Pak. J. Agri. Sci., Vol. 58(X), xxx-xxx; 2021
ISSN (Print) 0552-9034, ISSN (Online) 2076-0906
DOI: 10.21162/PAKJAS/21.70
http://www.pakjas.com.pk

COMPUTATION OF COMBINING ABILITY ESTIMATES FOR SOME PHYSIOLOGICAL AND MORPHOLOGICAL TRAITS IN BREAD WHEAT UNDER HIGH TEMPERATURE

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Climate change leads to increase in temperature of wheat growing regions with adverse effects on its yield. Breeding wheat genotypes for high temperature tolerance and yield related characters is a dire need of the day. This study was designed to evaluate eleven accessions of wheat including seven heat tolerant lines and four heat susceptible testers and they were crossed in line into tester mating design. The resultants F_1 hybrids and their parents were assessed for heat tolerance in open field and field covered with plastic sheet tunnel (to artificially induce heat stress). At maturity, data were taken on morphological and physiological factors for estimation of genetic variation and combining ability effects. Highly significant variability was detected among genotypes for all studied parameters. Existing genetic variability among genotypes, under natural and heat stress treatments, showed the potential of present breeding material. These entries may be used in future to develop heat tolerant genotypes. Combining ability analysis showed the variable trend of general combining effects between lines and testers, and specific combining effects among combinations. In lines HTSBWON-15-0079, HTSBWON-15-0040 and HTSBWON-15-0089 and testers HTSBWON-15-0014 and Millat-11 were best general combiners in both circumstances. Outcomes of specific combining ability showed that crosses HTSBWON-15-0079 × HTSBWON-15-0014, HTSBWON-15-0079 × Millat-11 and HTSBWON-15-0040 × Millat-11 were best specific combiners for heat related traits like canopy temperature and electrolyte leakage. Non additive type of genetic effect was exhibited by almost all characters.
Keywords: *Triticum aestivum*, heat stress, canopy temperature, leaf relative water content and gene action.

INTRODUCTION

Increasing population in any country is a major challenge to fulfill dietary demands of the country followed by climate change. Climate change is main cause of abiotic stresses. High temperature coupled with drought is most detrimental stress declining yield in many crop plants. High temperature damages the plant growth because of diverse physiological and morphological changes, among them most important one is plasma membrane disruption (Wahid and Close, 2007; Lipiec *et al*., 2013). In plants source activity is adversely affected by high temperature, which may be due to reduction in leaf size and process of photosynthesis (Katakpara *et al*., 2016; Tiwari *et al*., 2017).

Among cereals wheat is very responsive to elevated temperatures (Alexander *et al*., 2006; Hennessy *et al*., 2008; Habeeb *et al*., 2015) and undergoes heat stress to varying extent depending on the phenological stages, but stress is more detrimental at reproductive and grain filling stage than vegetative stage because of its direct effect on the dry weight and No. of seeds (Tiwari *et al*., 2017; Bala and Sikder, 2017). According to estimations it is concluded that for every single degree increase in temperature during the wheat developing period may reduce its yield about 3 to 10% (Khan *et al*., 2007; Mishra, 2007). High temperature at reproductive and grain development stages is problematic issue in about 40% of wheat growing areas results in less seed formation (Kumari *et al*., 2015; Akter and Islam, 2017), which is the most decisive stage of grain development. Temperature higher than 35 ºC can significantly reduce yield and quality of grain (Sial *et al*., 2005; Mondal *et al*., 2016).

Knowledge about genetic background of heat stress related characters would help in choosing parents for breeding programs. Consequently, evaluation of genetic material will be important in selection of high temperature tolerant lines as well as for improvement of seed yield at elevated temperatures. For adaptation of new cultivars in future climatic conditions, information about response of crops toward rise in temperature and improvement in heat tolerance related traits is necessary (Halford, 2009; Senapati *et al*., 2019).

For evaluation of combining ability and gene action, line in to tester is an effective method which aids desirable parental selection and cross combinations for breeding programs of wheat. Correspondingly it provide knowledge of genetic mechanisms that control different traits (Rashid *et al*., 2007;

Akula *et al*., 2016). General combining ability effects are constantly fixable and related to additive genetic effects. But non-additive gene action is non-fixable and attributed to specific combining ability (Bagheri and Jelodar, 2010). Incidence of non-additive gene action is the key purpose for induction of heterosis breeding (Pradhan *et al*., 2006; Fujimoto *et al*., 2018).

Four wheat accessions comprising one tolerant and three susceptible were crossed and evaluated by Irshad *et al*. (2012) under open field and heat stressed conditions. Mean square values under both conditions indicated additive genetic effects with incomplete dominance. Similarly Farooq *et al*. (2011) utilized several high yielding genotypes having tolerance, moderate tolerance and susceptibility toward heat. Genetic component analysis showed significant variability for all investigated parameters. There were significant differences between lines and testers for spike related characters under stress (Bibi *et al*., 2013). Determination of gene effects for physiological characters in stress conditions showed significant difference among genotypes and non-additive gene effect for relative water content. (Golparvar, 2012; Rad *et al*., 2013).

