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Combining Ability Estimates from Line × Tester Analysis of Grain Yield and Physiological Traits of Wheat Genotypes Under Water Stress Condition

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Abstract. Physiological parameters are good indicators for the development of water stress tolerant wheat genotypes through conventional plant breeding without involving of physiological traits it is hard task to developed the water stress tolerant thus present study is aimed to determine the general and specific combiners for yield and physiochemical trait. The mean square form analysis of variances showed that genotypes, treatment and treatment × genotypes were significant for all the traits like grain yield Kg/ha, biological yield Kg/ha, relative water content, leaf area, chlorophyll content, spike fertility and cell membrane stability. Among the genotypes TJ-83, NIA-Saarang, Sindhu, Benazir and TD-1 were proved good combiners for all the traits whereas F_1 hybrids Benazir × NIA-Saarang, Benazir × Imdad-05, Sindhu × NIA-Amber and TJ-83 × Imdad-05 were showed good specific combiners for all the traits under water stress conditions. Above parent and hybrids should be utilized in breeding programme for the development water stress tolerant wheat genotypes.

Keywords: combining ability, GCA, SCA, water stress, yield, physiological traits, wheat

Introduction

Water stress is one of the leading stresses in world food supply that affects plant growth and development, ultimately affecting yield and yield contributing traits (Sattar *et al*., 2018). The world wheat production stood at 767 million tons (FAO, 2018). It is one of the four main agricultural crops in Pakistan and 80% farmers are growing wheat on an area of around 9.0 million hectares which is close to 40% of the country's total cultivated land (Raza *et al.*, 2017). Wheat crop showed marginal increase of 0.5% (25.195 million tons) over last year's production of 25.076 million tons but failed to meet the target by 4.9%. Evolution of drought tolerant varieties is a long, hard and complex process when the motive involved is the incorporation of grain yield into otherwise desirable genotypes adapted for drought situations. To further identify ways for traditional or empirical approach where selection may focus on yield, analytical approach for selection seeks out character other than yield that may have agronomic advantages (Jatoi *et al*., 2021; Muneer *et al*., 2016). Line × tester analysis is one of the breeding strategies that efficiently evaluates the combining abilities of genotypes and also provides information regarding genetic mechanisms controlling polygenic traits. Knowledge of general combining ability (GCA) and specific combining ability (SCA) of inbred lines for yield and its components has become increasingly important to plant breeders in the choice of selecting parents for developing potential hybrids in many crop plants (Kempthorne, 1957).

Punjab and Sindh the major wheat growing provinces have faced water shortage up to 20% in Rabi season (IRSA, 2018). It was estimated that total water availability of 29.48 million acre feet (MAF) including 24 MAF will be achieved from river flows and about 7.8 MAF currently stored in two reservoirs. The major part of irrigation water is not utilized by the crop and the combined effect of leakage, wastage and seepage reaches upto 40% water losses. The wheat crop in Sindh faced acute shortage of irrigation water and it caused serious damage in the mid-February to whole month of March because at that time the crop was at critical stages like milky to grain formation that caused about 10-20% yield losses. Sindh province experienced very low rainfall and arid climate during most of the year. At present, an area of some 2.4 million acres is under wheat cultivation all over Sindh. If wheat crop fails to get last round of irrigation during anthesis to grain formation stages, the total yield could have been at 2.6 million

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tons against 3.5 million tons target set for Sindh (IRSA, 2018). Present studies therefore are aimed at determining the general and specific combining ability of parents thereby knowing gene actions functioning for various morpho-phyisological traits in bread wheat genotypes.

Materials and Methods

In this research, six female lines i.e. Benazir, Sindhu, Ujala-2015, Moomal-2002, TD-1 and TJ-83 were crossed with three testers (males) *viz*. Imdad-2005, NIA-Amber and NIA-Saarang into line x tester mating design, thus eighteen crosses were developed (Table 2). The F_1 hybrids and their parents were sown in split plot design with two treatments (stress and non-stress) in four replications at the experimental field of the Department of Plant Breeding and Genetics, Sindh Agriculture University, Tandojam. The data were analyzed for determining general and specific combining ability variances and their effects for grain yield (Kg/ha), biological yield (Kg/ha), relative water content in leaves, chlorophyll content (R.G), flag leaf area (cm^2), spike fertility (%) and cell membrane stability. The collected data were subjected to analysis of variance according to procedures outlined by Gomez and Gomez (1984). The software Statistics Version-8 was used for data analysis. The estimates of combining ability were computed by developing formula in excel version-10 and using lines × tester procedure development by Kempthorne (1957) and adopted by Singh and Chaudhary (1984). The characters were measured in the following method.

Grain yield (Kg/ha). It was calculated by using following formula;

Grain yield/plot (Kg) divided by plot size (m^2) multiplied with hectare (10,000 m^2).

Biological yield (Kg/ha). It was calculated by using following formula;

Biological yield/plot (Kg) divided by plot size (m^2) multiplied with hectare (10,000 m^2).

