., 2018; Kovalyshyna et al., 2020b), according to which the lesion is expressed in relative percentages of the leaf area covered with pathogen pustules.

Statistical analysis. Statistical calculation of the results of field and laboratory studies was performed using the methods of variational statistics and analysis of variance (Dospekhov, 1985) using the Microsoft Excel 2016 application package. Cluster analysis and dendrogram creation were performed using the Statistica 13 program.

RESULTS AND DISCUSSION

The main obstacle to the transition from varieties to hybrid breeding of bread winter wheat is the method of pollination. *Triticum aestivum L.* is a self-pollinating species, but it can cross-pollinate at a low frequency. While the frequency of cross-pollination is usually from a few tenths of a percent to several percent (Waines & Hegde, 2003), in some years in certain genotypes it can increase to 10% and above (Kozub et al., 2017). One of the main features of a genotype that promotes cross-pollination is its ability to extrude anthers to ensure sufficient levels of cross-pollination in this self-pollinating crop (Sade et al., 2022). Anther extrusion is an important trait in hybrid wheat breeding programs that can be quickly determined in the field. If a genotype exhibits a high percentage of anther extrusion, it is an excellent male parent for hybrid seed production. The selection of male parents with high pollination ability made it possible to create the first economically viable commercial wheat hybrids (Gupta et al., 2019).

Anther extrusion and heading synchrony. A study of plants of 78 varieties of bread winter wheat (Fig. 1) based on the anther extrusion from the flowers of the spike revealed 1 variety in which the anthers almost do not emerge from the flower scales (score 3) – the variety Perlyna Lisostepu. Most genotypes (26 varieties) threw out anthers at the level of 7 points, the maximum score was set in 4 varieties - Pam`yati Girka, Spivanka Poliska, Efektna, and Emil. Thus, according to the research results, it was established that in modern bread winter wheat varieties, included in the State Register of Varieties Suitable for Distribution in Ukraine, the anthers emerge from the flower scales at the level of 3–9 points, which is promising for heterosis breeding.

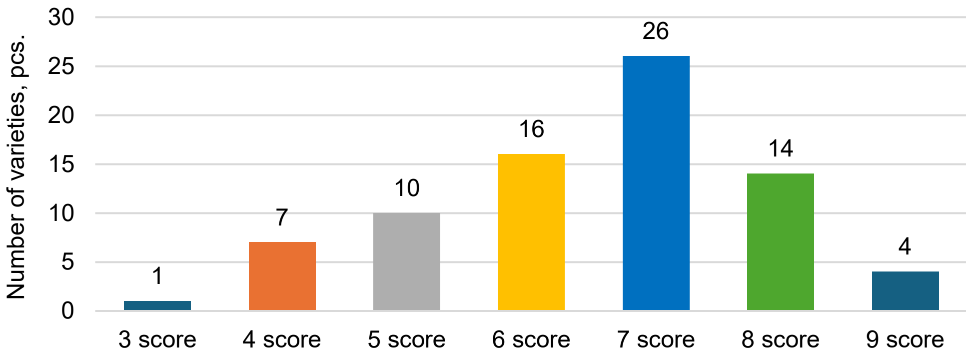

Figure 1. Distribution of anther extrusion among winter wheat varieties.

Based on the results of anther extrusion and morpho-biological traits, 11 varieties were identified as promising parental components for heterosis bread winter wheat breeding (Fig. 2).

