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Combining ability of inbred maize lines in breeding for grain quality

Abstract. The selection of the initial material (inbred lines) and the assessment of its combining ability are key tasks in developing maize hybrids. This study aimed to select the initial material for the creation of heterotic maize hybrids with enhanced grain quality and yield. The article presented the results of research on eight lines bred by the Genetics, Breeding and Seed Production named after Prof. M.O. Zelensky at the National University of Life and Environmental Sciences of Ukraine (lines: AK157 and AK159), as well as lines obtained from the National Centre for Plant Genetic Resources

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of Ukraine (lines: HLG1203, VK19, VK32, AE800, AE746, UHK686, UHK37, CO255, FV243, Q170). Additionally, four tester lines carrying mutant endosperm structure genes were analysed (lines VK13 and VK69 carrying the *wx* mutant endosperm structure gene, and lines AE801 and AE392 carrying the *ae* mutant endosperm structure gene). To assess combining ability, crosses were performed using the incomplete topcross method, resulting in 24 experimental hybrids. Field trials were conducted in 2020-2021. The article presented the results of an assessment of the obtained hybrid combinations based on grain quality and yield indicators. The highest protein content during the study years was recorded in the combination VK13 × CO255; the highest starch content in VK13 × UHK686 and VK69 × FV243; the highest oil content in AE801 × AE746 and AE801 × VK19; and the highest yield in VK13 × UHK686 and AE801 × UHK37. The effects of general combining ability, constants, and variances of specific combining ability were determined for protein, starch, and oil content in the grain, as well as for yield. The findings indicated that lines VK19, AE800, CO255, FV243, Q170, VK13, and AE801 exhibited increased protein content in the grain; lines VK19, AE746, UHK686, CO255, VK13, and AE392 showed increased oil content; and lines AK157, UHK37, and AE746 demonstrated superior yield performance. Based on the results, specific inbred lines are recommended for developing maize hybrids with improved grain quality characteristics

Keywords: trait source; heterosis; inbred line; hybrid; topcross; quality indicators

INTRODUCTION

The chemical composition of maize grain can vary significantly depending on growing conditions. High temperatures promote more intensive protein accumulation. Late-maturing varieties contain more protein in their grain during dry years compared to years with sufficient moisture. However, the primary role in improving maize grain quality belongs to breeding, which highlights the relevance of studying the general and specific combining ability of inbred lines when creating hybrid maize varieties with improved grain quality traits. The sharp increase in market demand for specific types of maize, such as high-lysine, super-sweet, waxy, and high-amylose, determines the direction of work for breeding and genetic institutions to expand genetic diversity, identify genetic regulation systems, and identify reliable sources and donors of these traits, as noted by D. Tymchuk *et al.* (2020).

According to the evaluation of 140 cross combinations using a tester scheme with 5 testers and 28 inbred lines, H. Kustanto & F. Hendrayana (2023) note that selecting the right inbred lines as parental forms is a challenge in maize hybrid development. The chosen inbred lines should form a hybrid pair with excellent characteristics, such as high yield. In addition to limited genetic resources, maize hybrid breeding also requires a lot of time. To address this challenge, M. Ali *et al.* (2019) recommend analysing and evaluating the combining ability of inbred lines during their creation, starting from the third generation of self-pollination. Combining ability analysis is an invaluable tool for assessing the compatibility of maize inbred lines with testers. In the research of M. Alam *et al.* (2022), the focus was on determining combining ability for traits related to yield potential. As a result of the research, they concluded that combining ability analysis is essential for determining the interaction of inbred lines and testers not only in maize but also for all cross-pollinated crops, as it helps identify parental forms that can be used to create hybrids and synthetic populations.

Investigating inbred lines and maize hybrids with elevated levels of provitamin A and resistance to contrasting stresses, O. Oluwaseun *et al.* (2022) concluded that both additive and nonadditive gene actions are important for the inheritance of grain yield and other quantitative traits. However, additive gene action predominated over non-additive gene action. This supports the assertion that analysing the combining ability of different maize inbred lines is the most effective tool for developing programs to create and compare the performance of hybrids derived from inbred lines. Information about the combining ability of inbred lines in hybrid combinations is also crucial for the successful improvement of maize hybrids.