Relative water content (%). Relative water content (RWC %) was determined according to the method adopted by Bayoumi *et al*. (2008) and Jatoi (2013). Ten fully expanded leaves were sampled from each of the three replications. The leaf sample were fresh weighed (FW), wilted for 4 h in distilled water and turgid weight (Tw) was calculated and after that leaves were oven dried for 24 h at 72 °C to obtain dry weight (DW). The relative water content was calculated as under:

$$\text{RWC \%} = [(\text{FW-DW}) / (\text{TW-DW})] \times 100$$

Flag leaf area/cm². Flag leaf area/cm^2 measurement was taken with the help of measuring tape. The leaf area was determined by measuring leaf length and width then multiplied them as follows:

$$\text{Leaf area} = (\text{length} \times \text{width}) \times b$$

Spike fertility. The spike fertility was recorded as the ratio of fertile and non-fertile spikelets.

Chlorophyll content. SPAD Chlorophyll was measured through SPAD chlorophyll meter.

Cell membrane stability (CMS). The CMS was determined by the procedure suggested by Blum and Ebercon (1981) using following formula:

$$\text{CMS (\%)} = \frac{1-(T_1/T_2)}{1-(C_1/C_2)} \times 100$$

where:

T and C refer to treatment and control, respectively and 1 and 2 refer to initial and final conductance readings, respectively.

Results and Discussions

The combined ANOVA of F_1 hybrids along with parents showed that treatments, genotypes and treatment × genotypes revealed significant differences for grain yield in Kg/ha, biological yield (Kg/ha), relative water content, leaf area, chlorophyll content, spike fertility and cell membrane stability. The significant mean squares indicated that genotypes performed differently for all the traits which indicated that they can be improved with simple phenotypic selection. Yield and physiological traits were significantly affected by water stress as reported by Jatoi (2013) and data shown in Table 1.

Mean performance of parents and F_1 hybrids for yield and physiological traits. The data regarding mean performance of parents and hybrids for yield and physiological traits are presented in Tables 2-3 which showed that Benazir, TJ-83, Ujala-2015, Moomal-2002 showed minimum declines for grain yield, while NIA-Saarang, TJ-83, Ujala-2015 and NIA-Amber expressed good performance. Among the eighteen hybrids developed from 6 line × 3 testers through line × tester crosses, hybrids Ujala-2015 × Imdad-05, TJ-83 × Imdad-05, TJ-83 × NIA-Amber, Ujala-2015 × NIA-Saarang, and TJ-83 × NIA-Saarang expressed good performance under water stress for various yield traits, while hybrids like Benazir × NIA-Amber, Sindhu × NIA-Amber, Ujala-2015 × Imdad-05, TJ-83 × Imdad-05 and Moomal-2002 × NIA-Saarang manifested minimum decline in total biomass. Among the parents, Benazir, TD-1, NIA-Saarang and Moomal-2002 recorded maximum relative water content in leaf (94.00%) and broader leaf area (30.25%), greater spike fertility (97.50%), more chlorophyll content (54.32%) and higher cell membrane stability (86.75%) under non-stress conditions (Tables 2 and 3). In water-stress conditions, TJ-83 and Imdad-05 maintained higher relative water content with 73.49% and 71.64% thus showed smaller relative decrease of -16.75 and -21.85% respectively. The NIA-Amber recorded wider leaves (23.87%) followed by Sindhu (23.25%) and correspondingly showed small relative decrease in flag leaf area as -5.25 and -6.75 cm^2 respectively (Table 2). Parent Imdad-05 recorded maximum spike fertility (72.19%) followed by TJ-83 (71.38%). Generally, the parents TD-1, NIA-Amber and Benazir were observed as highly drought tolerant and gave increased chlorophyll content of 67.50, 67.25 and 66.00 rg respectively. For cell membrane, only three out of nine parents such as Sindhu (87.03%), Imdad-05 (86.48%) and Benazir (85.67%) recorded higher cell membrane stability in stress condition.

Regarding the performance of F_1 hybrids per sec in non-stress, maximum relative water content (RWC) of 95.38, 95.06 and 94.34% were recorded by TJ-83 × NIA-Amber, TJ-83 × NIA-Saarang and Ujala × Imdad-05 respectively. Wider leaves (31.05 cm^2) (Table 2), greater spike fertility (96.92%), more chlorophyll content (67.52 rg) (Table 3) and the maximum cell membrane stability (87.19%). However, the hybrid Moomal × Imdad-05 (Table 3). Under stress conditions, cross Ujala × Imdad-05 showed maximum relative water content (74.58%) (Table 2), wider leaves of 26.23 cm^2, more spike fertility (77.21%) and higher chlorophyll content (68.67%), while the hybrid TJ-83 × Imdad-05 gave greatest cell membrane stability of 87.00%. Previous researchers like Praba *et al*. (2009) recorded 32% reduction in grain yield against control due to drought stress. Sokoto *et al*. (2013) noted that water stress at tillering stage significantly reduced spike length and number of grains per spike. Whereas, water stress during flowering and grain filling significantly reduced 1000-grain weight, grain yield and harvest index. Noorka *et al*. (2014) investigated and compared common physiological and morphological traits under normal and water-stressed conditions. Their results revealed that genotype-9252 and Dharwar performed best under both normal irrigation and water-stressed conditions for grain yield production. Ashraf *et al*. (2015) suggested that drought tolerance in wheat could be increased *via* breeding strategies and evolving new varieties. Drought tolerant wheat genotypes are expected to give the best production in rain-fed areas. Holasou *et al*. (2019) reported that drought stress is one of the most adverse environmental factors reducing crop production in the world. For the development of wheat genotypes suitable to adverse conditions, understanding the type and relative amount of genetic components become essential factors for determining the breeding methods appropriate for genetic improvement related to drought tolerance traits.

