UDC 631.527:633.11

EVALUATION OF THE NEW BREEDING LINES OF WINTER SOFT WHEAT WITH PURPLE GRAIN FOR PRODUCTIVITY AND GRAIN QUALITY

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Received July, 17, 2026; revised August 11, 2026; accepted August 24, 2026

Aim. To investigate the productivity and grain quality of new breeding lines of purple-grained winter soft wheat. **Methods.** Physiological: morphometric indicators and elements of the yield structure; physico-chemical: infrared spectroscopy and SDS-30 determination; technological: a single-phase method of dough preparation; mathematical statistics. The method of placing plots (10 sq.m.) was systematic. The samples were grown in blocks (400 thousand plants per hectare) and evaluated based on economically valuable traits (yield, morphometric parameters, components of productivity structure, grain quality indicators) as compared to the standard. The experiment had three repeats. The yield structure parameters (plant height, tillering, number of spikelets/grains, grain weight per spike/plant and thousand grain weight) were measured in three repeats (sampling ≥30 plants). Grain quality (content of protein and gluten) was determined by infrared spectroscopy with an Inframatic 8600 device. For the analysis, a 40-gram sample of meal was used, which was obtained by grinding in a Perten LM 3100 laboratory mill. The statistical analysis of the data was performed using ANOVA software and Tukey's post-hoc test for significant differences based on mean values. **Results.** The average yield of the created purple-grain wheat lines in the comparative trial in 2023–2025 varied within 91.2–109.8 centners/ha. The genotypes, significantly outperforming the standard purple-grain variety Chornozerna in terms of productivity, were identified. Most breeding lines did not significantly differ in plant height from the Chornozerna variety, but significantly exceeded the standard variety Favorytka by this indicator and were characterized by high resistance to lodging. All the investigated wheat lines with purple grain and standard varieties were characterized by high resistance to lodging (5 points) and had no differences. The lines, considerably exceeding both standards in terms of the length of the main spike and the number of spikelets therein, were identified. All the studied genotypes were inferior in terms of the number of grains in the main spike to the Favorytka variety, but some were found that significantly exceeded this indicator in the Chornozerna variety. The lines, which were at the level of the Favorytka variety in terms of the weight of grains from the main spike and significantly exceeded the Chornozerna variety, were obtained. In terms of the weight of grains per plant and the thousand grain weight, almost all the studied lines were inferior to the Favorytka variety. Half of the lines significantly exceeded the Favorytka variety in terms of protein content, but did not significantly differ from the Chornozerna variety. In terms of gluten content, six lines did not significantly differ from the Favorytka variety, while the others did not significantly differ from the Chornozerna variety. It was found that the sedimentation index in purple-grained lines was higher than in red-grained wheat. All the lines with purple grain had a considerably higher sedimentation index than the standard red-grained variety, Favorytka. **Conclusions.** A comprehensive analysis of 14 created breeding lines of purple-grained winter soft wheat was carried out by economically valuable traits. In terms of productivity, all the studied lines were inferior to the standard variety of red-grained wheat Favorytka, which is due to the smaller number of grains in the main spike and the thousand grain weight. Purple-grained wheat lines were obtained, which in terms of yield were significantly superior to the standard variety Chornozerna. The lines with a higher thousand grain weight are characterized by the highest yield, which emphasizes the importance of increasing the thousand grain weight while maintaining a stable number of grains per area unit as a key strategy for increasing the yield potential of colored wheat. The created purple-grain lines are technologically oriented towards a new direction in the selection of wheat for cereal use with improved nutritional value of grain. Some of the highest indicators in terms of all the analyzed parameters were noted for the line UK 4776/23, which was transferred to the State Variety Testing as a variety of colored winter soft wheat Chornozirka.

Keywords: winter soft wheat, purple grain, yield, grain quality.

DOI: https://doi.org/10.15407/agrisp13.02.063

INTRODUCTION

Wheat is one of the main food crops in the world and plays a leading role in the food supply for mankind (Erenstein et al., 2022). This cereal is the main food product for 36% of the global population (Mitura et al., 2023). The share of wheat grain covers 21% of the total calorie content of the diet, 20% of protein and 55% of carbohydrates, consumed by over 2.5 billion people around the world (Khalid et al., 2023). The grain of this crop is well stored and relatively easily processed into food and feed products, ensuring over 20% from the total calories content of the human diet. Wheat is used to produce hundreds of different products, grain is also directed for technical needs, the production of bioethanol and animal feeds. The total global area of wheat fields in 2026/27 cultivation season is about 215–220 mln ha (as per report of the US Department of Agriculture, USDA), which is less compared to previous years due to the reduction of areas in North America and Europe. According to the USDA, global wheat production in 2026 is forecast at the level of 819–821 mln tons which is approximately 23–25 mln tons less than in 2025. According to the data of the Ministry of economy, the total gross wheat yield in Ukraine is expected at the level of 22–23 mln tons.

The largest global wheat producers are China, India, the USA, Canada, France (Wheat Production by Country 2026: Official FAOSTAT Ranking). Ukraine is steadily ranked the 9th in the global rating of the largest wheat producers, with its cultivation of over 23 mln tons of grain per year, despite some reduction of sown areas due to the war actions. In 2026, Ukraine keeps its position in top 7 largest global exporters of wheat (usually taking the 6th–7th place in the global rating of suppliers according to the USDA forecast). The expected volume of Ukrainian wheat export in 2026/27 cultivation season is estimated within 13–14 mln tons at the background of the total yield of about 23 mln tons.

Unlike other countries, Ukraine's domestic market for bread products and its exports are based solely on varieties of winter red-grained wheat. When grain is milled, white flour loses the lion's share of its vitamins, minerals, and dietary fiber, and its nutritional value and the value of flour-based products is significantly reduced (Rybalka et al., 2024). The problem of deficiency of critical nutrients in food has taken on global, strategic significance, as it is linked to issues of growth, development, and immune system formation in children; mental and physical development in adults; the health of women of reproductive age; and other related concerns (Cardozo et al., 2019). To prevent the exacerbation of these problems, white wheat flour is specifically fortified with vitamins, minerals, and other critically important nutrients. However, artificial biofortification cannot in any way serve as an equivalent substitute for natural nutrients, valuable for health, nor can it improve the natural taste, texture, aroma, and organoleptic properties of foods (Rybalka et al., 2024).