Keeping in view the above facts, this research was planned to identify better performing genotypes and superior cross combinations along with identification of most suitable traits to be used as selection criteria under normal and high temperature.

MATERIALS AND METHOD

Source material consisting of 98 lines from international Maize and wheat improvement centre (CIMMYT)'s heat nurseries and three local checks was collected from Wheat Research Institute, Ayub Agricultural Research Institute, Faisalabad. After screening of the whole material, eleven genotypes were selected on the basis of heat tolerance and grown under normal field conditions for making crosses in line × tester mating design (Kempthrone, 1957).

Seven high temperature tolerant genotypes viz; HTSBWON-15-0002, HTSBWON-15-0029, HTSBWON-15-0040, HTSBWON-15-0079, HTSBWON-15-0087, HTSBWON-15-0089 and Faisalabad-08 were used as lines (female parent) whereas four high temperature sensitive genotypes viz; HTSBWON-15-0014, HTSBWON-15-0016, HTSBWON-15-0073 and Millat-11 were used as testers (male parent). After hybridization, F_0 seed of these 28 crosses was collected and sown in next crop season, to raise and evaluate F_1 generation.

This experiment was conducted in field of Department of Plant Breeding and Genetics, University of Agriculture, Faisalabad situated at 31° 26' N latitude and 73° 06' E longitude with an altitude of 184.4 m. Monthly average maximum and minimum temperatures during the research period as measured by Meteorological Unit, Crop Physiology Department, University of Agriculture, Faisalabad is presented in Figure 1.

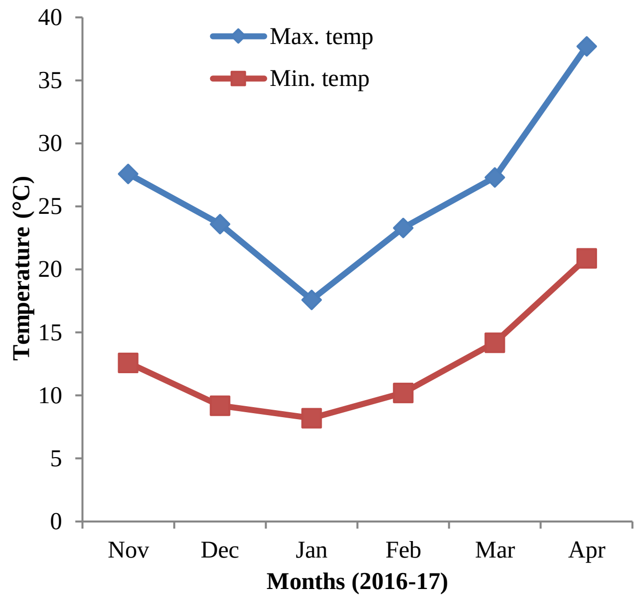

Figure 1. Monthly average max. and mini. temperature (ºC) during crop season 2016-17.

Twenty-eight crosses and their parents were grown in the field using two factors Factorial under Randomized Complete Block Design (RCBD) with three replications in two different growing environments (tunnel and open field) during Rabi season 2016-17. A dibbler was used for sowing 2-3 seeds were sown in one hole to attain uniformity in plant population. All agronomic practices were performed routinely for both treatments. One set of genotypes was covered with plastic sheet tunnel during grain-filling stage to expose the genotypes to high temperature stress throughout the sensitive crop development phases. Second set was remained in open field condition as control to allow the crop to grow in natural temperature. The temperature in the tunnel was maintained between 5-10ºC higher than the ambient temperature.

Data for some physiological and morphological parameters i.e., canopy temperature, cell membrane thermostability, plant height, flag leaf area, leaf relative water content, electrolyte leakage, tillers per plant, spike length, spikelets per spike, grains per spike, grain weight per spike, 1000-grain weight and grain yield per plant was measured on five selected guarded plants from each entry per repeat from both experimental units.

Statistical analysis was done on data measured for different characters through mean square analysis method as defined by Steel *et al.* 1997 for computation of significant genotypic variances between cross combinations along with their parents. Plant characters showing significant genotypic differences were further divided by using line × tester analysis

(Kempthorne, 1957). The estimations of GCA for lines and testers while SCA for cross combinations were attained.

RESULTS

Mean square analysis exhibited highly significant differences among studied genotypes for various morphological and physiological characters for both experimental units and presented in the Table 1 (bold values for normal temperature and unbold values for heat stress). Under normal temperature, the mean square of lines was highly significant for all parameters excluding spikelets per spike which was non-significant. Whereas variances due to testers and line × testers all parameters were highly significant except for spike length and spikelets per spike. In tunnel, among lines, significant variances were detected for all traits except spikelets per spike, while in case of testers highly significant mean squares were observed for all parameters except plant height, tillers per plant, spike length and spikelets per spike. Interaction of line with tester significantly varies for all components except for spike length and spikelets per spike.