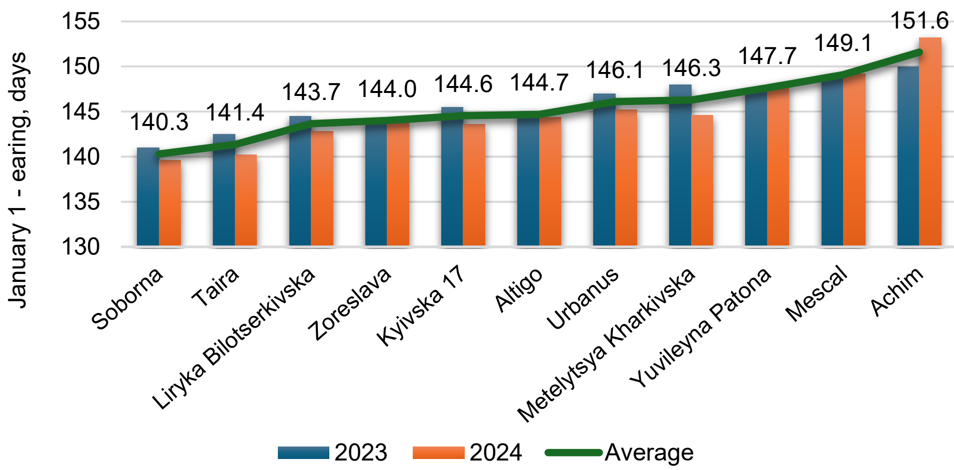

Figure 2. Days from January 1 to heading for different genotypes.

Heading time (days from January 1 to heading) ranged from 140.3 days (Soborna) to 151.6 days (Achim). Early-heading genotypes (Soborna, Taira, Liryka Bilotserkivska) contrasted with late- heading ones (Achim, Mescal, Yuvileyna Patona), providing an opportunity to design parental combinations with optimal synchrony between pollen release and stigma receptivity.

Significant variability was observed in the extent of anther extrusion among the evaluated genotypes. The highest average scores (7.4–7.8 score) were recorded in Altigo, Soborna, Taira, Metelytsya Kharkivska, Urbanus, and Kyivska 17 (Fig. 3), confirming their potential as pollen donors. In contrast, Achim and Mescal demonstrated relatively low extrusion (≤ 5.8 score) (Table 1), indicating limited cross-pollination capacity (Betul et al., 2022).

Figure 3. Anther extrusion in representative genotypes (2023–2024).

Table 1. Anther extrusion of winter wheat varieties

Varieties	Anther extrusion, score		
	2023	2024	Average
Altigo	8.0	6.8	7.4
Zoreslava	6.0	6.6	6.3
Metelytsya Kharkivska	6.0	7.8	6.9
Soborna	8.0	7.6	7.8
Taira	8.0	7.2	7.6
Achim	5.5	6.0	5.8
Mescal	5.0	5.0	5.0
Urbanus	7.0	6.6	6.8
Kyivska 17	7.5	7.4	7.5
Liryka Bilotserkivska	5.5	7.0	6.3
Yuvileyna Patona	6.0	6.5	6.3

Plant height. Plant height ranged from 71.4 cm (Altigo) to 89.8 cm (Liryka Bilotserkivska) (Table 2). According to the international wheat classifier, short-statured genotypes (Altigo, Soborna, Taira) represent suitable candidates for maternal forms, while taller genotypes (Kyivska 17, Liryka Bilotserkivska, Metelytsya Kharkivska) meet the requirements for effective pollen dispersal as male forms.

Yield components. Elements of the yield structure are morphological characteristics of the plant that directly shape the yield level. The most important of them include the length of the spike, the number of spikelets in the spike, the number of grains per spike, the weight of grains per spike, and the weight of 1,000 seeds. Each of these indicators plays a specific role in shaping the harvest.

Spike length is one of the first visual indicators that can be used to assess the potential productivity of the spike part of the plant. Typically, the longer the spike, the more spikelets and, consequently, grains it can contain. However, it is important to understand that length does not always directly correlate with productivity, as grain filling also matters (Gupta et al., 2019; Basnet et al., 2022).