The research of G. Sprague & L. Tatum (1942) was fundamental to the breeding of heterotic hybrids, as it was the first to distinguish between general and specific combining abilities, laying the groundwork for further methodological advancements in evaluating initial breeding material. General combining ability is defined as the average performance of a parental form in a hybrid combination and is primarily attributed to the additive effects of genes. Specific combining ability describes instances where certain hybrid combinations perform relatively better or worse than expected based on the average performance of the parental forms and is considered an estimate of non-additive gene action, such as dominance and epistasis. T. Begna (2021) notes that combining ability analysis allows for the identification of parental forms with high general combining ability (GCA) and hybrid combinations with high specific combining ability (SCA) for the commercial exploitation of heterosis.

When creating hybrids, it is necessary to select an appropriate crossing scheme (Dokukina *et al*., 2021). Although several crossing models are used in plant breeding, they all have certain advantages and disadvantages. The most comprehensive and reliable is the diallel cross scheme. However, using this scheme for analysing a large number of inbred lines is very timeconsuming. In such cases, W. Mogesse *et al.* (2020) recommend using a tester cross scheme, which evaluates both general and specific combining ability and is widely used in research. All of the above highlights the need for the continuous search, creation, and evaluation of inbred lines with high protein, starch, oil content, and yield based on combining the ability to ensure food security and intensify agricultural production. The aim and objectives of this experiment were to determine the general and specific combining ability of maize inbred lines in an incomplete topcross system based on grain protein, starch, oil content, and yield.

MATERIALS AND METHODS

The study involved 24 experimental maize hybrids obtained through the crossing of lines L_1 (HLG 1203), L_2 (AK 157), L_3 (AK 159), L_4 (VK 19), L_5 (VK 32), L_6 (AE 800), L_7 (AE 746), L_8 (UHK 686), L_9 (UHK 37), L_{10} (CO 255), L_{11} (FV 243), and L_{12} (Q 170) with testers T_1 (VK 13) and T_2 (VK 69) (sources of the *wx* endosperm structure gene mutation), as well as T_3 (AE 801) and T_4 (AE 392) (sources of the *ae* endosperm structure gene mutation) (Table 1). The inbred lines used in the crosses were developed by the Genetics, Breeding and Seed Production named after Prof. M.O. Zelensky at the National University of Life and Environmental Sciences of Ukraine, as well as lines obtained from the National Centre for Plant Genetic Resources of Ukraine.

Table 1. Scheme of incomplete topcross hybridisation, 2020-2021

	T_1	T_2	T_3	T_4
L_1		+	+	
L_2	+			+
L_3		+	+	
L_4	+			+
L_5		+	+	
L_6	+			+
L_7		+	+	
L_8	+			+
L_9		+	+	
L_{10}	+			+
L_{11}		+	+	
L_{12}	+			+

Source: compiled by the authors

Field trials were conducted in 2020-2021 on experimental plots of the Genetics, Breeding and Seed Production named after Prof. M.O. Zelensky at the NULES of Ukraine, a separate subdivision of the NULES of Ukraine "Agronomic Research Station", located in the Bila Tserkva District of Kyiv Region, Ukraine. The soils of the experimental plots were typical, low-humus chernozems (Ridey *et al.*, 2009). During the 2020 growing season, which lasted from 29 April to 10 October, 501 mm of precipitation fell. During the 2021 growing season, which lasted from 12 April to 8 October, 430 mm of precipitation fell (Fig. 1). The groundwater table was at a depth of 1.5-2 m, so additional irrigation was not applied.

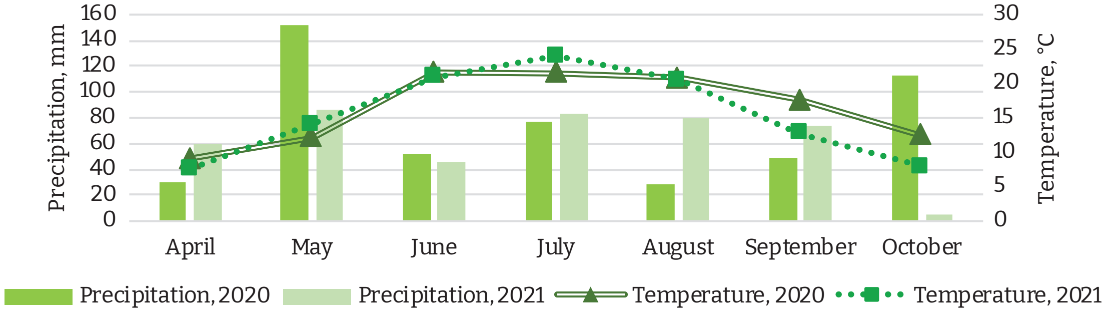

Figure 1. Average monthly precipitation (mm) and temperature (°C), 2020-2021
Source: developed by the authors based on data from Meteopost (n.d.)

