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Genetic analysis of wheat (*Triticum aestivum* L. em. Thell) hybrids using line × tester mating design for yield and its contributing traits

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Abstract
This study evaluated the combining ability (GCA and SCA) and genetic variability among 14 parental wheat lines (10 females, 4 males) and 40 F_1 hybrids developed using a line × tester mating design. The experiment was conducted during the *rabi* season 2020-21 and 2021-22 at the Research Farm of BRD (PG) College, Deoria, with randomized block design (RBD) in three replications. The study assessed multiple agronomic traits, including plant height, days to 50% flowering, spike length, and grain yield. ANOVA results confirmed significant genetic variability across hybrids, highlighting both additive and non-additive genetic effects. GCA analysis identified DBW-14 and PBW-550 as promising parents for improving yield, plant architecture, and protein content. SCA analysis revealed hybrids like NW-2036 × K-9107 and HD-2888 × HD-3171 as superior for early flowering, reduced plant height, and high grain yield. These findings provide valuable insights for breeders in selecting suitable parents and hybrid combinations to enhance wheat productivity and meet diverse agricultural demands.

Keywords: Wheat, hybrid, combining ability, mating design

1. Introduction
Wheat is a vital global food crop and holds a significant place in Indian agriculture, ranking second after rice. As a key cereal, it supports food security, poverty alleviation, and livelihoods (Kumar *et al.*, 2017) [11]. Contributing around 30% to the nation's food basket, wheat is cultivated extensively as a staple crop (Singh *et al*., 2023) [15]. Grain yield components show varied relationships with yield and each other (Edae *et al.*, 2014) [4]. Heterosis exploitation boosts productivity, and combining ability analysis helps breeders pick suitable parents (Begna, 2021) [2]. This process reveals gene actions behind trait expression, shaping breeding strategies. It aids in selecting desirable genotypes and viable cross combinations (Singh *et al.*, 2020) [14]. Assessing genotype performance is crucial for effective hybridization, with diallel, partial diallel, and line x tester designs offering useful methods. The line x tester design evaluates specific combining ability (SCA) for individual crosses and general combining ability (GCA) for lines and testers, refining breeding strategies (Maan and Yadav, 2022) [13].

2. Materials and Methods
The experimental materials for this study consisted of 55 wheat treatments, including 40 F_1 hybrids, 14 parental lines (10 females and 4 males), and one standard variety used as a check (HD-3086). The parental lines included 10 lines K-1006, NW-2036, HD-2888, PBW-343, DBW-14, RAJ-4120, PBW-550, PBW-502, HD-2643 and DBW-107, with 4 testers (males) viz., HD-2967, HD-3171, K-1317, K-9107. The experimental hybrids were developed using a line × tester mating design during the 2021-2022 *rabi* season at the Research Farm of BRD (PG) College, Deoria (Affiliated with DDU Gorakhpur University, Gorakhpur, Uttar Pradesh. These hybrids, along with their 14 parental lines and the standard check variety HD-3086, were evaluated using randomized block design (RBD) with three replications during *rabi* seasons in 2021-22.

3. Statistical Analysis

The analysis of variance (ANOVA) was conducted following Hayman (1954) [6], and combining ability for the line x tester design was analyzed using Kempthorne's method (1957) [9]. Data was processed in R using the Agricolae package (Version 1.3-5). Combining ability for each trait was calculated based on Hayes *et al.* (1955) [7].

4. Results and Discussion

4.1 Analysis of Variance (ANOVA)

The ANOVA for combining ability reveals significant genetic variability among hybrids, assessing both general (GCA) and specific combining ability (SCA). Crosses showed highly significant effects across all traits, emphasizing genetic diversity. Line effects were significant for maturity, while traits like spike length had non-significant line effects, indicating limited variability from lines. Tester effects were mostly non-significant but showed high variance for plant height. Significant line × tester interactions across multiple traits, including flowering, maturity, and yield-related traits, highlight the importance of specific parent combinations for effective trait improvement (Iannucci. and Codianni 2019) [8].

