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HETEROTIC EFFECTS OF SUGAR BEET (*BETA VULGARIS* L.) HYBRIDS FOR ROOT YIELD AND SUGAR CONTENT

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SUMMARY

Hybrids with heterotic effects manifest themselves with a significant enhancement in growth and productivity traits compared with their parental genotypes. However, inbreeding resulted in decreased heterosis. Researchers believe that a noteworthy increase in F_1 hybrids for economic and biological attributes is evident due to heterozygosity and overdominance of the corresponding genes of different parents combined in one genotype. The presented study sought to determine the heterotic effects of sugar beet hybrids for economically valuable traits and select the best parental lines with crossing potential for productivity. Five different sugar beet hybrids, analyzed during the crop seasons 2021 and 2022 for accurate and hypothetical heterosis and the degree of dominance in F_1 generation for economically valuable traits like productivity and sugar content, transpired at the LLP - Kazakh Research Institute of Agriculture and Plant Growing (KazRIAPG), Kazakhstan. The crossing of the sugar beet line KazMS with pollinators, viz., VP24, VP44, OP17231, OP17232, and OP14044, changed the type of inheritance in hybrids for productivity from negative dominance in variants with pollinators (VP24, OP17231) to overdominance in variants with pollinators (VP44, OP14044). Based on the results, the conclusion indicated that the type of productivity inheritance in F_1 hybrids involving the same maternal line differed.

Keywords: Sugar beet (*Beta vulgaris* L.), F_1 hybrids, heterotic effects, degree of dominance, crop productivity, sugar content, automated agricultural technologies

Key findings: The promising results may serve as a basis for developing a technological model to better manage sugar beet production at each specific stage of plant growth and development for various strengthening levels.

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INTRODUCTION

Heterosis is the property of hybrids obtained through crossing to surpass their parental genotypes for economically valuable parameters (Bogomolov and Vostrikova, 2022). Selecting sugar beet hybrids with significant heterosis over better parent and standard genotypes and determining the combination and crossing ability of the parental genotypes are the main tasks in the practical work of a plant breeder (Bogomolov, 2019).

The breeder's duties are constantly becoming more complicated, and the requirements for the characteristics of the base genetic material used in hybridization increase with time. A crucial requisite and selection of the source material for heterosis is the selection of parental genotypes based on hereditary factors that determine their ability to combine through hybridization (Kapustyan *et al.,* 2018). Vavilov (1966) also pointed out that the science in the study of varietal potential and its accurate assessment and use are primary selection factors. Evaluation of the crossing ability of the studied genotypes allows the researcher to predict the gain of future crossing and the cost of time and resources for obtaining the practical value (Savchenko, 1966).

The valuable traits owned by the original lines are the authentication of their manifestation in the hybrids, and it is necessary to evaluate the selection significance to recognize the genotypes with expression of high degree and desirable traits in crosses (Krivosheev and Ignatiev, 2015; Abekova *et al.,* 2022). The preliminary assessment of the combining ability of parental genotypes is an effective technique that allows concentrating attention on the base material, aside from having economically beneficial features (Ketthaisong *et al.,* 2014). Therefore, the success of hybridization results in correctly choosing the parental genotypes for a crossing program. The selection of parental pairs for crossing is one of the most challenging and crucial issues of practical choice. Its difficulty lies in the parental genotypes' traits indirectly transmitting to their offspring (Gulyaev and Dubinin, 1980).

In the present era, the main task of sugar beet breeding is developing highly productive hybrids based on CMS. The success of selection for the developed hybrids and the realization of beet productivity during harvest will depend upon the improved crossing of components, lines of sterility fixers (O-type), their male-sterile analogs (MS), and lines of multi-seeded pollinators (Balkov, 1978; Roik and Slivchenko, 2000; Volgin, 2007; Oshevnev *et al.,* 2009). Therefore, it is first necessary to develop lines of sterility fixers (O-type), their male-sterile analogs (MS), and stocks of multi-seeded pollinators, evaluate their genetic structure, and further crossbreed the best from them to obtain promising hybrids.

