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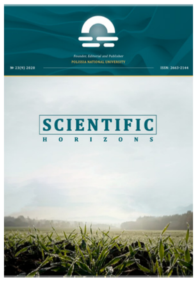

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Extension of the forming process in the selection of winter common wheat for productivity and quality by using the gene pool of related wheat species within the framework of food security

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Abstract. The formation process in the selection of winter common wheat for productivity and quality has been expanded by using the gene pool of related species. The purpose of this study was to expand the formative process in the selection of *Triticum aestivum* L. winter type of development with the further obtaining of genotypes with increased adaptability, plant productivity and grain quality through the use of winter common wheat with purple grain, whole grain wheat and Ethiopian wheat in

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hybridization. In the study, the methods of conducting the examination of plant varieties are used for carrying out phenological observations, morphological studies, evaluation of breeding material according to economic and valuable characteristics. In the creation of new forms, methods of hybridization and individual selection were used, and the TVEL method was used for pollination. The protein and gluten content were determined by infrared spectrometry. Parental components were studied and selected to expand the forming process to obtain productive grains from the main ear, thousand kernel weight, high grain quality, resistant to lodging, shedding of grain, drought-resistant and resistant to fungal pathogens, hybrid forms, specifically as a result of involvement of the source material *Triticum aestivum* L. and *Triticum sphaerococcum* Perc. in the hybridization. According to the results of the hybridization of winter common wheat and Ethiopian wheat, it was possible to obtain and breed in F_4 forms with a long ear (>10-11 cm), an increased amount of grain from the main ear (>55 pcs.) and a different colour of grain from dark brown to purple, as an indicator of increased anthocyanin content and high antioxidant capacity. The practical value of this study lies in the fact that the research results expand information on the use of winter common wheat in the selection of productivity and quality of other types of wheat: *Triticum sphaerococcum*, *T. aethiop.* var. *decoloratum*, and the developed proposals will allow considering the use of parental components of wheat in research, help improve methods of hybridization and selection of new forms with desirable traits in the system of interspecies crossings

Keywords: *Triticum aestivum* L.; *Triticum sphaerococcum* Perc.; *T. aethiopicum* var. *decoloratum* Jakubz.; selection for productivity and quality; interspecific hybridization; new hybrid forms

INTRODUCTION

Genetic variability is the key to successfully improving the quantitative and qualitative parameters of the harvest, which is important in the context of food security, which involves not only sufficient food, but also its high quality to ensure human health. Wheat is an important agricultural crop, the grain of which is the main food product for humankind, especially in developing countries.

As noted by Čurná & Lacko-Bartošová (2017), spelled grains produce groats for making high-tasting porridge, also suitable for dietary food. L.A. Vecherska *et al.* (2018) indicate that emmer wheat is widely used in breeding programs, especially for the improvement of durum and common wheat.

Scientists (Hospodarenko *et al.*, 2018; Diordieva, 2018) note the positive effect of crossing common wheat and spelled wheat, which results in the expansion of a new genetic diversity that combines the high protein and gluten content of spelled and the high productivity of wheat (Liubych *et al.*, 2019). The authors (Liubych, 2019) note that spelled wheat has a high content of protein, vitamins, macronutrients, carbohydrates and fats, which are easily and quickly absorbed by the human body.

Many scientists (Grausgruber *et al.*, 2018; Morgounov *et al.*, 2020; Garg *et al.*, 2022), based on many years of research, report that it is relevant to use the biopotential of wheat varieties with blue and purple grains – sources of anthocyanins, when consumed finished products from which their antioxidant properties are manifested, i.e., the absorption of free radicals, which is important for the prevention of many human diseases. According to studies (Lachman *et al.*, 2017; Hrivna *et al.*, 2018; Tian *et al.*, 2018), Ethiopian wheat grain is also characterized by high cereal and pasta properties.

H.H. Kassegn (2018) notes that in the 1960s and 1970s, commercial varieties of wheat with purple grains were created in China, Australia, New Zealand, and many European countries as part of a healthy diet. Saini (2021) and Gupta (2021) report that the Plant Genetic Resources Center of Canada has received constant requests from breeders for the Ethiopian Valgiorgio wheat genotype to be used in breeding for adaptability and quality. Since then, work on the creation of wheat with purple grain continues all over the world.

Specifically, in the Czech Republic, the scientific program of winter wheat breeding is aimed at creating productive genotypes in combination with high quality, including an increased content of anthocyanins, the latter is achieved by the "transfer" of purple colour to grain forms. Other scientists (Hong *et al.*, 2019) created five new mutations with purple grain colour using gamma irradiation of the hexaploid line of purple wheat K 4191 to improve its quality.

As noted by breeders (Leonov *et al.*, 2022), samples with blue and purple kernels were characterized by a lower yield compared to common wheat, but were characterized by a high content of phenols in the meal (over 800 μg/g of gallic acid equivalent), anthocyanins and increased antioxidant activity (over 500 μg/g of chlorogenic acid equivalent. Other scientists (Hong *et al.*, 2019), based on the results of the evaluation of wheat mutant lines with variable grain colour, also note that anthocyanins and phenolic compounds in wheat grain contribute to high antioxidant potential, and therefore, the purple colour of the grain is associated with a higher anthocyanin accumulation and antioxidant capacity.

According to the literature review of scientific studies (Morgounov *et al.*, 2020), anthocyanin pigmentation in wheat is controlled by dominant alleles of the genes Rc (coleoptile), Pc (culm), Plb (leaf plates), Pls (leaf sheaths), Pp (grain pericarp), Pan (anthers) and Ra (ear stigmas). Researchers (Ma *et al.*, 2021; Moskalets *et al.*, 2022) recommend using classical or modern methods of breeding and genetic engineering to increase the content of phenols, essential amino acids in wheat grains, which increase the nutritional value of cereals and bakery products, which is important in the context of healthy eating.