The growing awareness of the close link between diet and human health is currently significantly changing people's dietary preferences around the world, driving an increase in the consumption of foods with high nutritional value (Gamel et al., 2023). Starting in the 1990s, a fundamentally new trend began to emerge in the breeding of wheat and other cereal crops — the creation of color-grained varieties (purple, blue, black), which is now gaining significant momentum in many countries around the world (Rybalka et al., 2026). This is the latest global research trend aimed at significantly improving the nutritional characteristics of wheat varieties via biofortification using the bioactive pigments, anthocyanins (Garg et al., 2022). In countries such as China, India, Canada, Australia, Austria, the Czech Republic, and others, dozens of wheat varieties with colored grains have already been developed, and the production of various food products has begun (Gamel et al., 2023; Rybalka et al., 2026). India and China, vast countries with billions of populations, are currently global leaders in the development and comprehensive research of color-grained wheat varieties. Indian experts state that soon all wheat varieties in their country will have colored grains (Dhua et al., 2021). In China, a consortium has been specifically established to develop and study color-grained wheat varieties (Zhang et al., 2022). Several dozen varieties of black-grain wheat have already been registered in this country, the best known of which are Heibaoshi 1, Hedongwumai 526, Luozhen 1, and Heilixiaomai 1 (Rybalka et al., 2026). Practically the same products are produced as those made from flour of conventional wheat varieties; however, colored wheat-derived products are produced exclusively from whole-grain flour (Wei et al., 2022; Rybalka et al., 2023). Colored wheat is successfully used in the production of a wide range of food products, such as noodles, bread, cookies, pasta, and crackers (Saini et al., 2021). A significant advantage of colored wheat products is their long shelf life, which is attributed to their high anthocyanin content (Dziki et al., 2014).

The dark pigmentation of color-grained wheat is due to anthocyanins, which exhibit high antioxidant and anti-inflammatory activity, protect cells from the destructive effects of free radicals, and have a wide range of beneficial effects on the human body, related to the protection against metabolic syndromes, such as obesity, diabetes, hypertension, dyslipidemia, cancer, and cardiovascular diseases (Zhang et al., 2022; Wei et al., 2024). They slow down aging, have a neuroprotective effect, and wheat varieties with colored grains and high anthocyanin content have high functional nutritional value (Lin et al., 2017; Rybalka et al., 2026). Grain color is associated not only with high anthocyanin content but also with increased levels of vitamins and microelements in the grain, particularly iron and zinc. Grains containing anthocyanins have a more diverse composition of flavonoids and contain more protein and essential amino acids (Dhua et al., 2021; Rybalka et al., 2026).

Colored wheat is represented by three main grain color types: blue, purple, and black, depending on the type of anthocyanins and their localization within the anatomical structures of the kernel (Garg et al., 2022). Blue pigments are localized in the aleurone layer of the kernel, purple color is present in the grain coat (pericarp), and black color combines both blue and purple. The anthocyanin pigments responsible for these grain colors are found in the peripheral anatomical layers of the kernel and, during milling, are transferred to the fraction of technological bran.

The main anthocyanin pigments in blue wheat are delphinidin-3-glucoside, delphinidin-3-galactoside, delphinidin-3-rutinoside, and malvidin-3-glucoside (Sharma et al., 2020). In purple wheat, the main anthocyanins are cyanidin-3-glucoside, cyanidin-3-(6-malonylglucoside), cyanidin-3-rutinoside, peonidin-3-glucoside, and peonidin-3-(6-malonylglucoside) (Abdel-Aal et al., 2018). The main anthocyanin compounds in black-grain wheat are derivatives of six common anthocyanidins: delphinidin, cyanidin, pelargonidin, peonidin, petunidin, and malvidin (Garg et al., 2016). The anthocyanin content in red-grain wheat is approximately 5 mg/kg, in purple wheat — approximately 40 mg/kg, in blue wheat — approximately 80 mg/kg, and in black wheat — approximately 140 mg/kg (Rybalka et al., 2024).

The genes, controlling these colors, exotic for common wheat, were transferred to it by distant interbreeding with some wild and some cultivated relatives, such as *Triticum aephiopicum*, *Aegilops speltoides*, *Agropyron tricholphorum*, *Agropyron glaucum*, *Agropyron elongatum*, *Triticum boeoticum*, *Triticum monococcum*, *Thinopyrum ponticum*, *Thinopyrum besarabicum*, *Thinopyrum elongatum*, *Secale cereale*, etc. (Rybalka et al., 2025).

The accumulation of anthocyanins in the pericarp, which leads to purple color of the grain, is controlled by three dominant alleles: *Pp-B1*, located on chromosome 7BL, *Pp-D1*, located on chromosome 7D and *Pp3*, located on chromosome 2A (Knievel et al., 2009). Therefore, the development of purple pericarp requires two complementary components, located in different genomes, namely, A and B or A and D. Even if two other genes (*Pp-B1* and *Pp-D1*) are dominant, grain will not be purple in case of the presence of the recessive gene *Pp3*. The need for simultaneous availability of the functional alleles of two complementary genes from different genomes (A and B or A and D) explains the fact that the forms with purple pericarp in the grain are found only among hexaploid species *T. spelta* and *T. aestivum* (Garg et al., 2022). Jiang et al. (Jiang et al., 2018) assumed that two transcription factors — *R2R3-MYB* and *bHLH-MYC* — regulate the synthesis of anthocyanins in purple pericarp jointly, but the practical mechanism, controlling this trait, is still unknown. The blue color of aleurone encode the dominant gene *Ba1* (from chromosome 4AgL (*Ag. elongatum*) and semi-dominant *Ba2* (chromosome 4A from *T. monococcum*), dominant genes *Ba(c)* from *Th. bessarabicum* and *Ba(d)* from *Th. ponticum* (Martinek et al., 2014).

