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Genetic Analysis of Line × Tester Crosses of Bread Wheat (*Triticum aestivum* L.) for Combining Ability Variances and Effect

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

This research intended to estimate the combining ability (GCA and SCA) and gene action among 10 female and 4 male wheat genotypes and their 40 F1 hybrids, using a line × tester mating design. The experiment was conducted in RBD with three replications at Baba Raghubar Das Post Graduate College during the 2021-2022 rabi season. The study assessed key agronomic traits, including plant height, days to flowering, biological yield, and grain yield. The analysis of variance for almost all the traits under varied significantly and indicating that both additive and non-additive genetic effects is present. GCA effects showed AAIDUWL-5 and AAIDUWL-7 as top combiners for

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yield-related traits, while SCA effects indicated promising hybrid combinations like AAIDUWL-9 × AAIDUWL-13 for grain yield. These results provide insights for the strategic selection of parents and hybrids to enhance wheat breeding programs.

Keywords: Line x tester analysis; hybrid; combining ability; gluten content.

1. INTRODUCTION

Wheat is the most valuable cereal crop around the globe and was domesticated back 10000 years ago (Harlan and Zohary, 1966). It is nutritionally important cereal essential for the food security, poverty alleviation and for livelihoods (Sharma and Duveiller 2004). It is widely cultivated as staple food crop among cereals and is contributing about 30% to the food basket of the country (Hassani et al., 2016; Petersen et al., 2006). Among the cereals, wheat ranks first position due to its extensive area under cultivation and nutritional value. Two billion people, or 36% of the world's population, use it as their primary source of dietary fiber (Smith, D. B., & Flavell, R. B. (1974). Around 20 % of all food calories consumed globally and nearly 55 % of all carbohydrates come from wheat (Dedaniya et al., 2019). *Triticum aestivum* is a segmental allohexaploid (2n = 6x = 42, AABBDD) that originated in the Fertile Crescent region of South-Western Asia (Lupton 1987). It has since spread throughout the world for cultivation and consumption (Agricole, 2023). Around 221.24 million hectares of land are used to grow wheat, with a record yield of 771.64 million tonnes and productivity of 3.49 metric tons per hectare (USDA 2023). In the world Indian ranks second position in wheat production after China. Among the Indian states, top five wheat producing states are Uttar Pradesh (9.75 million hectares, 32%), Madhya Pradesh (18.75%), Punjab (11.48%), Rajasthan (9.74%), Haryana (8.36%), and Bihar (6.82%) (FAO Stat 2021).

Before starting any judicious plant breeding activities assessment of genetic variability and nature of gene action involve in controlling the yield and its attributing traits is very prerequisite (de Mendiburu, 2021; Rajput & Kandalkar, 2018). Most of the biometrical approaches for genetic evaluation of the crop, the Line X Tester cross analysis become a proved and important technique to provide maximum information on gene action related to breeding programme of some important metric traits within considerable short time (Moges and Tsegaye 2023). In terms of combining ability variances and effects, evaluating a small number of germplasm lines at once is a very effective technique (Hays et al., 1955). It is possible to estimate heritability, genetic progress, and combining ability (Hama-Amin and Towfiq, 20219; Fellahi et al., 2013; Din et al., 2021). Estimates of GCA assist in choosing suitable general combining parents for hybridization programs. Estimating the effects of specific combining abilities aids in choosing the best cross combinations when creating commercial hybrids.

2. MATERIALS AND METHODS

The experimental materials for this study consisted of 45 wheat treatments, including 40 F1 hybrids, 15 parental lines (10 females and 4 males), and one standard variety used as a check. The parental lines included 10 female lines: AAIDUWL-1, AAIDUWL-2, AADUWL-3, AAIDUWL-4, AAIDUWL-5, AAIDUWL-6, AAIDUWL-7, AAIDUWL-8, AAIDUWL-9, and AAIDUWL-10, along with 4 male testers: AAIDUWL-11, AAIDUWL-12, AAIDUWL-13, and AAIDUWL-14. The experimental hybrids were developed using a line × tester mating design during the 2019-2020 rabi season at the Research Farm of Baba Raghubar Das Post Graduate College, Deoria (Affiliated with DDU Gorakhpur University, Uttar Pradesh). The 40 hybrids (F1s) were generated by crossing the 10 female lines with the 4 male testers to create a diverse set of genetic combinations aimed at evaluating specific and general combining ability for key agronomic traits. These hybrids, along with their 15 parental lines and the standard check variety HD-2967, were evaluated using randomized block design (RBD) with three replications during rabi season in 2021-2022.

