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COMBINING ABILITY ANALYSIS IN SOYBEAN THROUGH NORTH CAROLINA MATING DESIGN II UNDER VARYING WATER LEVELS AND TEMPERATURE AT MATURITY STAGE

BAREERA NASIR[1*], HUMERA RAZZAQ[1], HAFEEZ AHMAD SADAQAT[1] AND MUHAMMAD ASHFAQ WAHID[2]

[1]*Department of Plant Breeding and Genetics, University of Agriculture, Faisalabad-38040, Pakistan*
[2]*Department of Agronomy, University of Agriculture, Faisalabad-38040, Pakistan*
**Corresponding author's email: bareeranasir64gmail.com*

Abstract

Soybean is a climate sensitive crop. Water and temperature is crucial factors for its cultivation. The objective of this study was to evaluate the performance of eight soybean parents and their crosses under various levels of water and temperature at maturity stage. Fifteen crosses resulting from North Carolina Mating Design II and their parents were evaluated for maturity traits under three levels of water and temperature i.e. T_0= Water level: 4 irrigations + Average weekly temperature= 36.50°C, T_1= Water level: 3 irrigations + Average weekly temperature= 33.83°C and T_2 = Water level: 2 irrigations + Average weekly temperature= 29.80°C. Recorded data were subjected to analysis of variance. Existence of genetic variability among most of the entries showed that this germplasm can be further used for breeding programme in soybean to improve yield and stability. General combining ability (GCA) effects of the parents and specific combining ability (SCA) effects of crosses were estimated. Our findings reveal that selected parents (17444, 24567 and 24581) and cross combinations (17444×24581 and 24567×24576) are the most promising for breeding soybeans under different climatic conditions and may be further evaluated to study their worth as potential parents and crosses.

Key words: Analysis of variance, General combining ability (GCA), Specific combining ability (SCA), Maturity traits, Different climatic conditions.

Introduction

Change in climate could cause reduction in yield of crops up to 5% by 2030 and up to 30% by 2080 (Havlík *et al*., 2015). It is important to assess level of impact of spatial and temporal variability in climate on crops (Cure and Acock, 1986). Thus, Plant breeder has to develop plants with optimum combination of different adaptive characters than plants with single adaptive characters and it is complex and difficult.

The demand for energy and protein rich food is high in developing countries. Soybean being the most important source of both vegetable oil and protein concentrates occupies premier position among many crops. Soybean (*Glycine max* L.) is known as “Golden Beans” that is also called “meat that grows on plant” because its seed contains 40% protein on an average (Ali *et al*., 2013). Food and agriculture organization classified it, as an oilseed crop rather than a pulse crop due to extensive use of its oil i.e. 16-23% in its seed (Hamayun *et al*., 2010; Amjad, 2014).

Soybean is a climate sensitive crop. Unavailability of locally developed, well adapted and climate specific cultivars is the major problem in tropical areas. Water and temperature are crucial factors for its cultivation. It develops under wide temperature ranges but regions with very low and high mean monthly temperature i.e. below 20ºC and above 40ºC are not suitable for production of soybean. Temperature effects on soybean germination as with 1ºC increase in temperature, there is 99% decrease in germination (Tayagi & Tripathi, 1983; Khalil *et al*., 2010). Germination of seeds can occur at temperature ranges from 5ºC to 40ºC but rapid germination occur around 30ºC (Berlato, 1981).

Soybean has two critical periods with respect to requirement of water: planting to emergence and pod fill. Deficit or excess water condition during germination can influence uniformity in number and distribution of plants/area (Sionit & Kramer, 1977). Water content should not less than 50 percent and not more than 85 percent during germination. During period of pod filling water deficit condition is more harmful than flowering stage. During critical seed development period an adequate water supply must be available for the achievement of maximum yield.