Table 2. Plant height of winter wheat varieties

Varieties	2023		2024		x,	min,	max,	R,
	x ± S x, cm	V, %	x ± S x, cm	V, %	cm	cm	cm	cm
Altigo	71.0 ± 6.2	8.7	71.8 ± 5.7	7.9	71.4	65.0	78.6	13.6
Zoreslava	81.0 ± 3.0	3.7	83.0 ± 4.1	4.9	82.0	77.1	88.9	11.8
Metelytsya Kharkivska	82.0 ± 6.8	8.3	89.0 ± 4.6	5.2	85.5	76.1	94.4	18.3
Soborna	70.0 ± 5.3	7.6	85.6 ± 4.4	5.1	77.8	64.3	91.5	27.2
Taira	71.0 ± 4.8	6.8	85.4 ± 3.0	3.5	78.2	66.7	91.9	25.2
Achim	78.0 ± 3.4	4.4	76.6 ± 3.0	3.9	77.3	71.7	84.3	12.6
Mescal	74.0 ± 4.8	6.5	82.0 ± 5.9	7.2	78.0	67.4	87.6	20.2
Urbanus	73.0 ± 5.1	7.0	87.6 ± 6.3	7.2	80.3	69.1	90.9	21.8
Kyivska 17	82.0 ± 4.7	5.7	93.2 ± 5.0	5.4	87.6	75.3	96.7	21.4
Liryka Bilotserkivska	85.0 ± 6.7	7.9	94.6 ± 4.4	4.7	89.8	78.9	99.9	21.0
Yuvileyna Patona	87.0 ± 4.9	5.6	89.4 ± 6.8	7.6	88.2	83.9	94.9	11.0
x	77.6	6.6	85.3	5.7	81.5	72.3	90.9	18.6
LSD_{05}	4.1		4.0					

The spikelets number in a spike is an important characteristic, as each spikelet can contain several flowers capable of developing grains. The greater the number of spikelets, the higher the potential for grain formation. This indicator depends on both the genetic characteristics of the variety and the growing conditions.

The number of grains per spike indicates the overall level of spike productivity. This indicator depends on the number of spikelets and the number of grains in each of them. Accordingly, the more grains are formed, the higher the potential yield from the plant. At the same time, it is important to consider not only the number, but also the quality and weight of these grains (Kyrylenko et al., 2021; Garst et al., 2023).

The grain mass per spike is an indicator that combines the number and size of grains. It is one of the key parameters that allows you to assess the efficiency of grain filling processes. If the mass is high, this indicates good growing conditions, moisture, and nutrition, as well as a high ability of the variety to form full-fledged grain (Demydov et al., 2024).

The weight of a thousand seeds is used as a standard for assessing grain size and quality. It depends on the genetic characteristics of the variety, the intensity of grain filling, growing conditions, and fertilizers. A higher the weight of a thousand seeds is often a sign of good filling, a high content of reserve substances (Kyrylenko et al., 2021; Basnet et al., 2022; Avagyan & Martirosyan, 2024).

All of the listed elements not only form yield, but also reflect the interaction of the variety with the environment. Therefore, when assessing the yield potential, it is important to comprehensively consider all these indicators (Schmidt et al., 2024).

According to the analysis of spike length (Fig. 4), the varieties Achim, Mescal, Yuvileyna Patona, and Metelytsya Kharkivska exhibited the longest spikes, measuring 10.3 cm, 10.8 cm, 9.8 cm, and 9.7 cm, respectively. On the other hand, the varieties with the shortest spike (8.1 cm) were Altigo, Soborna, and Taira. Other varieties had spike lengths from 8.8 cm in the Liryka Bilotserkivska variety to 9.3 cm in the Urbanus variety.