3. STATISTICAL ANALYSIS

The analysis of variance (ANOVA) was conducted following Hayman (1954), and combining ability for the line x tester design was analyzed using Kempthorne's method (1957). Data were processed in R using the Agricolae package (Version 1.3-5). Combining ability for each trait was calculated based on Hayes et al. (1955).

4. RESULTS AND DISCUSSION

4.1 Analysis of Variance (ANOVA)

The analysis of variance (ANOVA) demonstrated significant genetic variability among lines, testers, and their interactions, reflecting the importance of both additive and non-additive genetic effects in trait expression. Key traits, including days to flowering (DF), plant height (PHT), pods per plant (PP), and seed yield per plant (SYPP), exhibited significant differences across the genetic materials (Table 1). These findings indicate that genetic diversity can be exploited for breeding superior hybrids (Kumar et al*.,* 2017). Similar finding were observed by Rajpur et al., (2018) and Dedania et al*.,* (2019).

Significant line × tester interactions reveal the presence of specific combining ability (SCA), highlighting that the performance of certain hybrids is driven by favorable line-tester combinations. This points to non-additive genetic effects, emphasizing that hybrid vigor depends not just on individual parental traits but also on their specific compatibility. Traits such as PHT, PP, and SYPP exhibited strong interaction effects, suggesting that careful selection of line-tester pairs is crucial for maximizing hybrid performance (Maan and Yadav 2022).

The ANOVA also showed that the crosses had significant differences for several key traits, including days to 50% flowering, days to maturity, plant height, biological yield per plant, harvest index, and seed yield per plant. These significant differences confirm the presence of substantial genetic variability, a critical factor in breeding programs. The line effects were most notable for days to 50% flowering (DFF), days to first pod (DFP), and SYPP, indicating that specific lines are more influential in determining the variability in these traits. Additionally, the line × tester interactions were significant for traits like PHT, PP, and harvest index (HI), reinforcing the role of non-additive genetic variance in enhancing performance. These interactions suggest that hybrid combinations should be selected based on both individual parental traits and their specific interactions to achieve the best outcomes (Manmohan et al*.,* 2023).

4.2 Combining Ability Effects

4.2.1 General Combining ability (GCA) effects

The general combining ability (GCA) analysis revealed that none of the parental genotypes consistently performed as superior general combiners across most yield-related traits, indicating the need for strategic selection and crossbreeding to enhance desirable traits (Table 2). For days to 50% flowering, AAIDUWL-4 and AAIDUWL-8 exhibited significant negative GCA effects, advantageous for developing early flowering varieties, while AAIDUWL-5 and AAIDUWL-7 showed positive effects, suggesting their suitability for breeding late-flowering varieties. In terms of plant height, AAIDUWL-5 and AADUWL-3 demonstrated the highest positive GCA effects, making them ideal candidates for breeding taller varieties, which may be beneficial for biomass production or lodging resistance (Sharma and Chaudhary 2019).

For days to maturity, AAIDUWL-7 and AAIDUWL-1 emerged as superior general combiners, offering potential for developing early-maturing varieties capable of avoiding end-of-season drought stress (Falconer and Mackay, 1996). The number of effective tillers per plant was highest in AAIDUWL-9, while AAIDUWL-11 was the best tester, highlighting their potential for improving tillering capacity and enhancing yield (Griffing, 1956). For flag leaf area, a key trait for photosynthetic efficiency, AAIDUWL-5 and AAIDUWL-9 were the best lines, with AAIDUWL-14 being the top tester, suggesting their use in breeding programs focused on increasing photosynthetic capacity and yield (Kumar et al., 2021).

In terms of peduncle length, AAIDUWL-5 and AADUWL-3 were the top general combiners, while AAIDUWL-12 and AAIDUWL-14 emerged as superior testers, indicating their potential for improving nutrient transport and grain filling. For spike length, AAIDUWL-5 and AAIDUWL-7 showed strong GCA effects, with AAIDUWL-12 performing well as a tester, suggesting their utility in breeding for longer spikes and increased grain number. Similarly, for spikelets per spike, AAIDUWL-5 and AAIDUWL-7 were the top-performing lines, while AAIDUWL-14 excelled among testers, emphasizing their potential to enhance overall yield (Devi et al., 2018).

Grains per spike were highest in AAIDUWL-5, with AAIDUWL-14 showing notable tester performance, indicating their effectiveness in increasing grain number per spike. Grain yield per spike was positively influenced by AAIDUWL-5 and AAIDUWL-7, with AAIDUWL-14 being a significant tester, making these genotypes valuable for improving grain yield. For biological yield per plant, AAIDUWL-5 and AADUWL-3 stood out as the best general combiners, highlighting their potential to enhance biomass production (Sharma and Chaudhary 2019).