Triticum sphaerococcum Perc. is an endemic species for southern Pakistan and northwestern India, where it was one of the main crops, belonging to the group of hexaploid whole wheats, forming a hemispherical, with a shallow groove and high protein content and gluten in grain (Szczepanek *et al.*, 2020). As noted by M. Skrajda-Brdak *et al.* (2019), *Triticum sphaerococcum* grain is a source of common low molecular weight phytochemicals, especially phenolic acids, ferulic acid (93-95%), which was accompanied by higher quantitative and qualitative variability of homologs in sterols. Therefore, the hexaploid wheat species *Triticum sphaerococcum*, known as a source of grain quality traits, is recommended for use in common wheat breeding. H.S. Kolyucha (2011) indicates that lines with genetic material from *Triticum sphaerococcum* have the highest rates of sedimentation and gluten content.

The purpose of this study was to create new forms of common winter wheat *in* breeding for productivity and quality by using the gene pool of related wheat species.

MATERIALS AND METHODS

The scientific research program provided for a comprehensive evaluation of the source material for productivity, resistance to lodging, resistance to diseases, as well as for the created new forms of studying the laws of inheritance and relationships of valuable economic traits in the plant, selection of samples based on a complex of economic and useful traits.

The total set of source material was formed due to own efforts, as well as samples provided by the National Centre of Plant Genetic Resources of Ukraine. Agrotechnics of wheat cultivation were carried out according to the generally accepted for the Forest-Steppe zone of Ukraine. The collection of source material was established at the Nosivka Breeding and Research Station of the V.M. Remeslo Myronivka Institute of Wheat the National Academy of Agrarian Sciences of Ukraine (NAAS of Ukraine) (southern part of Polissia of Ukraine) in 2016 and stationary of the Institute of Horticulture of NAAS of Ukraine (Northern Forest Steppe of Ukraine) in 2017.

Parental forms for crossings were sown manually in the crossbreeding nursery on plots of 2 m^2, with a row width of up to 20 cm. Parent pairs for paired (simple) crosses and hybridization were selected in 2018 (Tables 1, 2). The main methods of creating new forms were hybridization and individual selection. Pollination method – TVEL method. Seeds F_{1-3} were sown manually.

Table 1. *Parental forms of winter common wheat, involved in crossing with round-grained wheat of the Donor Kyivskyi variety*

No.	Name of parent forms	Origin of parent forms
1.	KS 22-04 (UA0108013*)	♀Zoryana Nosivska (UA) × ♂Myronivska 61 (UA)
2.	L 41-95 (UA0108030)	♀Myrleben (DE&UA) × ♂Poliska 92 (UA)
3.	KS 21	♀ Zoryana Nosivska (UA) × Poliska 29 (UA)
4.	Donzorna	♀Donska n/a × ♂Zoryana Nosivska (UA)
5.	KS 14-05 (UA0123342)	(♀Marishuntsman (GB) × ♂ (♀Kyianka (UA) × ♂Pony (USA))
6.	L59-95 (UA0108016)	♀Donska n/a × ♂[♀(♀MarisMadler(GB) × ♂Rona (USA)) × ♂Donska n/a]
7.	Zoriana Nosivska (UA 0110603)	♀ (♀Obrii (UA) × ♂MarisYuntsman (GB)) × ♂MarisYuntsman (GB)
8.	Ariivka (a. c. 171136**)	♀Donska n/a × ♂K-6477/91

Note: ** is the number of the national catalogue assigned by the National Centre of Plant Genetic Resources of Ukraine; a.c. is the author's certificate for a plant variety suitable for distribution in Ukraine*
Source: *compiled by the authors*

Table 2. *Combinations with participation in the crossing of Ethiopian wheat and winter common wheat of the Chornobrova variety*

No.	Combination name
1.	*Triticum aethiopicum var. decoloratum (Vavilov)* Filat. × Ariivka
2.	*Triticum aethiopicum var. decoloratum (Vavilov)* Filat. × PKBRodika (Romania)
3.	*Triticum aethiopicum var. decoloratum (Vavilov)* Filat. × L 41-95
4.	L 59-95 × *Triticum aethiopicum* var. *decoloratum* (Vavilov) Filat.

Table 2, Continued

No.	Combination name
5.	*Triticum aethiopicum var. decoloratum (Vavilov)* Filat. × Donor Kyivskyi
6.	Chornobrova × KS 22-04 (UA0108013)
7.	(L 59-95 ×*Triticum aethiopicum* var. *decoloratum* (Vavilov) Filat.) × Chornobrova
8.	(*Triticum aethiopicum var. decoloratum (Vavilov)* Filat.× L 41-95) × Chornobrova
9.	Chornobrova × *Triticum aethiopicum* var. *decoloratum* (Vavilov) Filat.× L 41-95)

***Source**: compiled by the authors*

Hybrids (F_{2-3}) were analysed for morphological and economic characteristics (plant height, ear length, ear density, weight of grain from the main ear, a thousand kernel weight, protein, and gluten content in grain). The density of the main spike was calculated as the number of developed spikes per 10 cm of spike length. In the fourth generation (F_5), considering the indicators of productivity and grain quality of previous years, the best samples were selected, which are the object of research.

Plants were previously selected to determine plant height in laboratory conditions.

During the research, the weather conditions of 2016-2022 were characterized by contrast both in terms of temperature and the level of moisture supply. Notably, the 2016-2022 years of conducting research on changes in meteorological factors during the growing season of wheat differed among themselves and substantially deviated from the multi-year average value in individual months. Specifically, 2016 was excessively humid, 2017 was abnormally dry, and 2018 was also hot. The analysis of weather conditions in 2017-2018 showed that the vegetation of wheat plants took place during a moderately warm autumn, a long winter period with a significant cooling at the beginning of spring (the average monthly air temperature in March was 1.8°C, which is 3.6°C lower above the norm), a short-lived spring and a hot summer (the average air temperature was 18.8°C, which is 2.3°C higher than the norm). Precipitation during wheat growth and development was uneven. In autumn (October 2017), precipitation fell 80 mm or 197% of the norm, in winter – 130 mm or 290% of the norm, in summer (July) – more than 160 mm or 150% of the norm. Dry conditions were observed from mid-spring to the second decade of June. The weather conditions of 2019-2022 were more or less favourable for the development of wheat plants. Specifically, the weather conditions in 2019 and 2022 at the beginning of the growing season were moderately favourable for the development of winter crops, but the second half of the growing season was hot and dry.