Therefore, development and evaluation of new soybean cultivars to enhance its stability under changing climate could be a permanent solution. Due to self-pollination and narrow genetic base of soybean, North Carolina mating design II is best choice in it for the development of breeding material. Comstock & Robinson (1948) developed this mating design. In this each male is crossed with same set of females. It is also helpful for the measurement of combining ability effects (Hallauer *et al*., 2010; Acquaah, 2012). Combining ability is crucial tool in plant breeding for evaluation of newly developed breeding material. General combining ability (GCA) is effective tool for the selection of parents based on the performance of their progenies, usually F_1 (Salami & Agbowuro, 2016). A higher GCA effects indicated less environmental effects and higher heritability and large adaptability. It may also result in higher achievement in selection and less gene interaction (Rukundo *et al*., 2017; Zeinab & Helal, 2014).

Specific combining ability (SCA) indicates how much performance of the cross deviates from performance of parents that is predicted from GCA effects (Su *et al*., 2017). High SCA of crosses where both parents are good general combiners may be ascribed to additive × additive gene action and thus being fixable. High SCA from the crosses between good and poor combiners may be attributed to epistatic effect of poor combiner and additive effect of good combiner. High SCA from low × low crosses may be due to non-allelic and dominance × dominance type of interaction and thus being non-fixable (Shikano *et al*., 2000; Adebambo, 2011; Wang *et al*., 2014). It is also helpful in the reorganization of promising hybrids and selected on their prediction of GCA effects.

Keeping all above factors in consideration, objective of this study was to evaluate the performance of eight soybean parents and their crosses under various combinations of water and temperature treatments as these were never appeared to be tested before for their breeding potential per se in specific combinations (SCA) and their overall performance in crosses (GCA). These parents and crosses would be a valuable source of germplasm to enhance stability of soybean under different climatic regimes of temperature and water.

Materials and Methods

The experimental material comprised of eight soybean accessions (Five female parents and three male parents). These accessions were previously screened from eighty accessions at seedling stage. For screening, two independent experiments were conducted to select common parents under temperature treatments (T_0 = 30°C, T_1= 35°C and T_2= 40°C) and water treatments (T_0 = 100% water holding capacity, T_1= 60% water holding and T_2= 40% water holding capacity). Selected parents were then hybridized using North Carolina Mating Deign II (Table 1). Hybridization experiment was conducted in the research area of the Plant Breeding and Genetics, University of Agriculture, Faisalabad, Pakistan using through controlled pollination in autumn, 2019. Row to row and plant to plant distance were maintained 75cm and 25cm respectively. All agronomic practices were applied during growth period of soybean. Seeds of crosses were harvested and stored for the next season.

Table 1. North Carolina II mating scheme showing parents and their crosses in soybean.

Parents		Female parents				
		17418	**17434**	**17444**	**24566**	**24567**
Male parents	24576	17418×24576	17434×24576	17444×24576	24566×24576	24567×24576
	24581	17418×24581	17434×24581	17444×24581	24566×24581	24567×24581
	24582	17418×24582	17434×24582	17444×24582	24566×24582	24567×24582

Entries including crosses and their parents were evaluated with Randomized Complete Block Design using two factors factorial arrangements with three replications in field at maturity stage in the next growing season. Experiment was conducted in the research area of the Department of Plant Breeding and Genetics, University of Agriculture, Faisalabad, Pakistan. Row to row and plant to plant distance were maintained 75cm and 25cm respectively. Three different water levels were applied. Crop grown in a sunny and at high temperature needs more water than the same crop grown at low temperature. Weather forecast was kept in consideration so that sowing can be done at three different temperatures in combination with water level. Following three treatments were applied.

T_0 = Water level: 4 irrigations (i.e. 3 to 4 weeks after germination, initiation of flowering, pod formation stage and seed development stage) + Sowing on August 2, 2020 (Average weekly temperature= 36.50°C).

T_1= Water level: 3 irrigations (Irrigation was withdraw after pod formation) + Sowing on August 15, 2020 (Average weekly temperature= 33.83°C).

T_2 = Water level: 2 irrigations (Irrigation was withdraw after initiation of flowering) + Sowing on August 31, 2020 (Average weekly temperature= 29.80°C).