The Institute of Plant Physiology and Genetics of the National Academy of Sciences of Ukraine has launched large-scale and first in Ukraine programs with the purpose of creating breeding material for obtaining new varieties of these cereal crops with colored (purple, blue, and black) grain and significantly improved nutritional functional status of the grain due to high antioxidant activity. A winter wheat variety with purple grains, Chornozerna, has already been developed and entered into the State Register of Varieties of Ukraine. To develop color-grained wheat varieties, the breeding lines are created and their economically valuable traits are studied.

The previous studies have primarily focused on the grain quality of color-grained wheat (Zhang et al., 2023), while relatively little attention has been paid to the yield potential of such genotypes. It has been shown that the productivity of color-grained wheat is generally low, which limits the expansion of its cultivation area (Dong, 2022). Given the growing demand for color-grained wheat, increasing its yield is a particularly pressing task. In this regard, the aim of our study was to evaluate the productivity and grain quality of the developed breeding lines of purple-grained wheat.

MATERIALS AND METHODS

The field studies were conducted in 2023–2025 in the fields of the State Institution «Experimental Farm of the Institute of Plant Physiology and Genetics of the National Academy of Sciences of Ukraine» (Glevakha village, Fastiv District, Kyiv Oblast), the geographic coordinates are 50°15′43″ N and 30°17′25″ E. The fields are located on the Kyiv Plateau within the Near-Dnipro upland and the Polissia terraced plain. In terms of soil and ecology mapping, the fields of the State Institution belong to the Forest-Steppe increasingly moisturized subzone. It has moderate winter-cold climate with the precipitation of 120–140 mm in the cold period and the hydrothermal coefficient (HTC) of 1.1–1,2 in May–July. The soils under the crops were light gray, podzolized, sandy. The system of primary and pre-sowing soil cultivation is standard for the Forest-Steppe zone of Ukraine. A four-field crop rotation was used in the studies — cultivated fallow, soybeans (sunflower), mustard, winter wheat.

The climatic conditions during this period were characterized by contrasts in both temperature regime and moisture availability. The hydrothermal conditions of 2023 proved favorable for wheat vegetation in the Forest-Steppe zone, characterized by an optimal temperature sum and sufficient soil moisture. In 2024, a drought was observed in the northern part of the Forest-Steppe zone (hydrothermal coefficient (HTC) =0.8). In 2025, in the northern part of the Forest-Steppe zone, wheat plants grew predominantly under conditions of sufficient soil moisture. The HTC level during the growing season ranged from 0.8 to 2.2.

The experimental material used for the crossing was the high-yielding red-grain winter soft wheat variety Favorytka, a mid-early, high-intensity type, and the winter soft wheat variety Chornozerna with purple grain and elevated levels of iron and B vitamins, both developed by the Institute of Plant Physiology and Genetics of the NAS of Ukraine. The Chornozerna variety was created by crossing Ukraine's first colored variety, Chornobrova, with dark-purple grains, with a wheat line carrying the modified rye-wheat translocation 1RSm.1BL, in which the rye locus Sec-1, which is negative for baking qualities, has been replaced by the positive wheat cluster Gli-B1(Glu-B3). The anthocyanin pigment content in the grain of this variety ranges from 50 to 60 mg/kg; it is characterized by average baking quality indicators (grain protein content of 12–13% and flour «strength» ranging from 180 to 200 W) (Rybalka et al., 2026).

Initially, (♀) Favorytka × Chornozerna (♂) crossing was performed, yielding F_1 seeds. Then, Favorytka (♀) was pollinated with pollen from the F_1 hybrid of Favorytka × Chornozerna (♂), resulting in seeds from the first backcross, BC_1. Recombinant plants with purple grains were selected among the BC_1/F_2 plants. These plants were used in subsequent backcrosses with (♀) Favorytka. In 2019–2022, elite plants with purple grain were selected, tested for grain productivity and baking quality traits, and used for further propagation.

The experiments used a systematic method of placing plots with a calculated area of 10 sq.m. The plots were arranged in blocks with a plant density of 400,000 plants per hectare. The experiment had three repeats. The samples were evaluated based on a number of economically valuable traits (yield, morphometric parameters, components of productivity structure, and grain quality indicators) and compared with the standard. The standards were the winter soft wheat varieties Chornozerna (with purple grains) and Favorytka (with red grains). Throughout the growing season, field evaluations were conducted in accordance with the methodology for state variety testing (Tkachyk et al., 2016).

The measurements of yield structure parameters (plant height, productive tillering, main spike length, number of spikelets and grains per spike, grain weight per spike and per plant, and thousand grain weight) were conducted in three repeats on samples of at least 30 plants.

Grain quality parameters (protein and gluten content) were determined using infrared spectroscopy with an Inframatic 8600 device (Perten, Sweden). The measurements were conducted at 25°C. For the analysis, a 40-gram sample of meal was used, which was obtained by grinding in a Perten LM 3100 laboratory mill (Perten, Sweden).

The flour sedimentation index was determined using the SDS-30 method on an automated, software-controlled device developed at the Institute of Plant Breeding and Genetics — the National Center of Seed and Cultivar Investigation of the NAAS of Ukraine (Rybalka, 2011).

Laboratory bread baking using wheat flour was carried out using the straight dough method. To knead the dough, 100 g of wheat flour with a 70% yield (at 14% moisture content), compressed baker's yeast, salt (extra), sugar, potassium bromate, ascorbic acid, and tap water were used. The bread was baked for 25 minutes at 230°C. The total duration of the process, from the start of dough mixing to the end of baking, was 3.5–4.5 hours (Tkachyk et al., 2016).

The statistical analysis of the obtained data was performed using ANOVA software and Tukey's post-hoc test for significant differences based on mean values. The significance of differences between indicators was assessed at $p \leq 0.05$.

RESULTS

We conducted a study of 14 breeding lines of winter wheat with purple grains, evaluating their economically valuable traits. **Fig. 1** shows samples of winter soft wheat grains with different grain colors.