4.4. Combining ability effects

4.4.1 General Combining ability effects (GCA)

The GCA analysis identifies key parental lines based on their contributions to desirable traits, which is crucial for effective breeding programs. For early flowering, PBW-343 (-4.30**) and HD-2888 (-1.47*) emerge as strong general combiners. Reduced plant height is supported by HD-2643 (-3.90*) and RAJ-4120 (-3.11), while early maturity is favored by RAJ-4120 (-2.31**) and PBW-502 (-1.48*). For increased tillers, PBW-502 (0.635**) and PBW-550 (0.55**) show positive effects. In terms of leaf area, DBW-14 (2.78*) contributes significantly. Spike length is enhanced by DBW-14 (2.39**) and PBW-550 (2.37**). For grain yield, DBW-14 (1.91**) and PBW-550 (1.74**) demonstrate strong potential, while protein content is notably improved by K-9107 (2.78*) and DBW-14 (1.87). Overall, DBW-14 and PBW-550 exhibit consistently positive GCA effects across multiple traits, marking them as ideal candidates for breeding efforts. Meanwhile, RAJ-4120 and PBW-502 show negative GCA effects for traits like early flowering, reduced height, and early maturity, making them valuable for programs focusing on these characteristics (Khan *et al*., 2019) [10].

4.4.2 Specific Combining ability effects (SCA)

The specific combining ability (SCA) effects reveal valuable insights into various traits in wheat breeding. For days to 50% flowering (DF), negative SCA effects like in NW-2036 x K-9107 (-4.77**) indicate early flowering, while positive effects such as in DBW-14 x HD-3171 (9.19**) suggest delayed flowering. In plant height (PHT), crosses like NW-2036 x HD-3171 (-9.81**) show reduced height, whereas NW-2036 x K-1317 (9.24*) results in taller plants. For days to maturity (DTM), negative SCA effects (e.g., DBW-107 x HD-2967: -3.35*) signify early maturity, and positive ones (e.g., HD-2888 x HD-3171: 4.15**) indicate delayed maturity (Singh *et al*., 2020) [14].

The SCA effects for tillers per plant (TPP) show that fewer tillers are produced in PBW-550 x HD-2967 (-1.01**), while HD-2888 x HD-3171 (1.06**) leads to more tillers. In flag leaf area (FLA), crosses like DBW-14 x K-1317 (-3.78) have smaller leaves, and DBW-14 x K-9107 (3.52) larger ones. For peduncle length (PL), shorter lengths are observed in DBW-107 x K-9107 (-2.72**), whereas DBW-14 x K-1317 (3.53**) produces longer peduncles (Fasahat *et al*., 2016) [5].

Traits like spike length (SL) show shorter spikes in DBW-14 x K-1317 (-4.12**) and longer spikes in HD-2643 x K-1317 (5.31**). Similarly, spikelets per spike (SPP) are fewer in DBW-14 x K-1317 (-5.38**) but increase in HD-2643 x K-1317 (8.38**). For grains per spike (GPS), PBW-550 x K-1317 (-5.61**) has fewer grains, while HD-2643 x K-1317 (12.59**) produces more. Grain yield per spike (GYPS) is reduced in PBW-550 x HD-2967 (-0.60**) but enhanced in HD-2643 x K-1317 (1.49**). In biological yield per plant (BYPP), HD-2888 x K-9107 (-3.67*) shows lower yield, while HD-2888 x HD-3171 (3.94**) increases it. Harvest index (HI) decreases in RAJ-4120 x HD-3171 (-6.99**) but improves in HD-2888 x HD-3171 (5.27**). For test weight (TW), PBW-550 x K-1317 (-4.42**) has lower values, while HD-2888 x HD-3171 (2.66**) shows better weight. In grain yield per plant (GYPP), DBW-14 x K-1317 (-2.41**) results in lower yields, while DBW-107 x K-9107 (4.87**) boosts it. Grain hardness (GH) decreases in HD-2888 x HD-3171 (-6.2), but K-1006 x K-1317 (8.60*) shows harder grains. For protein content (PC), crosses like PBW-343 x K-1317 (-6.52**) have lower protein, whereas HD-2643 x HD-2967 (3.47**) enhances it. These SCA effects highlight the potential of specific parental combinations to achieve targeted traits like early flowering, shorter plants, or higher grain yield, crucial for effective wheat breeding programs (Edae *et al*., 2014. Liu *et al*., 2021) [4, 12].

