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COMBINING ABILITY ANALYSIS IN SPRING BARLEY (*HORDEUM VULGARE* L.) FOR YIELD TRAITS

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SUMMARY

For assessing the combining ability, the top cross method proved more economical and less laborious compared with the diallel analysis. It also allows the breeder to obtain valuable information about the inbred lines and their hybrids for various traits. In the existing research, determining the combining ability of barley (*Hordeum vulgare* L.) hybrids took place in two regions of Kazakhstan with contrasting soil and climatic conditions. The additive and non-additive genes played a vital role in determining almost all the traits in barley. Analysis of variance showed varying significance among the barley cultivars and their hybrids and testing sites for the majority of the traits. Analysis of variance also revealed significant differences in general combining ability (GCA) and specific combining ability (SCA) among the parental cultivars and their hybrids in barley. The predominance of additive gene interactions in controlling the traits under environmental conditions of the Aral Sea region indicates the possibility of effective selection already in the F_2 generation. However, in the piedmont zone of the Almaty region, the dominant genes managed the traits, and thus, necessary to differentiate the hybrid populations, starting from the first generation, until further selection from several cycles achieved the homozygosis of loci carrying dominant genes. Barley cultivars, Rihane, WI2291/Roho/WI2269 (ICARDA), and the tester, Odessa-100 (Odessa Selection and Genetic Institute, Ukraine), showed greater practical interest and therefore, recommended for use as reliable donors in future breeding programs.

Keywords: Barley (*Hordeum vulgare* L.), variability, hybrid populations, combining ability, top-cross, analysis of variance, additive effect of genes

Key findings: Analysis of variance showed significant differences for the barley cultivars, their hybrids, and testing sites for the majority of the traits. Parental cultivars, Rihane, WI2291/Roho/WI2269, and tester Odessa-100 revealed greater practical interest with higher combining ability effects and less dependent on growing conditions that can serve as donors for improving important parameters.

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INTRODUCTION

The Kyzylorda region of the Republic of Kazakhstan locates geographically in severe unfavorable conditions to implement crop production. A decreasing water resource exists at the transboundary Syrdarya River, Central Asia, creating certain threats to a secure water supply for irrigation, causing intense desertification, salinization, and soil blowing. These mainly consist of the obstacles to sustainable economic growth and social development in the region. In this regard, within the framework of the "green economy" and the diversification of crop production in the Kyzylorda region, the area under the crops with low-water consumption expands, including the fodder-grain crop – barley, one of the leading crops in the world, due to its adaptive capabilities, high yield, and versatile use (Tokhetova *et al*., 2017, 2020). However, the domestic production of fodder fails to meet the needs of the cattle of the Kyzylorda region due to low crop yield on saline soils, requiring importation. Therefore, one of the main tasks of research and selection work on barley in this region focuses on identifying high-yielding adaptive genotypes that are stable across seasons and determining their donor properties for their inclusion in the hybridization programs.

The effectiveness of selection largely depends on the genetic analysis of the hereditary characters of the source material. Ultimately from genetic analysis comes genetic counseling, preservation of the genetic health of the population, and protection of the existing gene pool. Consequently, further improvement in the methods of genetic analysis continues as the most important task of modern genetics (Olfati *et al*., 2012; Wiegmann *et al*., 2019). Therefore, it is very crucial to identify a cultivar of source materials that not only combine a valuable complex of traits but also have the ability to breed true, to select the cross combinations in which the desired transgressions can be obtained.