Combining ability estimates for yield and physiological traits. ***Grain yield Kg/ha.*** The tester Imdad-2005 and NIA-Amber ranked 2nd and 3rd respectively in exhibiting higher GCA estimates of 114.25 and 143.02 respectively for grain yield Kg/ha. Whereas, TJ-83 (134.02), Moomal-2002, Benazir (42.89) expressed grater GCA effects among the six female lines under

Table 1. Mean squares from analysis of variance for various morpho-physiological traits of parents and F_1 hybrids of wheat grown under water stress conditions

Traits	Mean squares					
	Replication D.F.=3	Treatment (T) D.F.=1	Error (a) D.F.=3	Genotypes (G) D.F.=26	T × G D.F.=26	Error (b) D.F.=156
Grain yield	4248.76	17190007**	6311.21	399903**	49083**	579.03
Biological yield	8636.61	230800007**	1965.54	1130914**	206563**	1129.74
Relative water content	4.10	37777.20**	2.30	177.60**	111.10**	1.10
Flag leaf area	2.89	1950.79**	0.89	55.41**	5.20**	1.74
Spike fertility	4.90	30279.90**	1.10	38.20**	16.90**	0.80
Chlorophyll content	15.77	2396.55**	17.17	164.86**	86.27**	5.35
Cell membrane stability	10.63	36.92**	0.87	61.10**	39.11**	1.22

**=Significant at 1 and 5% probability levels respectively; n.s.=non-significant.

stress (Table 4). Regarding specific combining ability of F_1 hybrids for seed yield Kg/ha, seven cross combinations exhibited positive GCA effects and their values varied from 217.26 to 946.14 while other eleven hybrids recorded negative GCA effects in the range of -51.73 to -1881.13 (Table 5). Among the eighteen hybrids examined, the top three higher scorers for grain yield were; Sindhu × NIA-Saarang, Benazir × NIA-Saarang and TJ-83 × NIA-Amber which expressed substantial positive SCA estimates of 946.14, 934.99 and 493.05 respectively in non-stress (Table 5). Whereas, the top three hybrids with greater SCA score in water stress conditions were; Benazir × NIA-Amber, Benazir × NIA-Saarang and Sindhu × NIA-Amber elucidated positive SCA estimates of 199.65, 135.89 and 119.10 respectively (Table 5). Results indicated that these higher SCA scoring hybrids may be utilized in future breeding programmes for obtaining higher grain yield Kg/ha.

Biological yield Kg/ha. Out of six, four female lines expressed higher positive GCA estimates and other two parents showed negative effects however, Moomal-2002 (198.25), Sindhu (96.28) and TD-1 (88.86) recorded higher GCA effect for biological yield. However, pollinator NIA-Saarang manifested highest GCA estimates of 101.05 in non-stress environment (Table 4). The maximum GCA estimates of 115.70 was expressed by the female lines TJ-83 followed by the Ujala-2015 (66.10) and Benazir (5.57) for this trait in

Table 2. Mean performance for grain yield Kg/ha, biological yield Kg/ha, relative water content and flag leaf area of wheat grown under water stress conditions