Sowing was carried out at a stable soil temperature of 10-12°C at the sowing depth. The predecessor in all years of the study was winter soft wheat. Chemical plant protection products, mineral and organic fertilisers were not used. Weed control was performed using organotropic methods. Experimental plots were arranged according to a Randomized Complete Block Design (RCBD) with three replications. Plot units: two central rows of the experimental plot, 7 m long, with a row spacing of 70 cm and a plant spacing in the row of 17 cm. Phenological observations, grouping by the magnitude of the average manifestation of traits, and comparison with standard samples were performed according to the classifier-directory of the species *Zea mays* L. (Kyrychenko *et al.*, 2009)

The content of protein, starch, and oil in the grain was determined using a FOSS Infratec 1241 Grain Analyzer. For this purpose, 5 random cobs were taken from each experimental plot, dried in the laboratory, threshed manually, and cleaned of impurities on sieves. The content of protein, starch, and oil is indicated in terms of standard grain moisture (Tkachyk, 2016). The general (GCA) and specific (SCA) combining ability of the studied maize inbred lines were determined using the method of incomplete topcrosses (Sych *et al.*, 2004). Statistical data processing was carried out using Microsoft Excel 2016 in combination with XLSTAT. The error of statistical analysis $P < 0.05$. The research was conducted following the ethical standards of the Convention on Biological Diversity (1992) and the Convention on the Trade in Endangered Species of Wild Fauna and Flora (1973).

RESULTS AND DISCUSSION

Results of trials of experimental hybrids in 2020-2021 showed that the protein content in the grain varied from 7.99% to 13.57% in 2020 and from 7.64% to 12.57% in 2021. It was characteristic that the highest protein content in the grain in the years of the study was in the cross combination $T1 \times L_{10}$, indicating a significant influence of the genotype on the control of this trait. When improving the quality of maize grain, it should be taken into account that its main criteria for hybrids of different uses vary. X. Yu *et al.* (2015) draw attention to the need to identify sources and donors of traits for improved grain quality. In particular, J. BeMiller & R. Whistler (2009) note that for food-grade hybrids, they consider protein content and fatty acid composition of oil, while for feed purposes and processing into bioethanol, protein content, starch content, and its fractional composition are important. G. Mingramm *et al.* (2024) recommend using genetically contrasting parental forms in breeding programs to obtain high-yielding maize hybrids with improved grain quality traits.

Significant variability in grain starch content was observed, both when comparing genotypes and between years. The range of variation for this trait in 2020 was from 64.62% (combination $T_3 \times L_9$) to 73.51% (combination $T_1 \times L_8$); in 2021, it was from 64.24% (combinations $T_3 \times L_1$ and $T_3 \times L_7$) to 73.80% (combination $T_2 \times L_{11}$). The obtained data indicate the low suitability of forms T_3 and T_4 for creating maize hybrids with high starch content. The amplitude of variation in oil content in the grain of the studied combinations ranged from 3.61% (combination $T_2 \times L_3$) to 5.13% (combination $T_3 \times L_7$) in 2020; from 3.39% (combination $T_2 \times L_3$) to 6.43% (combination $T_3 \times L_4$). It should be noted that the highest stability was observed for the trait of oil content in the grain over the years of the study. The yield of the studied samples varied significantly among cross combinations and years of the study. In 2020, yield ranged from 2.82 t/ha in the combination $T_3 \times L_7$ to 8.74 t/ha in the combination $T_1 \times L_8$; in 2021, it ranged from 2.99 t/ha in the combination $T_4 \times L_4$ to 8.78 t/ha in the combination $T_3 \times L_9$ (Table 2). As noted in previous research by R. Spriazhka *et al.* (2022), a portion of combinations typically exhibit high values for several traits simultaneously. Y. Long *et al.* (2024) obtained similar results when studying valuable economic traits of maize. Based on the research of L. Shah *et al.* (2015), such combinations are recommended for inclusion in breeding programs.