Table 1: Analysis of variance for combing ability

SOV	df	Days to 50% Flowering	Plant Height (cm)	Days to Maturity	Tillers per Plant	Flag Leaf Area (cm²)	Peduncle Length (cm)	Spike Length (cm)	Spikelets per Spike
Replicates	2	4.29	68.40	15.09	0.36	8.28	0.06	3.22*	15.86**
Crosses	39	70.32**	94.82**	22.98**	1.74**	16.67*	14.07**	18.97**	30.30**
Line Effect	9	92.08	82.52	41.07*	2.13	16.84	15.05	25.69	30.18
Tester Effect	3	85.09	200.99	35.26	2.80	40.78	20.87	16.83	31.90
Line * Tester Eff.	27	61.43**	87.13*	15.59**	1.49**	13.94	12.99**	16.97**	30.16**
Error	78	3.34	47.81	5.39	0.24	10.55	3.04	0.84	2.38
Total	119	25.31	63.57	11.32	0.73	12.52	6.61	6.82	11.76

SOV	df	Grains per Spike	Grain Yield per Spike (g)	Biological Yield per Plant (g)	Harvest Index (%)	Test Weight (g)	Grain Yield per Plant (g)
Replicates	2	2.21	0.09	5.53	28.64*	1.99	2.53
Crosses	39	47.36**	1.03**	10.70**	81.76**	22.80**	12.63**
Line Effect	9	41.42	0.88	13.17	146.01*	19.81	20.71
Tester Effect	3	34.84	1.77	4.05	153.55	50.11	9.87
Line * Tester Eff.	27	50.73**	1.01**	10.62**	52.36**	20.77**	10.25**
Error	78	8.10	0.04	2.23	7.94	2.90	0.95
Total	119	20.87	0.37	5.06	32.48	9.41	4.80

*, ** indicate significance at the 0.05 and 0.01 probability levels, respectively

Table 2: Estimation of general combining ability with respect to 14 characters in Wheat

Parents	Days to 50% Flowering	Plant Height (cm)	Days to Maturity	Tillers per Plant	Flag Leaf Area (cm²)	Peduncle Length (cm)	Spike Length (cm)	Spikelets per Spike
K-1006	-0.56	0.43	2.43**	0.04	-0.03	-0.23	-1.58**	-2.50**
NW-2036	0.11	-1.45	0.43	-0.56**	-0.27	0.03	-1.02**	-0.42
HD-2888	-1.47*	1.49	-1.15	-0.26	-0.74	0.44	-0.43	-0.59
PBW-343	-4.30**	-0.04	-1.73*	-0.31*	-0.39	-0.48	-0.68*	-1.08*
DBW-14	4.27**	5.5**	0.68	0.19	2.78*	2.19**	2.39**	2.74**
RAJ-4120	-1.64**	-3.11	-2.31**	-0.55**	-1.09	-0.39	-0.78**	-1.08*
PBW-550	4.02**	-0.03	3.10**	0.55**	0.2	0.36	2.37**	1.83**
PBW-502	-2.72**	1.29	-1.48*	0.63**	-1.33	-2.14**	-1.43**	-0.84
HD-2643	1.77**	-3.90*	1.18	0.18	1.02	0.86	0.94**	1.02*
DBW-107	0.52	-0.22	-1.15	0.1	-0.15	-0.64	0.24	0.913 *
HD-2967	-1.82	-0.49	-0.81	-0.45	-1.4	0.54*	-0.94**	-1.40**
HD-3171	2.22	1.81	1.01	0.13	0.19	0.60*	0.82**	0.29
K-1317	-0.4	-3.46	-1.05	-0.1	-0.22	0.04*	-0.12	0.04
K-9107	0.02	2.13	0.85	0.08	0.08	-1.19*	0.25	1.06**