Genotypes	Grains yield (Kg/ha)		Biological yield (Kg/ha)		Relative water content (%)		Flag leaf area (cm^2)	
	Non-stress	Water-stress	Non-stress	Water-stress	Non-stress	Water-stress	Non-stress	Water-stress
Benazir	4120.00	3351.37	8022.50	7042.60	94.00	69.67	28.50	21.12
Sindhu	4247.61	3456.40	8375.00	7318.72	91.25	71.03	30.00	23.25
Ujala-2015	4092.58	3571.42	8122.61	7347.72	89.75	67.68	26.50	19.25
Moomal-2002	4217.60	3330.12	8365.08	7445.15	87.75	69.72	29.50	22.00
TD-1	4327.57	3602.55	8385.08	7647.80	93.50	71.64	30.25	20.75
TJ-83	4157.60	3715.10	8217.77	7177.90	90.25	73.49	27.25	20.25
Imdad-05	4126.32	3325.02	8130.25	7051.03	92.25	71.22	30.00	21.50
NIA-Amber	4026.32	3436.32	8032.70	7461.83	89.25	67.24	29.12	23.87
NIA-Saarang	4057.58	3662.62	7995.25	7624.20	90.50	69.27	30.25	22.62
Benazir × Imdad-05	4237.60	3795.10	8390.11	8064.10	91.18	52.76	28.73	21.37
Sindhu × Imdad-05	4307.72	3873.78	8655.17	8054.23	92.08	50.31	25.57	19.60
Ujala × Imdad-05	4552.60	4131.35	8565.21	8332.90	94.34	74.58	29.64	22.25
Moomal × Imdad-05	4342.73	3535.05	8772.73	7515.31	90.32	55.25	22.93	17.62
TD -1 × Imdad-05	4460.18	3870.60	8947.53	8067.95	92.09	57.64	21.47	16.72
TJ-83 × Imdad-05	4602.55	4081.47	8690.31	8350.48	94.12	70.99	30.75	25.70
Benazir × NIA-Amber	4272.71	3811.70	8565.22	8494.45	90.15	57.59	20.50	15.85
Sindhu × NIA-Amber	4187.67	3740.37	8440.10	8392.98	92.50	56.17	24.65	19.24
Ujala × NIA-Amber	4170.18	3536.65	8315.27	7745.38	88.97	54.43	26.40	21.75
Moomal × NIA-Amber	4352.62	3755.40	8685.54	7855.36	87.46	51.50	27.80	22.85
TD-1 × NIA-Amber	4440.26	3930.37	8882.96	8182.85	91.60	61.50	23.97	17.85
TJ-83 × NIA-Amber	4750.12	4115.37	9147.99	8337.85	95.38	73.50	29.45	25.15
Benazir × NIA-Saarang	4350.19	3977.87	8684.79	8240.63	87.03	61.78	27.50	21.77
Sindhu × NIA-Saarang	4390.10	3652.80	8795.57	7758.01	85.18	66.42	28.49	20.30
Ujala × NIA-Saarang	4650.21	4147.85	8907.94	8432.92	93.77	73.94	29.40	25.15
Moomal × NIA-Saarang	4382.67	3962.85	8712.99	8349.47	90.45	55.45	25.35	22.32
TD-1 × NIA-Saarang	4152.75	3825.37	8347.90	7854.20	86.54	63.47	26.60	23.00
TJ-83 × NIA-Saarang	4737.71	4285.40	9223.02	8577.95	95.06	74.30	31.05	26.23
Mean	4168.38	3624.36	8227.77	7597.35	87.77	62.30	28.50	21.12
LSD (5%) (T)	34.40		19.20		0.65		0.40	
LSD (5%) (G)	23.76		33.19		1.04		1.30	
LSD (5%) (T × G)	33.61		46.94		1.47		1.84	

Table 3. Mean performance for spike fertility, chlorophyll content and cell membrane stability of wheat genotypes grown under water stress conditions

Genotypes	Spike fertility (%)		Chlorophyll content (rg)		Cell membrane stability	
	Non-stress	Water-stress	Non-stress	Water-stress	Non-stress	Water-stress
Benazir	94.50	69.23	51.79	66.00	83.25	85.67
Sindhu	96.75	71.06	53.05	67.25	85.00	87.03
Ujala-2015	95.50	68.59	51.50	64.25	81.00	84.47
Moomal-2002	94.75	68.26	51.41	66.75	86.75	85.48
TD-1	97.50	69.55	53.44	67.50	78.00	81.34
TJ-83	97.00	71.38	49.99	66.00	81.00	83.07
Imdad-05	95.75	72.19	50.42	65.25	86.25	86.48
NIA-Amber	95.25	70.47	49.69	67.25	81.00	83.11
NIA-Saarang	96.50	68.81	54.32	65.00	81.25	83.51
Benazir × Imdad-05	94.82	66.75	61.77	64.82	83.25	85.44
Sindhu × Imdad-05	96.92	68.77	55.70	61.90	84.99	81.50
Ujala × Imdad-05	95.55	73.52	66.60	66.75	81.42	85.17
Moomal × Imdad-05	93.56	70.10	51.55	60.17	87.19	77.45
TD -1 × Imdad-05	91.17	66.97	55.40	56.68	84.53	74.44
TJ-83 × Imdad-05	95.85	72.68	64.70	67.30	86.20	87.00
Benazir × NIA-Amber	90.25	68.25	51.97	50.60	85.93	81.75
Sindhu × NIA-Amber	93.41	67.37	55.01	61.85	81.22	77.35
Ujala × NIA-Amber	90.62	68.97	51.40	55.34	81.60	84.00
Moomal × NIA-Amber	94.35	71.61	55.08	50.01	81.34	86.65
TD-1 × NIA-Amber	90.36	68.05	57.62	53.10	85.30	78.67
TJ-83 × NIA-Amber	95.33	74.60	63.50	66.50	86.03	86.86
Benazir × NIA-Saarang	87.59	70.05	58.35	60.45	86.75	78.25
Sindhu × NIA-Saarang	91.97	70.16	50.25	56.05	77.72	71.57
Ujala × NIA-Saarang	96.42	75.58	50.43	56.95	81.55	84.01
Moomal × NIA-Saarang	89.50	69.18	50.88	60.30	86.08	81.37
TD-1 × NIA-Saarang	93.37	71.62	51.58	51.78	77.88	78.10
TJ-83 × NIA-Saarang	95.85	77.21	67.52	68.67	84.26	84.65
Mean	90.76	67.96	53.07	59.51	80.27	79.51
LSD (5%) (T)	0.14		1.79		0.40	
LSD (5%) (G)	0.90		2.28		1.09	
LSD (5%) (T × G)	1.28		3.23		1.54	