Table 2. Protein, starch, oil content, and yield of experimental maize hybrids, 2020-2021

Combination		Grain content, %						Yield, t/ha	
		Protein		Starch		Oil			
		2020	2021	2020	2021	2020	2021	2020	2021
T_1	L_2	10.09	9.95	71.58	70.84	4.40	4.39	4.40	5.23
	L_4	11.21	11.13	64.86	70.34	4.93	5.01	4.01	4.87
	L_6	10.56	10.40	70.67	70.63	4.28	4.32	4.46	5.84
	L_8	8.30	7.64	73.51	71.63	5.01	5.13	8.74	6.52
	L_{10}	13.57	12.57	69.17	65.89	4.54	4.40	6.85	6.75
	L_{12}	10.46	10.94	67.67	68.99	4.17	4.23	4.72	4.56
T_2	L_1	8.27	8.39	70.51	68.09	4.78	5.02	5.52	4.22
	L_3	8.60	7.80	72.30	70.42	3.61	3.39	4.97	5.47
	L_5	8.61	8.46	71.97	69.50	3.85	4.15	5.92	5.46
	L_7	9.15	8.79	66.27	68.73	4.57	4.16	5.59	7.18
	L_9	8.53	8.87	71.26	69.60	3.89	3.77	8.19	6.73
	L_{11}	8.39	8.35	70.80	73.80	4.58	4.50	4.39	5.77
T_3	L_1	9.99	9.74	70.56	64.24	4.18	4.56	4.32	5.75
	L_3	10.21	9.25	69.21	66.79	4.16	3.97	5.53	5.75
	L_5	8.81	9.32	66.63	72.04	3.83	3.84	5.14	4.42
	L_7	11.02	11.51	66.69	64.24	5.13	5.14	2.82	3.18
	L_9	9.86	9.21	64.62	68.98	4.00	4.34	6.59	8.78
	L_{11}	11.62	10.74	67.14	69.60	4.67	4.23	6.27	6.09
T_4	L_2	9.73	10.07	67.68	68.85	5.08	4.99	6.55	5.90
	L_4	10.51	10.55	65.07	69.13	5.11	6.43	3.31	2.99
	L_6	10.42	10.72	69.79	65.34	4.30	4.43	3.75	3.72
	L_8	7.99	8.05	66.02	68.76	4.15	4.25	3.91	3.17
	L_{10}	10.41	11.19	68.27	67.73	4.80	5.06	4.65	3.70
	L_{12}	10.46	9.67	70.37	66.03	4.56	4.24	2.75	3.55

Source: developed by the authors

The results of the study revealed insignificant variability in protein and oil content in the grain over different years of the study. At the same time, a significant influence of year-to-year conditions on starch content in the grain and yield was observed, as evidenced by significant differences in these indicators in different years of the study.

Evaluation of the GCA effect of parental material based on grain quality and yield is a leading criterion in breeding work. It is important to note that combining ability, to some extent, depends on the location of the study and climatic conditions. S. Vasal (1998) notes that the correct selection of parental material for creating maize hybrids is a decisive factor in the effectiveness of the selection process, which was later confirmed by A. Karim *et al.* (2022). In the current study, positive, significantly significant, and stable GCA effects over the years for grain protein content were observed in lines L_4, L_6, L_{10}, and L_{12}. However, in 3 of the 4 mentioned lines, significantly negative GCA effects were recorded for yield. For the yield trait, significantly high GCA values were established for lines L_2 and L_9; however, line L_9 was characterised by a significantly negative GCA effect for grain protein content, indicating an inverse correlation between these traits ($r = -0.19$ in 2020 and $r = -0.21$ in 2021). In lines L_4 and L_{10}, in addition to high GCA values for protein content, a significantly positive GCA effect for oil content in the grain was also noted (Table 3).

Table 3. General combining ability effects of inbred lines for grain protein, starch, oil content, and yield, 2020-2021