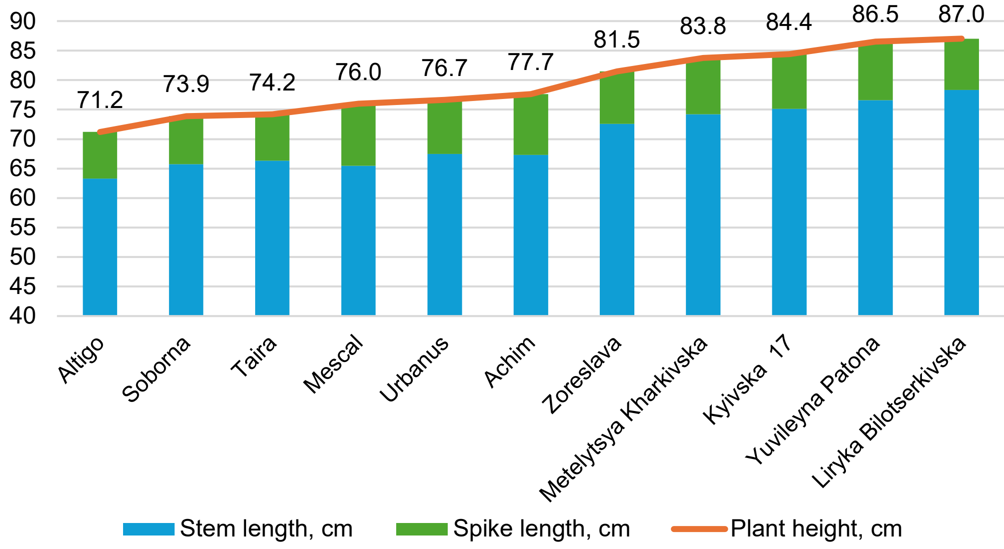

Figure 4. Stem and spike length of selected winter wheat varieties.

The highest spike density was observed in the Yuvileyna Patona variety - 20.6 (Table 3), which significantly exceeds other varieties. Close to it in value are Metelytsya Kharkivska and Mescal, which had 18.8 and 19.2, respectively. The Achim, Altigo, Zoreslava, and Urbanus varieties demonstrated average values within 15.3–18.0, which indicates an optimal combination of spike compactness and potential grain number.

Table 3. Spike density and number of spikelets per spike of tested varieties

Varieties	Spike density			Spikelet number, pcs		
	2023	2024	x	2023	2024	x
	x ± S x	x ± S x		x ± S x	x ± S x	
Altigo	14.5 ± 1.3	16.1 ± 1.7	15.3	15.9 ± 1.2	17.3 ± 1.6	16.6
Zoreslava	15.9 ± 1.6	15.5 ± 1.6	15.7	17.1 ± 1.5	16.6 ± 1.5	16.9
Metelytsya Kharkivska	17.9 ± 1.7	19.6 ± 1.2	18.8	19.0 ± 1.6	20.6 ± 1.1	19.8
Soborna	14.8 ± 1.6	14.9 ± 1.6	14.9	16.1 ± 1.4	16.2 ± 1.5	16.2
Taira	14.2 ± 1.4	14.6 ± 1.6	14.4	15.5 ± 1.3	15.9 ± 1.4	15.7
Achim	18.5 ± 1.7	17.4 ± 1.9	18.0	19.5 ± 1.6	18.4 ± 1.8	19.0
Mescal	18.1 ± 1.7	20.2 ± 2.1	19.2	19.1 ± 1.6	21.1 ± 2.1	20.1
Urbanus	16.2 ± 1.8	14.4 ± 2.0	15.3	17.3 ± 1.7	15.4 ± 1.8	16.4
Kyivska 17	14.5 ± 1.4	12.8 ± 1.5	13.7	15.6 ± 1.3	13.9 ± 1.4	14.8
Liryka Bilotserkivska	13.9 ± 1.5	14.7 ± 1.6	14.3	15.1 ± 1.4	15.8 ± 1.5	15.5
Yuvileyna Patona	20.2 ± 2.3	21.0 ± 1.3	20.6	21.2 ± 2.2	22.1 ± 1.3	21.7
X	16.2	16.5	16.4	17.4	17.6	17.5
LSD_{05}	1.5	1.5		1.4	1.4	

The highest average number of spikelets in the spike was observed in the varieties Metelytsya Kharkivska (19.8 pcs), Mescal (20.1 pcs), and Yuvileyna Patona (21.6 pcs). The lowest number was in Kyivska 17 (14.8 pcs), Liryka Bilotserkivska (15.5 pcs), and Taira (15.7 pcs). In other varieties, the indicator ranged from 16.2 pcs in Soborna to 18.9 pcs in the Achim variety.