Table 4. General Combining Ability (GCA*)* effects for grain yield Kg/ha and biological yield Kg/ha of six female lines and three testers of wheat under water stress condition

Lines/Female	Grain yield (Kg/ha)		Biological yield (Kg/ha)	
	Non-stress	Water-stress	Non-stress	Water-stress
Benazir	704.97**	42.89**	-170.41**	5.57
Sindhu	807.49**	-61.48**	96.28**	-166.92**
Ujala-2015	549.18**	-194.28**	-267.04**	66.10**
Moomal-2002	853.33**	43.20**	198.25**	-19.48
TD-1	-360.06**	35.65*	88.86**	-0.98
TJ-83	-2554.91**	134.02**	54.06**	115.70**
S.E(gi-gj)	6.05	12.51	11.81	15.40
Testers/Pollinators				
Imdad-2005	114.25**	-84.19**	-72.01**	-58.28*
NIA-Amber	143.02**	-74.97**	-29.04**	-93.13**
NIA-Saarang	-257.27**	159.16**	101.05**	151.41**
S.E (gi-gj)	4.28	15.68	8.35	19.30

stress, while from tester NIA-Saarang showed maximum effect of 151.41. Among the eighteen cross combinations examined, seven recorded negative SCA effects in the range of -72.67 to -384.37, while desirable positive SCA effects varied from 6.50 to 360 for biological yield (Table 5). The cross TJ-83 × NIA-Saarang recorded highest positive SCA value (360.67) followed by Benazir × NIA-Amber (197.04) and TD-1 × Imdad-05 (173.04). These combinations which involved parents with high × high general combiners indicated the additive × additive gene interaction between favourable alleles contributed by both the parents which are considered to be fixable in nature (Table 5) in non-stress. Among the eighteen F_1 hybrids, Benazir × NIA-Amber (341.79), Sindhu × NIA-Amber (275.17) and TJ-83 × Imdad-05 (221.16) displayed maximum SCA effects, while seven hybrids exhibited negative effects for biological yield

Table 5. Specific combining ability (SCA) effects of F_1 hybrids for grain yield Kg/ha and biological yield Kg/ha of eighteen hybrids of wheat derived from crosses of six female lines with three testers under water stress condition

F_1 hybrids	Grain yield Kg/ha		Biological yield Kg/ha	
	Non- stress	Water-stress	Non-stress	Water-stress
Benazir × Imdad-05	-242.62**	-54.12*	-74.71**	-28.03
Sindhu × Imdad-05	-201.27**	15.34	147.37**	-3.05
Ujala × Imdad-05	443.89**	38.78	-72.67**	31.08
Moomal × Imdad-05	-240.00**	-209.80**	41.22*	-404.33**
TD -1 × Imdad-05	-151.33**	116.53**	173.04**	183.17**
TJ-83 × Imdad-05	391.33**	93.27**	-214.26**	221.16**
Benazir × NIA-Amber	-51.73**	199.65**	197.04**	341.79**
Sindhu × NIA-Amber	-165.53**	119.10**	28.94	275.17**
Ujala × NIA-Amber	217.26**	-318.75**	-225.98**	-616.97**
Moomal × NIA-Amber	-275.96**	-94.12**	-147.95**	-211.71**
TD-1 × NIA-Amber	-217.09**	71.63**	6.50	150.63**
TJ-83 × NIA-Amber	493.05**	22.50	141.44**	61.08*
Benazir × NIA-Saarang	934.99**	135.89**	-39.30	155.06**
Sindhu × NIA-Saarang	946.14**	-198.41**	28.51	-292.71**
Ujala × NIA-Saarang	-1881.13**	62.51*	10.79	137.65**
Moomal × NIA-Saarang	-124.68**	22.50	23.70	147.21**
TD-1 × NIA-Saarang	-210.92**	-124.20**	-384.37**	-313.21**
TJ-83 × NIA-Saarang	335.60**	101.70**	360.67**	166.00**
S.E. (Sij-Skr)	10.47	21.68	20.46	26.67

in stress as recoded in Table 7. Ishaq *et al*. (2018) reported desirable specific combining ability (SCA) effects and the cross PK-108 × Faisalabad-2008 was the best specific combiner for biological yield.

Relative water content (RWC%). In non-stress, top two female lines such as Benazir and Sindhu recorded greater desirable GCA effects of 1.52 and 1.16 for relative water content (%), while pollinator NIA-Saarang showed high GCA effects of 2.59 among the all testers (Table 6). In stress conditions, three parents such as TD-1 (5.63), TJ-83 (2.65) and Moomal-2002 (0.41) recorded positive GCA effects however only one tester (NIA-Saarang) gave maximum (8.54) GCA effects for this trait. Among the eighteen crosses, Sindhu × NIA-Amber (2.98), Ujala × NIA-Saarang (2.51) and TJ-83 × NIA-Saarang (1.78) expressed higher SCA estimates in non-stress however, eight crosses showed negative SCA effects which indicated quite poor performance of hybrids for RWC% as shown in Table 7.