Inbred line	Protein, %		Starch, %		Oil, %		Yield, t/ha	
	2020	2021	2020	2021	2020	2021	2020	2021
L_1	-0.74**	-0.66**	1.55	-2.59*	0.04	0.29**	-0.22*	-0.25*
L_2	0.04	0.29	0.65	1.09	0.30**	0.19*	0.34**	0.33**
L_3	-0.46*	-1.20**	1.77	-0.15	-0.56**	-0.82**	0.11	0.38**
L_4	0.99**	1.12**	-4.02**	0.98	0.58**	1.22**	-1.48**	-1.30**
L_5	-1.16**	-0.83**	1.82	2.01	-0.60**	-0.50**	0.39**	-0.29*
L_6	0.62**	0.84**	1.25	-0.77	-0.15*	-0.12	-1.03**	-0.45**
L_7	0.22	0.43*	-2.50*	-2.27*	0.41**	0.15	-0.93**	-0.05
L_8	-1.72**	-1.88**	0.78	1.44	0.14*	0.19*	1.19**	-0.39**
L_9	-0.67**	-0.68**	-1.04	0.53	-0.50**	-0.44**	2.25**	2.52**
L_{10}	2.12**	2.16**	-0.26	-1.95	0.23**	0.23**	0.61**	-0.01
L_{11}	0.14	-0.18	-0.01	2.94**	0.18*	-0.13	0.19	0.70**
L_{12}	0.59**	0.58**	0.04	-1.25	-0.08	-0.26**	-1.40**	-1.18**
SE_{dgi}	0.17	0.15	1.02	0.99	0.07	0.07	0.10	0.10
$LSD_{0.05}$	0.36	0.31	2.17	2.09	0.14	0.16	0.21	0.22
$LSD_{0.01}$	0.49	0.43	2.99	2.88	0.19	0.21	0.29	0.30

Note: * and ** indicate significance at 5% and 1% levels, respectively
Source: developed by the authors

Using the tester-cross scheme, M. Murtadha *et al.* (2018) noted a significant influence of testers on the formation of grain quality traits. Analysis of the GCA effect of testers showed that testers T_1 and T_3 had a stable, significantly high positive effect on grain protein content over the years. A stable significant trend towards increasing oil content in the grain was found in tester T_4, and for yield – in testers T_1 and T_2. It should be noted that no trend towards a decrease in any of the studied traits was recorded for tester T_1, which characterises the possibility of its wide use (Table 4). The effectiveness of breeding programs depends on the level of genetic variability inherent in inbred lines, testers, and their combining ability, as indicated in their research by M. Alam *et al.* (2024). Since the focus is on lines, testers, and cross combinations, the identified lines, testers, and combinations have a clear potential for strategic integration into breeding programs to create high-yielding maize hybrids with improved quality traits.

Table 4. General combining ability effects of testers for grain protein, starch, oil content, and yield, 2020-2021

Inbred line	Protein, %		Starch, %		Oil, %		Yield, t/ha	
	2020	2021	2020	2021	2020	2021	2020	2021
T_1	0.83**	0.72**	0.59	0.96	0.11**	0.08	0.39**	0.40**
T_2	-1.27**	-1.28**	1.53*	1.27*	-0.23**	-0.33**	0.62**	0.57**
T_3	0.39**	0.24**	-1.01*	-1.11*	-0.11**	-0.15**	-0.03	0.43**
T_4	0.05	0.32**	-1.12*	-1.12*	0.23**	0.40**	-0.99**	-1.40**
SE_{dgj}	0.09	0.08	0.53	0.51	0.03	0.04	0.05	0.05
$LSD_{0.05}$	0.19	0.16	1.13	1.09	0.07	0.08	0.11	0.11
$LSD_{0.01}$	0.26	0.23	1.56	1.51	0.10	0.11	0.15	0.16

Note: * and ** indicate significance at 5% and 1% levels, respectively
Source: developed by the authors

The values of SCA constants for grain protein content varied from -1.63 ($T_4 \times L_{10}$) to 1.23 ($T_3 \times L_{11}$) in 2020, and from -1.01 ($T_4 \times L_{10}$) to 1.12 ($T_3 \times L_7$) in 2021. A characteristic feature of the studied cross combinations is the relative stability of the SCA effect over the years of the study. Significantly high, positive, and stable SCA effects were recorded in crosses $T_2 \times L_5$, $T_2 \times L_9$, $T_3 \times L_7$, and $T_3 \times L_{11}$. High values of SCA variances, even with low or negative GCA values, indicate the possibility of obtaining individual highly heterozygous combinations involving such parental forms, as noted by O. Haydash (2016). Analysis of line variances (δ^2_{si}) compared to their mean ($\bar{x}\delta^2_{sj}$) indicates that lines L_{10} and L_{11} tend to increase protein content in the grain. The values of tester variances (δ^2_{si}) compared to their mean ($\bar{x}\delta^2_{sj}$) were inverse over the years of the study, suggesting a low impact of the testers used on the inheritance of grain protein content in maize (Table 5).