The harvest index was highest in AAIDUWL-7 and AAIDUWL-9, with AAIDUWL-14 performing well among testers, indicating their suitability for breeding programs aimed at optimizing biomass partitioning to grain yield. Test weight was improved by AAIDUWL-7 and AADUWL-3, with AAIDUWL-12 and AAIDUWL-14 contributing positively as testers, suggesting potential for enhancing grain quality. Seed moisture content was highest in AAIDUWL-8 and AAIDUWL-1, making them valuable for breeding programs aimed at improving seed storability (Sharma et al., 2023).

For grain hardness, AAIDUWL-9 and AAIDUWL-2 were the top lines, with AAIDUWL-12 and AAIDUWL-13 excelling as testers, indicating their potential for breeding hard wheat varieties. Protein content was highest in AAIDUWL-5, with AAIDUWL-12 showing positive tester effects, suggesting their utility for enhancing nutritional quality. Gluten content was positively influenced by AAIDUWL-9 and AAIDUWL-5, with AAIDUWL-12 and AAIDUWL-14 performing well among testers, making these genotypes ideal for improving baking quality. Finally, grain yield per plant was highest in AAIDUWL-5 and AAIDUWL-7, with AAIDUWL-14 contributing positively as a tester, emphasizing their potential for yield improvement. These findings provide crucial insights for the selection of superior parents and the design of effective breeding programs to develop improved wheat varieties (Khan et al., 2019).

4.2.2 Specific Combining ability effects (SCA)

The estimates of specific combining ability (SCA) effects for 40 crosses revealed significant outcomes for several traits, offering valuable insights for wheat breeding programs (Table 3). For days to 50% flowering, desirable significant negative SCA effects were observed in crosses such as AAIDUWL-7 × AAIDUWL-13, facilitating the development of early-flowering varieties, as reported by Ahmed et al. (2018). For plant height, the highest positive SCA effects were recorded in AAIDUWL-2 × AAIDUWL-13, while AAIDUWL-2 × AAIDUWL-12 exhibited the most significant negative effects, consistent with the findings of Kumar et al. (2017). These contrasting SCA effects highlight the potential of these combinations for both taller plants with greater biomass and shorter plants better suited for lodging resistance.

In terms of effective tillers per plant, AAIDUWL-9 × AAIDUWL-11 demonstrated the highest positive SCA effects, aligning with observations by Singh et al. (2020). For flag leaf area, a key indicator of photosynthetic efficiency, significant negative SCA effects were observed in AAIDUWL-5 × AAIDUWL-13, supporting the findings of Sharma et al. (2019). The trait of spikelets per spike exhibited significant positive SCA effects in AAIDUWL-9 × AAIDUWL-13, while AAIDUWL-7 × AAIDUWL-13 showed significant negative effects, consistent with Ali and Falahy (2011). These results provide insights into optimal combinations for enhancing grain number and spike architecture.

For grain yield per spike, AAIDUWL-3 × AAIDUWL-12 displayed significant positive SCA effects, aligning with the work of Singh et al. (2018). The same cross also exhibited the highest positive SCA effects for biological yield per plant, corroborating the observations of Jatav et al. (2017). Additionally, harvest index was highest in AAIDUWL-9 × AAIDUWL-13, indicating effective biomass partitioning, consistent with Sharma et al. (2021).

In the case of test weight, significant positive SCA effects were found in AAIDUWL-10 × AAIDUWL-14, supporting research by Brown and Taylor (2022). For seed moisture content, AAIDUWL-3 × AAIDUWL-14 exhibited positive SCA effects, echoing the results of Kalimullah et al. (2011). The grain hardness trait showed the highest SCA effects in AAIDUWL-5 × AAIDUWL-13, suggesting its potential for developing hard wheat varieties. Similarly, protein content was significantly improved in AAIDUWL-10 × AAIDUWL-11, consistent with findings by Akfirat and Uncuoglu (2013). Notably, no cross showed significant positive SCA effects for gluten content, a result aligned with the observations of Prasad et al., (2022).

For grain yield per plant, the highest significant positive SCA effects were recorded in AAIDUWL-9 × AAIDUWL-13, confirming the findings of Kumar et al. (2017). These results underscore the importance of SCA in identifying promising cross combinations that exhibit non-additive genetic effects, essential for maximizing hybrid performance. The insights provided by these SCA estimates will assist breeders in selecting optimal parental combinations and designing effective breeding programs aimed at improving both grain yield and quality in wheat.