Out of eighteen hybrids studied, eight F_1 hybrids exhibited negative SCA effects for water relative content % (Table 7). Most of the crosses involved the parents with low or average in performance may have substantiated the effect of non-additive gene action in the expression of this trait. The cross combination Benazir × NIA-Amber exhibited maximum positive specific combining ability (7.56) effects followed by Ujala × Imdad (6.83) and TJ-83 × NIA-Amber (2.79). These combinations retained more moisture in stress condition, hence exhibited more tolerance (Table 7).

Table 6. General combining ability (GCA) effects for relative water content, chlorophyll content and flag leaf area of six female lines and three testers of wheat under water stress conditions

Lines/ Female	RWC %		Chlorophyll content		Flag leaf area	
	Non-stress	Water-stress	Non-stress	Water-stress	Non-stress	Water-stress
Benazir	1.52*	-2.54*8	4.73**	5.07**	1.30*	-0.30
Sindhu	1.16*	-0.46	0.59	1.96	-1.63*	-1.36**
Ujala-2015	-0.47	-5.69**	-3.84**	-3.49**	-2.83**	-2.43**
Moomal-2002	0.47	0.41	2.11*	-2.77**	0.40	0.57
TD-1	-2.35**	5.63**	-3.62**	-1.61*	1.78**	1.03**
TJ-83	-0.33	2.65**	0.03	0.83	0.98	2.48**
S.E(gi-gj)	0.51	0.34	1.05	0.82	0.66	0.38
Testers/Pollinators						
Imdad-2005	-1.58**	-6.03**	-1.69*	-1.70	-1.21*	-1.08*
NIA-Amber	-1.01**	-2.50**	-2.37**	-2.53*	-1.56**	-1.92**
NIA-Saarang	2.59**	8.54**	4.06**	4.22**	2.77**	3.00**
S.E (gi-gj)	0.36	0.42	0.74	1.03	0.47	0.47

The positive GCA and SCA effects for RWC under water stress and non-stress conditions reported by (Jatoi, 2013; Jatoi *et al*., 2012). It may be concluded that the above cited lines, testers and F_1 hybrids could be utilized in breeding programme for the development of water stress tolerant varieties.

Chlorophyll content. Out of six female parents, the line Benazir elucidated maximum GCA estimates (4.73) followed by Moomal-2002 (2.11) whereas third and last pollinator NIA-Saarang manifested greater positive GCA effects of 4.06 (Table 6) under non-stress. Whereas in stress, positive effects are more useful as compared negative effects hence the parent Benazir recorded maximum effects of 4.73 followed by Moomal-2002 (2.11) and among the three testers, only one NIA-Amber expressed the high GCA effects (4.22) under stress for chlorophyll content (Table 6). From eighteen crosses, the combinations like Benazir × NIA-Saarang, TJ-83 × NIA-Saarang and Sindhu × NIA-Amber exhibited higher SCA effects of 7.03, 6.80 and 4.58 respectively and such hybrids which expressed higher positive SCA effects contained maximum dominant genes in non-stress Table 7. A group of hybrids such as Sindhu × NIA-Amber (8.45), TJ-83 × NIA-Amber (5.97) and Benazir × NIA-Saarang (4.33) which expressed greater positive SCA effects in stress conditions were the most desirable crosses for the chlorophyll content. The value of desirable positive SCA effects varied from 0.49 to 8.45 in nine out of eighteen hybrids, while nine cross combinations recorded negative SCA effects in the range of -0.06 to -5.94. These crosses with high negative SCA effects revealed their deleterious recessive genes. The hybrid TD-1 × NIA-Saarang showed maximum negative SCA effects of -5.94 followed by the Ujala × NIA-Saarang (-5.09) in stress condition being highly undesirable crosses (Table 7). Comparable results were noted by Jatoi *et al*. (2011) who revealed positive GCA and SCA effects for rg chlorophyll content in parents and F_1 hybrids of wheat genotypes under stress conditions at anthesis stage.

Flag leaf area. The results in Table 6 indicated that female line TD-1 recorded highest GCA estimate of 1.78 for flag leaf area followed by the parent Benazir and TJ-83 (1.30 and 0.98) respectively. Similarly from testers, NIA-Saarang gave maximum effects of 2.77 in non-stress conditions (Table 6). Whereas, under stress, half of the female lines recorded undesirable negative GCA effects and another half expressed desirable positive GCA effects. Out of the pollinator, NIA-Saarang recorded high GCA estimate of 3.00 (Table 6). The highest SCA effects for this trait were exhibited by the crosses of TJ-83 × Imdad-05 (2.93) followed by Sindhu

Table 7. Specific combining ability (SCA) effects of F_1 hybrids for RWC%, chlorophyll content and flag leaf area of eighteen hybrids of wheat derived from crosses of six female lines with three testers under water stress condition