Table 5. Constants and variances of specific combining ability for grain protein content, 2020-2021

Combination of crosses	2020					2021				
	T_1	T_2	T_3	T_4	δ^2_{si}	T_1	T_2	T_3	T_4	δ^2_{si}
L_1		0.41	0.47		0.46		0.60	0.43		0.60
L_2	-0.65			-0.23	0.54	-0.78			-0.26	0.72
L_3		0.47	0.42		0.46		0.55	0.48		0.59
L_4	-0.48			-0.40	0.46	-0.43			-0.61	0.60
L_5		1.17	-0.29		1.52		0.85	0.19		0.80
L_6	-0.76			-0.12	0.66	-0.88			-0.16	0.84
L_7		0.34	0.55		0.48		-0.08	1.12		1.31
L_8	-0.68			-0.21	0.57	-0.92			-0.12	0.91
L_9		0.61	0.28		0.51		1.11	-0.07		1.28
L_{10}	0.75			-1.63	3.29	-0.03			-1.01	1.07
L_{11}		-0.34	1.23		1.69		0.08	0.95		0.97
L_{12}	-0.83			-0.05	0.76	-0.08			-0.96	0.97
δ^2_{sj}	0.54	0.42	0.42	0.54		0.44	0.49	0.49	0.44	
$LSD_{0.05}$	0.37					0.33				
$LSD_{0.01}$	0.52					0.45				
$\bar{x}\delta^2_{si}$	0.95					0.89				
$\bar{x}\delta^2_{sj}$	0.48					0.47				

Source: developed by the authors

Typically, the influence of the general combining ability of parental forms is also reflected in the specific combining ability for most traits studied, as noted by M. Matin *et al.* (2017). SCA consists of positive and negative values. H. Kustanto & F. Hendrayana (2023) determined that the results of the SCA effect analysis often demonstrate differences between observed crosses and traits. Inbred lines with significant positive GCA effects, when forming significantly positive SCA values, are recommended by D. Gurjar *et al.* (2022) not only for the creation of simple interline hybrids but also for developing new inbred lines through reciprocal recurrent selection.

A significantly high, positive SCA effect for grain starch content was established only in the combination of $T_1 \times L_8$ in 2020. In 2021, this combination was also characterised by a positive value of the SCA constant, but this excess was not significant. When evaluating the variances of the studied lines and testers, a stable, positive manifestation of the trait of increasing starch content in the grain was not detected (Table 6).

Table 6. Constants and variances of specific combining ability for grain starch content, 2020-2021

Combination of crosses	2020					2021				
	T_1	T_2	T_3	T_4	δ^2_{si}	T_1	T_2	T_3	T_4	δ^2_{si}
L_1		-1.56	1.03		5.78		0.66	-0.82		3.23
L_2	1.36			-0.83	4.82	0.03			0.12	2.14
L_3		0.01	-0.54		2.57		0.55	-0.71		2.93
L_4	-0.70			1.22	4.26	-0.36			0.51	2.52
L_5		-0.36	-0.16		2.44		-2.54	2.38		14.22
L_6	-0.15			0.68	2.76	1.68			-1.53	7.29
L_7		-1.74	1.22		6.81		0.98	-1.14		4.37
L_8	3.15			-2.63	19.12	0.47			-0.32	2.45
L_9		1.79	-2.31		10.81		-0.96	0.80		3.68
L_{10}	-0.14			0.67	2.75	-1.88			2.04	9.82
L_{11}		0.30	-0.82		3.04		0.83	-0.99		3.80
L_{12}	-1.94			2.47	12.14	0.52			-0.36	2.52
δ^2_{sj}	1.39	-0.05	-0.05	1.39		-0.30	0.25	0.25	-0.30	
$LSD_{0.05}$	2.26					2.19				
$LSD_{0.01}$	3.12					3.01				
$\bar{x}\ \delta^2_{si}$	6.44					4.91				
$\bar{x}\ \delta^2_{sj}$	0.67					-0.03				

Source: developed by the authors

For grain oil content in experimental maize hybrids, SCA constants varied from -0.66 to 0.53 in 2020 and from -0.84 to 0.64 in 2021. Stable, significantly positive SCA effects were recorded in combinations $T_1 \times L_8$, $T_2 \times L_1$, $T_2 \times L_5$, $T_3 \times L_3$, and $T_3 \times L_7$. Lines L_7 and L_8 were characterised by a significant and stable influence on grain oil content, according to variance analysis, with an excess over the mean of 0.01 and 0.38 in 2020 and 0.12 and 0.52 in 2021, respectively. Testers T_1 and T_4 were characterised by a stable influence on grain oil content, in contrast to grain protein and starch content, where the influence of testers was reversed over the years of the study (Table 7).