Combining ability analysis allows the evaluation of the genetic properties of the crop genotypes and traits with their nature of inheritance, which makes the researcher anticipate the results of crosses in the future and focus on promising material, saving time from useless hybrids. To determine the general (GCA) and specific combining ability (SCA) effects and gene action through hybridization employs the half and full diallel and line-by-tester schemes (Griffing, 1956; Kaeppler, 2012; Kanfany *et al*., 2018; Bouchetat and Aissat, 2019) and the system of top cross-breeding (Savchenko, 1984; Patil *et al*., 2012; Owusu *et al*., 2020). The top cross method for assessing the combining ability effects is more economical and less laborious compared with the diallel analysis and also allows the breeder to obtain valuable information about the inbred lines and their hybrid populations. Also, a widely used method to assess the combining ability effects of parental lines and their hybrids, the essence of the top cross method lies in the fact that all studied lines undergo crossing with a common tester. Lines, hybrids, and cultivars display usefulness as testers, and, as a rule, there should be at least two testers. Testers can be used as both female and male parents. The more testers are used in crossing, the more genetically diverse they are, more accurate the assessment of the general and specific combining ability will be.

Barley (*Hordeum vulgare* L.) appeared largely neglected in hybrid breeding research of autogamous cereals (Mühleisen *et al*., 2013). A two-stage analysis calculates the best linear unbiased estimators and variance components of hybrids and parental lines. Accuracy to predict hybrid performance was moderate based on mid-parent values and GCA effects. Consequently, a need for alternative approaches to predict hybrid performance in barley requires attention. The findings of Philipp *et al*. (2016) also confirmed the benefits of barley hybrids usage on yield and yield stability compared with their parental genotypes and advanced inbred lines. Their research disclosed that hybrid forecasting based on GCA serves as a useful tool in breeding hybrid barley, and also for combined GCA analysis of two- and three-sided hybrids.

Studies have shown that the additive effects of genes appeared more significant than the non-additive gene effects, confirming that GCA effects showed less susceptibility to the environment than the SCA effects (Yap and Harvey, 1971). In particular, many plant breeders have been investigating the possibility of developing hybrid cultivars in self-pollinated crops, especially barley (*Hordeum vulgare* L.) and wheat (*Triticum aestivum* L.). The expediency of using hybrid cultivars still confirms relevant today and depends on the degree of knowledge of the parental forms in terms of combinational ability.

Thus the past review has shown that different genes are involved in the determination of traits and sometimes have a contradictory character in the limit of one crop, which seemingly depends on the parental lines involved in hybridization, and determining the polygenic inheritance results from the growth conditions of plants (Hasan *et al.*, 2015; Labdi *et al*., 2015). Combining ability estimates help to evaluate genotypes and determine the nature and degree of gene activities in the inheritance of various agronomic traits (Islam *et al*., 2022). The latest study aimed determination of the combining ability and the identification of best donors' parents and their hybrids for economically valuable traits of spring barley using the method of top-cross analysis.

Particularly noteworthy, the stress factors of the environment (salinity, drought, and dry hot winds) characteristic of the soil and climatic conditions of the Kyzylorda region greatly reduce the grains setting during hybridization and average at 3%–5%. Therefore, the difficulty in obtaining the entire set of planned hybrid populations in diallel crossings occurs. Many hybrid combinations 'fallout' and become impossible to carry out the genetic analysis. In this regard, the existing research widely used the top cross method to generate valuable genetic material and identify salt-tolerant, high-yielding fodder barley cultivars suitable for the country's requirements.

MATERIALS AND METHODS

Experimental sites, breeding material, and procedure

The latest research took place simultaneously in two zones of Kazakhstan, with contrasting soil and climatic conditions, i.e., a) rice systems of the Kyzylorda region and b) piedmont zone of the Almaty region. The climate of the Kyzylorda region is sharply continental, with hot, dry summers and cold winters, with unstable snow cover. The average annual air temperature and rainfall are 9.8°C and 129 mm, respectively. In some dry years, rainfall can be 40-70 mm. The soil of the experimental field comprised meadow-boggy, typical for rice crop rotation in the region. It has a low humus content of 0.9% and a high value of dissolved solids (0.88%). Salinization is average and chloride-sulfate (Table 1).