***General combining ability effects*:** General combining ability effects for some morphological as well as physiological characters under open field and heat stress conditions are displayed in Table 2. In open field conditions, lines HTSBWON-15-0040, HTSBWON-15-0079 and HTSBWON-15-0089 had significant and positive GCA effects for most of yield and heat stress related traits. Between testers, positive and significant GCA effects were observed in HTSBWON-15-0073 for cell membrane thermo stability, electrolyte leakage, flag leaf area and 1000 grain weight. Parents revealed different degree and magnitude of general combining ability effects under heat stress for studied traits. Among lines, HTSBWON-15-0029, HTSBWON-15-0040, HTSBWON-15-0079 and Faisalabad-08 had positive and significant GCA effects for heat tolerance related traits along with yield attributes. Among testers, HTSBWON-15-0014, HTSBWON-15-0016 and Millat-11 had positive and significant GCA effects for most of high temperature tolerance and yield related traits.

***Specific combining ability effects*:** Specific combining ability effects of cross combination for plant characters in natural

Table 1. Variances for some physiological and morphological characters in normal temperature (bold) and heat stress.

Source of variation	Treatments	Parents	Parents vs Crosses	Crosses	Lines	Testers	Line × Testers	Error
df	38	10	1	27	6	3	18	76
Canopy temperature	**24.69****	**42.31****	**12.77****	**18.60****	**18.99****	**16.07****	**18.90****	**0.25**
	77.63**	139.19**	49.30**	55.87**	94.67**	6.79**	51.12**	0.26
Cell membrane thermostability	**507.49****	**986.11****	**526.70****	**329.52****	**222.70****	**234.95****	**380.89****	**1.86**
	890.43**	1352.72**	2612.04**	655.46**	914.14**	86.89**	657.32**	3.09
Leaf relative water content	**275.15****	**617.15****	**17.11***	**158.14****	**43.82****	**195.32****	**189.89****	**3.28**
	203.38**	334.10**	68.08**	159.98**	180.63**	275.72**	133.81**	1.74
Electrolyte leakage	**888.93****	**1911.58****	**70.69****	**540.47****	**258.75****	**191.88****	**692.47****	**2.23**
	1031.41**	1973.41**	210.44**	712.93**	866.06**	381.76**	717.09**	2.73
Plant height	**49.88****	**89.43****	**405.49****	**22.06****	**20.22****	**29.55****	**21.43****	**3.11**
	108.21**	333.21**	5.06^{ns}	28.69**	44.46**	1.11^{ns}	28.03**	2.48
Flag leaf area	**261.04****	**462.78****	**201.73****	**188.52****	**175.75****	**120.97****	**204.04****	**1.88**
	216.65**	419.36**	68.23**	147.07**	82.55**	212.72**	157.63**	1.96
Tillers per plant	**16.63****	**37.35****	**35.74****	**8.24****	**14.49****	**5.66***	**6.59****	**1.57**
	10.88**	21.68**	16.07**	6.69**	4.74*	5.34^{ns}	7.57**	1.97
Spike length	**8.66****	**19.79****	**1.36**^{ns}	**4.81***	**9.61****	**3.34**^{ns}	**3.45**^{ns}	**2.47**
	9.31**	23.90**	5.60^{ns}	4.04**	7.99**	2.14^{ns}	3.04^{ns}	1.77
Spikelets per spike	**6.37****	**19.85****	**0.16**^{ns}	**1.61**^{ns}	**1.71**^{ns}	**0.57**^{ns}	**1.75**^{ns}	**2.45**
	5.29*	12.65**	4.13^{ns}	2.61^{ns}	2.60^{ns}	3.34^{ns}	2.49^{ns}	2.98
Grains per spike	**332.46****	**995.05****	**0.26**^{ns}	**99.37****	**116.08****	**42.23****	**103.32****	**2.67**
	285.34**	701.27**	6.60^{ns}	141.62**	160.16**	145.93**	134.72**	3.09
Grain weight per spike	**1.81****	**5.26****	**3.20****	**0.48****	**0.06****	**0.12****	**0.68****	**0.01**
	1.12**	2.81**	0.52**	0.51**	0.25**	0.44**	0.61**	0.01
1000 grain weight	**192.30****	**396.40****	**326.25****	**111.74****	**100.72****	**63.77****	**123.41****	**3.51**
	145.69**	282.00*	13.59**	100.09**	72.90**	73.76**	113.55**	2.89
Grain yield per plant	**228.23****	**309.32****	**53.84****	**204.66****	**226.26****	**102.32****	**214.51****	**2.73**
	167.44**	287.51**	45.26**	127.49**	38.84**	93.24**	162.75**	1.86

**=Highly significant; *=Significant; n.s= Non significant

Table. 2. General combining ability effects of lines and testers for some physiological and morphological traits of wheat under normal temperature (Bold) and heat stress conditions.