Clear differences were recorded for spike productivity. The highest number of grains per spike was observed in Mescal (62.0 pcs), Achim (61.2 pcs), and Yuvileyna Patona (63.6 pcs) (Table 4). Grain mass per spike was also highest in these varieties (2.8–3.4 g). By contrast, Altigo and Soborna produced fewer grains (40–42 pcs) with lower grain mass (< 2.2 g).

Table 4. Grain number per spike and spike weight of winter wheat varieties

Varieties	Number of grains per spike, pcs.			Weight of grains per spike, g		
	2023	2024	x	2023	2024	x
	x ± S x	x ± S x		x ± S x	x ± S x	
Altigo	38.3 ± 5.9	45.4 ± 10.2	41.9	2.2 ± 0.4	2.1 ± 0.6	2.2
Zoreslava	46.6 ± 10.0	45.0 ± 11.0	45.8	2.3 ± 0.6	2.2 ± 0.7	2.3
Metelytsya Kharkivska	51.2 ± 8.4	54.6 ± 7.7	52.9	2.5 ± 0.5	2.6 ± 0.5	2.6
Soborna	43.5 ± 8.8	37.6 ± 7.9	40.6	2.0 ± 0.4	1.3 ± 0.4	1.7
Taira	44.0 ± 8.8	47.9 ± 11.4	46.0	2.2 ± 0.5	2.3 ± 0.6	2.3
Achim	71.3 ± 11.2	51.1 ± 13.0	61.2	3.7 ± 0.7	1.9 ± 0.8	2.8
Mescal	64.3 ± 9.7	59.7 ± 10.7	62.0	3.3 ± 0.7	2.7 ± 0.7	3.0
Urbanus	46.6 ± 8.1	47.6 ± 11.1	47.1	2.7 ± 0.5	2.6 ± 0.6	2.7
Kyivska 17	49.9 ± 7.3	44.7 ± 8.3	47.3	2.9 ± 0.5	2.5 ± 0.6	2.7
Liryka Bilotserkivska	54.1 ± 8.3	52.0 ± 8.3	53.1	2.9 ± 0.4	2.5 ± 0.7	2.7
Yuvileyna Patona	65.9 ± 13.5	61.2 ± 7.0	63.6	3.7 ± 0.8	3.1 ± 0.6	3.4
X	52.3	49.7	51.0	2.8	2.3	2.6
LSD_{05}	8.4	8.9		0.5	0.6	

The thousand-kernel weight ranged from 40.9 g (Soborna) to 57.1 g (Kyivska 17) (Table 5). Genotypes Urbanus, Kyivska 17, and Yuvileyna Patona showed a favorable combination of large kernels and high grain unit (> 820 g L^{-1}), indicating good grain quality.

Table 5. Weight of a thousand seeds and grain unit of selected genotypes

Varieties	Weight of a thousand seeds, g					Grain unit, g L^{-1}		
	2023		2024		x	2023	2024	x
	x ± S x	V, %	x ± S x	V, %				
Altigo	57.4 ± 2.6	4.5	46.0 ± 2.6	5.7	51.7	761.3	734.0	747.6
Zoreslava	49.4 ± 2.4	4.9	49.6 ± 2.8	5.6	49.5	767.0	780.0	773.5
Metelytsya Kharkivska	48.8 ± 2.2	4.5	48.3 ± 2.6	5.4	48.6	746.9	788.0	767.4
Soborna	46.0 ± 2.4	5.2	35.7 ± 2.5	7.0	40.9	779.5	816.0	797.8
Taira	50.0 ± 2.9	5.8	47.6 ± 1.9	4.0	48.8	793.0	843.0	818.0
Achim	51.3 ± 2.8	5.5	36.7 ± 2.2	6.0	44.0	742.1	780.0	761.0
Mescal	52.9 ± 2.4	4.5	32.1 ± 1.6	5.0	42.5	725.8	780.0	752.9
Urbanus	57.9 ± 1.7	2.9	54.3 ± 1.4	2.6	56.1	779.5	819.0	799.3
Kyivska 17	58.1 ± 2.1	3.6	56.1 ± 1.0	1.8	57.1	846.7	809.0	827.9
Liryka Bilotserkivska	53.6 ± 1.0	1.9	48.1 ± 3.0	6.2	50.9	784.3	807.0	795.7
Yuvileyna Patona	56.1 ± 2.7	4.8	50.4 ± 2.0	4.0	53.3	737.3	788.0	762.6
X	52.9	4.4	45.9	4.8	49.4	873.9	897.3	782.2
LSD_{05}	1.7		1.8			7.8	7.9	