Cold winters, hot and dry summers, and warm and dry autumns characterize the climatic conditions of the piedmont zone of the Almaty region. The average air temperature reaches 7.6°C, and the annual rainfall peaks at 414 mm. The soil cover exhibits light chestnut (non-saline) soils. The humus content reaches 3%. Detailed meteorological characteristics of the climatic conditions of the two regions appear in Table 2.

The study employed the top cross method for F_2 hybrids, the general (GCA) and specific (SCA) combining ability of parental cultivars of barley and their 12 hybrid populations. Genotypes WI2291*2/WI2269, WI2291/Roho/WI2269, Rihane, and Harmal (ICARDA) served as female parents, while the cultivar-testers, i.e., Donetskiy8, Odessa-100 (Ukraine), and Saule (Kazakhstan) as male parents. Early maturity and dwarfness served as the main criteria for the selection of female parents, while for male parents, the high grain content, grain size, and tallness (Lepekhov, 2017). Table 3 shows the values of economically valuable traits of parental forms in saline soils.

Table 1. Chemical characteristics of the experimental soil (Kyzylorda region), 2021

Horizon, cm	pH	mV	Dense residue %	Anion, %/mg.eq. 100 g^{-1} soil			Cation, %/mg.eq. 100 g^{-1} soil			Sum of salts %
				HCO_3	Cl	SO_4	Ca	Mg	Na	
0-20	7.64	-24	0.78	0.023 0.462	0.015 1.564	0.830 12	0.16 8.3	0.046 3.75	0.016 0.758	0.896
20-40	7.55	-19	0.65	0.029 0.351	0.067 1.902	0.835 15.92	0.15 8.4	0.046 3.75	0.025 0.802	0.848

Table 2. Meteorological characteristics of conditions, 2021.

Months	2020–2021 Agricultural Year							
	Average daily air temperature, °C				Rainfall, mm			
	Kyzylorda region		Almaty region		Kyzylorda region		Almaty region	
	average monthly	± to medium-long-term	average monthly	± to medium-long-term	per month	% of the norm	per month	% of the norm
September	17.9	-0.7	16.8	-0.8	0	0	27	74
October	10.0	-0.1	9.7	-0.2	0.4	4	9	14
November	-1.4	-3.2	0.2	-2.5	13	77	23	41
Autumn	*8.8*	*-1.3*	*8,9*	*-1,2*	*13.4*	*43.2*	*59*	*43*
December	-11.0	-6.3	-6.3	-3.5	2	11	13	30
January	-8.8	-2.0	-5.7	-1.1	13	68	13	37
February	-2.2	+2.3	1.7	+4.7	20	142	51	118
Winter	*-7.3*	*-2.0*	*-3,4*	*+0,03*	*35*	*70*	*77*	*61,7*
March	3.0	-1.0	4.9	+0.4	39	279	113	156
April	15.7	+1.7	12.5	+0.4	10	47	54	47
May	25.6	+4.5 (record)	19.5	+2.4	0.9	5	70	71
Spring	*14.8*	*+1.73*	*12,3*	*+1,06*	*49.9*	*95.9*	*237*	*91,3*
June	28.7	+0.2	23	+0.9	0.9	11	20	34
July	30.5	+2.2	27.2	+2.8	0.8	17	23	53
August	26.2	+0.6	24.6	+1.3	0.5	14	23	70
Summer	*28.5*	*+1.0*	*24.9*	*+1.66*	*2.2*	*12.9*	*66*	*52.3*
For the agricultural year	11.2	+0,62	10.67	+0.38	109	56.3	439	62.1
During the growing season	20.7	+1.52	17.4	+0.9	51.6	24.7	280	35.7

Note: source of meteorological data http://pogodaiklimat.ru/monitor.

Table 3. Characteristics of parental forms according to economically valuable characteristics on saline soils (average for 2018-2021).