The highest differentiation of SCA constants over the years of the study was found for the yield trait, with a variation from -1.56 to 2.06 in 2020 and from -2.43 to 1.73 in 2021. However, combinations $T_1 \times L_8$, $T_1 \times L_{10}$, $T_2 \times L_7$, $T_4 \times L_2$, and $T_4 \times L_4$ were characterised by significantly high and stable positive SCA constants. According to the results of variance analysis, a significant stable influence on hybrid yield was observed when using lines L_2 and L_7 (Table 8).

Table 7. Constants and variances of specific combining ability for grain oil content, 2020-2021

Combination of crosses	2020					2021				
	T_1	T_2	T_3	T_4	δ^2_{si}	T_1	T_2	T_3	T_4	δ^2_{si}
L_1		0.53	-0.19		0.32		0.56	-0.08		0.33
L_2	-0.45			0.11	0.23	-0.38			-0.10	0.17
L_3		-0.05	0.39		0.16		0.04	0.44		0.21
L_4	-0.20			-0.14	0.07	-0.79			0.31	0.73
L_5		0.24	0.10		0.08		0.49	0.00		0.25
L_6	-0.12			-0.22	0.07	-0.14			-0.35	0.15
L_7		-0.05	0.39		0.17		-0.16	0.64		0.45
L_8	0.32			-0.66	0.54	0.36			-0.84	0.85
L_9		0.17	0.17		0.07		0.05	0.44		0.20
L_{10}	-0.24			-0.10	0.08	-0.41			-0.07	0.19
L_{11}		0.18	0.16		0.07		0.47	0.02		0.23
L_{12}	-0.31			-0.03	0.11	-0.09			-0.40	0.18
δ^2_{sj}	0.10	0.07	0.07	0.10		0.21	0.15	0.15	0.21	
$LSD_{0.05}$	0.15					0.16				
$LSD_{0.01}$	0.20					0.22				
$\bar{x}\ \delta^2_{si}$	0.16					0.33				
$\bar{x}\ \delta^2_{sj}$	0.08					0.18				

Source: developed by the authors

Table 8. Constants and variances of specific combining ability for yield, 2020-2021

Combination of crosses	2020					2021				
	T_1	T_2	T_3	T_4	δ^2_{si}	T_1	T_2	T_3	T_4	δ^2_{si}
L_1		-0.02	-0.57		0.35		-1.34	0.34		1.92
L_2	-1.47			2.06	6.42	-0.73			1.73	3.55
L_3		-0.90	0.31		0.93		-0.71	-0.29		0.61
L_4	-0.04			0.64	0.43	0.55			0.46	0.53
L_5		-0.23	-0.36		0.21		-0.05	-0.95		0.93
L_6	-0.04			0.63	0.42	0.67			0.34	0.58
L_7		0.76	-1.36		2.44		1.43	-2.43		7.96
L_8	2.02			-1.43	6.16	1.28			-0.28	1.74
L_9		0.18	-0.77		0.65		-1.60	0.60		2.93
L_{10}	0.71			-0.11	0.54	1.13			-0.13	1.32
L_{11}		-1.56	0.97		3.40		-0.73	-0.27		0.63
L_{12}	0.59			0.00	0.37	0.11			0.89	0.83
δ^2_{sj}	1.40	0.77	0.77	1.40		0.82	1.47	1.47	0.82	
$LSD_{0.05}$	0.22					0.23				
$LSD_{0.01}$	0.30					0.31				
$\bar{x}\ \delta^2_{si}$	1.86					1.96				
$\bar{x}\ \delta^2_{sj}$	1.09					1.14				

Source: developed by the authors

The results of the study demonstrate significant differentiation in general and specific combining ability for grain protein, starch, and oil content, and yield in the incomplete topcross mating system. A similar conclusion was reached by O. Makarchuk & V. Zhemoida (2009) in their research. Similarly to grain protein and starch content, tester variances for the yield trait were reversed over the years, indicating an unstable influence of testers on the formation of these traits.