A general view of the plants from our breeding line of wheat UK 4776/23 with purple grains is shown in **Fig. 2**.

The average yield of the purple-grain wheat breeding lines, developed by us in the comparative trial in 2023–2025 ranged from 91.2 to 109.8 centners/ha **(Table 1)**.

The results of our study show that the yield of purple-grain wheat lines is lower than that of modern red-grain wheat varieties, which is consistent with the findings of other studies (Ma et al., 2020). At the same time, some genotypes, significantly outperforming the standard variety Chornozerna with purple grains in terms of yield, were identified. The breeding lines with the highest average grain yields were: UK 4383/22 — 109.8 centners/hectare, UK 4280/22 — 105.6 centners/hectare, and UK 4776/23 — 105.0 centners/hectare, all of which significantly exceeded the yield of the Chornozerna variety. The highest grain yield was recorded in the breeding line UK 4383/22 — 109.8 centners/ha, while the lowest was in line UK 5022/23 — 91.2 centners/ha.

The lines UK 4287/22, UK 4270/22, UK 4280/22, UK 4383/22, UK 4775/23, and UK 4776/23 have significantly higher productivity than the Chornoz-

Fig. 1. The grain samples (from left to right): Favorytka variety (red), Chornozerna variety (purple), Chornozirka variety (dark purple)

Fig. 2. The purple-grain winter wheat plants

erna variety. The lines UK 5021/23, UK 5024/23, UK 5025/23, UK 5037/23, UK 5038/23, UK 5055/23, and UK 5056/23 do not differ significantly from it. In UK 5022/23 line, this indicator is significantly lower than in this variety.

We also analyzed the morphological traits and key elements of the productivity structure of color-grained wheat breeding lines **(Table 2)**.

It was found that most breeding lines did not differ significantly in plant height from the Chornozerna variety, but all analyzed genotypes significantly exceeded the Favorytka variety in this trait. The analysis of morphological traits showed that the plant height of the purple-grain wheat lines ranged from 106.3 to 115.0 cm. Only two lines — UK 5038/23 and UK 5056/23 — had plant height of 106.3 and 108.6 cm, respectively, which was significantly lower than those of the Chornozerna variety.

A very important trait is plant resistance to lodging, as it determines the feasibility of mechanized harvesting, as well as the technological and sowing qualities of the grain. Plant height is one of the factors influencing this trait. Therefore, we evaluated lodging resistance on a five-point scale in the purple-grain lines and the standard varieties Chornozerna and Favorytka. All the studied purple-grain wheat lines

Table 1. The productivity of the breeding lines of winter wheat with purple grain in the comparative trial

Breeding line, variety	Yield, centners/ha		
	Average value in 2023–2025	Deviation from the standard variety, Chornozerna, centners/ha	Deviation from the standard variety, Favorytka, centners/ha
Favorytka variety, standard	128.9[a]	—	—
Chornozerna variety, standard	96.0[b]	—	—
UK 4287/22	104.2[c]	+8.2	–24.7
UK 4270/22	104.8[c]	+8.8	–24.1
UK 4280/22	105.6[c]	+9.6	–23.3
UK 4383/22	109.8[c]	+13.8	–19.1
UK 4775/23	103.7[c]	+7.7	–25.2
UK 4776/23	105.0[c]	+9.0	–23.9
UK 5021/23	92.2[b]	–3.8	–36.7
UK 5022/23	91.2[d]	–4.8	–37.7
UK 5024/23	96.3[b]	+0.3	–32.6
UK 5025/23	98.8[b]	+2.8	–30.1
UK 5037/23	99.3[b]	+3.3	–29.6
UK 5038/23	98.7[b]	+2.7	–30.2
UK 5055/23	96.2[b]	+0.2	–32.7
UK 5056/23	93.9[b]	–2.1	–35.0
$LSD_{0.05}$	5.6	—	—

Note. Probable differences at $p \leq 0.05$ are indicated by different letters.

Table 2. Indicators of morphological traits and elements of the productivity structure of wheat breeding lines with purple grain in a competitive test (average values for 2023–2025)

Breeding line, variety	Number of productive shoots, items	Height of plants, cm	Length of the main spike, cm	Number of spikelets in the main spike, items	Number of grains in the main spike, items	Weight of grain from the main spike, g.	Weight of grain from the plant, g.	Weight of 1,000 grains, g.
Favorytka variety, standard	4.8^{a}	94.7^{a}	9.8^{a}	20.2^{a}	56.2^{a}	3.6^{a}	5.3^{a}	52.7^{a}
Chornozerna variety, standard	4.0^{b}	115.7^{b}	9.4^{b}	19.2^{b}	41.7^{b}	2.2^{b}	4.2^{b}	47.1^{b}
UK 4287/22	4.2^{b}	112.3^{b}	9.4^{b}	19.5^{b}	43.6^{b}	2.6^{b}	4.4^{b}	48.5^{b}
UK 4270/22	$4.4^{a,b}$	114.1^{b}	10.4^{c}	$19.8^{a,b}$	44.8^{b}	3.4^{a}	4.6^{b}	51.6^{a}
UK 4280/22	4.0^{b}	110.4^{b}	9.2^{b}	20.3^{a}	49.4^{c}	3.2^{a}	4.2^{b}	48.6^{b}
UK 4383/22	5.0^{a}	113.7^{b}	10.2^{a}	$19.6^{a,b}$	50.6^{c}	3.3^{a}	5.1^{a}	52.1^{a}
UK 4775/23	4.6^{a}	111.8^{b}	$9.6^{a,b}$	19.1^{b}	42.9^{b}	2.3^{b}	4.5^{b}	48.5^{b}
UK 4776/23	5.2^{a}	112.3^{b}	10.7^{c}	22.8^{c}	51.8^{c}	3.3^{a}	5.2^{a}	51.1^{a}
UK 5021/23	3.8^{b}	111.7^{b}	9.2^{b}	21.2^{d}	46.6^{c}	2.8^{c}	4.3^{b}	48.4^{b}
UK 5022/23	4.2^{b}	113.3^{b}	8.9^{b}	20.4^{a}	44.5^{b}	2.7^{b}	4.1^{b}	45.8^{b}
UK 5024/23	3.9^{b}	110.5^{b}	9.1^{b}	19.1^{b}	45.5^{b}	2.6^{b}	4.2^{b}	47.1^{b}
UK 5025/23	4.0^{b}	112.8^{b}	$9.5^{a,b}$	20.6^{a}	47.8^{c}	3.1^{a}	4.6^{b}	48.9^{c}
UK 5037/23	$4.4^{a,b}$	115.0^{b}	10.5^{c}	21.8^{d}	43.9^{b}	2.7^{b}	4.7^{b}	48.0^{b}
UK 5038/23	4.2^{b}	106.3^{c}	10.3^{a}	21.2^{d}	46.8^{c}	2.8^{c}	4.6^{b}	48.4^{b}
UK 5055/23	4.6^{a}	113.9^{b}	$9.8^{a,b}$	20.8^{a}	42.9^{b}	2.3^{b}	4.4^{b}	47.2^{b}
UK 5056/23	3.7^{b}	108.6^{c}	8.9^{b}	19.3^{b}	43.6^{b}	2.5^{b}	4.0^{b}	46.8^{b}
$LSD_{0.05}$	0.4	4.5	0.5	0.6	4.0	0.5	0.5	1.6