F_1 hybrids	RWC%		Chlorophyll		Flag leaf area	
	Non-stress	Water-stress	Non-stress	Water-stress	Non-stress	Water-stress
Benazir × Imdad-05	0.23	-0.42	2.11	2.03	1.96	1.38*
Sindhu × Imdad-05	0.56	-6.41**	-3.29	-0.06	-0.86	0.45
Ujala × Imdad-05	-0.79	6.83**	1.18	-1.96	-1.10	-1.82**
Moomal × Imdad-05	-0.28	-0.01	-3.97*	0.49	-0.91	-1.32*
TD -1 × Imdad-05	0.93	-1.15	0.55	-2.18	-2.02	-1.37*
TJ-83 × Imdad-05	-0.65	1.16*	3.42	1.69	2.93*	2.69**
Benazir × NIA-Amber	1.19	7.56**	0.87	-3.64*	-2.14	-2.02**
Sindhu × NIA-Amber	2.98**	2.61**	4.58*	8.45**	2.36*	2.22**
Ujala × NIA-Amber	-4.16**	-10.17**	-5.46**	-4.81**	-0.22	-0.20
Moomal × NIA-Amber	-2.44*	-4.64**	-1.96	-4.95**	1.94	1.98**
TD-1 × NIA-Amber	1.14	1.84**	1.26	-1.03	-1.55	-2.18**
TJ-83 × NIA-Amber	1.31	2.79**	0.70	5.97**	-0.39	0.20
Benazir × NIA-Saarang	-0.04	0.43	7.03**	4.33**	0.25	0.44
Sindhu × NIA-Saarang	-2.47*	1.54*	-0.39	0.76	1.59	-0.19
Ujala × NIA-Saarang	2.51*	-1.97**	-6.64**	-5.09**	-1.83	-0.25
Moomal × NIA-Saarang	1.35	-2.93**	-4.09*	1.74	-1.10	-0.45
TD-1 × NIA-Saarang	-3.13**	1.57*	-2.71	-5.94**	0.49	1.07
TJ-83 × NIA-Saarang	1.78*	1.36*	6.80**	4.20*	0.62	-0.62
S.E. (Sij-Skr)	0.88	0.58	1.82	1.42	1.15	0.65

× NIA-Amber (2.36) and Benazir × Imdad-05 (1.96) among the eighteen crosses in non-stress. Whereas in stress conditions, eight hybrids recorded positive SCA effects and other ten combinations showed negative effects, however, the cross TJ-83 × Imdad-05 expressed the highest positive SCA effects (2.69) followed by Sindhu × NIA-Amber (2.22) and Moomal × NIA-Amber (1.98) for flag leaf area (Table 7). Muneer *et al*. (2016) reported higher negative GCA effects in cvs. WN-36 (-1.53) and WN-36 (-1.53) for flag leaf area.

Spike fertility. Half female lines, such as Benazir, Sindhu and Moomal-2002 expressed superior positive GCA effects of 2.60, 0.37 and 0.19 respectively, while remaining half of lines, like Ujala-2015, TD-1 and TJ-83 revealed inferior negative GCA effects of -1.74, -1.16 and -0.25 respectively, showing their poor combining ability for spike fertility (Table 8). NIA-Saarang as a tester parent elucidated higher positive GCA effect (1.78) from three pollinators in non-stress conditions, while in stress environment, from six lines three parents *viz*. TJ-83 (2.03), TD-1 (1.29) and Moomal (0.79) recorded superior desirable GCA effects for spike fertility (Table 8) and other three lines showed negative GCA effects, whereas among the testers NIA-Amber and Imdad-2005 reflected desirable negative effects of (-1.81 and -1.31) respectively, while tester NIA-Saarang gave desirable positive (3.12) GCA effects for spike fertility.

From eighteen crosses, twelve combinations expressed desirable positive SCA effects varying from 0.21 to 2.65, while further suggested that positive SCA effects were greater than negative SCA effects in the hybrids for spike fertility (Table 9). The combination like Ujala-× NIA-Saarang, Moomal × NIA-Amber and Sindhu × NIA-Amber were noted highest SCA effects of 2.65, 2.49 and 2.28 respectively in non-stress. Among the eighteen F_1 hybrids, seven hybrids manifested negative SCA effects in the range of -0.36 to -2.35 (Table 9). The F_1 hybrid like TJ-83 × NIA-Amber (1.41) followed by the cross Moomal × NIA-Amber (1.50) and Benazir × NIA-Amber (1.37) were top scorer in respect to SCA effects for spike fertility in water stress conditions. Comparable results were reported by Jatoi (2013) who observed positive GCA and SCA effects for spike fertility in parents and their F_1 hybrids under water stress conditions.