CONCLUSIONS

Results of testing experimental hybrids revealed a significant impact of genotype on controlling the protein content trait in the grain of combination $T_1 \times L_{10}$. The highest starch content in the grain (over 73%) was recorded in combination with $T_1 \times L_8$ in 2020 and in combination with $T_2 \times L_{11}$ in 2021. A low suitability of inbred lines T_3 and T_4 for creating maize hybrids with high starch content was determined. A high oil content in the grain is characteristic of combinations $T_3 \times L_7$ and $T_3 \times L_4$. The highest stability for this trait was observed across the years of the study. A yield of over 8 t/ha was recorded in combination with $T_1 \times L_8$ in 2020 and $T_3 \times L_9$ in 2021. When selecting maize hybrids with improved quality traits and high heterosis, it is recommended to use parental forms (inbred lines) with significantly high, stable positive effects of general and specific combining ability over the years. The obtained data on GCA and SCA indicate that the selected samples are valuable sources of traits for improved grain quality and yield, specifically for protein content in the grain: lines L_4, L_6, L_{10}, L_{12}, T_1, and T_3 with stable significant high GCA effects; lines L_{10} and L_{11} – according to SCA variance analysis; for oil content in the grain: lines L_4, L_{10}, and T_4 with stable significant high GCA effects; lines L_7, L_8, T_1, and T_4 – according to SCA variance analysis; for yield: lines L_2, L_9, with high significant and stable GCA effects; lines L_2, L_7 – according to SCA variance analysis; for a complex of traits: lines L_4, and L_{10} – with stable significant high GCA effects for protein and oil content; line L_7 – according to SCA variance analysis for oil content and yield.

The exploitation of heterosis provides a significant increase in the yield of agricultural crops, which is the basis for global food security in the face of the ever-growing world population. In turn, determining the effects of the general and specific combining ability of maize inbred lines for a complex of valuable traits, including grain protein, starch, oil content, and yield, is the basis for creating hybrid varieties, which determines the prospects for further research in this direction.

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CONFLICT OF INTEREST

None.

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Комбінаційна здатність інбредного матеріалу кукурудзи при селекції на якість зерна

Анотація. Підбір вихідного матеріалу (інбредних ліній) та оцінка його комбінаційної здатності є ключовим завданням при створенні гібридів кукурудзи. Метою досліджень був підбір вихідного матеріалу для створення гетерозисних гібридів кукурудзи з підвищеними показниками якості зерна та урожайності. У статті представлено результати досліджень 8 ліній селекції кафедри генетики, селекції і насінництва ім. М.О. Зеленського Національного університету біоресурсів і природокористування України (лінії: АК157 та АК159), ліній, отриманих з Національного центру генетичних ресурсів рослин України (лінії: HLG1203, VK19, VK32, AE800, AE746, UHK686, UHK37, CO255, FV243, Q170), а також 4 ліній-тестерів – носіїв мутантних генів структури ендосперму (лінії VK13 та VK69 – носії мутантного гену структури ендосперму wx та лінії АЕ801 і АЕ392 – носії мутантного гену структури ендосперму ae). Для визначення комбінаційної здатності було проведено схрещування за методом неповних топкросів, за результатом яких отримано 24 експериментальних гібриди. Польові дослідження проводили у 2020-2021 роках. У статті наведено результати оцінки отриманих комбінацій схрещувань за показниками якості зерна та урожайності. Зокрема, найвищий вміст білка в роки досліджень зафіксовано у комбінації ВК13 × CO255; крохмалю – у комбінацій ВК13 × UHK686 та ВК69 × FV243; олії – AE801 × AE746 та AE801 × VK19; урожайність – у комбінацій ВК13 × UHK686 та AE801 × UHK37. Встановлено ефекти загальної комбінаційної здатності, константи і варіанси специфічної комбінаційної здатності за показниками вмісту у зерні білка, крохмалю, олії та урожайністю. Отримані дані свідчать, що лінії VK19, AE800, CO255, FV243, Q170, ВК13 та AE801 мали підвищений вміст білка у зерні; лінії VK19, AE746, UHK686, CO255, BK13 та AE392 – підвищений вміст олії; AK157, UHK37, AE746 були найкращими за урожайністю. За результатами досліджень рекомендовано інбредні лінії для створення гібридів кукурудзи з поліпшеними показниками якості зерна

Ключові слова: джерело ознаки; гетерозис; інбредна лінія; гібрид; топкрос; показники якості