Note. Probable differences at $p \leq 0.05$ are indicated by different letters.

and standard varieties were characterized by high resistance to lodging (5 points) and did not differ from one another. Although the Chornozerna variety and most purple-grain wheat breeding lines were 15–20 cm taller than the Favorytka variety, this did not affect their resistance to lodging.

In the purple-grain wheat breeding lines, studied by us, the number of productive shoots varied significantly — from 3.7 to 5.2. Most analyzed lines did not differ significantly in their productive tillering from the standard variety, Chornozerna. Line UK 4776/23 stood out, having the highest number of productive shoots, 5.2, which significantly exceeds this index in the purple-grain variety. Some lines were on par with the Favorytka variety in this trait **(Table 2)**, while such genotypes as UK 4287/22, UK 4280/22, UK 5021/23, UK 5022/23, UK 5024/23, UK 5025/23, UK 5038/23, and UK 5056/23 were significantly inferior to the red-grain wheat variety in terms of the number of productive shoots.

The average length of the main spike in the breeding lines ranged from 8.9 to 10.7 cm **(Table 2)**. Three lines — UK 4776/23 (10.7 cm), UK 4270/22 (10.5 cm), and UK 5037/23 (10.4 cm) — significantly exceeded both standards in terms of the main spike length. All other lines were on par with the Chornozerna or Favorytka varieties and were not statistically different from them.

The number of spikelets in the main spike of the breeding lines ranged from 19.1 to 22.8 **(Table 2)**. Four lines: UK 4776/23, UK 5021/23, UK 5037/23, and UK 5038/23 significantly outperformed the standard varieties for both red-grain and purple-grain wheat **(Table 2)**. This indicator was the highest in lines UK 4776/23 (22.8 pieces) and UK 5037/23 (21.8 pieces). All other lines were on par with the Chornozerna or Favorytka varieties and were not statistically different from them.

Over the years of research, the average number of grains in the main spike among the lines varied significantly from 42.9 to 51.8 grains. The genotypes UK 4383/22 (50.6 grains) and UK 4776/23 (51.8 grains) had the highest values for this indicator. At the same time, all genotypes studied were inferior to the Favorytka variety in this respect. Some lines did not differ significantly from the Chornozerna purple-grain wheat variety **(Table 2)**. Genotypes, significantly exceeding this index for this variety, specifically the lines UK 4280/22, UK 4383/22, UK 4776/23, UK 5021/23, UK 5025/23, and UK 5038/23, were also identified.

The breeding lines also differed significantly from one another in terms of grain weight per main spike, ranging from 2.3 to 3.4 g. Line UK 4270/22 had the highest value– 3.4 g, while lines UK 4775/23 and UK 5055/23 had the lowest one — 2.3 g. A total of 5 lines: UK 4270/22, UK 4280/22, UK 4383/22, UK 4776/23, and UK 5025/23 met the standard for this characteristic, the Favorytka variety, and significantly outperformed the Chornozerna variety **(Table 2)**. The other genotypes were inferior to red-grained wheat but did not differ significantly from the standard variety of purple-grain wheat.

In terms of grain weight per plant, almost all the studied breeding lines were inferior to the Favorytka variety. The best performers in this regard were lines UK 4383/22 (5.1 g) and UK 4776/23 (5.2 g), which did not differ significantly from the standard red-grain wheat variety. The other breeding lines did not differ significantly in grain weight per plant from the standard Chornozerna variety.

We analyzed the thousand grain weight of the purple-grain wheat breeding lines and found significant variation in this trait, ranging from 45.8 to 52.1 g. The highest value was observed in breeding line UK 4383/22 — 52.1 g. In terms of the thousand grain weight, lines UK 4270/22, UK 4383/22, and UK 4776/23 did not differ significantly from the standard variety, Favorytka red-grain wheat. All other lines did not differ significantly from the standard variety Chornozerna (purple-grain), but their thousand grain weight was significantly lower than that of the red-grain standard variety Favorytka.

Grain quality and the baking properties of flour, in which the grain storage proteins play a leading role, are the most important indicators for soft wheat (Rybalka et al., 2024). Thus, protein content is closely correlated with gluten content, flour strength, and sedimentation index.

Protein content is one of the main indicators of winter soft wheat grain quality, to which we pay particular attention when evaluating breeding lines with purple grains. In our study, the highest protein content was recorded in lines UK 5037/23 (12.7%) and UK 5024/23 (12.5%) **(Table 3)**.

Seven lines: UK 4287/22, UK 4383/22, UK 4775/23, UK 4776/23, UK 5024/23, UK 5025/23, UK 5037/23, UK 5038/23 significantly exceeded the Favorytka variety in this characteristic but did not differ significantly from the Chornozerna variety. The other genotypes did not differ significantly from the Favorytka variety in protein content.