By crossing sterile types with multi-seeded fertile pollinators, complete hybridization of the fruitless component and obtaining heterotic effects in the generation needs guarantee. In first-generation hybrids, one of the advantages is that it is possible to implement the trait combinations that are difficult to manage during variety development (Kornienko *et al.,* 2007). In sugar beet, productivity, sugar content, and resistance to biotic and abiotic factors are the most focal parameters in Southeast Kazakhstan. The successful selection for developing sugar beet hybrids resistant to stress factors depends on the available gene sources and their preferences, the developed lines based on them, and the various selection techniques employed for creating high-yielding hybrids.

In sugar beet selection and development of new hybrids, one of the critical problems is having an adaptive complex of economically valuable traits capable of realizing the genetic potential inherent in them under adverse environmental conditions, with a minimal decline in productivity (Bastaubayeva *et al*., 2023). Concrete progress in sugar beet assortment these days is impractical without engaging advanced technology to develop the base material resistant to adverse environmental conditions (Zhuchenko, 2001; Maui *et al*., 2016). Establishing high-yielding hybrids with effective heterosis and a complex of handy traits is decisive. Past findings also revealed that the share of options in increasing the productivity of sugar beet reaches 30%–

40%, and the selection provides an increase in the yield of refined sugar by 0.17 t/ha in sugar beet (Shpaar *et al*., 2004). Zhuchenko (2001) states that the selection development was characteristic of qualitatively new requirements for varieties and hybrids and the process of their progress, variety testing, seed production, and their practical use.

In the advancement of base genetic material and lines, recently, the sugar beet hybrids obtained from utilizing CMs are widely applicable, in which with MS-forms and lines, the sterility fasteners play an essential role as multi-seeded pollinators. The LLP - Kazakh Research Institute of Agriculture and Plant Growing (KazRIAPG) conducts sugar beet breeding research in Kazakhstan. Eight hybrids of sugar beet selection at the KazRIAPG are allowed for use in the Republic of Kazakhstan; however, the research on hybrids' development is unique. Breeders use constant (homozygous) initial lines with high combining ability, which also causes inbreeding depression and reduced genetic variability, for obtaining hybrids. Currently, within the framework of the grant of the Ministry of Education and Culture of the Republic of Kazakhstan, research on developing sugar beet hybrids pushes through in KazRIAPG. The objective of the presented study was to evaluate the effect of sugar beet hybrids for economically valuable traits versus parental lines, with the best combining ability for productivity resulting in selecting the best crossing genotypes.

MATERIALS AND METHODS

Breeding material

The said research on sugar beet happened during the crop seasons 2021 and 2022 in the field using generally accepted methods at the LLP - Kazakh Research Institute of Agriculture and Plant Growing (KazRIAPG), Kazakhstan (Balkov, 1978; Dospekhov, 1985). The object of study was the lines used for developing hybrids as components of the KazRIAPG collection. The research material featured the samples obtained from FGBNU - All-Russian Research Institute of Sugar Beet and Sugar named after A.L. Mazlumov (Ramon, Russia), Institute of Bioenergy Cultures of Sugar Beet (Kiyev, Ukraine), in different crop seasons and sample selection of KazRIAPG.

Experimental conditions

Weather conditions during the research period had estimations from the hydrothermal coefficient (GTK) (Table 1), with calculations according to the formula of Selyaninov (1958). The plot was in a scientific station, and the predecessor was the winter wheat. The research method was laboratory-field. The hybrids testing in field conditions followed the basic variety testing in four replicates with a systematic placement of plots. The length of the parcel was 10 m, and the registered area was 15 m^2.

The combining ability determination of multi-seeded pollinators went on according to economically valuable traits (root yield and sugar content) in various variants of crossing with the MS form. The selection of the best hybrid combinations of sugar beet and, consequently, the choice of pairs of parental lines for effective crossing ensued according to the earlier-mentioned characteristics. Productivity and sugar content evaluation of the sugar beet lines proceeded by taking an average sample from the experimental plot. The research was according to standard methods (Savchenko, 1966; Boroevich, 1984). However, the reliability of the obtained data estimates used the formula of one-factor analysis of variance (Dospekhov, 1985).