Data of three random tagged plants per treatment per replication of each entry were recorded on maturity traits i.e. plant height (PH) (in cm from ground level to the top of the tagged plants with the help of meter rod), plant fresh weight (PFW) (in grams by using weight balance Setra-BL 4105), plant dry weight (PDW) (dried samples at 70°C in an oven (Model= 655-F) until a constant weight is achieved. The dried plant weights were recorded in grams using weight balance Setra-BL 4105), number of nodes/plant (NN/P), number of seeds/pod (NS/P), number of pods/plant (NP/P), oil content (OC) and protein content (PC) (in % through near infrared reflectance spectroscopy (Model= MPW-352), days to 50% flowering (DOF) (from sowing date to the day when 50% of plants of each tagged plant started flowering), days to 50% maturity (DOM) (from sowing date to the day when 50% of plants of each tagged plant reached to maturity), electrolyte membrane leakage (EML) (in % according to Lutts *et al*., 1996), proline content (Pl.C) (in µg according to bates *et al*., 1973), leaf temperature (LT) (in°C with temperature gun), chlorophyll content (CC) (in mg by using chlorophyll meter SPAD-502), leaf area (LA) (Leaf width (cm) × leaf length (cm)) and 100 seed weight (100SW) (in grams by using electronic balance Setra-BL 4105).

Recorded data were subjected to analysis of variance for North Carolina Mating Design II (Comstock and Robinson, 1948). When significant differences were detected, data were subjected to estimate general combining ability (GCA) of parents and specific combining ability (SCA) of crosses using following formulas.

Estimation of GCA effects

Female parents: gi = {(xj../mr) – (x…/fmr)**}**

Male parents: gm = {(x.j./fr) – (x…/fmr)}

where,

f = Number of female parents

m = Number of male parents

r = Number of replications

xi..= Total number of F_1 resulting from crossing ith female parent with all the male parents

x...= Total of all the crosses

Standard error (female parents)

(Error mean sum of square/rm)$^{1/2}$

Standard error (male parents)

(Error mean sum of square/rf)$^{1/2}$

Estimation of SCA effects

si= {(xij.)/r) – (xi../mr) – (xj../fr) + x…/fmr

where,

xij = Total of F_1 resulting from crossing ith female parent with jth male parent

xi = Total of all the crosses of ith female parent with all male parents

xj = Total of all the crosses of jth male parent with all female parents

Standard error (crosses)

(Error mean sum of square/r)$^{1/2}$

Results

Analysis of variance: Analysis of variance of soybean entries for maturity traits for North Carolina Mating Design II under various combinations of water and temperature treatments is presented in (Table 2). Sources of variations i.e. parents, parents vs crosses, crosses, female parents, male parents and interaction of male and female showed significant differences for most of the traits under all treatments. Existence of genetic variability among most of the entries showed that this germplasm can be further used for breeding programme in soybean to improve yield and stability.

General combining ability (GCA) effects of parents: General combining ability effects of parents for maturity traits under T_0= Water level: 4 irrigations + Average weekly temperature= 36.50°C are presented in (Table 3). Among female parents, 24567 had positive and significant GCA effects for most of the traits followed by 17444 and 24566. Positive and significant GCA effects were observed in 24567 for PFW, LT, NP/P, PC, Pl.C, EML, DOF and DOM. 17444 had positive and significant GCA effects for PFW, PDW, LA, CC, PC, Pl.C and EML. Positive and significant GCA effects were observed in 24566 for CC, EML, DOF, NNP, 100SW and DOM. Among male parents, 24582 had positive and significant GCA effects for most of the traits i.e. PFW, LT, NP/P, EML, DOF, DOM, 100SW and NN/P.

General combining ability effects of parents for maturity traits under T_1= Water level: 3 irrigations + Average weekly temperature= 33.83°C are presented in (Table 4).

Among female parents, 17444 had positive and significant GCA effects for most of the traits followed by 24567 and 24566. Positive and significant GCA effects were observed in 17444 for PH, PDW, PFW, CC, LT, NS/P and PC. 24567 had positive and significant GCA effects for PH, PFW, OC, Pl.C, EML and DOM. Positive and significant GCA effects were observed in 24566 for CC, NP/P, 100SW, Pl.C, DOM and NN/P. Among male parents, 24581 had positive and significant GCA effects for most of traits i.e. PH, PDW, CC, LT, NP/P, PC, Pl.C, EML and NN/P.