Standard cultivars and numbers	Growing period, days	Plant height, cm	Flag leaf area, cm^2	Upper internode length, cm	Spike length, cm	Number of grains per spike, pcs	Thousand grain weight, g	Grain weight per spike, g	Number of productive spikes, pcs/m^2	Grain yield, centner/ha
Syr Aruy, St	79	72.0	3.08	18.5	8.0	22.5	41,0	0.95	338	18,4
WI2291*2/WI2269	82	80.7	3.03	24.5	8.5	24.0	41.5	0.99	335	25.5
WI2291/Roho/WI2269	81	81.3	3.23	23.6	9.2	46.5	42.9	1.9	330	27.4
Rihane	82	82.0	4.56	28.2	9.0	42.0	43,9	1.76	330	25.1
Harmal	82	80.0	6.35	20.4	10.5	26.5	44.5	1.18	332	27.8
Donetskiy8	82	85.3	3.54	24.3	8.9	48.0	42.5	1.94	320	27.5
Odessa-100	79	82.7	3.08	21.7	8.5	42.0	44.0	1.72	325	26.5
Saule	80	83.0	4.26	23.5	10.5	26.0	42.0	1.09	342	76.0
LSD_{05}	0.23	1.36	0.24	1.07	0.34	0.65	0.31	0.08	2,3	1.38

Figure 1. Pollination process and installation of parchment insulators.

Figure 2. Nesting method of seeding F_1 (ear in the hole).

Figure 3. Sowing hybrids F_2 on one-meter plots.

After castration of the ears, a parchment insulator was put on each of them. After carefully checking the quality of castration, pollination took place by direct transfer of pollen with tweezers to each spike in the morning (individually forced method). Given the low grain tying in the Kyzylorda region, at least 20 bars got castrated for each combination (Figure 1). Each ear of the F_1 hybrid population was sown in a square-nesting way, that is, in each well, one ear and on the edges of the parent forms (Figure 2). Seeds of the F_2 hybrids underwent sowing on 1 m rows with 15 cm row spacing in three replications, and harvesting of plants by hand together with roots took place (Figure 3).

Analysis of 50 typical plants for each hybrid population proceeded according to individual quantitative traits, i.e., productivity (grain weight of a plant), its structural elements (productive tilling capacity, grains per spike, thousand-grain weight), as well as, plant height and spike length. Assessment of the reliability of the impact of factors on the variability of combining ability indicators under the influence of environmental factors used the method of Tarutina and Khotyleva (1973). Based on the average value of eight plants, calculations of mid-parent (MP) and better-parent (BP) heterosis for all traits used the formula by Zhang *et al*. (2015) as follows:

Mid-parent heterosis = F_1 - ([P_1 + P_2] / 2)

Better parent heterosis = F_1 – Pb

Where,
Pb: stands for the performance of the better parent

In the top cross breeding program, the analysis of combining ability followed the method of Savchenko (1984).

General model for top cross analysis of variance :

Xijk = m + g i + g j + sij + eijk

Where,
Xijk: the value of the hybrid (i × j)
k: replication
m: mean value of the trait in the experiment
gi и gj: GCA of the line and tester
sij: line-tester interactions, otherwise SCA
eijk: a random error

RESULTS AND DISCUSSION

Analysis of variance revealed significant differences among the parental genotypes and their hybrids and testing sites, except for the GCA of grain weight per plant of male parents and the productive tilling capacity of female lines. The values of the variability of the general combinational ability appear in Table 4. Analysis of variance revealed significant differences for GCA and SCA of the traits under study (Fact>Ftabl), which made it possible to proceed to the estimates of the GCA and SCA effects. The determination of the studied traits involved additive (GCA) and non-additive effects (SCA), and the predominance of certain types of gene interactions depended on the cultivation conditions (Table 5).