Gluten is a continuous, viscoelastic protein network that forms when flour is mechanically mixed with water; it is an important parameter determining the quality of baked goods, as it affects water absorption capacity, cohesiveness, viscosity, and elasticity of dough. The crude gluten content in different genotypes ranged from 22.3 to 26.7% **(Table 3)**. In terms of gluten content, the following six lines: UK 4270/22, UK 4280/22, UK 5021/23, UK 5022/23, UK 5055/23, and UK 5056/23 did not differ significantly from the standard variety, Favorytka. The other lines under study did not differ significantly from the purple-grain wheat variety Chornozerna.

The most common method for indirect assessment of the technological quality of wheat grain is the SDS-30 sedimentation method, which is based on the swelling and precipitation of gluten proteins in a sodium dodecyl sulfate (SDS) solution. This parameter, also known as the sedimentation index, is used in breeding to quickly predict the «strength» of the flour and the baking properties of a future variety during the early stages of selection. The method involves preliminary autolysis of meal or flour for 30 minutes followed by sedimentation with sodium dodecyl sulfate; it simulates the autolytic process of dough formation and utilizes the unique ability of the SDS medium to induce swelling of flour particles, which is directly related to baking quality. A high SDS-30 sedimentation index indicates high baking quality of the flour.

This index in the analyzed breeding lines of purple-grain wheat ranged from 36 ml to 62 ml **(Table 3)**. All the purple-grain lines have a significantly higher sedimentation index than the red-grained standard variety Favorytka. Only line UK 4776/23 does not

Table 3. The grain quality indicators for purple grain wheat breeding lines (average values for 2023–2025)

Genotype	Protein content, %	Crude gluten content, %	SDS-30, ml
Favorytka, st.	11.1[a]	23.3[a]	31.3[a]
Chornozerna, st.	12.3[b]	25.9[b]	60.0[b]
UK 4287/22	12.0[b]	25.1[b]	52.0[c]
UK 4270/22	11.2[a]	23.4[a]	43.0[d]
UK 4280/22	11.5[a]	24.0[a]	49.0[c]
UK 4383/22	12.0[b]	25.1[b]	41.0[d]
UK 4775/23	12.0[b]	25.1[b]	36.0[e]
UK 4776/23	12.1[b]	26.3[b]	62.0[b]
UK 5021/23	11.6[a]	24.3[a]	48.0[c]
UK 5022/23	11.5[a]	24.2[a]	50.0[d]
UK 5024/23	12.5[b]	25.3[b]	47.0[c]
UK 5025/23	11.8[b]	24.6[c]	55.0[c]
UK 5037/23	12.7[b]	26.7[b]	42.0[d]
UK 5038/23	11.8[b]	24.5[c]	42.0[d]
UK 5055/23	10.8[a]	22.3[a]	36.0[e]
UK 5056/23	11.5[a]	23.9[a]	41.0[d]
$LSD_{0.05}$	0.5	1.0	4.3

Note. Probable differences at $p \leq 0.05$ are indicated by different letters.

differ significantly from the value of the Chornozerna variety, while all other genotypes have a significantly lower sedimentation value than that variety.

Fig. 3 shows the results of a pilot laboratory bread-baking experiment: the purple-grain Chornozirka variety is to the right of the standard varieties Favorytka and Chornozerna. The loaves were baked from white flour with a 70% yield. The volume of loaves baked from the flour of these varieties was 860 ± 41 ml for the Favorytka variety; 980 ± 46 ml for the Chornoz-

Fig. 3. The results of the laboratory bread-baking test (from left to right): Favorytka variety, Chornozerna variety, Chornozirka variety

erna variety; and 1,120 ± 51 ml for the Chornozirka variety.

DISCUSSION

The development of varieties with colored (purple, blue, black) grains is currently gaining significant momentum in many countries around the world, including Ukraine. At present, this effort involves 60 research and breeding institutions in 16 countries, including Ukraine (Garg et al., 2022). This is a cutting-edge area of research aimed at significantly improving the nutritional characteristics of grain via biofortification using bioactive anthocyanins with high antioxidant activity.

As early as in 1970, by crossing soft wheat (*Triticum aestivum*) with blue wheatgrass (*Agropyron glaucum*), scientists created the first blue-grain wheat variety, «blue 1.» Twenty years later, by crossing soft wheat (*Triticum aestivum*) with thick-eared wheatgrass (*Elymus dasystachys*), a wheat variety with purple grains, «purple 12-1,» was created, and the «blue-purple 114» variety was created by crossing «blue 1» with a tetraploid wheat variety with purple grains (Beta et al., 2019). The first black-grain wheat variety was developed at the Institute of Crop Genetics of the Shanghai Academy of Agricultural Sciences by combining genes from previously developed wheat varieties with purple and blue grains. By crossing «purple 12-1» as the male parent and «blue-purple 114» as the female parent, the black-grain wheat variety «black 76» was obtained (Beta et al., 2019).

The main challenge in developing new varieties of colored wheat is grain yield. The breeding lines of such wheat are characterized by relatively low yields, due to the negative effect of genes responsible for grain color that are inherited from wild species (Garg et al., 2022). The genes responsible for blue or purple grain color are often transferred into the soft wheat genome from its wild or closely related relatives (such as wheatgrass or wild species of Aegilops). Other traits from wild ancestors are also inherited along with the color genes, such as lower spike grain number, smaller grain size, or poorer plant architecture, which reduces the overall grain yield per hectare. The yield of purple- and blue-grain wheat typically reaches only 60.1–85.6% and 76.2–84.3%, respectively, of the yield of modern red-grain soft wheat varieties (Akman et al., 2025). For example, the Austrian commercial blue-grain wheat variety Skorpion had a 25% lower yield than the control varieties of red-grain wheat (Martinek et al., 2013). Lower yields of four different colored wheat varieties were recorded under organic farming systems (Zrckova, 2018). The yield of the S29 isogenic wheat lines was found to be half that of the Seri variety (Morgounov et al., 2020).