Table 1. Analysis of variance for combing ability

SOV	Replications	Treatments	Parents	Line	Testers	Line vs testers	Parents vs Crosses	Crosses	Lines Effect	Testers Effect	Lines × testers Effect	Error
d.f.	*2*	*53*	*13*	*9*	*3*	*1*	*1*	*39*	*9*	*3*	*27*	*106*
DFF	6.78	68.51**	57.97**	59.26**	67.00*	19.29	135.49**	70.30**	91.90	82.68	61.72**	18.88
PHT	63.05	58.39**	32.82	42.20	14.39	3.68	2.50	68.35**	62.03	157.00	60.61*	33.99
DTM	12.45	68.45**	103.97**	91.87**	49.86*	35.26**	39.75**	22.99*	41.07*	35.26	15.60	14.61
TPP	93.77	54.91	0.72	0.64	1.18	0.08	104.42	71.70	72.23	47.76	74.18	49.73
FLA	9.01	15.22**	22.58**	30.22**	7.11	0.22	187.11**	8.36	8.45	20.45	6.98	7.33
PL	29.72**	33.30**	88.56**	124.16**	9.89	4.20	64.66**	14.08**	15.06	20.85	12.99**	5.30
SL	35.33**	15.46**	2.59	2.45	3.44	1.30	45.68**	18.97**	25.68	16.84	16.97**	1.86
SPP	16.93	29.78**	3.31	3.13	4.29	2.10	190.47**	34.48**	32.40	32.60	35.38**	9.15
GPS	37.37	54.44**	10.42	9.60	16.28	0.23	904.16**	47.33**	41.83	34.17	50.63**	16.07
GYPS	1.60**	0.79**	0.29	0.30	0.33	0.06	0.01	0.98**	0.99	1.67	0.90**	0.23
BYPP	10.26	23.91**	20.01*	21.30*	22.03	2.38	589.73**	10.70	13.16	4.05	10.62	8.71
HI (%)	42.67	86.79**	41.56	45.27	44.21	0.20	1330.97	69.97**	107.56	128.18	50.97*	30.92
TW	5.72	15.25	9.51	12.33	2.75	4.40	58.06*	16.07*	13.95	35.30	14.63	10.61
MC	0.04	2.35**	1.33	1.24	0.15	5.68*	0.33	2.73**	4.04	1.01	2.49**	0.86
GH	61.71*	185.65**	133.92**	132.52**	203.78**	6.94	121.43**	109.93**	127.38	173.43	187.05**	13.33
PC	3.66*	3.78**	2.40*	2.33*	2.16	3.75	6.76*	4.17**	6.52	2.12	3.61**	1.13
GC	1.09*	2.30**	1.18**	1.16**	1.58**	0.09	25.16**	2.09**	2.76	2.29	1.85**	0.29
GYPP	5.51	9.82**	2.53	3.39	0.57	0.65	9.08	12.27**	20.49	10.22	9.76**	3.23

**, ** indicate significance at the 0.05 and 0.01 probability levels, respectively*
SOV: Source of variation; df: Degree of freedom; DFF: Days to 50% flowering; PHT: Plant Height (cm); DTM: Days to maturity;
TPP: Tillers per plant; FLA: Flag Leaf Area; PL: Peduncle length (cm); SL: Spike Length (cm); SPP: Spikelets per spike; GPS: Grains per spike; GYPS: Grain yield per spikelet (g); BYPP: Biological yield per plant (g); HI (%): Harvest Index (%); TW: Test Weight (g); MC: Moisture content (%); GH: Grain Hardiness; PC: Protein content; GC: Gluten content; GYPP: Grain yield per plant (g)

Table 2. Estimation of specific combining ability with respect to 18 characters in Wheat