General combining ability effects of parents for maturity traits under T_2= Water level: 2 irrigations + Average weekly temperature= 29.80°C are presented in (Table 5). Among female parents, 17444 had positive and significant GCA effects for most of the traits followed by 24567. Positive and significant GCA effects were observed in 17444 for PH, PFW, PDW, CC, LT, PC, NS/P, EML and DOF. 24567 had positive and significant GCA effects for PFW, LA, OC, 100SW, DOF and DOM. Among male parents, 24581 had positive and significant GCA effects for most of the traits i.e. PH, PDW, CC, LT, NP/P, PC, Pl.C and 100SW.

Hence, on the basis of general combining ability effects of parents under various treatments of water and temperature at maturity stage, 17444, 24567 and 24581 were selected as best general combiners.

Specific combining ability effects of crosses: Specific combining ability effects of crosses for maturity traits under T_0= Water level: 4 irrigations + Average weekly temperature= 36.50°C are presented in (Table 6). Cross 24567×24576 had positive and significant specific combining ability effects for most of the traits followed by 17444×24581 and 17434×24581. Cross 24567×24576 had positive and significant SCA effects for PDW, CC, LT, NP/P, NS/P, Pl.C, PC, EML, DOM, DOF and NN/P. Positive and significant SCA effects were observed in cross 17444×24581 for PH, PFW, PDW, 100SW, LA, CC, LT, PC, Pl.C and DOF. Cross 17434×24581 had significant and positive SCA effects for PH, NP/P, OC, PC, Pl.C, DOF, DOM and NN/P.

Specific combining ability effects of crosses for maturity traits under T_1= Water level: 3 irrigations + Average weekly temperature= 33.83°C are presented in (Table 7).

Crosses 24567×24576 and 17444×24581 had positive and significant specific combining ability effects for most of the traits followed by 17418×24576 and 24566×24581. Positive and significant SCA effects were observed in cross 24567×24576 for 100SW, PH, PDW, CC, NP/P, Pl.C, EML, DOF and NN/P. Cross 17444×24581 had positive and significant SCA effects for PH, PFW, PDW, LA, CC, Pl.C, PC, DOF and 100SW. Cross 24566×24581 had significant and positive SCA effects for PH, PFW, NP/P, CC, PC, EML and DOM. Positive and significant SCA effects were observed in cross 17418×24576 for PH, PFW, PDW, LA, PC, NN/P and 100SW.

Table 2. Mean squares from analysis of variance for maturity traits in soybean under various water and temperature treatments.