	Canopy temperature	Cell membrane thermostability	Leaf relative water content	Electrolyte leakage	Flag leaf area	Plant height	Tillers per plant	Spike length	Spikelets per spike	Grains per spike	Grain weight per spike	1000 grain weight	Grain yield per plant
Lines													
HTSBWON-15-0002	**-0.15***	**-6.70***	**-0.92***	**4.79***	**0.17**	**1.45***	**-1.14***	**0.45**	**-0.02**	**-3.41***	**0.05***	**-0.63***	**-7.45***
	-1.06*	7.01*	-3.61*	6.08*	-3.18*	1.89*	-1.29*	0.42*	0.69*	-5.95*	-0.27	-2.16*	-3.70*
HTSBWON-15-0029	**-0.60***	**1.22***	**-2.29***	**-2.97***	**5.79***	**-1.62***	**-0.22**	**-0.41**	**0.47***	**2.66***	**-0.03***	**-3.09***	**4.58***
	-2.41*	5.74*	-0.15	4.21*	2.18*	-1.64*	0.11	-0.24	-0.47	2.04*	0.04*	0.74*	0.19
HTSBWON-15-0040	**-2.17***	**-0.07**	**2.55***	**-6.2***	**-0.55***	**1.07***	**0.35**	**0.71***	**0.31**	**5.16***	**0.01**	**2.87***	**2.68***
	-4.44*	-19.15*	3.99*	-17.85*	3.82*	-3.48*	-0.29	1.2*	0.35	5.63*	0.03	2.30*	2.20*
HTSBWON-15-0079	**1.12***	**-4.95***	**1.67***	**-5.07***	**2.26***	**0.36**	**1.85***	**1.41***	**-0.19**	**-1.16***	**0.10***	**4.17***	**1.62***
	1.41*	1.25*	5.40*	1.63*	-0.49*	1.31*	0.53*	0.72*	0.19	1.71*	0.13*	3.74*	0.81*
HTSBWON-15-0087	**-0.54***	**2.05***	**1.64***	**3.78***	**-4.62***	**0.08**	**-0.05**	**-0.43**	**0.31**	**0.25**	**-0.11***	**-1.03***	**2.93***
	0.64*	3.60*	-1.41*	6.6*	-0.52*	1.18*	0.36	-0.62*	-0.14	-2.03*	-0.08*	-0.40	-0.009
HTSBWON-15-0089	**0.92***	**4.80***	**-0.97***	**4.01***	**-4.89***	**0.58***	**0.60***	**-1.21***	**-0.35**	**-0.16**	**0.0004**	**1.19***	**-0.11**
	2.24*	1.84*	-5.36*	2.19*	-3.09*	1.80*	0.28	-1.13*	-0.64*	-0.11	-0.0001	-0.93*	0.31
Faisalabad-08	**1.42***	**3.64***	**-1.68***	**1.66***	**1.85***	**-1.92***	**-1.39***	**-0.52***	**-0.52***	**-3.33***	**-0.02**	**-3.49***	**-4.26***
	3.62*	-0.31	1.15*	-2.88*	1.27*	-0.06	0.28	-0.34	0.02	-1.28*	0.14*	3.29*	0.18
Testers													
HTSBWON-15-0014	**-0.28***	**-0.49***	**-1.43***	**-1.27***	**-1.87***	**-0.03**	**0.67***	**-0.22**	**0.04**	**-0.64***	**0.09***	**-2.15***	**1.66***
	0.22*	-2.98*	-4.04*	-5.24*	-4.61*	-0.11	-0.34*	-0.12	0.54*	2.23*	0.13*	-0.97*	1.93*
HTSBWON-15-0016	**-0.60***	**-4.54***	**1.21***	**-3.67***	**-2.1***	**0.36**	**0.10**	**-0.39***	**0.14**	**0.45***	**-0.07***	**-0.55***	**1.93***
	-0.62*	0.48*	-0.01	-1.55*	2.62*	-0.26	-0.20	-0.21	-0.02	-0.38	0.05*	0.89*	1.28*
HTSBWON-15-0073	**-0.41***	**2.48***	**-3.37***	**2.3***	**2.82***	**-1.58***	**-0.51***	**0.11**	**0.04**	**-1.54***	**-0.04***	**1.84***	**-0.89***
	-0.27*	0.96*	-0.68*	2.54*	0.65*	0.13	-0.20	0.47*	-0.40*	-3.57*	-0.2*	-2.06*	-2.77*
Millat-11	**1.29***	**2.55***	**3.6***	**2.64***	**1.15***	**1.25***	**-0.27***	**0.50***	**-0.23**	**1.73***	**0.02***	**0.85***	**-2.70***
	0.67*	1.53*	4.74*	4.26*	1.32*	0.24	0.75*	-0.13*	-0.11	1.71*	0.02	2.13*	-0.44*

temperature are shown in Table 3. The cross combination HTSBWON-15-0079 × Millat-11 displayed significant and positive SCA effects for maximum parameters. Combination HTSBWON-15-0040 × Millat-11 and Faisalabad-06 × HTSBWON-15-0016 showed highest significant and positive SCA effects for electrolyte leakage presented maximum positive and significant SCA effects for heat related characters.