True heterosis (H_i) characterizes a sturdy manifestation of the trait in F_1 compared with the best parental genotype. For evaluation and calculating the coefficients of true heterosis followed the methodology of Omarov (1975).

$$H_i = \frac{F_1 - P_{max}}{P_{max}} \text{ x } 100\%$$

Where:
F_1 = examined indicator in the hybrid
Pmax = an indicator of the best parent

Table 1. Meteorological data for the study period 2021–2022.

Research period	Sum of precipitation (mm)	Sum of active temperatures (°C)	Hydrothermal coefficient	Moisture supply
April-September 2021	211.7	2835	0.7	dry
April-September 2022	253.5	3907	0.6	dry
Average of growing season	232.6	3371	0.65	

Table 2. Phenotypic manifestation of the yield sign in MS-F_1 hybrids of sugar beet (based on the KazMS line).

Cross combinations	1st year			2nd year		
	Hp	Heterosis (%)		Hp	Heterosis (%)	
		True	Hypothetical		True	Hypothetical
F_1KazMS x VP24	-0.35	-6.79	-1.86	+11.59	+7.1	+7.82
F_1KazMS x VP44	+2.68	+7.68	+12.86	+26.79	+13.62	+14.22
F_1KazMS x OP17231	-2.33	-5.25	-3.73	+3.05	+4.27	+6.48
F_1KazMS x OP17232	+0.47	-2.26	+2.11	+5.89	+8.43	+10.33
F_1KazMS x OP14044	+7.30	+10.91	+12.86	+7.55	+16.74	+19.81

Hypothetical heterosis (H_h) was the superiority of the hybrid over the average characteristic of both parents, determined with the following formula:

$$H_h = \frac{F_1 - P_p}{P_p} \text{ x } 100\%$$

Where:
F_1 = examined indicator in the hybrid
P_p = is the average indicator between parental genotypes, i.e., (P1+P2)/2.

Determining the degree of phenotypic dominance (an indicator of inheritance of traits) in controlled crossings employed the Griffing method as follows (Savchenko, 1966; Griffing, 1956):

$$H_p = \frac{F_1 - P_p}{P_{max} - P_p};$$

Where:
H_p = the indicator of inheritance
Values of H_p can vary from -∞ to +∞. At $H_p < -1$ - indicates observing the hybrid depression; at $-1 \leq H_p \leq -0.5$ - the depression caused by the effects of negative dominance; at $-0.5 \leq H_p \leq +0.5$ - intermediate inheritance caused by additive effects of genes; $+0.5 \leq H_p \leq +1$ - the dominance, and $H_p > 1$ - was the superdominance (true heterosis).

RESULTS

F_1s heterotic effects for yield

In the process of sugar beet research, five hybrid combinations underwent analysis through true and hypothetical heterosis and the degree of dominance for productivity. Crossing the line KazMS with pollinators, VP24, VP44, OP17231, OP17232, and OP14044, changed the type of inheritance of the root yield in hybrids from negative dominance in the variants with pollinators (VP24, OP17231) to overdominance in the variants with pollinators (VP44, OP14044). Based on the results, it was possible to conclude that the inheritance type of productivity in hybrids with participation of F_1 of the same maternal line was different (Table 2).

One must note that the expression of true and hypothetical heterosis varies. For example, during the first year in the hybrid combination with the pollinator OP17232, the true and hypothetical heterotic values were 2.26% and 2.11%, respectively, with a degree of dominance of +0.47, which is an indicator of intermediate inheritance of this trait. However, in the second year, this hybrid combination showed the values of true and hypothetical heterosis of 8.43% and 10.33%, respectively, with a degree of dominance of +5.89, and such a trait showed overdominance.

A similar situation was visible in the variant with the pollinator VP24; the hybrid in the first year showed true (-6.79%) and hypothetical (-1.86%) heterosis values, with a degree of negative dominance of -0.35. Contrastingly, in the second year, positive true (7.1%) and hypothetical (7.82%) heterosis scores appeared, with a degree of dominance of +11.59, showing overdominance. It should also be notable that if the index of dominance assessment (H_p) was broad, the closer the true and hypothetical heterosis was. Thus, in the first year of the hybrid obtained from the crossing of line KazMS and pollinator OP14044, the dominance index for productivity was +7.3, and the true and hypothetical heterotic values were 10.91% and 12.86%, respectively. The hybrid obtained from the crossing with the same maternal line and the pollinator VP44 in the second year revealed true and hypothetical heterosis of 13.62% and 14.22%, respectively, and the dominance index was +26.79.