Disease resistance and winter hardiness. Resistance to septoria and powdery mildew varied significantly (Table 6). Achim, Yuvileyna Patona, and Altigo demonstrated the lowest infection levels (< 13%), whereas Urbanus and Taira showed the highest susceptibility (> 28%). Winter hardiness scores ranged from 7.8 scores (Achim) to 8.9 scores (Taira, Kyivska 17), confirming high adaptation to cold stress across the collection.

Table 6. Disease resistance and winter hardiness of winter wheat varieties

Varieties	Septoria leaf spot, %			Powdery mildew, %			Winter hardiness, score		
	2023	2024	x	2023	2024	x	2023	2024	x
Altigo	5.0	24.0	14.5	5.0	16.8	10.9	9.0	8.4	8.7
Zoreslava	20.0	20.4	20.2	15.0	18.0	16.5	9.0	8.6	8.8
Metelytsya Kharkivska	20.0	21.6	20.8	10.0	30.0	20.0	8.5	8.6	8.6
Soborna	10.0	21.6	15.8	20.0	24.0	22.0	9.0	8.6	8.8
Taira	30.0	27.6	28.8	10.0	19.2	14.6	9.0	8.8	8.9
Achim	3.0	15.6	9.3	3.0	13.5	8.3	7.0	8.6	7.8
Mescal	5.0	20.4	12.7	3.0	18.0	10.5	9.0	8.4	8.7
Urbanus	35.0	33.6	34.3	5.0	24.0	14.5	9.0	8.2	8.6
Kyivska 17	5.0	18.0	11.5	8.5	34.8	21.7	9.0	8.8	8.9
Liryka Bilotserkivska	12.5	24.0	18.3	5.0	16.8	10.9	9.0	8.4	8.7
Yuvileyna Patona	3.0	21.6	12.3	3.0	15.0	9.0	8.0	8.0	8.0

Productive tillering and grain yield. The productive tillering coefficient varied from 2.1 (Soborna) to 3.3 (Metelytsya Kharkivska) ( ). The highest average yields over two years were recorded for Urbanus (6.7 t ha^{-1}), Achim (6.2 t ha^{-1}), Metelytsya Kharkivska (6.1 t ha^{-1}), and Yuvileyna Patona (6.1 t ha^{-1}). Lower yields were observed in Altigo and Soborna (≤ 5.0 t ha^{-1}).