The above-mentioned weather conditions during 2016-2022 helped comprehensively evaluate the source material by a set of features and to single out the most valuable samples adapted to the conditions of the northern part of the Forest Steppe of Ukraine.

The studies used generally accepted methods and their modifications, which ensured high objectivity of the obtained results. Phenological observations, visual assessment of breeding material for disease resistance, and laying were carried out pursuant to the Methods of examination of plant varieties (Tkachyk *et al*., 2016). The content of protein and gluten was determined by infrared spectrometry (Chen *et al*., 2017). Harvesting was carried out manually during the full ripeness phase. The reliability of the research results and the degree of variation of the signs were evaluated using the MS Excel program.

RESULTS

The raw material of wheat was studied according to the productivity of the ear and its elements. On average, during the 2016-2017 research, the highest grain mass of the head ear, its grain size was determined in samples of winter common wheat KS 22-04, L 41-95, L 59-95, Zoryana Nosivska, Ariivka, KS 14 and KS 21, which were involved in hybridization. In 2018, hybrid grains were obtained, and in 2019 – the first generation, which was impressive with its morphological features and physiological features.

During the study of the source material, it was found out that the Donor Kyivskyi round-grained wheat has a number of positive economic characteristics: high heat resistance, vertical type of placement of the flag leaf, low stem, high resistance to lodging, high grain quality and baking quality. However, there are some negative signs, such as low grain mass from the main ear and a thousand kernel weight, high ear density, fine grain.

Crossing hexaploid common wheat with durum wheat, which also belongs to the group of hexaploid wheats, makes it possible to obtain fertile offspring, etc. Since this group of crosses (*Triticum aestivum* L. × *Triticum sphaerococcum* Perc. and *Triticum sphaerococcum* Perc. × *Triticum aestivum* L.) is characterized by normal seed setting by hybrid plants, as viable gametes are formed during normal chromosome conjugation in meiosis, the fusion of which produces a viable hybrid seed.

To obtain competitive forms with good grain and flour quality indicators based on the involvement of this species in crossbreeding, high-yielding common wheat samples with complex resistance to common pathogens were used as parental forms (Fig. 1).

Figure 1. *Parental and hybrid forms (varieties, lines) of winter wheat involved in crossing: 1. Donor Kyivskyi; 2. Nosivochka (L 59-95); 3. F_1(♀Donor Kyivskyi x ♂KS 22); 4. F_1 (♀Donor Kyivskyi x ♂KS 21); 5. Zoriana Nosivska; 6. L 41-95; 7. KS 14-05; 8. Donzorna (KS 5); 9. KS 21; 10. KS 22-04; 11. Ariivka*

Source: *photographed by the authors*

The Donor Kyivskyi round-grained wheat variety, as the mother form, was short (71.5-75.5 cm) and resistant to lodging (9 points), its ear is characterized as dense. Line KS 22-04, which is characterized by high strength of the stem near the second and upper internodes, increased weight of grain from the ear and a thousand kernel weight, high winter hardiness (9 points), high resistance to lodging (9 points), high resistance to pathogens of brown rust, root rot and powdery mildew (9 points) was used in the cross-breeding as both the maternal and paternal forms.

The analysis of the crop structure suggests that the hybrids of the first generation of common wheat from round-grained wheat were represented by a low and strong stem, a medium or short ear, a spherical ear scale and a rounded grain. In the second-third generations, plants were selected that were mostly close to common wheat in terms of morphotype (shape, density, and length of the ear, number and weight and size of grain, thousand kernel weight, etc.) and were endowed with the characteristics of round-grained wheat (strength of the stem, vertical placement of the flag leaf, etc.).

The most vivid examples of the selected forms are selection number 0271/18 (Donor Kyivskyi × Ariivka), which forms an ear 11.8 cm long, white, pyramidal, spiny, while the spiny spikes are lobed, their length is 4.3-8 cm; the number of spikelets – 20-21 pcs., 4-6 grains per spike and up to 80 grains from the main spike, weighing up to 3.6 g (Table 3).

Table 3. *Indicators of comparative study of parental components and selected new breeding material*

Selection number	Name of the parent forms involved in crossing	Plant height, cm	Ear length, cm	Ear density***	Number of grains per ear, pcs.	Grain weight per ear, g	TKW, g
100/18	♀Donor Kyivskyi	71.5	6.5	26.5	41	1.63	38.7
101/18	♂KS 22-04*	88.5	9.3	17.5	52	2.37	51.2
0270/18	F_4 (♀Donor Kyivskyi × ♀KS 22)	90.3	8.4	14.8	45	1.85	46.8
0153/18/11	F_4(♀KS 22 × ♂Kyivskyi Donor)	80.2	9.8	16.6	57	2.28	49.4
0304/18	♂L 41-95*	83.5	7.6	18.5	65.7	2.17	50.6
0288/18	F_4(♀Donor Kyivskyi × ♂L 41-95)	69.7	6.7	20.3	58.5	1.76	48.5
0272/18/1	F_4(♀L 41-95 × ♂Donor Kyivskyi)	89.5	7.0	17.7	68.4	2.05	50.0
0272/18/2	F_4(♀L 41-95 × ♂Donor Kyivskyi)	77.5	7.5	18.0	60.5	2.31	52.6
103/18	♂L59-95*	85.8	7.9	18.4	45.6	2.11	50.5
0231/18	F_4(♀Donor Kyivskyi × ♂L 59-95)	80.2	8.3	16.5	47	2.30	51.1

Table 3, Continued

Selection number	Name of the parent forms involved in crossing	Plant height, cm	Ear length, cm	Ear density***	Number of grains per ear, pcs.	Grain weight per ear, g	TKW, g
104/18	♂Zoriana Nosivska	91.5	6.8	15.6	42	2.0	48.9
0230/18	F_4(♀Donor Kyivskyi × ♂Zoriana Nosivska)	78.5	6.4	19.6	39	1.89	44.8
0180/18	F_4(♀Zoriana Nosivska × ♂Donor Kyivskyi)	84.5	7.2	17.7	46	2.14	49.6
105/18	♂Ariivka* (a.c. 171136)	82.0	7.7	16.9	56	2.28	50.5
0271/18	F_4(♀Donor Kyivskyi × ♂Ariivka)	76.5	11.8	17.5	77	3.62	52.4
107/18	♂KS 14-05*	81.5	7.9	16.8	54	2.09	48.6
0227/18	F_4(♀Donor Kyivskyi × ♂KS 14)	76.3	7.5	18.5	44	1.88	46.4
0235/18/4	F_4(♀KS 14 × ♂Donor Kyivskyi)	85.7	8.6	15.9	56	2.45	53.5
109/18	♂KS 21	97.5	9.8	17.0	48	1.95	46.9
0233/18	F_4(♀Donor Kyivskyi × ♂KS 21)	86.5	8.2	19.4	53	2.22	48.2