Regardless of the growing locations, additive effects prevailed in traits determination, i.e., plant height, spike length, grains per spike, grain weight per spike, and productive tilling capacity. The studies of Milomirka *et al.* (2014) revealed the predominance of the additive component of genetic variability in the length of the ear, the weight of grain per ear, and the yield index of the ear. However, the SCA variance for grain weight per ear was higher than the GCA variance, indicating the predominance of non-additive action of genes. Past studies on combining ability in wheat also showed that the additive gene effects managed the traits viz., plant height, biomass plant, number of grains spike, and grain yield per plant, while the non-additive gene effects controlled the number of tillers per plant and thousand-grain weight (Muhammad *et al*., 2007).

In the demonstration of thousand-grain weight under environmental conditions of the Kyzylorda region, the main influence came from the no allelic effects of genes, in contrast to the piedmont zone conditions of the Almaty region. In the Kyzylorda region, the allelic effects of genes exceeded the no allelic ones in the length of the growing season, while in the piedmont zone of the Almaty region, both additive and non-additive gene interactions equally controlled the said trait. Although, when determining the peculiarities of the combinational ability of spinous and spineless cultivars of spring barley and their parent forms in F_1, strong SCA effects resulted in thousand-grain weight (Kompanets *et al*., 2017). Therefore, this feature depends not only on the influence of the environment but also on the barley cultivars.

The proportion of the additive effects of the genes of seed parents also depends on the influence of the environment. In contrast to the piedmont zone of the Almaty region, in the conditions of the Aral Sea region, the mean squares due to the GCA of the female lines exceeded the GCA values of the testers, being inferior in terms of the SCA in the plant height and spike length. The yield-related traits, i.e., grains per spike, thousand-grain weight, grain weight per spike, and the length of the growing season in both zones, were mainly determined by the additive genes of male parents. However, in the Kyzylorda region conditions, a slight decrease was observed.

The cultivation zones significantly impacted the demonstration of the specific combining ability of the thousand-grain weight and the length of the growing season. More pronounced no allelic interactions influenced the thousand-grain weight under the saline soil conditions of the Aral Sea region and the length of the growing season in the piedmont zone of the Almaty region. In the piedmont zone of the Almaty region, positive selection results showed possible in both additive and non-additive effects of genes, in the inheritance of plant height and the duration of the growing season, as a result of the appearance of homozygous forms.

Table 4. Analysis of variance of combining ability and its interaction with the growing locations of the barley hybrids.

Sources of variation	Plant height	Spike length	Grains spike^{-1}	Thousand-grain weight	Grain weight spike^{-1}	Grain weight plant^{-1}	Productive tilling capacity	Length of growing season
GCAi × growing location	84.7**	2.0**	43.1**	1.89*	0.009**	0.12*	0.44ns	2.7**
GCAj × growing location	179.8**	9.8**	116.5**	10.99**	0.078**	0.02 ns	1.15*	10.1**
SCA × growing location	68.71**	0.8*	52.8**	28.1**	0.008**	0.12*	1.06*	1.62**
Chance differences	2.23	0.194	0.17	0.05	0.003	0.008	0.49	7.48

i, j - Lines and Testers, respectively, * Significant at $P < 0.05$, ** - Significant at $P < 0.01$, NS - Nonsignificant

Table 5. Analysis of variance of general and specific combining ability for various traits at two testing sites.

Sources of variation	Plant height	Spike length	Grains spike^{-1}	Thousand-grain weight	Grain weight spike^{-1}	Grain weight plant^{-1}	Productive tilling capacity	Length of growing season
Rice systems of the Kyzylorda region (Saline soils)								
GCAi	344.6**	21.9**	67.0**	36.43**	0.144**	0.37*	2.1 ns	175.6*
GCAj	103.2**	14.8**	178.0**	51.19*	0.245**	0.35*	2.4*	712.5**
SCA	110.2**	5.9*	37.3*	696.6**	0.132**	0.21 ns	2,.*	725.8**
Proportion of GCA %	80	87	87	11	65	55	65	77
Piedmont zone of the Almaty region (Nonsaline soils)								
GCAi	195.9*	14.3*	125.3**	58.9**	0.152*	0.24*	1.8*	170.0*
GCAj	814.5**	50.25**	200.5**	84.0**	0.453**	0.23*	1.4 ns	622.7**
SCA	633.3**	24.7**	196.5**	40.5**	0.227**	0.18 ns	1.3ns	804.3**
Proportion ofGCA %	61	72	59	78	73	72	71	49