Parents	Grains per Spike	Grain Yield per Spike (g)	Biological Yield per Plant (g)	Harvest Index (%)	Test Weight (g)	Grain Yield per Plant (g)
K-1006	-0.95	0.05	-0.59	0.2	-0.85	-0.34
NW-2036	-1.44	-0.20**	-1.25*	1.85*	-1.57**	-0.38
HD-2888	0.63	0.26**	0.91	-0.55	0.9	0.25
PBW-343	-1.17	-0.26**	-0.92	-2.07*	-0.48	-1.17**
DBW-14	3.72**	0.31**	1.52**	3.85**	-0.91	1.91**
RAJ-4120	-1.37	-0.22**	-1.09*	-6.99**	-0.98*	-1.92**
PBW-550	2.32**	0.46**	0.74	4.55**	2.68**	1.74**
PBW-502	-2.14**	-0.141 *	-0.92	-3.33**	-0.35	-1.50**
HD-2643	0.7	0.04	0.63	2.39**	1.13*	0.99**
DBW-107	-0.29	-0.300 ***	0.99	0.1	0.43	0.41
HD-2967	-1.55**	-0.266**	-0.42	-0.52	-1.87**	-0.37*
HD-3171	0.3	0.09**	0.05	0.41	0.88**	0.11
K-1317	0.3	-0.11**	0.46	-2.67**	0.15	-0.50**
K-9107	0.94	0.28**	-0.09	2.78**	0.83	0.76**

Table 3: Estimation of specific combining ability with respect to 15 characters in Wheat

Crosses	Days to 50% Flowering	Plant Height (cm)	Days to Maturity	Tillers per Plant	Flag Leaf Area (cm²)	Peduncle Length (cm)	Spike Length (cm)	Spikelets per Spike
K-1006 x HD-2967	1.75	2.07	-0.26	0.39	3.05	-0.54	1.78**	2.56**
K-1006 x HD-3171	-1.64	-8.23*	-1.09	0.91**	-0.90	-1.94*	-1.60**	-0.13
K-1006 x K-1317	-1.00	1.70	-0.70	-0.96**	-1.42	-0.37	0.61	0.79
K-1006 x K-9107	0.89	4.45	2.06	-0.35	-0.72	2.85**	-0.79	-3.22**
NW-2036 x HD-2967	3.09**	-3.07	3.39	0.48	2.81	3.20**	0.88	-1.18
NW-2036 x HD-3171	1.35	-9.81**	-1.03	-0.06	0.74	0.81	-1.42*	-0.21
NW-2036 x K-1317	0.32	9.24*	-0.03	-0.39	-2.60	-1.29	1.09	-2.45**
NW-2036 x K-9107	-4.77**	3.64	-2.26	-0.02	-0.95	-2.72**	-0.55	-0.48
HD-2888 x HD-2967	-2.99*	-0.73	-2.34	-0.99**	-1.89	-0.54	0.62	0.65
HD-2888 x HD-3171	5.27**	8.68*	4.15**	1.06**	-0.19	-1.27	3.47**	2.28*
HD-2888 x K-1317	-0.42	-5.13	-1.44	0.18	1.16	0.62	-1.27*	-2.45**
HD-2888 x K-9107	-1.80	-2.81	-0.35	-0.26	-0.95	1.19	-2.82**	-0.48
PBW-343 x HD-2967	2.50	1.72	1.90	0.78**	-0.83	-1.29	1.71**	2.82**
PBW-343 x HD-3171	-1.22	-0.54	-0.93	-0.28	-2.43	-2.69**	-1.20*	-1.21
PBW-343 x K-1317	-0.92	-1.28	0.79	-0.19	3.16	3.53**	0.45	0.70
PBW-343 x K-9107	-0.35	0.10	-1.76	-0.30	0.10	0.44	-0.96	-2.31*
DBW-14 x HD-2967	-4.40**	-2.45	0.15	-0.44	-1.18	-0.95	-3.26**	-1.01
DBW-14 x HD-3171	9.19**	8.19*	-0.01	0.75**	1.44	0.69**	2.48**	3.28
DBW-14 x K-1317	-4.50**	-2.59	-1.61	-0.56*	-3.78	3.53**	-2.96**	-4.12**
DBW-14 x K-9107	-0.27	-3.14	1.48	0.25	3.52	1.44	3.75**	1.85*
RAJ-4120 x HD-2967	3.84**	8.60*	3.48	-0.44	0.34	-0.38	0.57	0.48
RAJ-4120 x HD-3171	-2.22	-1.54	-3.09*	0.75**	-0.31	-0.11	-0.21	-0.88
RAJ-4120 x K-1317	0.74	-4.80	1.05	-0.56*	0.57	0.12	0.54	1.04
RAJ-4120 x K-9107	-2.36**	-2.25	-1.51	0.25	-0.59	0.36	-0.90	-0.64
PBW-550 x HD-2967	-3.49**	-6.20	-1.93	-1.01**	-2.36	-0.79	-1.94**	-1.09
PBW-550 x HD-3171	1.77	2.35	2.23	0.31	3.09	1.80*	1.12	0.20
PBW-550 x K-1317	-6.52**	-1.68	-1.69	0.85**	-0.71	-0.29	-1.95**	-4.54**
PBW-550 x K-9107	8.30**	5.52	1.39	-0.11	-0.01	-0.72	2.77**	5.43**
PBW-502 x HD-2967	0.59	0.62	-0.68	-0.41	-0.36	0.70	1.66**	0.23
PBW-502 x HD-3171	-6.30**	-0.90	0.48	-0.81**	-0.55	3.30**	-0.52	0.86
PBW-502 x K-1317	2.15	5.77	1.55	0.63*	2.69	-1.45	-0.23	0.45
PBW-502 x K-9107	0.72	-5.49	-1.34	0.73**	-1.77	-2.55**	-0.90	-1.56
HD-2643 x HD-2967	-1.91	2.33	-0.35	0.90**	-0.36	-1.62	-1.28	-2.62**
HD-2643 x HD-3171	-6.30**	1.97	-0.18	-0.81**	1.80	-2.02*	-1.34*	-0.99
HD-2643 x K-1317	10.32**	-2.06	2.21	0.33	0.34	1.20	5.31**	8.38**
HD-2643 x K-9107	-2.10	-2.23	-1.68	-0.42	-1.77	2.43**	-2.69**	-4.76
DBW-107 x HD-2967	1.01	-2.90	-3.35*	-0.14	0.81	2.20*	-0.74	-0.85
DBW-107 x HD-3171	-2.72*	-0.16	-0.51	-0.19	-2.67	1.47	-0.76	-3.21**
DBW-107 x K-1317	-0.08	0.84	-0.12	-0.10	0.57	-0.95	-1.60**	-0.62
DBW-107 x K-9107	1.80	2.22	3.98**	-0.44	1.28	-2.72**	3.11**	4.68**