Note: *the variety is erytrospermum; ** variety is spikatum; *** pieces of ears of corn/10 cm of spike rod length*
Source: *compiled by the authors*

Table 3 shows that individual selection numbers exceed the parental components in a number of features. Specifically, the numbers 0153/18/11, 0272/18/2, 0235/18/4 and 0233/18 exceed the number of grains from the main ear. Breeding numbers 0235/18/4, 0233/18 and others exceed the parents by the thousand kernel weight. Notably, the samples that substantially exceed the parental forms in terms of the length of the main ear were selected, namely, these are 0153/18/11, 0180/18, 0271/18, 0235/18/4, etc. Therewith, the combination of common wheat and round-grained wheat makes it possible to select samples with a lower ear density in the formation.

The degree of heterosis in the first generation helps predict the occurrence of transgressions in subsequent generations, which increases the efficiency of selecting samples with the desired traits in hybrid populations. In 2019, the degree of dominance and the degree of heterosis in the first generation were determined. The dominance and super-dominance of the mother component is established by the following characteristics: ear length, amount and mass of grain from the main ear. In terms of ear length, number and mass of grains in the ear, plants in the first generation exceeded one of the parent components. Therewith, the degree of phenotypic dominance was 1.14%, 1.63%, and 1.54%, respectively, which indicates positive over-dominance.

In the F_{2-3} generations, plants that were similar in phenotype to common wheat, but combined the characteristics of round-grained wheat, but also characterized by different stem heights (59.5-92.7 cm), as well as from spherical to the ovoid shape of the spikelet scale, rounded, oval, and ovoid grains, glabrous, semi-spinous, and spinous samples (Fig. 2).

Figure 2. *Formation in F_2 according to the ear of the hybrid combination Donor Kyivskyi × L 59-95: 1-3 – hybrids of the second generation*
Source: *photographed by the authors*

From one of the best combinations, it was possible to get hybrid forms, namely 0153/18/1, 0153/18/62, 0153/18/18, 0153/18/33, which inherited from the pollinator a strong stem of the semi-dwarf type, vertical placement of the flag leaf. The formation of common wheat and spherical wheat during hybridization helped select forms with gray and dark green colours of the ground part, with an increased number and mass of grains from the main ear, and different grain shapes (Table 4). Through interspecific hybridization, forms with increased productive bushiness were selected, namely, selection number 0153/18/11 (Fig. 3). Hybrid forms of the donor KS 22 combination are also characterized by a different ear morphotype (Fig.4). It is worth noting that the new forms of the above combination are characterized by increased resistance to fungal diseases, namely powdery mildew and fusarium head blight, as well as resistance to grain shedding and lodging (Table 5).

***Table 4**. Indicators of comparative study of parental components and selected new breeding material*

Variety/hybrid name	Plant height, cm	Ear length, cm	Ear density	Number of grains from the main ear, pcs.	Mass of grain from the main ear, g	Grain shape
♀Winter common wheat KS 22-04	88.5	9.3	17.5*	52	2.23	ovoid
♂Winter round-grained wheat Donor Kyivskyi	67.9	6.5	26.5	41	1.63	rounded
$F_4$0153/18/1	60.9	6.7	21.5	48	1.71	rounded
$F_4$0153/18/11	80.2	9.8	16.6	57	2.28	oval
$F_4$0153/18/62	62.6	8.8	16.2	54	2.42	ovoid
$F_4$0153/18/18	65.5	7.3	20.5	47	1.72	ovoid
$F_4$0153/18/7	89.5	8.2	18.7	44	1.85	oval
$F_4$0153/18/81	92.7	6.9	25.6	43	1.56	rounded
$F_4$0153/18/33	79.5	9.1	17.2	49	1.94	ovoid

***Note**: *17-22 – ear of medium density; 23-28 – dense ear*
***Source**: compiled by the authors*

***Figure 3**. Crossbreeding scheme: ♀KS 22-04 × ♂Donor Kyivskyi, selection in the first-third generations and the result of selection in the fourth generation ($F_4$0153/18/11)*
***Source**: photographed by the authors*

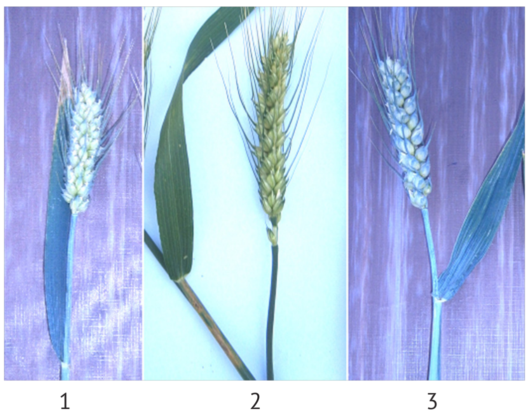

***Figure 4**. Comparison of the parent forms with the original hybrid form according to the characteristics of the main ear: 1 – round-grained wheat of the Donor Kyivskyi variety; 2 – common wheat of the KS 22 line; 3 – F_4 (Donor Kyivskyi × KS 22)*
***Source**: photographed by the authors*

***Table 5**. Results of field studies of indicators of economic suitability of new hybrid forms in comparison with parent components*

Variety/hybrid name	Resistance to adverse abiotic and biotic factors, score						
	lodging	abscission	droughts	powdery mildew	brown rust	fusariosis	winter hardiness
♀Winter common wheat KS 22-04 (UA0108013)	8	9	8	7	8	8	9
♂Winter round-grained wheat Donor Kyivskyi	8	9	7	8	8	9	8
F_4 0153/18/1	8	8	8	8	8	9	9
F_4 0153/18/11	8	9	8	8	8	9	9
F_4 0153/18/62	8	9	8	8	8	8	9
F_4 0153/18/18	8	9	8	8	8	9	9
F_4 0153/18/7	8	9	8	8	8	9	9
F_4 0153/18/81	8	9	7	8	8	8	8
F_4 0153/18/33	8	9	7	8	8	8	8

***Source**: compiled by the authors*

It was found that through interspecies hybridization of winter common wheat and round-grained wheat, both through direct crossing and backcrossing, it is possible to increase the content of protein and gluten in new forms (Fig. 5) and to improve the properties of the dough, namely elasticity, extensibility, and gas retention ability of the dough, which positively affected the baking characteristics (Fig. 6).