* Significant at $P < 0.05$, ** Significant at $P < 0.01$, NS - Nonsignificant

Table 6. Estimates of the GCA effects and SCA variances for various traits of barley at the two testing sites.

Lines and cultivars	Site	Plant height		Spike length		Length of growing season	
		GCA	SCA	GCA	SCA	GCA	SCA
WI2291/Roho/WI2269	A	- 8.6	30.93	- 2.5	4.9	- 2	95.2
	B	- 12.4	280.5	+ 0.3	- 0.9	- 4	125.2
WI2291*2/WI2269	A	+ 0.2	- 4.4	+ 1.3	7.1	+ 1	71.3
	B	+ 4.4	123.2	- 2.6	0.5	+ 3	101.3
Rihane	A	- 6.6	160.9	- 1.8	4.7	- 10.5	160.5
	B	- 1.4	270.1	+ 1	16.9	- 7.5	190.5
Harmal	A	+ 15	210.5	+ 3	2.8	+ 3.5	125.0
	B	+ 9.4	164.5	+ 1.3	2.5	+ 8.5	155.5
$LSD_{0.05}$		7.8	146.7	2.9	8.7	5.0	63.3
Saule	A	- 3.4	23.3	- 1	3.8	- 3	135.7
	B	+ 1.6	46.7	- 1	2.6	- 3	165.5
Donetskiy8	A	- 2.4	50.2	- 1.2	2.8	+ 10.4	71.0
	B	- 4	141.9	+ 2	2.7	+ 0.6	101.6
Odessa 100	A	+ 5.8	136.6	+ 2.2	6.2	+ 0.6	72.4
	B	+ 2.4	142.0	- 1	5.8	+ 2.4	102.3
$LSD_{0.05}$		2.1	82	0.9	2.9	7.6	73.6

Sites: A – Kyzylorda region, B – Almaty region

Plant height

Their dwarfness makes for a distinctive feature of the Syrian barley samples (not higher than 50 cm), most possibly serving as the genetic source of short-stature, which is of certain interest for breeding cultivars under the irrigated zone of the Almaty region. In breeding terms, the best cultivars indicated WI2291/Roho/WI2269 and Rihane as distinguished by persistent low GCA in height and positive in the number of grains, thousand-grain weight, and grain weight per spike. In combination with the low GCA effects, the length of the growing season simultaneously exhibited in two zones (sources of early maturity). Cultivar-testers, Saule and Donetskiy-8, have a fairly low GCA in height, but in the course of further analysis of the combining ability, their negative impact on the productivity traits has been recorded. However, according to Dianga *et al*. (2020), the results of one population cannot be extrapolated to another, and the effects of the various genes must be assessed for each population, taking into account assessing the specific combining ability.

The plant height specifies one of the determining factors in the zoning of a particular cultivar of barley under the conditions of the Kyzylorda region, which is mainly cultivated as a cover crop of perennial grasses. Therefore, the development of cultivars with optimal stem sizes (not lower than 75 cm), combining early maturity to avoid overgrowth of grasses, calls for an urgent direction in barley breeding for this region. Considering the greatest practical value of these traits, the best seed parents for recognition point to the cultivars Odessa-100 and Harmal, in which a favorable combination of the high GCA and SCA got noted. Besides, the additive variance in quantitative terms somewhat has predominated over the non-additive one, indicating the possibility of positive transgressions in subsequent generations.