Table 7. Productive tillering coefficient and grain yield

Varieties	Productivity tillering coefficient			Yield, t ha^{-1}		
	2023	2024	x	2023	2024	x
	x ± S x	x ± S x		x ± S x	x ± S x	
Altigo	1.6 ± 0.4	3.3 ± 0.4	2.5	4.6 ± 0.3	4.6 ± 0.4	4.6
Zoreslava	1.7 ± 0.1	4.4 ± 0.2	3.1	5.2 ± 0.4	6.5 ± 0.2	5.9
Metelytsya Kharkivska	2.2 ± 0.1	4.4 ± 0.4	3.3	5.2 ± 0.4	6.9 ± 0.3	6.1
Soborna	2.1 ± 0.1	2.1 ± 0.4	2.1	3.6 ± 0.2	6.3 ± 0.2	5.0
Taira	1.7 ± 0.4	3.7 ± 0.4	2.7	3.8 ± 0.4	6.1 ± 0.4	5.0
Achim	1.8 ± 0.3	2.8 ± 0.1	2.3	5.0 ± 0.2	7.3 ± 0.4	6.2
Mescal	1.2 ± 0.2	3.4 ± 0.1	2.3	4.2 ± 0.4	6.8 ± 0.4	5.5
Urbanus	2.1 ± 0.2	3.4 ± 0.3	2.8	4.7 ± 0.2	8.6 ± 0.4	6.7
Kyivska 17	1.8 ± 0.4	3.3 ± 0.2	2.6	3.5 ± 0.2	7.9 ± 0.3	5.7
Liryka Bilotserkivska	2.4 ± 0.2	2.7 ± 0.3	2.6	5.0 ± 0.4	7.0 ± 0.2	6.0
Yuvileyna Patona	2.2 ± 0.4	3.4 ± 0.3	2.8	3.7 ± 0.2	8.4 ± 0.4	6.1
X	1.9	3.4	2.6	4.4	6.9	5.7
LSD_{05}	0.2	0.2		0.3	0.2	

Cluster analysis. Cluster analysis grouped the 11 most promising varieties into three distinct clusters (Fig. 5):

Group 1: Achim, Mescal, Yuvileyna Patona – high spike productivity and yield, but moderate anther extrusion.

Group 2: Altigo, Soborna, Taira – early maturity, short plant height, high anther extrusion → recommended as maternal forms.

Group 3: Zoreslava, Metelytsya Kharkivska, Urbanus, Liryka Bilotserkivska, Kyivska 17 – tall plants with high anther extrusion → suitable as male forms.

These results confirm the existence of complementary parental pools for hybrid breeding under Ukrainian growing conditions.

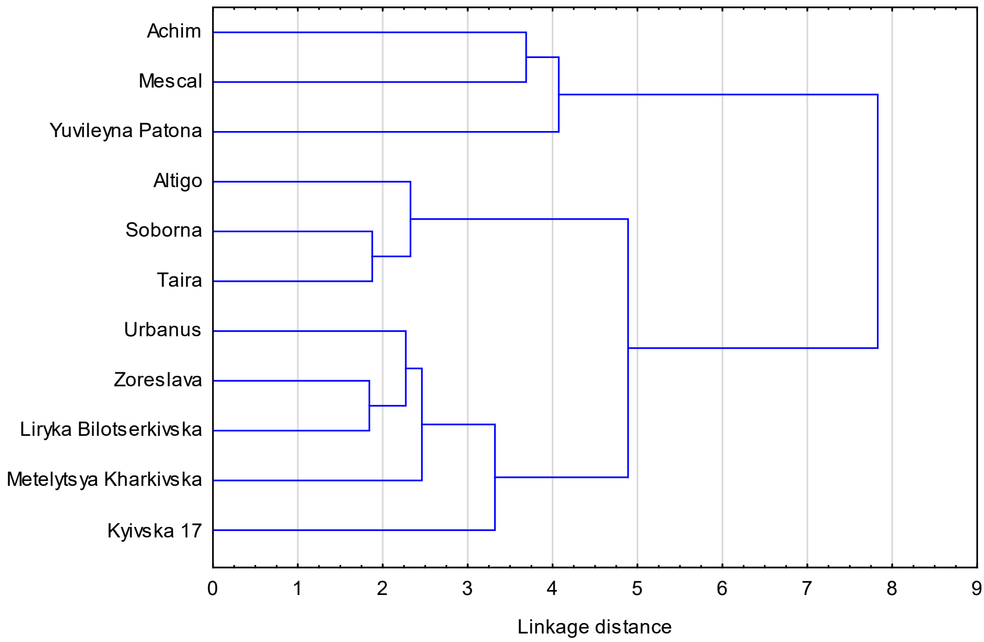

Figure 5. Cluster analysis of wheat varieties based on agronomic traits.