SCA effects for studied characters of genotypes in tunnel are presented in Table 4. The cross combination HTSBWON-15-0079 × Millat-11 showed significant and positive SCA effects for number of characters under high temperature treatment i.e., leaf relative water content, flag leaf area, tillers per plant, spike length, spikelets per spike, grain weight per spike, 1000 grain weight and grain yield. For heat related characters like canopy temperature as well as cell membrane thermostability the cross combination HTSBWON-15-0040 × Millat-11 showed maximum SCA effects. For electrolyte leakage the cross HTSBWON-15-0079 × HTSBWON-15-0014 showed maximum significant and positive SCA effects.

***Gene action*:** Gene action monitoring the hereditary of various physiological as well as morphological characters in wheat was estimated by combining ability analysis. Mean squares due to GCA, SCA along with their potence ratio for all studied traits are given in Table 5. SCA variances were greater than GCA variances for most studied parameters under both treatments indicating non-additive gene action.

DISCUSSION

Main objective of this research was selection of genotypes to be exploited as parental lines in hybridization programme. The varying extent of general combining ability in parents proposed that these genotypes could widely be used for improvement of economically important characters (i.e., grain yield and its related traits) in crossing programs. Significant and positive GCA effects has also been reported by different scientist for canopy temperature, cell membrane thermostability, leaf relative water content, electrolyte leakage (Ibrahim and Quick, 2001), plant height, flag leaf area, spike length, spikelets per spike, grains per spike, grain weight per spike (Majeed *et al.*, 2011; Shabbir *et al.*, 2012), 1000 grain weight (Oettler *et al.*, 2008) and grain yield per plant (Kapoor *et al.*, 2011). Greater effects of general combining ability suggests that characters are more linked to genotype's basic genetic makeup and less affected by its mean (Cifci and Yagdi, 2010; Elbnna *et al*., 2020) and selection in early generations could be beneficial (Yao *et al.*, 2011; Rashid *et al.*, 2012; Ahmad and Khaliq, 2016). The occurrence of a great general combining ability, indicated the incidence of additive genetic effects proposed a wider adaptability and great potential of the lines used as parents in development of crosses having

Table 3. Specific combining ability effects of cross combinations for some physiological and morphological traits of wheat under normal temperature