The values of true and hypothetical heterosis were contradictory in the different years of testing and the same hybrids. The hybrid with pollinator OP17232 showed positive superdominance in the second year, and in contrast to the first year, it had a dominance and intermediate type of inheritance. In other hybrids with pollinators VP24 and OP17231, on the contrary, negative superiority occurred in the first year, while in the second, the assessment provided positive overdominance.

F_1s heterotic effects for sugar content

In this sugar beet research, the said five hybrids also attained an analysis of true and hypothetical heterosis and the degree of dominance for sugar content. In hybrid combinations, the control varied from negative to overdominance for the sugar content. Unequal manifestation of the true and hypothetical heterosis values and assessment of dominance over the years of testing were also characteristic signs of sugar content. In variants, the hybrid combinations with pollinators VP24 and OP17232 showed intermediate inheritance during the first year, while negative heterosis in the second year (Table 3).

The hybrid combination with pollinators VP44 and OP14044 had an overdominance score (4.41 and 23.0) for sugar content. The values of true heterosis by years of testing varied from 0.87 to 0.96 and 0.5 to 1.31 for the above cross combinations. However, the rates of hypothetical heterosis fluctuated from 0.91 to 1.25 and 1.48 to 1.56, respectively, for the said trait. Based on the sugar content, it was also noteworthy that the greater the degree of dominance, the closer the indicators of true and hypothetical heterosis.

Table 3. Phenotypic manifestation of the sugar content sign in MS-F_1 hybrids of sugar beet (based on the KazMS line).

Cross combinations	1st year			2nd year		
	Hp	Heterosis (%)		Hp	Heterosis (%)	
		True	Hypothetical		True	Hypothetical
F_1KazMS x VP24	+0.32	-0.46	+0.22	-0.27	-2.5	-0.54
F_1KazMS x VP44	+4.41	+0.96	+1.25	+23.0	+0.87	+0.91
F_1KazMS x OP17231	-1.69	-0.99	-0.62	-5.59	-1.42	-1.2
F_1KazMS x OP17232	+0.2	-0.46	+0.12	-1.55	-0.49	-0.3
F_1KazMS x OP14044	+1.51	+0.5	+1.48	+6.36	+1.31	+1.56

DISCUSSION

Different indicators of the type of inheritance can have coverage and explanation by unstable values of productivity grown under diverse environmental conditions. There is shaky dominance when the same allele can be dominant or recessive depending on varied genotypic and external surrounding environments in crop plants (Alikhanyan *et al.*, 1985; Dubinin, 1986). Sugar content is essential in sugar beet productivity, a primary breeding goal when developing hybrids based on CMS. The sign of sugar content is distinguishable through a significant coefficient of variation (15%–21%), which is significantly lower than the root yield in sugar beet (Balkov, 1978; Nemeata-Alla and Helmy *et al*., 2022)

The variability of sugar content in sugar beet depends both on genotypic factors and environmental conditions and their interaction in populations — mainly managed by additive gene effects, while in interline hybrids – controlled by additive and non-additive gene effects (Korneeva and Vakulenko, 2006; Korneeva and Ermantraut, 2007; Roik and Korneeva, 2010). However, the phenotypic expression of sugar content has substantial influences from other factors (environmental and agrotechnical), which "mask" the genetic parameters that determine the said trait and create difficulties in the selection of valuable sugar beet genotypes (Nenka and Nenka, 2014; Bastaubayeva *et al*., 2022).

Logvinov (2022) emphasized the concept of the phenotype system as a reflection of the sugar beet genotypes, manifested by the coordinated function of the various genes in reproduction, transformation, and implementation of hereditary information processes. Bogomolov and Vostrikova (2022) stated that productivity indicators, namely, yield and sugar content, can change depending on weather conditions in *Beta vulgaris* L. According to several past studies, it was notable that in sugar beet populations, the sugar content's inheritance was according to an intermediate type of gene action (Savitsky, 1940; Berezhko, 1971; Negovsky, 1971; Bormotov and Turbines, 1972; Sukhopursky, 1975). However, by studying breeding material, a discovery revealed that hybridization can result in a higher sugar content than in the parental genotypes.