Spike length

None of the barley cultivars with stable high estimates of the GCA gained identification simultaneously at both experimental sites for the spike length. The relatively stable positive estimates characterized the cultivar Harmal, independent of the environmental differences between high and average GCA. Under the conditions of the Aral Sea region, cultivar Odessa-100 also gave the highest variances of the SCA, which can be used in heterosis and linear selection to improve this trait (Table 6). The prevalence of non-additive components in the inheritance of the studied traits corresponds to the results of Patial *et al*. (2016) and Pesaraklu *et al*. (2016).

Grains per spike

With environmental conditions of the Aral Sea region, the GCA identified the lines WI2291*2/WI2269 and Harmal and tester Odessa-100, also characterized by the highest values for grains per spike (on average 22–24 pieces) in comparison with other studied

Table 7. Estimates of the GCA effects and SCA variance for various traits of barley at the two testing sites.

Lines and cultivars	Site	Grains spike^{-1}		Thousand-grain weight		Grain weight spike^{-1}	
		GCA	SCA	GCA	SCA	GCA	SCA
WI2291/Roho/WI2269	A	- 5.6	0.127	- 0.25	59.4	- 3	1.42
	B	+ 8.3	4.1	+ 5.8	18.9	+ 2	3.13
WI2291*2/WI2269	A	+ 4	6.4	- 3.9	158.3	+ 1.7	0.52
	B	- 3.3	1.2	+ 1.2	3.0	- 2.7	1.21
Rihane	A	- 1.9	32.0	+ 4.5	55.3	- 0.2	0.56
	B	+ 4.2	2.5	+ 1.7	6.9	+ 2	1.2
Harmal	A	+ 3.5	71.9	- 0.31	36.1	+ 1.5	1.76
	B	- 9.2	1.0	- 8.7	32.9	- 1.3	- 0.38
$LSD_{0.05}$		3.4	38.1	4.5	36.5	1.5	1.46
Saule	A	- 5.7	41.1	- 3.8	95.5	- 2.3	1.11
	B	+ 1	- 0.85	- 3	23.9	+1	0.94
Donetskiy 8	A	- 1.6	1.07	+ 0.39	25.8	- 0.4	0.07
	B	- 2	17.3	- 1	24.5	- 2.5	0.53
Odessa 100	A	+ 7.3	31.1	+ 3.37	51.6	+ 2.7	1.39
	B	+ 1	0.56	+ 4	10.1	+ 1.5	0.95
$LSD_{0.05}$		4.9	31.6	2.6	45.2	1.2	0.73

Sites: A – Kyzylorda region, B – Almaty region

genotypes. The high variances of the SCA distinguished the lines Rihane and Harmal and testers Odessa-100 and Saule , thus, recommended for use to obtain certain sustainable heterotic combinations.

In specific combinations, the best crosses resulted with the hybrids WI2291*2/WI2269 × Odessa-100, WI2291/Roho/WI2269 × Saule, WI2291*2/WI2269 × Donetskiy-8, and Harmal × Saule. Under the conditions of the piedmont zone of the Almaty region, positive estimates of the GCA effects showed for the lines WI2291/Roho/WI2269 and Rihane. According to this trait, no stable cultivar ensued in terms of GCA. However, Odessa-100 received merit by the highest positive and average estimates of the GCA effects, also characterized by the high mean values for grains per spike as compared with other genotypes. The greatest expression of the trait dominates, therefore, it has the largest number of alleles that positively determine the trait. Table 7 presents the GCA and SCA effects in terms of productivity traits.