DISCUSSION

The success of hybrid wheat breeding largely depends on the identification of parental components with complementary flowering biology, pollination efficiency, and agronomic performance. In this study, the evaluation of 78 winter wheat varieties revealed substantial genetic diversity for traits directly influencing cross-pollination, yield formation, and stress resistance.

Anther extrusion proved to be one of the most critical traits for selecting male parents. High values recorded in varieties such as Soborna, Taira, Kyivska 17, and Altigo confirm their potential for hybridization schemes. Similar results were reported by Langer et al. (2014) and Sade et al. (2022), who emphasized that strong anther extrusion is associated with enhanced pollen dispersal and improved seed set. However, some high-yielding varieties (e.g., Achim, Mescal) displayed lower extrusion levels, which may limit their efficiency as pollen donors but does not exclude them from use as female parents.

Flowering synchrony is another key determinant of hybrid seed production. In our study, early-heading varieties (Soborna, Taira, Liryka Bilotserkivska) contrasted with late-heading ones (Achim, Mescal, Yuvileyna Patona). Such diversity is advantageous for designing hybridization schemes, as it allows the combination of early-flowering females with slightly later male forms, thereby maximizing overlap between pollen release and stigma receptivity (Garst et al., 2023; Schmidt et al., 2024).

Plant height differences further support the division into potential maternal and paternal components. Shorter genotypes (Altigo, Taira, Soborna) are suitable for use as cmS-sterile female parents, as previously highlighted in hybrid wheat programs (Whitford et al., 2013). Conversely, taller varieties (Liryka Bilotserkivska, Kyivska 17, Metelytsya Kharkivska) provide an advantage as pollen donors due to improved pollen dispersal.

Yield-related traits also revealed clear contrasts. High spike productivity and grain weight were typical for Yuvileyna Patona, Mescal, and Achim, confirming their value as productivity donors. Previous studies demonstrated that the combination of high grain number with efficient grain filling is essential for achieving heterotic effects (Gupta et al., 2019; Basnet et al., 2022). At the same time, Altigo and Soborna displayed lower yield components, but their favorable flowering biology justifies their role as maternal forms.

Biotic and abiotic stress resistance is crucial under Ukrainian conditions, where climate instability and pathogen pressure have increased. The identification of Achim, Yuvileyna Patona, and Altigo as genotypes combining resistance to both septoria and powdery mildew provides valuable sources of tolerance for future hybrids. In contrast, Urbanus and Taira demonstrated higher susceptibility, suggesting a need for cautious use in breeding programs.

Finally, cluster analysis allowed the classification of genotypes into three distinct groups with clear functional differentiation into potential male and female components. Such clustering confirms the existence of complementary parental pools, which is consistent with findings from hybrid wheat breeding programs in Europe and Asia (Longin et al., 2014; Hanafi et al., 2022).

Overall, this study highlights the importance of integrating morphological, physiological, and resistance traits when selecting parental components. The identified varieties not only represent valuable breeding resources but also provide a practical basis for launching topcross experiments to evaluate combining ability and heterosis effects under Ukrainian growing conditions.

CONCLUSIONS

Significant genetic diversity was revealed among 78 winter wheat varieties for traits important in hybrid breeding, including anther extrusion, flowering synchrony, plant height, and yield structure.

Varieties Achim, Mescal, and Yuvileyna Patona combined high spike productivity and yield potential, making them suitable as paternal forms.

Varieties Altigo, Soborna, and Taira were characterized by early maturity, short plant height, and high anther extrusion, which are favorable traits for maternal components.

Varieties Zoreslava, Metelytsya Kharkivska, Urbanus, Liryka Bilotserkivska, and Kyivska 17 demonstrated high anther extrusion and tall stature, confirming their potential as male components.

Cluster analysis grouped the collection into three clusters, clearly separating maternal and paternal candidates for hybrid breeding.

The identified varieties form a basis for further evaluation of combining ability and heterosis expression in topcrosses under Ukrainian growing conditions.

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