Crosses	Grains per Spike	Grain Yield per Spike (g)	Biological Yield per Plant (g)	Harvest Index (%)	Test Weight (g)	Grain Yield per Plant (g)
K-1006 x HD-2967	1.17	0.433**	-0.40	1.61	0.46	0.36
K-1006 x HD-3171	1.19	0.10	-0.21	-2.62	1.79	-0.77
K-1006 x K-1317	0.28	-0.14	1.70	-2.51	1.21	0.16
K-1006 x K-9107	-2.65	-0.39**	-1.07	3.53*	-3.47**	0.57
NW-2036 x HD-2967	0.94	0.32**	0.25	3.32*	1.50	1.41**
NW-2036 x HD-3171	2.18	-0.07	-0.55	-4.15*	-2.52**	-2.25**
NW-2036 x K-1317	-4.61**	0.14	0.70	2.42	-0.16	-0.41
NW-2036 x K-9107	1.49	-0.39**	-0.40	-1.59	1.18	-2.01**
HD-2888 x HD-2967	1.69	-0.14	-0.91	-2.55	1.45	-1.21*
HD-2888 x HD-3171	-1.13	0.56**	3.94**	5.27**	2.66**	3.63**
HD-2888 x K-1317	2.74	-0.15	-1.30	0.96	-1.48	-0.41
HD-2888 x K-9107	-1.79	-0.26*	-1.90	-3.67*	-2.63**	-2.01**
PBW-343 x HD-2967	1.69	0.58**	-0.74	4.09*	3.15**	0.87*
PBW-343 x HD-3171	-1.13	-0.37**	1.11	-5.98**	-1.43	-1.27*
PBW-343 x K-1317	2.74	-0.15	-0.96	-0.89	-0.38	-0.66
PBW-343 x K-9107	-3.30*	-0.26*	0.59	2.77	-1.33	1.06*
DBW-14 x HD-2967	0.27	-0.23*	1.42	-0.75	-1.54	-0.54
DBW-14 x HD-3171	1.44	0.70**	-1.05	4.54**	2.25*	2.30**
DBW-14 x K-1317	-5.38**	-1.24**	1.20	-2.87	-1.11	-2.41**
DBW-14 x K-9107	3.67*	0.77**	-1.57	-0.92	0.40	1.06*
RAJ-4120 x HD-2967	-1.57	0.01	1.42	2.35	-1.69	1.28*
RAJ-4120 x HD-3171	-0.89	-0.15	-1.05	-0.88	0.70	-0.52