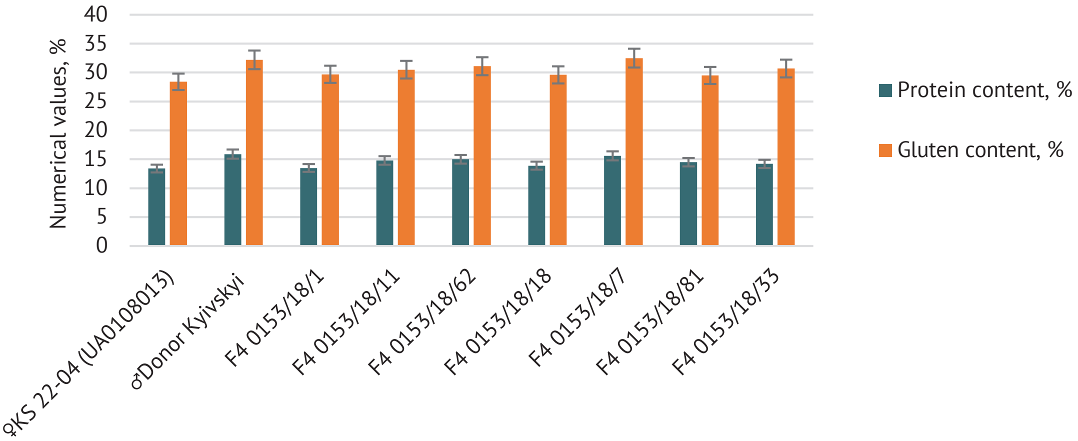

***Figure 5**. Protein and gluten content in new wheat samples compared to parental components*
***Source**: compiled by the authors*

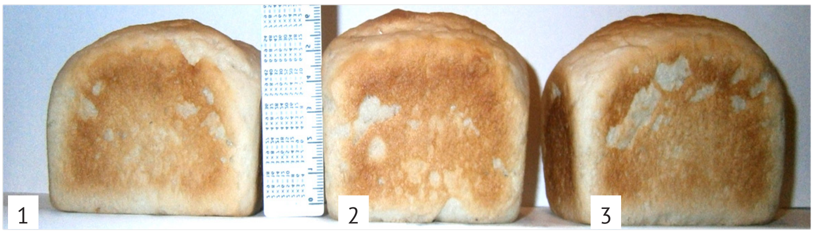

***Figure 6**. Comparison of loaves from the flour of the parent components and the hybrid form $F_4$0153/18/11: 1 – winter common wheat line KS 22-04; 2 – winter round-grained wheat of the Donor Kyivskyi variety; 3 – hybrid form $F_4$0153/18/11*
***Source**: photographed by the authors*

For the second group of crosses, species of the same genus, with a slightly different genomic composition, were selected: ♀*Triticum aestivum* L. (genomic formula AABBDD) and ♂*Triticum aethiopicum* Jakubz. var. *decoloratum* (Vavilov) Filat. (genomic formula AABB), but with the same A and B genomes, and therefore in hybrid populations, plants with an intermediate number of chromosomes will be gradually eliminated, and in the end, only two groups of plants will remain, approaching the original species in terms of phenotype.

The use of Ethiopian wheat as a pollinator had certain difficulties. Firstly, Ethiopian wheat is of a spring type of development, and to use it as a pollinator as best as possible, the mother form was subjected to vernalization and sown in the spring. This made it possible to obtain conditioned parent components for crossing. Second, Ethiopian wheat was sown in the fall at different times (midterm – September 30, late – October 15, and very late – November 10). The following growing year, the best ones were selected from the surviving Ethiopian wheat plants for further use in hybridization as pollinators. In such crossings, there is a significant part of homologous chromosomes. In F1 hybrids, during meiosis, many fertile gametes of parental species with 14 and 24 chromosomes are formed, which, during fusion, give rise to the formation of 28- and 42-chromosome parent species of wheat with stable heredity. Therewith, a fairly high percentage of seed set (⩾48%) and field similarity of 23=65% was noted, depending on the combination of crossing. In subsequent generations, among the main mass of plants, hybrid variability was already observed in the group of hexaploid and tetraploid wheat species, which increased with each generation. Part of the plants in F_2 and F_3 retained F_1 traits, which sharply decrease in subsequent hybrid generations. In this group of hybrids, recombinations were noted according to genetic morphological features and physiological and biochemical properties. For example, increasing the winter hardiness of plants morphologically similar to Ethiopian wheat, acquired from common winter wheat, a change towards decreasing grain mass from the main ear, the brown colour of the grain of common wheat to dark brown and purple through the expression of genes in Ethiopian wheat, etc.

Thus, the type of crossing of wheat species with different numbers of chromosomes is *T. aestivum* × *T. aethiopicum* var. *decoloratum* is accompanied by splitting and a relatively quick return of the hybrid offspring to the original parental species in terms of morphogenetic structure. For instance, in some hybrids of hexaploid wheat (*T. aestivum*) with tetraploid wheat (*T. aeth.* var. *decoloratum*), 42- and 28-chromosomal wheats with a stable species constitution of the parental species, but not the original varieties, were isolated already in F_2. In the F_3 and F_4 generations, the highest level of the shape-forming process was noted, while a significant range of variability was noted for several morphological signs and physiological properties: plant height; the length, shape, density, colour and grain size of the ear; the degree of manifestation of thorniness; the colour and placement of the flag leaf, the shape, mass and colour of the grains; the colour of spike scales, the duration of the growing season and winter hardiness of plants. Specifically, the forming process was dominated by samples with a loose, mostly spindle-shaped ear, oval in cross-section, while both spiny and semi-spiny forms, which had a light threshing, were selected. We also selected plants with a weak wax coating, a long ear (about 9 cm), spines with long and thin, almost parallel spikelets, with a clear sharp keel tooth on the spikelet scale, elongated-oval, purple, rarely dark brown grain, which was inherent in the paternal form, and with such features as a thickened stem, high grain size, average density of the ear, increased mass of grains from the main ear and plant, etc., which are more inherent in the maternal form.