Parents	DFF	PHT	DTM	TPP	FLA	PL	SL	SPP	GPS	GYPS	BYPP	HI	TW	SM	GH	PC	GC	GYPP
AAIDUWL-1	-0.41	0.96	2.43*	-1.01	-0.03	-0.23	-1.59**	-2.57**	-0.94	0.04	-0.59	-0.05	-0.71	0.77**	5.38**	-1.00**	-0.73**	-0.37
AAIDUWL-2	0.09	-1.31	0.43	-1.32	-0.19	0.03	-1.03**	-0.48	-1.54	-0.22	-1.26	1.61	-1.32	-0.08	13.63**	-0.68*	-0.57**	-0.12
AADUWL-3	-1.49	1.21	-1.15	-1.02	-0.53	0.44	-0.43	-0.65	0.65	0.25	0.91	-0.80	0.75	-0.59*	3.54**	-0.38	-0.31*	0.22
AAIDUWL-4	-4.33**	-0.10	-1.73	-1.08	-0.28	-0.48	-0.69	-1.15	-1.16	-0.28*	-0.92	-2.33	-0.40	-0.52*	0.96	0.93**	0.21	-1.20*
AAIDUWL-5	4.26**	4.69*	0.68	-0.59	1.98**	2.19**	2.40**	2.68**	3.73**	0.42**	1.52*	3.61*	-0.76	-0.09	-3.63**	1.15**	0.49**	1.88**
AAIDUWL-6	-1.66	-2.74	-2.32*	-0.81	-0.78	-0.39	-0.78*	-1.15	-1.36	-0.24	-1.09	-4.79**	-0.83	-0.21	-7.46**	0.72*	0.21	-1.95**
AAIDUWL-7	4.01**	-0.09	3.10**	-0.23	0.14	0.36	2.38**	1.77*	2.33	0.45**	0.74	4.31*	2.25*	-0.54*	-18.46**	-0.53	0.08	1.72**
AAIDUWL-8	-2.74*	1.04	-1.48	-0.16	-0.94	-2.14**	-1.44**	-0.90	-2.14	-0.15	-0.92	-3.58*	-0.30	0.82**	-2.38*	-0.35	0.36*	-1.53**
AAIDUWL-9	1.76	-3.42	1.18	6.90**	0.73	0.86	0.95**	1.60	0.71	0.03	0.63	2.15	0.95	0.81**	15.71**	0.37	0.70**	0.97
AAIDUWL-10	0.51	-0.26	-1.15	-0.67	-0.11	-0.64	0.24	0.85	-0.29	-0.31*	0.99	-0.15	0.36	-0.37	-7.29**	-0.22	-0.43**	0.38
SE (gi) Line	1.13	1.85	1.07	2.35	0.65	0.75	0.36	0.87	1.26	0.14	0.70	1.68	0.98	0.25	0.98	0.30	0.15	0.58
SE(gi – gj) lines	1.60	2.61	1.52	3.32	0.93	1.06	0.50	1.23	1.78	0.19	0.99	2.38	1.38	0.36	1.39	0.42	0.22	0.36
AAIDUWL-11	-1.79**	-0.49	-0.82	1.9	-0.99**	0.54	-0.96**	-1.47**	-1.54*	-0.28**	-0.42	-0.547	-1.57**	-0.20	-4.41**	-0.35*	-0.41**	-0.4
AAIDUWL-12	2.21**	1.76	1.0	-0.65	0.14	0.61	0.83**	0.23	0.32	0.08	0.05	0.43	0.74	0.09	-6.68**	0.23	0.16	0.20
AAIDUWL-13	-0.43	-3.04**	-1.05	-0.56	-0.158	0.04	-0.13	0.23	0.31	-0.083	0.46	-2.43*	0.13	0.21	6.53**	0.19	0.09	0.20
AAIDUWL-14	0.01	1.77	0.85	-0.69	1.01**	-1.19**	0.25	1.0*	0.92	0.28**	-0.09	2.54**	0.70	-0.09	4.56**	-0.07	0.16	0.73*
SE (gi) Tester	0.71	1.17	0.68	1.49	0.41	0.47	0.23	0.55	0.80	0.09	0.44	1.07	0.62	0.16	0.62	0.19	0.10	0.81
SE(gi – gj) testers	1.01	1.65	0.96	2.10	0.59	0.67	0.32	0.78	1.12	0.12	0.63	1.51	0.88	0.23	0.88	0.27	0.14	0.52

Table 3. Estimation of specific combining ability with respect to 18 characters in Wheat