Careful breeding is necessary to develop lines with high anthocyanin content and satisfactory yield levels. The breeding efforts have increased the yield and agronomic traits of various breeding lines/varieties compared to donor wheat lines (Žofajová et al., 2017; Garg, 2018 a,b). A study (Morgounov et al., 2020) examined two different isogenic lines with purple grains (Purple, Purple Feed) in comparison with the S-29 variety. The lines derived from Purple Feed significantly improved grain yield compared to S-29. Black-grain wheat lines have been developed that combine high yield with enhanced benefits for human health (Sharma et al., 2018). In many years of selection, we have also obtained breeding lines of wheat with purple grains that significantly outperformed the standard variety Chornozerna in terms of yield.

Another important trait is adaptability to the environment. Morgounov et al. (Morgounov et al., 2020) reported that the environment has a more significant impact on the productivity of purple wheat than genotype. Garg et al. (Garg et al., 2016) demonstrated that colored wheat varieties have adapted to different environments through breeding strategies such as crossing exotic winter wheat lines with locally adapted spring wheat varieties. They developed colored wheat lines for cultivation in India that are high in anthocyanins and have higher yields. The application of high doses of nitrogen also increased grain yield in purple-grain wheat (Ma et al., 2018). Fan et al. (Fan et al., 2020) identified various colored wheat genotypes that demonstrated tolerance to low-nitrogen conditions.

Grain number per unit area (number of spikes per unit area × number of grains per spike) and thousand grain weight are considered important factors influencing wheat yield (Zheng et al., 2020). Increases in the yield of color-grained wheat are primarily attributed to an increase in the number of grains per unit area (Garcia et al., 2019; Zhu et al., 2025). In particular, for colored wheat, the number of spikes shows a very strong positive correlation or a strong positive correlation with yield, indicating that increasing the number of spikes is an important way to improve yield in most varieties (Zhu et al., 2025).

It has been shown that soft wheat grain yield is 20% dependent on the thousand grain weight (Abdipour et al., 2016). A study by Yao et al. (Yao et al., 2022) demonstrated a strong positive correlation between the thousand grain weight and yield in soft wheat varieties. The yield can also be increased by increasing the thousand grain weight while keeping the number of grains per unit area a constant value (Quintero et al., 2018). Akman et al. (Akman et al., 2025) found that the thousand grain weight of wheat genotypes was ranked as follows: red-grain (45.2–45.8 g) > black-grain (40.1 g) > purple-grain (26.9–41.0 g) > blue-grain (28.1–41.2 g). Koksel et al. (Koksel et al., 2023) demonstrated significant differences in the thousand grain weight among genotypes with red (31.4 g), purple (32.9–33.3 g), and blue (29.2 g) grain. It was found that the thousand grain weight was higher in lines with purple grains than in lines with red grains, at 34.0 g and 32.7 g, respectively (Morgounov et al., 2020). In our study, most breeding lines with purple grain were inferior to the red-grain variety Favorytka, and only three genotypes did not differ significantly from it by this trait. Among the purple-grain wheat samples, the UK 4383/22 line has the highest thousand grain weight and significantly outperforms the Chornozerna variety, which accounts for its highest productivity among the colored lines. These results highlight the importance of increasing the thousand grain weight while maintaining a stable number of grains per unit area as a key strategy for enhancing the yield potential of colored wheat.

Colored wheats generally have higher protein and crude gluten content than soft red wheat (Giordano et al., 2017; Sebestiková et al., 2023; Akman et al., 2025; Zhu et al., 2025). In genotypes with blue and purple grains, the protein content ranges from 15.06% to 16.35%, whereas in red-grain genotypes, this figure is approximately 13.47% (Fan et al., 2020). Some studies indicate that black-grain wheat has the highest protein content among colored wheat varieties (Sharma et al., 2022; Koksel et al., 2023). In a study (Zhu et al., 2025), the crude protein content in purple- and blue-grain wheat was significantly higher than in modern white-grain wheat. Akman et al. (Akman et al., 2025) reported that colored wheat varieties may also have low gluten quality indices. It is also important to consider the negative correlation between yield and protein content, as well as the strong dependence of protein content on growing conditions (Jolánkai et al., 2018). In our studies, only half of the lines significantly exceeded the Favorytka variety in protein content, but did not differ significantly from the Chornozerna variety.

It was shown that modern red-grain wheat typically falls into the medium-gluten category, whereas colored wheat is classified as high-gluten flour, highlighting its potential for the production of high-quality food products (Wei, Chen, 2015). It was found that purple-grain wheat had higher dry and crude gluten content than modern white-grain wheat (Zhu et al., 2025). However, some studies indicate that red-grain varieties may have higher levels of crude gluten than genotypes with blue and purple grains (Sharma et al., 2022; Koksel et al., 2023). In our studies, six lines did not differ significantly from the Favorytka variety in terms of crude gluten content, while the other lines studied did not differ significantly from the Chornozerna variety.

The SDS-30 sedimentation index for purple wheat varieties is an important technological indicator of the quality of the protein complex and averages approximately 40 ml (Rybalka et al., 2019). This indicator has a high correlation with key dough elasticity characteristics, such as the W value of flour strength (W) and the dough elasticity index Ie (%). All breeding lines of purple-grain wheat showed average sedimentation index (SDS-30) values ranging from 35 to 62 mL. Due to its moderate sedimentation rate and the characteristic dark color of the shell, purple wheat flour is most often used in blends or for the production of whole-grain bread, dietary products, crackers, and functional foods (Rybalka et al., 2019). This allows for the preservation of a high antioxidant content without a loss of baked goods volume. The developed lines with purple grain are technologically oriented toward a new direction in the breeding of wheat for cereal use with improved nutritional value of the grain; therefore, they do not require high baking characteristics.