Sr	Crosses	Canopy temperature	Cell membrane thermostability	Leaf relative water content	Electrolyte leakage	Flag leaf area	Plant height	Tillers per plant	Spike length	Spikelets per spike	Grains per spike	Grain weight per spike	1000 grain weight	Grain yield per plant
1	HTSBWON-15-0002 × HTSBWON-15-0014	1.73*	1.07*	-1.15*	-12.29*	-4.86*	0.6	-1.09*	-0.17	0.11	-2.77*	-0.49*	-0.46	-8.61*
2	HTSBWON-15-0002× HTSBWON-15-0016	-0.11	6.12*	2.94*	13.00*	5.30*	-5.49*	1.14*	-0.04	0.69	-4.2*	0.24*	3.6*	3.86*
3	HTSBWON-15-0002× HTSBWON-15-0073	-0.80*	-2.23*	-0.03	-10.68*	3.32*	3.52*	0.76*	0.80	0.11	4.13*	0.10*	0.76	-1.3*
4	HTSBWON-15-0002× Millat-11	-0.81*	-4.97*	-1.76*	9.97*	-3.76*	1.35*	-0.80*	-0.57	-0.92*	2.84*	0.14*	-3.89*	6.05*
5	HTSBWON-15-0029 × HTSBWON-15-0014	0.51*	-4.5*	6.39*	5.22*	0.95*	-1.24*	-0.01	-0.08	0.28	-3.52*	0.41*	1.91*	-0.89
6	HTSBWON-15-0029× HTSBWON-15-0016	-1.96*	1.53*	6.82*	-9.81*	4.42*	-0.47	0.55	-0.45	-0.47	9.38*	0.05*	5.53*	3.77*
7	HTSBWON-15-0029× HTSBWON-15-0073	-2.28*	9.51*	-3.95*	17.36*	-4.37*	1.27*	0.17	0.56	0.28	-6.28*	-0.13*	-2.26*	-7.63*
8	HTSBWON-15-0029× Millat-11	3.73*	-6.55*	-9.26*	-12.77*	-1.00*	0.44	-0.72*	-0.02	-0.09	0.42	-0.33*	-5.19*	4.75*
9	HTSBWON-15-0040 × HTSBWON-15-0014	-1.57*	-2.88*	0.15	-2.84*	5.17*	-3.27*	0.4	-0.24	-0.21	-0.02	0.67*	2.18*	4.84*
10	HTSBWON-15-0040 × HTSBWON-15-0016	-0.75*	-1.82*	2.6*	-0.52	0.41	2.28*	-1.02*	-0.01	1.02*	-4.45*	-0.12*	1.65*	1.75*
11	HTSBWON-15-0040 × HTSBWON-15-0073	-2.01*	-15.30*	-2.6*	-8.00*	7.81*	-1.42*	1.92*	1.07*	-1.54*	4.54*	0.29*	6.05*	7.61*
12	HTSBWON-15-0040 × Millat-11	4.34*	20.06*	-0.14	11.37*	-13.39*	2.4*	-1.3*	-0.81	0.73	-0.07	-0.84*	-9.89*	-14.21*
13	HTSBWON-15-0079 × HTSBWON-15-0014	0.59*	-0.01	-15.47*	4.83*	-8.21*	3.06*	-1.09*	-1.2*	-1.04*	0.3	-0.33*	-8.68*	-1.02*
14	HTSBWON-15-0079 × HTSBWON-15-0016	1.35*	-3.62*	-4.88*	-1.89*	0.2	0.03	0.14	0.32	-0.47	-6.78*	-0.13*	-4.8*	4.78*
15	HTSBWON-15-0079× HTSBWON-15-0073	3.79*	14.35*	7.99*	16.73*	-5.99*	-1.51*	-2.23*	-1.68*	0.95*	-4.78*	-0.6*	-2.04*	-15.7*
16	HTSBWON-15-0079 × Millat-11	-5.74*	-10.7*	12.36*	-19.67*	13.99*	-1.58*	3.19*	2.56*	0.57	11.26*	1.07*	15.53*	11.94*
17	HTSBWON-15-0087 × HTSBWON-15-0014	-0.4*	-0.34	5.27*	-3.5*	-8.93*	-2.95*	0.48	1.07*	0.45	-2.44*	-0.27*	-1.18*	-3.49*
18	HTSBWON-15-0087 × HTSBWON-15-0016	0.14	-5.29*	2.19*	-10.31*	-0.46	2.51*	1.05*	-0.16	-0.3	3.13*	0.24*	-1.74*	2.32*
19	HTSBWON-15-0087 × HTSBWON-15-0073	-0.61*	-3.98*	2.09*	-3.27*	4.33*	-0.39	-1.65*	-0.17	-0.21	0.46	-0.04	-0.14	6.33*
20	HTSBWON-15-0087 × Millat-11	0.87*	9.61*	-9.57*	17.08*	5.05*	0.83	0.10	-0.72	0.07	-1.15*	0.07*	3.07*	-5.16*
21	HTSBWON-15-0089 × HTSBWON-15-0014	-0.5*	-6.75*	4.42*	-1.65*	5.02*	1.08*	0.82*	0.38	0.45	6.3*	-0.29*	7.81*	2.9*
22	HTSBWON-15-0089 × HTSBWON-15-0016	1.61*	-9.37*	1.62*	-14.82*	-9.99*	1.48*	-1.60*	1.32*	0.35	-1.45*	0.04	-1.41*	-10.48*
23	HTSBWON-15-0089 × HTSBWON-15-0073	0.29*	9.26*	-9.56*	3.21*	-3.46*	-2.22*	1.67*	-0.86	-0.21	3.54*	0.14*	-7.006*	8.63*
24	HTSBWON-15-0089 × Millat-11	-1.41*	6.86*	3.51*	13.26*	8.42*	-0.33	-0.89*	-0.84	-0.59	-8.4*	0.1*	0.59	-1.05*
25	Faisalabad-08 × HTSBWON-15-0014	-0.36*	13.4*	0.37	10.24*	10.85*	2.72*	0.48	0.26	-0.04	2.14*	0.31*	-1.58*	6.26*
26	Faisalabad-08 × HTSBWON-15-0016	-0.28	12.45*	-11.31*	24.37*	0.10	-0.34*	-0.27	-0.97*	-0.8	4.38*	-0.33*	-2.84*	-6.01*
27	Faisalabad-08 × HTSBWON-15-0073	1.62*	-11.5*	6.07*	-15.35*	-1.63*	0.74	-0.65	0.28	0.61	-1.61*	0.23*	4.64*	2.06*
28	Faisalabad-08 × Millat-11	-0.98*	-14.3*	4.87*	-19.26*	-9.32*	-3.12*	0.44	0.42	0.23	-4.9*	-0.21*	-0.21	-2.32*

Table 4. Specific combining ability effects of cross combinations for some physiological and morphological characters of wheat under heat stress.