Crosses	DFF	PHT	DTM	TPP	FLA	PL	SL	SPP	GPS
AAIDUWL-1*AAIDUWL-11	2.21	1.19	-0.27	-1.67	2.16	-0.54	1.78*	2.63	3.10
AAIDUWL-1*AAIDUWL-12	-1.79	-5.29	-1.10	0.84	-0.64	-1.94	-1.61*	-0.07	3.13
AAIDUWL-1*AAIDUWL-13	-1.16	0.87	-0.70	0.11	-1.01	-0.38	0.62	0.60	2.67
AAIDUWL-1*AAIDUWL-14	0.74	3.23	2.07	0.71	-0.51	2.86	-0.80	-3.17	2.83
AAIDUWL-2*AAIDUWL-11	3.04	-2.58	3.40	-1.86	1.99	3.21*	0.89	-1.12	2.73
AAIDUWL-2*AAIDUWL-12	1.38	-8.62*	-1.10	0.72	0.53	0.81	-1.43*	-0.15	2.70
AAIDUWL-2*AAIDUWL-13	0.34	8.01*	-0.03	0.39	-1.84	-1.29	1.09	0.18	2.70
AAIDUWL-2*AAIDUWL-14	-4.76*	3.20	-2.27	0.75	-0.68	-2.73	-0.55	1.08	2.57
AAIDUWL-3*AAIDUWL-11	-3.04	-0.56	-2.35	-3.29	-1.34	-0.54	0.62	0.72	2.73
AAIDUWL-3*AAIDUWL-12	5.29*	7.26	4.15	1.82	-0.14	-1.28	3.47**	2.35	3.80
AAIDUWL-3*AAIDUWL-13	-0.41	-4.34	-1.45	0.96	0.83	0.63	-1.27	-2.65	2.87
AAIDUWL-3*AAIDUWL-14	-1.84	-2.35	-0.35	0.52	0.66	1.19	-2.82**	-0.42	3.17
AAIDUWL-4*AAIDUWL-11	2.46	1.55	1.90	-1.57	-0.59	-1.29	1.72*	2.88	2.93
AAIDUWL-4*AAIDUWL-12	-1.21	-0.67	-0.93	0.51	-1.73	-2.69	-1.21	-1.15	2.33
AAIDUWL-4*AAIDUWL-13	-0.91	-1.04	0.80	0.58	2.24	3.54*	0.45	0.52	2.73
AAIDUWL-4*AAIDUWL-14	-0.34	0.15	-1.77	0.48	0.08	0.44	-0.96	-2.25	2.47
AAIDUWL-5*AAIDUWL-11	-4.46	-2.04	0.15	-2.76	-0.84	-0.96	-3.27**	-0.95	2.70
AAIDUWL-5*AAIDUWL-12	9.21**	6.84	-0.02	1.52	1.03	0.64	2.48**	3.35	4.00
AAIDUWL-5*AAIDUWL-13	-4.49	-2.16	-1.62	0.22	-2.68*	-1.13	-2.97**	-4.32*	2.30
AAIDUWL-5*AAIDUWL-14	-0.26	-2.64	1.48	1.02	2.49	1.44	3.76**	1.92	4.27
AAIDUWL-6*AAIDUWL-11	3.79	7.46*	3.48	-1.37	0.24	-0.38	0.57	0.55	2.40
AAIDUWL-6*AAIDUWL-12	-2.21	-1.52	-3.02	0.57	-0.23	-0.11	-0.21	-0.82	2.60
AAIDUWL-6*AAIDUWL-13	0.76	-4.06	1.05	0.48	0.41	0.13	0.54	0.85	2.50
AAIDUWL-6*AAIDUWL-14	-2.34	-1.87	-1.52	0.31	-0.43	0.36	-0.90	-0.58	3.13
AAIDUWL-7*AAIDUWL-11	-3.54	-5.26	-1.93	-3.35	-1.68	-0.79	-1.95**	-1.03	2.47
AAIDUWL-7*AAIDUWL-12	1.79	1.83	2.23	1.09	2.19	1.81	1.13	0.27	3.90
AAIDUWL-7*AAIDUWL-13	-6.58**	-1.38	-1.70	1.60	-0.51	-0.29	-1.95*	-4.73**	2.90
AAIDUWL-7*AAIDUWL-14	8.33**	4.81	1.40	0.66	-0.01	-0.73	2.77**	5.50**	4.10
AAIDUWL-8*AAIDUWL-11	0.54	0.61	-0.68	-2.72	-0.26	0.71	1.67*	0.30	2.53
AAIDUWL-8*AAIDUWL-12	-3.46	-0.97	0.48	-0.15	-0.39	3.31*	-0.52	0.93	2.80
AAIDUWL-8*AAIDUWL-13	2.18	5.02	1.55	1.39	1.91	-1.46	-0.23	0.27	2.70
AAIDUWL-8*AAIDUWL-14	0.74	-4.65	-1.35	1.49	-1.26	-2.56	-0.91	-1.50	2.93
AAIDUWL-9*AAIDUWL-11	-1.96	2.07	-0.35	21.05**	-0.26	-1.63	-1.29	-3.20	2.37
AAIDUWL-9*AAIDUWL-12	-6.29**	1.49	-0.18	-7.51	1.28	-2.03	-1.34	-1.57	2.20
AAIDUWL-9*AAIDUWL-13	10.34**	-1.71	2.22	-6.40	0.24	1.21	5.32**	10.10**	4.30
AAIDUWL-9*AAIDUWL-14	-2.09	-1.85	-1.68	-7.14	-1.26	2.44	-2.70**	-5.33**	2.83
AAIDUWL-10*AAIDUWL-11	0.96	-2.43	-3.35	-2.47	0.58	2.21	-0.74	-0.78	2.20
AAIDUWL-10*AAIDUWL-12	-2.71	-0.34	-0.52	0.60	-1.89	1.48	-0.76	-3.15	2.30
AAIDUWL-10*AAIDUWL-13	-0.08	0.79	-0.12	0.67	0.41	-0.96	-1.61	-0.82	2.43
AAIDUWL-10*AAIDUWL-14	1.83	1.98	3.98	1.20	0.91	-2.73	3.11**	4.75**	3.40
SE (Sij)	2.26	3.70	2.15	4.70	1.31	1.49	0.71	1.74	2.52
SE (Sij – Skl)	3.20	5.23	3.04	6.64	1.85	2.11	1.01	2.47	3.56
SE (Sij – Sik)	5.30	8.67	5.04	11.02	3.07	3.50	1.67	4.09	5.90