Below are breeding samples that substantially exceed their parent forms in terms of economic characteristics. One of the interesting forms is selection number 0260/18 (*T. aethiopicum* var. *decoloratum* × Pekabe). The height of the plant exceeds 98 cm, the ear is white, spiny, 11.2 cm long, the lobes are 3.5-8 cm long, it contains 21 ears. Keel to the base, the shoulder is narrow or very narrow and bevelled, the tooth is straight up to 5 mm. The shape of the grain is oval or elongated-ovoid, the colour is dark brown with fragments of purple, the groove is of medium depth, the hair is short. The number of grains from an ear is 62 pcs., the weight of grains from an ear is 3.18 g, the thousand kernel weight is 52.0 g (Table 6).

***Table 6**. Indicators of comparative study of parental components and selected new breeding material*

Variety/hybrid name	Plant height, cm	Productive bushiness, pcs.	Ear length, cm	Number of grains from the main ear, pcs.	Mass of grain from the main ear, g	TKW, g	Grain colour	Winter hardiness, points
♀*T. aethiopicum*var. *decoloratum*	85.7	1.8	8.2	27.2	1.12	36.8	purple	3.1
♀Winter common wheat Pekabe variety	99.5	2.4	9.3	52.1	2.23	44.6	brown	8.8
0260/18	98.2	2.6	11.2	62.0	3.18	52.0	dark brown	6.5
0266/18 (T. aethiop. var. *decolor.* × Donor Kyivskyi)	86.5	2.1	7.1	54	2.19	40.8	brown	5.5
0262/18 (*T. aethiop.*var. *decolor.* × L 41-95)	88.3	3.5	10.8	61	2.48	50.4	brown	6.0
0143/18 (L 59-95 × *T. aethiop.* var. *decolor.*)	108.5	2.4	11.1	49	1.9	54.4	purple	6.3

***Source**: compiled by the authors*

Another selection number 0266/18 (*T. aethiopicum* var. *decoloratum* x Donor Kyivskyi), which in economic terms substantially ($p>0.05$) exceeds the parent forms. The specimen forms plants with a height of 86.5 cm, white, prismatic, 7.1 cm long, semi-spiny ear, and the length of the spikelets is 3-3.6 cm; scales are ovoid-rounded, the number of spikelets is about 19 pcs., the keel is clear, the tooth is bent, 1 mm long, the shoulder is short, narrow and bevelled. The seeds are brown, round-oval, the hair is medium, the groove is not deep. Number of seeds – 54 pcs., weight – 2.19 g, thousand kernel weight – 40.8 g. Sample 0262/18 (*T. aethiop.* var. *decolor.* × L 41-95) is 88.3 cm tall, has a white, spiny spike, 10.8 cm long spike, 5.3-7.7 cm long spikes, contains 22 ears. The keel of the spikelet scale is distinct, the shoulder is medium, straight with a hump, the tooth is straight up to 10 mm long. The seeds are dark brown with a purple tint, elongated-ovoid in shape, 7-9 mm long, the hair is medium, the groove is not deep. The number of grains from an ear is 61, the weight of grains from an ear is 3.48 g, the TKW is 60.4 g (Fig. 7).

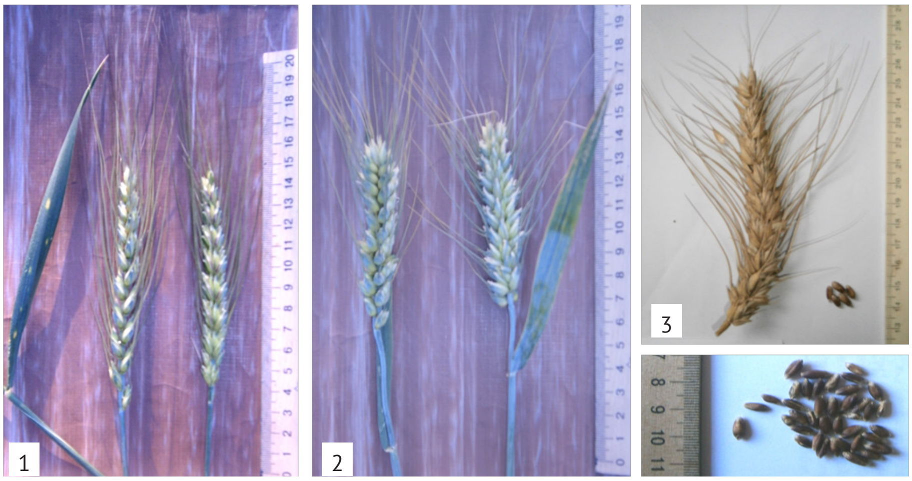

Figure 7. *Comparison of parental components and hybrid forms by ear: 1. ♀Triticum aethiopicum var. decoloratum (Vavilov) Filat.; 2. ♂ winter common wheat variety L 41-95; 3.* F_4*0262/18 (Triticum aethiopicum var. decoloratum (Vavilov) Filat. × L 41-95)*

Source*: photographed by the authors*

Sample 0143/18 (L 59-95 × *T. aethiopicum* var. *decoloratum*) forms productive plants 108 cm tall, while the spike length is over 11 cm. The spikelet is white, pyramidal, spiny, spikelets 3.7-9 cm long, contains 22 spikelets. The keel is clear, the tooth is straight, 4 mm long, the shoulder is narrow and straight. The sample is characterized by anthocyanin on the stem under the ear. The seeds are brown, elongated-ovoid, wrinkled. The number of grains from the main ear is 49 pcs., the mass from the main ear is 1.82 g, the TKW is 54.4 g. The length of the upper internode is 14 cm (Fig. 8).