Sr.	Crosses	Canopy temperature	Cell membrane thermostability	Leaf relative water content	Electrolyte leakage	Flag leaf area	Plant height	Tillers per plant	Spike length	Spikelets per spike	Grains per spike	Grain weight per spike	1000grain weight	Grain yield per plant
1	HTSBWON-15-0002 × HTSBWON-15-0014	1.51*	-10.34*	-2.12*	-7.46*	0.36	2.14*	0.01	0.23	-0.21	-5.23*	-0.54*	-1.53*	-7.27*
2	HTSBWON-15-0002× HTSBWON-15-0016	2.29*	6.51*	5.79*	7.27*	3.78*	-4.57*	0.86*	-0.81*	0.35	-0.28	0.71*	0.86	3.35*
3	HTSBWON-15-0002× HTSBWON-15-0073	-1.47*	2.36*	0.57	-3.63*	-7.31*	2.72*	-0.79	0.86*	0.73	7.9*	0.04	3.16*	1.38*
4	HTSBWON-15-0002× Millat-11	-2.33*	1.46*	-4.24*	3.81*	3.16*	-0.28	-0.08*	-0.28	-0.88	-2.38*	-0.22*	-2.49*	2.52*
5	HTSBWON-15-0029 × HTSBWON-15-0014	-1.03*	-4.74*	1.07*	1.35*	-2.65*	2.51*	0.59	0.16	0.95	-6.57*	0.25*	-1.31*	-2.17*
6	HTSBWON-15-0029× HTSBWON-15-0016	-2.95*	-19.28*	9.42*	-22.76*	7.76*	-1.5*	1.45*	0.28	0.19	12.38*	0.08	4.17*	11.60*
7	HTSBWON-15-0029× HTSBWON-15-0073	-1.32*	11.3*	-10.24*	12.52*	-3.69*	-1.1*	-1.88*	0.46	-0.09	-2.42*	-0.23*	-0.31	-6.60*
8	HTSBWON-15-0029× Millat-11	5.31*	12.73*	-0.25	8.88*	-1.41*	0.09	-0.16*	-0.92*	-1.04*	-3.38*	-0.1*	-2.54*	-2.82*
9	HTSBWON-15-0040 × HTSBWON-15-0014	-2.44*	0.14	2.02*	-8.84*	8.43*	-6.64*	1.01*	-0.14	0.78	2.17*	0.39*	3.38*	7.94*
10	HTSBWON-15-0040 × HTSBWON-15-0016	-1.39*	-6.64*	-2.83*	7.84*	-6.8*	3.3*	-1.46*	0.58	-1.30*	-0.86	-0.57*	-8.13*	-0.89
11	HTSBWON-15-0040 × HTSBWON-15-0073	-3.07*	-12.80*	3.19*	-12.05*	4.44*	1.6*	2.53*	0.95*	-0.26	7.65*	0.44*	11.07*	5.42*
12	HTSBWON-15-0040 × Millat-11	6.91*	19.30*	-2.38*	13.05*	-6.17*	1.73*	-2.08*	-1.39*	0.78	-8.96*	-0.26*	-6.32*	-12.47*
13	HTSBWON-15-0079 × HTSBWON-15-0014	0.86*	16.08*	-4.07*	23.89*	-4.28*	1.85*	-1.82*	-0.99*	0.28	-0.23	-0.05	-2.10*	-3.10*
14	HTSBWON-15-0079 × HTSBWON-15-0016	5.41*	-0.71	-5.23*	-3.13*	-5.77*	-0.36	0.03	-0.47	-0.47	-2.61*	-0.26*	-4.89*	-1.47*
15	HTSBWON-15-0079× HTSBWON-15-0073	2.60*	19.12*	-3.56*	18.45*	-4.84*	-1.36*	-1.63*	-0.76	-0.76	-8.42*	-0.61*	-5.60*	-8.64*
16	HTSBWON-15-0079 × Millat-11	-8.88*	-34.48*	12.87*	-39.21*	14.90*	-0.13	3.41*	2.23*	0.95	11.28*	0.92*	12.59*	13.21*
17	HTSBWON-15-0087 × HTSBWON-15-0014	-1.90*	-7.93*	4.61*	-11.02*	2.92*	-0.67	0.67	0.15	-0.71	3.51*	-0.3*	-1.59*	-0.39
18	HTSBWON-15-0087 × HTSBWON-15-0016	-0.41*	6.27*	4.79*	9.48*	-8.16*	3.77*	-0.79	0.20	-0.14	-6.86*	0.31*	2.66*	0.59
19	HTSBWON-15-0087 × HTSBWON-15-0073	-1.02*	-11.88*	-4.34*	-9.55*	3.68*	-0.76	0.86*	0.21	0.23	-2.67*	0.23*	-3.35*	3.71*
20	HTSBWON-15-0087 × Millat-11	3.35*	13.54*	-5.06*	11.09*	1.55*	-2.33*	-0.75	-0.57	0.61	6.03*	-0.24*	2.28*	-3.9*
21	HTSBWON-15-0089 × HTSBWON-15-0014	1.96*	2.14*	-3.48*	-0.93	-1.55*	0.39	-0.9*	0.34	-0.21	5.26*	0.04	-0.73	0.07
22	HTSBWON-15-0089 × HTSBWON-15-0016	-4.25*	5.01*	-3.92*	-2.18*	5.22*	1.64*	0.95*	0.48	1.69*	-3.11*	0.01	4.46*	-7.40*
23	HTSBWON-15-0089 × HTSBWON-15-0073	2.10*	0.20	5.81*	-0.04	-0.74	-4.05*	-0.04	-0.30	-0.59	-0.92	-0.17*	2.68*	6.85*
24	HTSBWON-15-0089 × Millat-11	0.18	-7.36*	1.59*	3.16*	-2.92*	2.01*	0.00	-0.52	-0.88	-1.21*	0.12*	-6.40*	0.46
25	Faisalabad-08 × HTSBWON-15-0014	1.05*	4.65*	1.97*	3.01*	-3.23*	0.40	0.42	0.23	-0.88	1.09*	0.21*	3.91*	4.92*
26	Faisalabad-08 × HTSBWON-15-0016	1.30*	8.85*	-8.01*	3.46*	3.98*	-2.27*	-1.04*	-0.27	-0.30	1.38*	-0.29*	0.85	-5.78*
27	Faisalabad-08 × HTSBWON-15-0073	2.19*	-8.30*	8.56*	-5.68*	8.47*	2.95*	0.95*	-1.43*	0.73	-1.09*	0.29*	-7.64*	-2.13*
28	Faisalabad-08 × Millat-11	-4.55*	-5.20*	-2.52*	-0.79	-9.21*	-1.08*	-0.33	1.47*	0.45	-1.38*	-0.20*	2.88*	2.99*