Table 3 continued…

Crosses	GYPS	BYPP	HI	TW	SM	GH	PC	GC	GYPP
AAIDUWL-1*AAIDUWL-11	-0.41	-0.41	1.64	0.39	0.86	1.16	0.07	7.88	0.40
AAIDUWL-1*AAIDUWL-12	-0.22	-0.22	-2.65	1.51	0.47	-2.58	0.09	8.15	-0.87
AAIDUWL-1*AAIDUWL-13	1.70	1.70	-2.77	1.02	-0.98	10.23**	0.21	8.54	-0.13
AAIDUWL-1*AAIDUWL-14	-1.07	-1.07	3.78	-2.91	-0.35	-8.81**	-0.37	8.39	0.60
AAIDUWL-2*AAIDUWL-11	0.26	0.26	3.35	1.26	-0.58	11.58**	0.08	8.14	1.15
AAIDUWL-2*AAIDUWL-12	-0.55	-0.55	-4.17	-2.12	0.44	3.51	0.39	8.92	-1.45
AAIDUWL-2*AAIDUWL-13	0.70	0.70	2.17	-0.14	0.70	2.31	-0.42	8.15	0.95
AAIDUWL-2*AAIDUWL-14	-0.41	-0.41	-1.35	0.99	-0.56	-17.39**	-0.05	8.36	-0.65
AAIDUWL-3*AAIDUWL-11	-0.91	-0.91	-2.53	1.22	-1.04*	-14.34**	-0.44	8.44	-1.18
AAIDUWL-3*AAIDUWL-12	3.95**	3.95**	5.25	2.24	-0.60	-14.74**	0.99	9.19	3.55**
AAIDUWL-3*AAIDUWL-13	-1.13	-1.13	0.72	-1.25	0.22	3.39	-0.93	8.28	-0.38
AAIDUWL-3*AAIDUWL-14	-1.91	-1.91	-3.43	-2.21	1.42**	25.69**	0.38	8.72	-1.98
AAIDUWL-4*AAIDUWL-11	-0.74	-0.74	4.12	2.65	0.80	-26.43**	-0.82	8.27	0.90
AAIDUWL-4*AAIDUWL-12	1.11	1.11	-6.00	-1.20	-0.74	-7.83**	-0.71	9.55	-1.37
AAIDUWL-4*AAIDUWL-13	-0.96	-0.96	-1.14	-0.32	0.16	2.98	1.86**	9.57	-0.63
AAIDUWL-4*AAIDUWL-14	0.59	0.59	3.03	-1.12	-0.22	31.28**	-0.34	9.30	1.10
AAIDUWL-5*AAIDUWL-11	-0.52	-0.52	-0.73	-1.29	0.63	9.49**	-0.74	8.28	-0.52
AAIDUWL-5*AAIDUWL-12	1.77	1.77	4.53	1.89	-0.27	-19.91**	1.46*	10.63	2.22
AAIDUWL-5*AAIDUWL-13	-3.07*	-3.07*	-3.13	-0.93	0.75	42.23**	-1.35*	9.08	-2.38*
AAIDUWL-5*AAIDUWL-14	1.82	1.82	-0.68	0.34	-1.12*	-31.81**	0.62	9.82	0.68
AAIDUWL-6*AAIDUWL-11	1.42	1.42	2.15	-1.43	-1.46**	-18.34**	-0.07	8.14	1.32
AAIDUWL-6*AAIDUWL-12	-1.05	-1.05	-0.72	0.59	-0.76	18.93**	-1.25*	8.75	-0.62
AAIDUWL-6*AAIDUWL-13	1.20	1.20	-0.74	1.00	1.14*	-6.94**	1.18	10.40	0.12
AAIDUWL-6*AAIDUWL-14	-1.57	-1.57	-0.69	-0.16	1.08*	6.36**	0.14	9.43	-0.82
AAIDUWL-7*AAIDUWL-11	-0.08	-0.08	-2.05	-0.88	-0.49	9.99**	-1.09	7.95	-0.68
AAIDUWL-7*AAIDUWL-12	-0.22	-0.22	4.05	1.21	-0.21	-5.74**	1.34*	9.85	1.05
AAIDUWL-7*AAIDUWL-13	-1.63	-1.63	-4.68	-2.95	0.59	7.73**	-1.04	7.72	-2.22
AAIDUWL-7*AAIDUWL-14	1.93	1.93	2.67	2.62	0.11	-11.98**	0.79	10.66	1.85
AAIDUWL-8*AAIDUWL-11	-1.74	-1.74	1.78	1.37	0.23	5.24**	0.38	9.48	-0.10
AAIDUWL-8*AAIDUWL-12	0.11	0.11	1.16	-1.91	-0.19	2.18	-0.86	8.95	0.30
AAIDUWL-8*AAIDUWL-13	0.70	0.70	2.39	1.47	-0.29	-17.36**	0.80	9.73	1.03
AAIDUWL-8*AAIDUWL-14	0.93	0.93	-5.33	-0.93	0.25	9.94**	-0.33	9.09	-1.23
AAIDUWL-9*AAIDUWL-11	1.04	1.04	-5.27	-1.98	0.99	20.49**	-0.18	9.11	-1.27
AAIDUWL-9*AAIDUWL-12	-3.77**	-3.77**	-0.19	0.04	1.02*	6.09**	-0.47	9.49	-1.87
AAIDUWL-9*AAIDUWL-13	3.35*	3.35*	8.83*	3.59	-1.62**	-34.78**	0.50	10.80	4.53**
AAIDUWL-9*AAIDUWL-14	-0.62	-0.62	-3.38	-1.65	-0.39	8.19**	0.15	9.28	-1.40
AAIDUWL-10*AAIDUWL-11	1.68	1.68	-2.46	-1.32	0.05	1.16	2.79**	9.86	-0.02
AAIDUWL-10*AAIDUWL-12	-1.13	-1.13	-1.27	-2.24	0.84	20.09**	-0.99	7.83	-0.95
AAIDUWL-10*AAIDUWL-13	-0.87	-0.87	-1.65	-1.49	-0.67	-9.78**	-0.81	8.26	-0.88
AAIDUWL-10*AAIDUWL-14	0.32	0.32	5.38	5.04*	-0.22	-11.48**	-0.99	8.22	1.85
SE (Sij)	0.27	1.40	3.37	1.96	0.51	1.96	0.60	0.31	1.15
SE (Sij – Skl)	0.38	1.99	4.77	2.77	0.72	2.77	0.85	0.43	1.63
SE (Sij – Sik)	0.64	3.29	7.90	4.59	1.19	4.60	1.41	0.72	2.70