Thus, in experiments of Oldemeyer (1954) and Oldemeyer and Bucn (1960), 18 out of 90 hybrids showed heterosis for sugar content, and dominance gene action occurred in 16 crosses in sugar beet. Makogon (1969), Peretyatko and Orlovsky (1971), Balkov *et al.* (1976), and Petrenko (1985) also pointed out facts of a significant excess of sugar content in interline hybrids over the best parental genotypes in sugar beet. These facts deserve focus in breeding for heterosis, where the primary criterion for selecting parental genotypes had the basis on the combinational value for the said trait and not upon the lines' productivity. In confirmation of the above findings, the study on yield and sugar contents' expression in the cross populations ran for two years (Table 4).

Table 4. Expression of the productivity of the various crossing combinations.

Cross combinations	Root weight (kg)	Density (1000 plants ha^{-1})	Root yield (t/ha)	Sugar content (%)
First year				
F_1KazMS x VP24	0.59	54.93	32.41	15.75
F_1KazMS x VP44	0.64	58.97	37.74	16.07
F_1KazMS x OP17231	0.60	55.07	33.04	15.66
F_1KazMS x OP17232	0.58	59.13	34.29	15.93
F_1KazMS x OP14044	0.68	59.00	40.12	16.22
Second year				
F_1KazMS x VP24	0.71	55.16	39.16	16.51
F_1KazMS x VP44	0.72	58.63	42.21	17.09
F_1KazMS x OP17231	0.66	57.80	38.15	16.69
F_1KazMS x OP17232	0.70	56.14	39.30	16.85
F_1KazMS x OP14044	0.73	61.65	45.00	17.24

Table 5. Results of the analysis of variance.

Factors	d.f.	Sum of squares	Mean squares	F-value	Pr(>F)
Year	1	0.2053	0.20535	30.14	1.71e-07 ***
Residuals	148	1.0084	0.00681		

***: 0.001. **: 0.01. *: 0.05

```
Regression analysis of the influence of various factors on the mass
of root crops

Call:
lm(formula = Root_weight ~ combinations + Year + Density, data =
data)

Residuals:
      Min        1Q    Median        3Q       Max
-0.162797 -0.058029 -0.008877  0.054291  0.203524

Coefficients:
combinations       Estimate      Error        t  value    Pr(>|t|)
                   Std.
F1KazMSxOP14044    0.956118      0.112065     8.532       1.89e-14 ***
(Intercept)
F1KazMSxOP17231    -0.088255     0.021266     -4.150      5.68e-05 ***
F1KazMSxOP17232    -0.083864     0.020706     -4.050      8.36e-05 ***
F1KazMSxVP24       -0.085197     0.022273     -3.825      0.000195 ***
F1KazMSxVP44       -0.041537     0.020215     -2.055      0.041721 *
Year2022           0.076578      0.012697     6.031       1.32e-08 ***
Density            -0.004958     0.001848     -2.683      0.008155 **
Note: * Sig. ≤ 0.05, ** Sig ≤ 0.01, *** Sig ≤ 0.001.

Residual standard error: 0.07753 on 143 degrees of freedom
Multiple R-squared:  0.2918,    Adjusted R-squared:  0.2621
F-statistic: 9.819 on 6 and 143 DF,  p-value: 4.696e-09

Regression analysis of the influence of various factors on sugar
content
Call:
lm(formula = Sugar_content ~ combinations + Year + Density, data =
data)

Residuals:
     Min       1Q   Median       3Q      Max
-1.36706 -0.47815  0.00736  0.55907  1.25427

Coefficients:
combinations       Estimate      Error        t value     Pr(>|t|)
                   Std.
F1KazMSxOP14044    15.97544      0.91010      17.554      < 2e-16 ***
(Intercept)
F1KazMSxOP17231    -0.53028      0.17270      -3.070      0.00256 **
F1KazMSxOP17232    -0.39786      0.16816      -2.366      0.01932 *
F1KazMSxVP24       -0.57387      0.18088      -3.173      0.00185 **
F1KazMSxVP44       -0.16067      0.16417      -0.979      0.32937
Year2022           0.92629       0.10312      8.983       1.4e-15 ***
Density            0.00482       0.01501      0.321       0.74854
Note: * Sig. < 0.05, ** Sig < 0.01, *** Sig < 0.001.

Residual standard error: 0.6296 on 143 degrees of freedom
Multiple R-squared:  0.415,     Adjusted R-squared:  0.3905
F-statistic: 16.91 on 6 and 143 DF,  p-value: 1.068e-14
```