SOV	DF	PH	PFW	PDW	LA	CC	LT	NP/P	NS/P	OC	PC	PL.C	EML	DOF	DOM	NN/P	100SW
		Treatment 0 (T_0= Water level: 4 irrigations + Average weekly temperature= 36.50°C)															
Replications	2	114	3.91	1.30	5.60	1.29	1.06	2.69	3.36	20.11	2.66	0.00	2.77	12.24	2.46	0.00	0.00
Entries	22	77.4**	237.7**	28.1**	16.7**	4.85**	9.01**	5.37*	1.6**	16.16	11.8**	0.01**	27.56**	48.24**	124.96**	1.65**	0.19**
Parents	7	50.8*	336.0**	31.1**	15.2**	3.11**	11.7**	5.63*	0.69	23.16	13.1**	0.01**	16.86**	67.26**	159.34**	1.53**	0.13**
Parents vs Crosses	1	224**	16.2	93.6**	35.9**	1.35	0.01	12.1*	0.10	0.44	6.27	0.01**	19.45*	46.54**	141.77**	1.51**	0.02**
Crosses	14	80.1**	204.4**	21.9**	16.1**	5.97**	8.2**	4.76	2.2**	13.79	11.5**	0.01**	33.50**	38.85**	106.57**	1.73**	0.23**
Female parents	4	136.2**	277.4**	35.2**	7.42	5.57**	5.76	4.06	2.5**	23.27	9.69**	0.01**	19.38**	18.46**	73.70**	4.33**	0.35**
Male parents	2	14.1	105.3**	17.1**	5.55	2.26*	26.9**	3.80	2.2*	2.49	12.8**	0.00	32.17**	73.07**	323.49**	0.76**	0.13**
Female × Male	8	68.6*	192.9**	16.5**	23.0**	7.10**	5.02	5.34*	2.6*	11.87	12.2**	0.02**	40.89**	40.48**	68.78**	0.66**	0.19**
Error	44	20.5	6.29	2.50	2.84	0.46	3.01	2.13	0.63	24.29	2.11	0.00	3.00	1.73	1.72	0.01	0.00
		Treatment 1 (T_1= Water level: 3 irrigations + Average weekly temperature= 33.83°C)															
Replications	2	42.0	1.69	1.54	0.05	0.56	1.42	12.4	3.36	0.61	0.91	0.00	2.77	5.27	0.13	0.03	0.00
Entries	22	76.2**	186.1**	23.1**	20.7**	4.11**	3.4**	48.2**	1.6**	10.75	14.3**	0.01**	27.56**	42.87**	116.26**	0.14**	0.10**
Parents	7	38.3**	237.6**	24.4**	18.4**	3.01**	7.05	67.2**	0.69	7.98	12.3**	0.01**	16.86**	64.36**	149.06**	0.21**	0.18**
Parents vs Crosses	1	383.4**	19.3	66.1**	2.85	0.02	4.77	46.5**	0.10	4.17	0.62	0.00	19.45*	3.42*	85.83**	0.13**	0.25**
Crosses	14	73.2**	172.2**	19.3**	23.2**	4.95**	4.81	38.8**	2.5**	12.60	16.2**	0.01**	33.50**	34.95**	102.04**	0.11**	0.05**
Female parents	4	104.7**	193.4**	31.2**	24.3**	4.96**	8.36	18.4**	2.4**	7.66	11.5**	0.01**	19.38**	26.69**	73.08**	0.08**	0.04**
Male parents	2	45.9*	128.2**	10.9**	8.5**	1.62**	3.6**	73.0**	2.2*	1.61	53.0**	0.01**	32.17**	11.55**	293.73**	0.17**	0.20**
Female × Male	8	64.4**	172.6**	15.5**	26.9**	5.78**	21.6	40.4**	2.6*	17.83	9.4**	0.01**	40.89**	44.93**	68.60**	0.11**	0.02**
Error	44	11.7	6.70	0.78	1.15	0.27	7.28	1.73	0.63	8.52	0.93	0.00	3.00	0.56	1.29	0.02	0.00
		Treatment 2 (T_2= Water level: 2 irrigations + Average weekly temperature= 29.80°C)															
Replications	2	33.7	0.16	0.86	1.95	0.24	1.42	0.33	0.32	1.09	0.14	0.00	11.78	1.36	1.29	0.03	0.00
Entries	22	62.7**	179.8**	20.4**	24.4**	3.07**	6.7**	9.5**	1.7**	14.7**	11.1**	0.04**	120.95**	46.26**	121.19**	0.14**	0.06**
Parents	7	37.7*	236.8**	21.2**	22.7**	2.77**	2.93	7.9**	0.6*	9.90*	12.0**	0.03**	85.31**	63.97**	149.66**	0.21**	0.06**
Parents vs Crosses	1	333.2**	47.9**	56.8**	0.79	0.40	13.7*	8.6**	0.09	29.9**	7.82**	0.51**	159.63**	91.37**	156.63**	0.13**	0.50**
Crosses	14	55.9*	160.4**	17.3**	27.1**	3.42**	8.08**	10.0**	1.6**	16.0**	11.0**	0.01**	136.00**	34.19**	104.43**	0.11**	0.02**
Female parents	4	78.3**	182.8**	29.0**	44.7**	3.57**	1.82	6.4**	0.9**	10.6*	11.5**	0.01**	257.55**	29.31**	73.07**	0.08**	0.02**
Male parents	2	55.9*	123.3**	12.2**	11.6**	2.46**	9.8*	30.6**	3.5**	0.66	33.9**	0.01**	24.08*	12.21**	314.08**	0.17**	0.05**
Female × Male	8	44.7*	159.0**	12.8**	22.2**	3.59**	10.8*	7.52**	1.5**	22.0**	6.3**	0.01**	103.21**	42.12**	67.69**	0.11**	0.02**
Error	44	15.64	3.624	0.56	2.59	0.23	2.19	0.99	0.21	3.78	0.69	0.00	5.45	0.46	2.46	0.02	0.00