Figure 8. *Comparison of parental components and hybrid forms by ear: 1.♀Triticum aethiopicum var. decoloratum (Vavilov) Filat.; 2. ♂ winter common wheat variety Nosivochka (L 59/95); 3.* F_1*0143/18; 4.* F_4*0143/18 (L 59-95 × T. aethiop.var. decolor.)*

Source*: photographed by the authors*

Notably, one of the disadvantages of the above-mentioned hybrids is low complex resistance to all adverse abiotic factors in the winter and early spring periods, such as sharp temperature drops, long thaws, i.e., the winter hardiness of winter-spring hybrids did not exceed 6 points, which is determined by the strong influence of the spring component, which was taken in simple crosses as a pollinator. This fact is confirmed by the research of scientists of the V.M. Remeslo Myronivka Institute of Wheat of the National Academy of Sciences of Ukraine (Vlasenko *et al.*, 2012).

In this regard, selection numbers 0260/18, 0266/18, 0262/18, 0143/18, which are superior in terms of economic characteristics, are involved in hybridization with common wheat samples characterized by increased winter and frost resistance. It was possible to expand the forming process of obtaining winter-resistant and samples with purple grain due to the involvement of the Chornobrova winter wheat variety in the crossbreeding.

DISCUSSION

According to the international organization IGC (2021), hexaploid bread wheat (*Triticum aestivum* L., 2 n=6 x=42, BBAuAuDD) accounts for about 90% of wheat production in the world. Researchers (Kopecky *et al.*, 2022) note that the genetic diversity of cultivated wheat is narrowing and increasingly becoming unsatisfactory in resistance to new pathogenic races and adverse environmental factors. Therefore, in the breeding of common wheat, the diversity of wheat species is a rich source of useful genes that can expand the shaping process and provide new forms with high nutritional quality and resistance to adverse abiotic and biotic factors. J. Zhou *et al.* (2022) note that such breeding approaches help introduce valuable genes from distant species into cultivated species, and are an important driving force for their improvement. In this context, the selection of wheat varieties with better resistance to biotic and abiotic stresses is crucial and, therefore, as J. Laugerotte *et al.* (2022) state, is a priority for agriculture.

The analysis of data on the quality of grain of round-grained wheat and common wheat hybrids indicates an increased content of protein and gluten, compared to the parental form. This is also noted by J.B. Alvarez *et al.* (2017) based on the results of an analogous research on interspecies hybridization regarding the improvement of grain quality in new forms of wheat. S. Michel *et al.* (2018) are convinced that in this way it is possible not only to influence the quality indicators of the grain, but also to improve the baking quality of bread wheat. This is also noted in the research. However, I.I. Motsnyi *et al.* (2019), based on the results of research, demonstrated that the increase in the protein content of the grain, which is observed in distant crossings, is not always associated with an improvement in the quality of flour.

Biologist, geneticist (Hughes, 2020) claims that the yield of flour from hemispherical grains was higher in hybrids obtained by crossing common wheat and round-grained wheat than in hybrids with more elongated grains. W. Hughes (2020) also notes that the localization of the *s* gene, which is considered responsible for the sphericity of the grains, was investigated in the hybrids created by interspecies hybridization, but this question is open. This is noted by Salina *et al.* (2000), who mapped the *S*1, *S*2, and *S*3 genes of an induced spherococcal mutation in common wheat (*Triticum aestivum*) using the resulting F_2 hybrid populations that were obtained with the participation of round-grained wheat. And considering this difference, W. Hughes (2020) identified the gene Tasg-D1, which is responsible for the round grain phenotype, and allows directing the future selection or genetic engineering of round-grained wheat varieties, with the purpose of obtaining high-yielding forms of wheat with increased flour yield. Scientists (Cheng *et al.*, 2020) isolated the Tasg D1 gene (Ta – *Triticum aestivum*; sg – hemispherical grain; D1 – the first sg gene identified in the D genome) in round-grained wheat, which is responsible for the spherical or spheroid shape of the grain. Previous studies by the above authors were also based on hybridization of *T. aestivum* with *T. sphaerococcum*, where they observed complete dominance of *T. aestivum* over *T. sphaerococcum*, indicating that the inheritance of *T. sphaerococcum* is controlled by a single pleiotropic gene. The scientists noted the expression of the discovered TaSG-D1 gene in various plant tissues, specifically, it was clearly expressed in the meristem of the shoot, roots, ear, grain, stem, and ovary tissue. Therefore, based on the above, the effect of Tasg-D1 on plant architecture associated with the *s* locus is pleiotropic. As noted by *Vlasenko et al.* (2012), the corresponding cleavage ratio corresponded to H. Mendel's model – 3:1 (plants with elongated grains/plants with hemispherical grains), indicating that the trait of hemispherical grains is controlled by a single nuclear gene, which is consistent with previous findings that the Tasg-D1 gene homologue in the A genome contributes to the development of hemispherical grain.

Most researchers (Osmachko *et al.*, 2020; Motsnyi *et al.*, 2021) note that as a result of introgressive hybridization, i.e., in genetics, it is the transfer of a gene from one species to the gene pool of another through repeated backcrossing of an interspecies hybrid with one of the parent species, it is possible to create valuable raw material for use in wheat improvement programs both in terms of quality and resistance to a complex of pathogens.