Figure 1. Analysis of various variants.

Statistical processing and compilation of research results for 2021–2022 ran in the R-open source programming language - R version 3.2.3 (2015-12-10) (Wooden Christmas-Tree) (https://www.r-project.org /alt-home/). Statistical significance determination used the analysis of variances program. The results of a simultaneous test from the analysis of variance are in Table 5. Comparison of the reliability of differences in the values of the mass of sugar beet roots and with the year of research showed that the differences were quite significant ($P < 0.001$) (Table 5), which confirmed that different environmental conditions affect the productivity indicators.

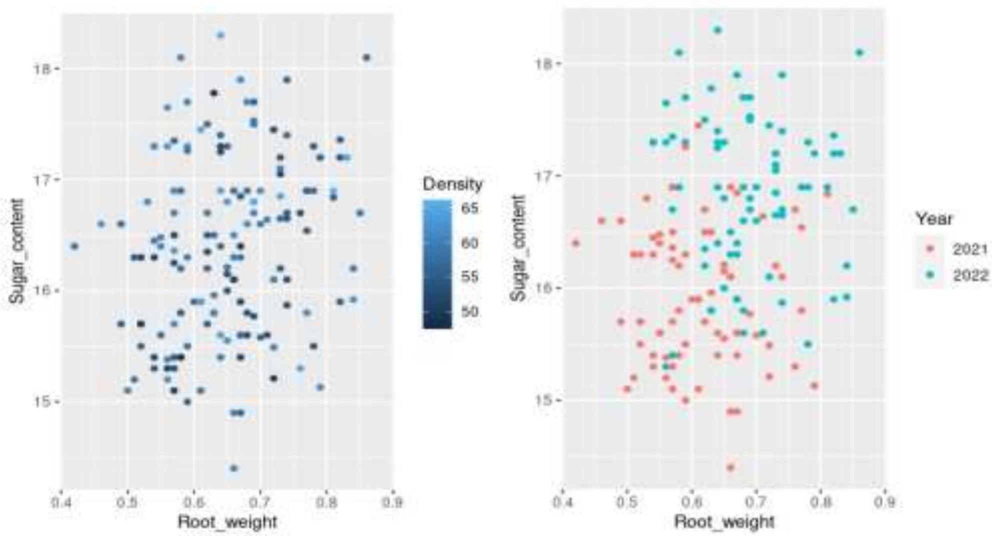

Figure 2. Analysis of variants for root yield (kg), density (1000 plants ha^{-1}), and sugar content (%).

From Figure 1, the highest t-value resulted from the F_1 hybrid KazMS × OP14044, with significant values of $P < 0.001$ compared with other hybrids. Environmental conditions of different crop seasons also influenced the rates of crop productivity and the sugar content, which confirms the values of 1.32e-08*** and 1.4e-15***. However, the effect of plant density on the studied traits was insignificant (Figures 1 and 2). Thus, based on the results of heterosis and degree of dominance for root yield and sugar content, the conclusion can be that the hybrid combination KazMS × OP14044 has the best potential and combination ability by showing significant heterotic effects in various years of the study.

CONCLUSIONS

Results revealed that hybrid heterotic effects mainly depend to a greater extent on the productivity potential of the parental lines. The general combining ability was due to inheritance by the simple addition of the characteristics of parental forms, and the specific ability was the result of the dominance effects. In hybrids, heterosis can be expected for root yield even when the crossing components do not differ much in sugar content. The incidence of heterosis in productivity was much higher than in sugar content. When crossing genotypes were contrasting in sugar content, an intermediate type of inheritance usually emerged.

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