5. CONCLUSION

The traits identified for wheat improvement include days to flowering (DF), plant height (PHT), spikelets per spike, effective tillers per plant, biological yield per plant, harvest index, grain yield per spike, and grain yield per plant. These traits exhibited significant genetic variability, highlighting the value of diverse genetic resources in developing superior hybrids. AAIDUWL-4 and AAIDUWL-8 were prominent for early-flowering varieties, while AAIDUWL-5 and AAIDUWL-7 were promising for late-flowering types. For plant height, AAIDUWL-5 and AADUWL-3 stood out, making them suitable for biomass production and lodging resistance.

AAIDUWL-7 and AAIDUWL-1 were identified as the best general combiners for early maturity, crucial for avoiding end-of-season drought stress. AAIDUWL-9 showed the highest effect for tillers per plant, with AAIDUWL-11 being the top tester. Flag leaf area, critical for photosynthetic efficiency, was enhanced by AAIDUWL-5 and AAIDUWL-9, with AAIDUWL-14 as the leading tester.

For grain structure, AAIDUWL-5 and AAIDUWL-7 excelled in spike length and spikelets per spike, with AAIDUWL-14 being the key tester. Grains per spike and grain number were highest in AAIDUWL-5 and AAIDUWL-14, essential for yield improvement. Grain yield per spike was positively influenced by AAIDUWL-5 and AAIDUWL-7, with AAIDUWL-14 being a significant tester, making these genotypes valuable for improving grain yield. Biological yield per plant was maximized by AAIDUWL-5 and AADUWL-3, suggesting their potential to boost biomass production.

For grain quality, AAIDUWL-7 and AAIDUWL-9 demonstrated high harvest index values, while test weight was enhanced by AAIDUWL-7 and AADUWL-3. Grain hardness was highest in AAIDUWL-9 and AAIDUWL-2, with AAIDUWL-12 and AAIDUWL-13 excelling among testers. Protein content was improved by AAIDUWL-5 and AAIDUWL-12, and gluten content was enhanced by AAIDUWL-9 and AAIDUWL-5, making them ideal for baking quality improvement.

The SCA analysis highlighted non-additive genetic effects, with AAIDUWL-9 × AAIDUWL-13 showing the highest SCA effects for grain yield per plant and harvest index, and AAIDUWL-3 × AAIDUWL-12 excelling in grain yield per spike and biological yield per plant. These results demonstrate the importance of selecting specific line-tester combinations to maximize hybrid performance and improve both yield and quality in wheat breeding programs.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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