Breeding work with Ethiopian wheat made it possible to obtain valuable lines characterized by disease resistance, dark brown and purple grain colour, but with medium and weak winter hardiness. Interspecific hybridization between hexaploid and tetraploid wheat species leads to the development of pentaploid F1 hybrids with a unique chromosomal structure. But the hybrids obtained by crossing common wheat (*Triticum aestivum* L.) and Ethiopian wheat (*Triticum aethiopicum*) can improve the genetic origin of either parent through the transfer of interesting traits in further selection. Genetic variability derived from the two wheat species and transferred to pentaploid hybrids has the potential to improve disease resistance, abiotic tolerance and grain quality, as well as to improve agronomic traits. Therefore, as noted by S. Padmanaban *et al.* (2017), interploid hybridization can be a promising tool for the development of wheat genotypes that can have high productive and adaptive potential under changing climatic conditions. To obtain hybrids with increased winter resistance and purple and high-quality grain, the Chornobrova variety was used in the hybridization. According to Zhygunov *et al.* (2018), from the grain of common wheat of the Chornobrova variety, the yield of varietal flour exceeds 67%, which is 7% higher, and the yield of bran is 32.5%, which is 15% less than that of the best Kuialnyk variety. Therewith, the Chornobrova variety has even higher indicators of flour strength, indices of stretchability and elasticity of the dough, the yield of groats, compared to the above-mentioned variety. Other researchers (Homichak *et al.*, 2018) note that it is possible to obtain modified flour from the grain of the Chornobrova common wheat variety. As noted by G.M. Hospodarenko *et al.* (2021), winter common wheat wheat of the Chornobrova variety is promising for obtaining new types of modified wheat flour with changed technological parameters. Additionally, the grain of the common wheat variety Chornobrova has an increased content of essential amino acids. The following scientists, authors of the Chornobrova variety (Rybalka *et al.*, 2018) also claim that the Chornobrova variety is also gaining popularity in technologies for the production of nutritionally useful bread from sprouted grain (without flour and yeast) and healing juice from green 8-9-day sprouts. Therefore, the Chornobrova variety is also recommended to be used in breeding programs to create new varieties of winter common wheat, since modern breeding programs require constant enrichment with new genetic plasma and this is a condition without which progress in breeding is impossible.

Summarizing the above, as a result of interspecies hybridization, it is possible to obtain new forms of common wheat with desirable economic characteristics for further selection and crossings to obtain constant lines with increased productivity and quality for further breeding.

CONCLUSIONS

According to the results of interspecies hybridization, it was possible to expand the form-making process of obtaining hybrid populations and select the best forms of wheat with desired economic characteristics such as productivity and quality.

With the participation of selected types of wheat *T. aethiopicum* var. *decoloratum* and *Triticum sphaerococcum* Perc., new semi-dwarf (up to 85 cm tall) and short (over 85-105 cm tall) forms of winter wheat with purple grain, high resistance to lodging, and prominent protein content were created. The scientific provisions regarding the effectiveness of involving in the selection process of common wheat the related species of wheat – *T. aethiopicum* var. *decoloratum* and *Triticum sphaerococcum* Perc. – found further development.

The hybrid forms of the parent forms – common wheat x round-grained wheat are characterized mostly by a strong stem, short and semi-dwarf type, loose or medium-density ears, rounded spike scales and grains. Furthermore, the forms of the above combination are characterized by increased resistance to fungal diseases, in particular powdery mildew and fusarium head blight, as well as resistance to grain shedding and lodging.

Through the hybridization of winter common wheat and Ethiopian wheat, it was possible to form and select the best selection numbers 0260/18, 0266/18, 0262/18, 0143/18, which differ from the parental forms in the length of the ear, the number and mass of grains from the main ear, thousand kernel weight, increased drought resistance. Their lower winter hardiness compared to winter common wheat prompted to continue the selection work with them and involve them in hybridization with more winter- and frost-resistant varieties (lines). Specifically, this was achieved due to the involvement of the Chornobrova winter wheat variety in the crossbreeding, which helped obtain from combinations (L 59-95 × *Triticum aethiopicum* var. *decoloratum* (Vavilov) Filat.) × Chornobrova; *Triticum aethiopicum* var. *decoloratum* (Vavilov) Filat.× L 41-95) × Chornobrova; Chornobrova × (*Triticum aethiopicum* var. *decoloratum* (Vavilov) Filat.× L 41-95) winter-hardy hybrid forms with purple and dark brown grains. A promising direction of further research is the involvement of new forms of winter common wheat in the breeding process to create adaptive, high-yielding varieties with high grain quality.

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CONFLICT OF INTEREST

None.

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Розширення формотворчого процесу в селекції пшениці м'якої озимої на продуктивність і якість шляхом використання генофонду споріднених видів пшениць у рамках продовольчої безпеки

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Анотація. Розширено формотворчий процес у селекції пшениці м'якої озимої на продуктивність і якість шляхом використання генофонду споріднених видів. Метою досліджень було розширити формотворчий процес в селекції *Triticum aestivum* L. озимого типу розвитку з подальшим отриманням генотипів з підвищеною адаптивністю, продуктивністю рослин і якістю зерна за рахунок використання в гібридизації пшениці м'якої озимої з фіолетовим зерном, пшениці шарозерної і пшениці ефіопської. В роботі використані методики проведення експертизи сортів рослин з проведення фенологічних спостережень, морфологічних досліджень, оцінки селекційного матеріалу за господарсько-цінними ознаками. В створенні нових форм використані методи гібридизації і індивідуального добору, щодо запилення – твел-метод. Вміст білка, клейковини визначали методом інфрачервоної спектрометрії. Вивчено і підібрано батьківські компоненти, щоб розширити формотворчий процес з отримання продуктивних за кількістю і масою зерен з головного колосу, масою 1000 зерен, високою якістю зерна, стійких до вилягання, обсипання зерна, посухостійких і резистентних до збудників грибних хвороб гібридні форми, зокрема у результаті залучення до гібридизації вихідного матеріалу *Triticum aestivum* L. і *Triticum sphaerococcum* Perc. За результатами гібридизації пшениці м'якої озимої і пшениці ефіопської вдалося отримати і добрати в F_4 форми з довгим колосом (>10-11 см), підвищеною кількістю зерна з головного колоса (>55 шт.) і різним забарвленням зерна від темно-коричневого до фіолетового, як показника підвищеного вмісту антоціану та високої антиоксидантної здатності. Практична цінність роботи полягає в тому, що результати досліджень розширюють відомості про використання в селекції пшениці м'якої озимої на продуктивність і якість інших видів пшениць: *Triticum sphaerococcum*, T. aethiop. var. *decoloratum*, а розроблені пропозиції дозволять узяти до уваги використанні в дослідженнях батьківські компоненти пшениці, покращити способи проведення гібридизації та добору нових форм з бажаними ознаками в системі міжвидових схрещувань

Ключові слова: *Triticum aestivum* L.; *Triticum sphaerococcum* Perc.; T. aethiopicum var. *decoloratum* Jakubz.; селекція на продуктивність і якість; міжвидова гібридизація; нові гібридні форми