RAJ-4120 x K-1317	1.34	-0.04	1.20	-2.98	1.19	0.08
RAJ-4120 x K-9107	1.31	0.18	-1.57	1.51	-0.19	-0.84
PBW-550 x HD-2967	-2.89	-0.60**	-0.07	-2.07	-1.04	-0.71
PBW-550 x HD-3171	2.94	0.46**	-0.22	4.07*	1.43	1.13*
PBW-550 x K-1317	-4.98**	-0.32**	-.1.63	-4.42**	-3.51**	-2.24**
PBW-550 x K-9107	4.93**	0.47**	1.93	2.42	3.12**	1.82**
PBW-502 x HD-2967	2.93	0.05	-1.74	1.76	1.63	-0.04
PBW-502 x HD-3171	-0.72	-0.03	0.22	1.18	-2.27*	-0.86
PBW-502 x K-1317	-0.68	0.07	-1.63	2.63	1.75	-0.91
PBW-502 x K-9107	-1.52	-0.09	1.93	-5.57**	-1.10	1.82**
HD-2643 x HD-2967	-2.58	-0.29*	1.03	-5.28**	-2.35*	1.65**
HD-2643 x HD-3171	-4.10**	-0.81**	-3.76**	-0.16	0.04	0.06
HD-2643 x K-1317	12.59**	1.49**	3.35**	9.07**	4.27**	2.65**
HD-2643 x K-9107	4.93**	-0.38**	-0.62	-3.62*	-1.96*	3.87**
DBW-107 x HD-2967	-1.08	-0.11	1.68	-2.48	-1.57	1.32
DBW-107 x HD-3171	-3.74*	-0.37**	-1.12	-1.25	-2.66**	4.87**
DBW-107 x K-1317	0.86	-0.03	-0.87	-1.40	-1.77	-1.23
DBW-107 x K-9107	3.95*	0.53	0.32	5.13**	6.01**	4.54**

5. Conclusion
The analysis of variance (ANOVA) and combining ability effects reveal significant genetic variability among hybrids, emphasizing the importance of both general (GCA) and specific combining ability (SCA) in wheat breeding. The ANOVA results highlight those certain traits, such as plant height, exhibit substantial genetic variability, while others, like spike length, show limited variation from parental lines. Significant line × tester interactions across key traits, including flowering, maturity, and yield, indicate the value of specific parental combinations for enhancing desirable characteristics.

GCA analysis identifies promising parental lines such as DBW-14 and PBW-550, which show positive effects across multiple traits, making them ideal candidates for breeding programs aimed at improving yield, plant architecture, and protein content. On the other hand, RAJ-4120 and PBW-502 demonstrate negative GCA effects, making them suitable for developing varieties with reduced height, early flowering, and maturity.

The SCA effects further emphasize the importance of targeted crosses, with combinations like NW-2036 x K-9107 promoting early flowering, and NW-2036 x HD-3171 reducing plant height. Hybrids such as HD-2888 x HD-3171 excel in multiple traits, including grain yield, biological yield, and harvest index, showcasing the potential of heterosis in wheat breeding. These insights into GCA and SCA provide a roadmap for selecting parent lines and hybrid combinations to achieve specific breeding goals, ultimately contributing to the development of improved wheat varieties tailored to diverse agricultural needs.

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7. Conflict of interest declaration
The authors declare no conflicts of interest.

8. Ethical issues
None.

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