Table 5. Dominance variance, additive variance and potence ratio for some physiological and morphological traits under normal temperature and heat stress.

Traits	Normal temperature			Heat Stress		
	σ^2GCA	σ^2SCA	Potence ratio	σ^2GCA	σ^2SCA	Potence ratio
Canopy temperature	-0.0065	6.210	-0.0010	0.1050	16.950	0.0062
Cell membrane thermostability	-1.1400	126.340	-0.0090	-0.0410	218.070	-0.0002
Leaf relative water content	-0.7080	62.200	-0.0114	0.5820	44.020	0.0132
Electrolyte leakage	-3.3700	230.080	-0.0146	-0.0920	238.110	-0.0004
Flag leaf area	-0.3450	67.380	-0.0051	-0.2350	51.880	-0.0045
Plant height	0.0140	6.100	0.0023	0.0146	8.510	0.0017
Tillers per plant	0.0360	1.670	0.0216	-0.0190	1.860	-0.0102
Spike length	0.0301	0.328	0.0918	0.0220	0.423	0.0520
Spikelets per spike	-0.0031	-0.234	0.0132	0.0026	-0.161	-0.0161
Grains per spike	-0.0880	33.550	-0.0026	0.1530	43.870	0.0035
Grain weight per spike	-0.0044	0.226	-0.0195	-0.0022	0.198	-0.0112
1000 grain weight	-0.2590	39.960	-0.0065	-0.2990	36.880	-0.0081
Grain yield per plant	-0.2190	70.590	-0.0031	-0.7840	53.630	-0.0146

high temperature tolerance with high seed yield (Dhandhal *et al*., 2008; Pimentel *et al*., 2013). Lines HTSBWON-15-0040 and HTSBWON-15-0079 under both environments and testers HTSBWON-15-0014 and Millat-11 under heat stress with highest GCA effects were the best general combiners for few morphological and physiological traits and may be consumed in crossing schemes directing to increase seed yield and characters related to heat tolerance.

Effects of specific combining ability solely are insufficient for selection of parents to initiate a breeding programme, consequently, specific combining ability effects may be used along with general combining ability of the relevant parental line (Bagheri and Jelodar, 2010; Montazeri *et al.,* 2014). Crosses HTSBWON-15-0079 ×Millat-11 and HTSBWON-15-0040 × Millat-11 had significant and positive SCA effects for many characters in genotypes of open field as well as covered with plastic sheet. Crosses with maximum values of specific combining ability effects and including one of the parent having high general combining ability, will increase the frequency of desirable genes (Mahmood and Chowdhry, 2002; Mahpara *et al*., 2017). According to results we can conclude that crosses having positive and significant specific combing ability effects can be attained by combining high × high general combiners such as HTSBWON-15-0079 × Millat-11 and HTSBWON-15-0040 × Millat-11 (high × high) for different characters in open field and in tunnels. In our research crosses achieved by combining general combiners in high × high manner, exhibited great specific combining ability effects, it may be because of interactions of dominant genes from best combiners (Saeed *et al*., 2016; Kanwal *et al*., 2019).

Relative estimates of GCA and SCA variances showed the variances due to SCA effect were predominant for all traits and in turn it disclosed the manifestation of non-additive and non-fixable gene action (Fasahat *et al*., 2016). Characters governed by non-additive genetic effect indicated the scope of improvement in these traits though hybrid development (Pradhan *et al*., 2006; Singh *et al*., 2013; Dash *et al*., 2020). Additive gene effects are accredited to general combining ability and are constant (Irshad *et al*., 2012; Bello and Olawuyi, 2015).

Conclusion: Genetic variability existing between the genotypes can be used for enhancement of seed yield contributing characters under heat stress conditions in wheat. All morphological and physiological traits at maturity with non-additive type of genetic effects might be upgraded via selection in segregating generations. Cross combinations like HTSBWON-15-0079 × Millat-11 and HTSBWON-15-0040 × Millat-11 may be further evaluated in warm areas for checking their potential under different agro climatic conditions.

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