Thousand-grain weight

In the Kyzylorda region, the GCA defined the lines Rihane and Odessa-100 for the trait and WI2291*2/WI2269 according to the SCA, which can be used to highlight certain successful cross combinations when crossing by this trait. The piedmont zone of the Almaty region determined the highest combined value of the lines WI2291/Roho/WI2269, in contrast to the Aral Sea zone, which negatively affected the grain size. Regardless of the growing areas, in the cultivar Odessa-100 the GCA effects showed highly significant in combination with a high SCA in the Aral Sea zone, which is of great value for both synthetic and heterosis selection. In specific cross combinations, the best crosses include the hybrids, i.e., WI2291*2/WI2269 × Donetskiy-8, WI2291*2/WI2269 × Odessa-100, and Harmal × Saule. Mansour and Moustafa (2016) also reported similar results regarding GCA effects. The research identified the Giza-2000 lines as good donors by the number of spikelets per plant under normal conditions and by the thousand-grain weight during salinization. Consequently, the use of these genotypes can improve the creation of segregating populations in barley breeding programs.

Grain weight per spike

The saline soils of the Aral Sea region revealed the negative GCA effects of the cultivars WI2291/Roho/WI2269, Saule, Donetskiy-8, and Saule in terms of grain weight per spike, however, effected no change on the GCA estimates of the cultivar Odessa-100. The piedmont zone, on the contrary, had positive GCA effects for lines WI2291/Roho/WI2269 and Rihane, which also had the highest GCA effects for thousand-grain weight and grains per spike, respectively. The hybrids obtained based on these cultivars were characterized by high productivity. Therefore, special attention should focus on the barley cultivars Harmal and WI2291/Roho/WI2269, which exhibited the highest SCA variance in the rest of the productivity traits and can be recommended for obtaining promising combinations for the selection of transgressive lines. The research aligns with the results of Gocheva and Valcheva (2021) that the trait of grain weight per spike is controlled by an additive-dominant genetic system, where the dominant effect of genes surpasses the additive. In this regard, the selection by weight of grain per ear should proceed in later segregating generations.

Thus, based on the GCA values in Tables 6 and 7, the barley genotypes identified as the best donor parents for various economic traits include, i.e., cultivar Odessa-100 (growing season length and thousand-grain weight), Donetskiy-8 (grains per spike and thousand-grain weight), Saule (spike length, growing season length, and thousand-grain weight), Rihane (plant height and grain weight per spike), and three cultivars WI2291/Roho/WI2269, WI2291*2/WI2269, and Harmal (plant height, spike length, and growing season length).

Overall, in contrast to SCA variance, GCA effects showed higher and more stability across most of the traits. The variability of the SCA dispersion depending on the years and test sites is associated with the determination of this parameter by genes with dominant and epistatic effects, which are characterized by high sensitivity to numerous environmental factors. In general, the cultivars Rihane, WI2291/Roho/WI2269, and Odessa-100 obtained the highest GCA and SCA effects and showed less dependent on growing conditions, acquiring great practical interest to serve as donors for important selection parameters.

The existent study revealed a huge genetic diversity for plant height, ear length, grains per spike, early maturity, resistance to lodging, morphological features (double-row, intermediate, six-row forms, awnless, bush type, and hulless), allowing the breeders to conduct high-quality selection. Such studies avoid the process of unification of the germplasm of grain crops and increase the success of breeding work. Currently, studies on breeding pure lines selected from the hybrid populations obtained in this study continue in the breeding nursery for the second year (Figure 4).

Figure 4. Breeding of barley on saline soils of the Aral region, Kazakhstan.

CONCLUSIONS

The efficiency of selection and the appearance of transgressed forms in early segregating populations can be predicted, except for the thousand-grain weight and length of the growing season. In contrast to the variance of the SCA, the GCA effects proved higher and more stable in most of the traits. Thus, the genetic analysis of economically valuable traits in the spring barley genotypes showed the role of additive genes in the genetic control of all the analyzed traits. The variances, due to SCA dependent upon the crop seasons and testing sites, were associated with the determination of these traits by genes with dominant and epistatic effects and were also characterized by high sensitivity to numerous environmental factors. The identified donors of economically valuable traits can widely help in hybridization programs to create highly productive barley cultivars that are adaptive to stressful environmental conditions.

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