Cell membrane stability. Two out of six female lines exhibited positive GCA effects and four showed negative effects in non-stress for cell membrane stability as

Table 8. General combining ability (GCA) effects for spike fertility and cell membrane stability of six female lines and three testers of wheat under water stress condition

Female/lines	Spike fertility		Cell membrane stability	
	Non-stress	Water-stress	Non-stress	Water-stress
Benazir	2.60**	-0.96*	-0.29	2.69**
Sindhu	0.37	-0.72	2.46**	-1.71**
Ujala-2015	-1.74**	-2.44**	-0.60	-0.31
Moomal-2002	0.19	0.79*	0.71	2.71**
TD-1	-1.16**	1.29**	-1.51*	-3.40**
TJ-83	-0.25	2.03**	-0.77	0.03
S.E(gi-gj)	0.38	0.37	0.53	0.36
Testers/Pollinators				
Imdad-2005	-1.48**	-1.31**	1.58**	0.47
NIA-Amber	-0.29	-1.81**	-1.57**	-4.41**
NIA-Saarang	1.78**	3.12**	0.00	3.94**
S.E (gi-gj)	0.27	0.47	0.37	0.45

Table 9. Specific combining ability (SCA) effects of F_1 hybrids spike fertility and cell membrane stability of eighteen hybrids of wheat derived from crosses of six female lines with three testers under water stress condition

F_1 hybrids	Spike fertility		Cell membrane stability	
	Non-stress	Water-stress	Non-stress	Water-stress
Benazir × Imdad-05	0.54	-1.62*	-1.55	0.94
Sindhu × Imdad-05	1.45*	0.90	3.35**	1.87*
Ujala × Imdad-05	-1.99**	0.72	-1.80	-2.80**
Moomal × Imdad-05	1.52*	1.50*	-0.36	-2.66**
TD -1 × Imdad-05	-2.06**	-1.14	0.13	-0.78
TJ-83 × Imdad-05	0.54	-0.36	0.23	3.44**
Benazir × NIA-Amber	0.30	1.37*	1.44	0.24
Sindhu × NIA-Amber	2.28**	0.99	-0.12	0.72
Ujala × NIA-Amber	-2.58*	-2.35**	-1.31	-0.97
Moomal × NIA-Amber	2.49*	1.50*	-4.46**	2.12**
TD-1 × NIA-Amber	-2.70*	-1.56*	2.65*	-0.98
TJ-83 × NIA-Amber	0.21	0.06	1.81*	-1.13
Benazir × NIA-Saarang	-2.92**	-0.57	3.16**	-0.17
Sindhu × NIA-Saarang	0.27	0.05	-2.71*	-1.96**
Ujala × NIA-Saarang	2.65*	0.52	-0.45	2.13**
Moomal × NIA-Saarang	-1.92*	-2.18**	1.76	-0.47
TD-1 × NIA-Saarang	0.76	0.76	-3.29**	1.13
TJ-83 × NIA-Saarang	1.16	1.41*	1.52	-0.66
S.E. (Sij-Skr)	0.65	0.64	0.91	0.63

mentioned in Table 8. Nonetheless, the female line Sindhu displayed highest GCA effects (2.46) followed by the parent Moomal-2002 (0.71) in non-stress while the tester Imdad-05 expressed maximum positive GCA effect (1.58) for cell membrane stability. In water stress condition, Moomal (2.71) and Benazir (2.69) demonstrated maximum positive GCA effects, while the pollinator NIA-Saarang mentioned maximum positive GCA effects of 3.94 in stress condition (Table 8). The range of positive and desirable SCA effects varied from 0.13 to 3.35 in half of the crosses out of eighteen F_1 hybrids, while half (nine) crosses recorded negative SCA effects in the range of -0.45 to -4.46 for cell membrane stability. The crosses which displayed higher positive SCA effects contained maximum dominant genes whereas the hybrids with high negative SCA effects revealed their recessive genes. The cross combinations which showed highest positive SCA effects were; Sindhu × Imdad-05, Benazir × NIA-Saarang and TJ-83 × NIA-Amber which reflected SCA effects of 3.35, 3.16 and 1.81 respectively (Table 9) in non-stress. In stress conditions, the F_1 hybrids TJ-83 × Imdad-05 manifested highest (3.44) value followed by Ujala × NIA-Saarang (2.13) and Moomal × NIA-Amber (2.12) for cell membrane stability (Table 9). Knezevicl *et al*. (2006) determined general combination ability (GCA) and specific combining ability (SCA) in F_2 hybrids and noted higher values of SCA over GCA suggesting preponderance of non-additive gene effects for most of the yield and some physiological traits.

By and large, our results are in conformity with previous researcher like Chowdhary *et al*. (2007) who reported significant general combining ability (GCA) and specific combining ability (SCA) for flag leaf area and other physiological traits. Predominantly, additive genes controlled the expression of the traits and it was evident by greater mean squares for general combining ability. Kamaluddin *et al*. (2007) observed that GCA effects were relatively more important than the SCA effects, indicating that additive genetic effects were predominant. Crosses displaying high SCA effects for seed weight and yield were observed to be derived from parents having various types of GCA effects (high × high, high × low, low × low and medium × low).

Conclusion

Genotypes, treatments and treatment × genotype interactions were significant for all the traits like grain yield Kg/ha, biological yield Kg/ha, relative water content%, leaf area cm^2, chlorophyll content rg, spike fertility and cell membrane stability. Among the genotypes TJ-83, NIA-Saarang, Sindhu, Benazir and TD-1 proved as good general combiners for all the traits whereas F_1 hybrids such as Benazir × NIA-Saarang, Benazir × Imdad-05, Sindhu × NIA-Amber and TJ-83 × Imdad-05 recorded good specific combiners for all the traits under water stress conditions.

Conflict of Interest. The authors declare that they have no conflict of interest.

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