CONCLUSIONS

A comprehensive analysis was conducted of 14 breeding lines of purple-grain winter soft wheat, developed by us, in terms of economically valuable traits. It was found that in terms of productivity, all the studied lines were inferior to the standard red-grain wheat variety Favorytka, which is due to a lower number of grains per main spike and a lower thousand grain weight. At the same time, the study demonstrated the possibility of obtaining genotypes with purple grains and relatively high yields. It was found that lines with a higher thousand grain weight are characterized by the highest yield, which highlights the importance of increasing this value while maintaining a stable number of grains per unit area as a key strategy for enhancing the yield potential of colored wheat. Most lines did not differ in height from the Chornozerna variety, significantly exceeded the Favorytka variety, and demonstrated high resistance to lodging. All the investigated wheat lines with purple grain and standard varieties were characterized by high resistance to lodging (5 points) and had no differences. The developed lines with purple grains have low or moderate baking quality, as they are technologically oriented toward a new direction in wheat breeding for cereal use with improved nutritional value of the grain. However, the possibility of creating genotypes with purple grains and a relatively high sedimentation rate has been demonstrated. However, all the lines with purple grain had a considerably higher sedimentation index than the standard red-grained variety, Favorytka. Some of the highest indicators in terms of all the analyzed parameters were noted for the line UK 4776/23, which was transferred to the State Variety Testing as a variety of colored winter soft wheat Chornozirka.

Adherence to ethical principles. This article does not contain results of any studies, involving humans and animals, conducted by any authors.

Conflict of interests. The authors claim the absence of any conflict of interests.

Financing. The article presents the results of the studies, conducted within the framework of the project, financed by the Cabinet of Ministers of Ukraine, «Creating and transferring the first domestic varieties of new cereal crops with unique characteristics of grain for the production of healthy food products and ensuring food safety of Ukraine» (program budget classification code 6541230; state registration number 0125U000707).

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УДК 631.527:633.11

ОЦІНКА НОВИХ СЕЛЕКЦІЙНИХ ЛІНІЙ ПШЕНИЦІ ОЗИМОЇ М’ЯКОЇ З ФІОЛЕТОВИМ ЗЕРНОМ ЗА ПРОДУКТИВНІСТЮ І ЯКІСТЮ ЗЕРНА

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Мета. Дослідити продуктивність і якість зерна нових селекційних ліній озимої м’якої пшениці з фіолетовим кольором зерна. **Методи.** Фізіологічні: морфометричні показники та елементи структури врожаю; фізико-хімічні: інфрачервоної спектроскопії та визначення SDS-30; технологічні: однофазний метод приготування тіста; математичної статистики. Метод розміщення ділянок (10 м^2) — систематичний. Зразки вирощували блоками (400 тис. шт./га) та оцінювали за господарсько-цінними ознаками (врожайність, морфометричні показники, елементи структури продуктивності, показники якості зерна) порівняно зі стандартом. Повторність досліду триразова. Показники структури врожаю (висоту, кущистість, довжину колоса, кількість колосків/зерен, масу зерна з колоса/рослини та масу 1000 зерен) вимірювали у триразовій повторності (вибірка ≥30 рослин). Якість зерна (вміст білка й клейковини) визначали методом інфрачервоної спектроскопії на приладі Inframatic 8600. Для аналізу використовували 40 г шроту, отриманого на лабораторному млині Perten LM 3100. Статистичний аналіз даних проведено за допомогою програмного забезпечення ANOVA та критерію достовірних відмінностей Tukey's-тесту за середніми значеннями. **Результати.** Середня врожайність створених ліній пшениці з фіолетовим зерном у конкурсному випробуванні протягом 2023–2025 рр. варіювала у межах 91,2–109,8 ц/га. Виділені генотипи, які за продуктивністю достовірно переважали сорт — стандарт Чорнозерна з фіолетовим зерном. Більшість селекційних ліній достовірно не відрізнялись за висотою рослин від сорту Чорнозерна, але істотно перевищували за цим показником сорт-стандарт Фаворитка. Усі досліджені лінії пшениці з фіолетовим зерном і сорти — стандарти характеризувалися високою стійкістю до вилягання (5 балів) і не розрізнялись між собою. Виділені лінії, які істотно переважали обидва стандарти за довжиною головного колоса та кількістю колосків у ньому. Всі досліджені генотипи поступались за кількістю зерен у головному колосі сорту Фаворитка, проте виявлені такі, які істотно перевищували цей показник у сорту Чорнозерна. Отримані лінії, які за масою зерна з головного колоса були на рівні сорту Фаворитка та істотно перевищували сорт Чорнозерна. За масою зерна з рослини та масою 1000 зерен майже всі досліджені лінії поступалися сорту Фаворитка. Половина ліній істотно перевищували сорт Фаворитка за вмістом білка, але достовірно не відрізнялись від сорту Чорнозерна. За вмістом клейковини шість ліній достовірно не відрізнялись від сорту Фаворитка, тоді як інші суттєво не відрізнялися від сорту Чорнозерна. Всі лінії з фіолетовим зерном мають істотно більший показник седиментації, ніж у сорту-стандарту з червоним зерном Фаворитка. **Висновки.** Проведено комплексний аналіз 14 створених селекційних ліній пшениці м'якої озимої з фіолетовим зерном за господарсько-цінними ознаками. За продуктивністю всі досліджені лінії поступалися сорту-стандарту червонозерної пшениці Фаворитка, що зумовлено меншою кількістю зерен у головному колосі та масою 1000 зерен. Отримані лінії пшениці з фіолетовим зерном, які за врожайністю вірогідно переважають сорт-стандарт Чорнозерна. Лінії, які мають більшу масу 1000 зерен, характеризуються найбільшою врожайністю, що підкреслює важливість збільшення маси тисячі зерен при збереженні стабільної кількості зерен на одиницю площі, як ключової стратегії для підвищення потенціалу врожайності кольорової пшениці. Створені лінії з фіолетовим зерном технологічно орієнтовані на новий напрям селекції пшениці круп'яного використання з поліпшеною харчовою цінністю зерна. Одні з найвищих показників за всіма проаналізованими параметрами мала лінія УК 4776/23, яка була передана в Державне сортовипробування, як сорт кольорової м'якої озимої пшениці «Чорнозірка».

Ключові слова: озима м'яка пшениця, фіолетове зерно, врожайність, якість зерна.