**= Significant at 0.01 probability level *=Significant at 0.05 probability level

SOV= Sources of variation, DF= Degrees of freedom, PH= Plant height, PFW= Plant fresh weight, PDW= Plant dry weight, LA= Leaf area, CC= Chlorophyll content, LT= Leaf temperature, NP/P= Number of pods/plant, NS/P= Number of seeds/pod, OC= Oil content, PC= Protein content, Pl.C= Proline content, EML= Electrolyte membrane leakage, DOM= Days to 50% maturity, DOF= Days to 50% flowering, NN/P= Number of nodes/plant, 100SW= 100 seed weight

Table 3. General combining ability effects of parents for maturity traits in soybean under treatment level T_0.

Accessions	PH	PFW	PDW	LA	CC	LT	NP/P	NS/P	OC	PC	Pl.C	EML	DOF	DOM	NN/P	100SW
Female parents																
17418	-0.78	-0.36	2.28	0.65	-0.73	-0.38	-0.45	-0.01	2.08	-1.74	-0.05	-2.65	-2.40	-2.84	-0.83	-0.14
17434	-5.56	-5.22	-1.88	0.27	-0.16	0.07	0.53	0.26	-1.53	0.33	0.01	-3.06	0.60	0.38	1.00	0.24
17444	5.11	7.95	1.93	0.96	0.54	-1.11	-0.29	0.67	-1.07	0.61	0.01	1.07	-0.18	-3.01	-0.35	-0.23
24566	-0.44	-5.05	-1.65	-1.16	1.06	0.42	-0.68	-0.13	-0.84	-0.09	-0.01	1.36	1.21	2.27	0.33	0.16
24567	1.67	2.69	-0.69	-0.72	-0.71	1.00	0.89	-0.78	1.36	0.89	0.03	3.28	0.77	3.21	-0.15	-0.03
Standard error	1.51	0.83	0.52	0.56	0.22	0.57	0.48	0.26	1.64	0.48	0.00	0.48	0.43	0.43	0.03	0.00
Male parents																
24576	0.11	-2.61	0.28	0.45	-0.39	-1.47	-0.45	0.40	0.42	-0.52	0.00	0.34	-2.52	-4.43	-0.15	-0.09
24581	0.91	-0.07	0.90	0.24	0.39	0.39	-0.10	-0.33	-0.03	1.07	0.00	-1.24	0.94	-0.40	-0.11	0.00
24582	-1.02	2.68	-1.18	-0.69	0.00	1.08	0.54	-0.06	-0.39	-0.55	0.00	0.90	1.58	4.83	0.26	0.09
Standard error	1.17	0.64	0.40	0.43	0.17	0.44	0.37	0.20	1.27	0.37	0.00	0.37	0.33	0.33	0.02	0.00

PH= Plant height, PFW= Plant fresh weight, PDW= Plant dry weight, LA= Leaf area, CC= Chlorophyll content, LT= Leaf temperature, NP/P= Number of pods/plant, NS/P= Number of seeds/pod, OC= Oil content, PC= Protein content, Pl.C= Proline content, EML= Electrolyte membrane leakage, DOM= Days to 50% maturity, DOF= Days to 50% flowering, NN/P= Number of nodes/plant, 100SW= 100 seed weight

Table 4. General combining ability effects of parents for maturity traits in soybean under treatment level T_1.

Accessions	PH	PFW	PDW	LA	CC	LT	NP/P	NS/P	OC	PC	Pl.C	EML	DOF	DOM	NN/P	100SW
Female parents																
17418	-0.96	0.13	2.42	-1.79	-0.77	-0.26	0.09	-0.03	0.68	-1.00	-0.04	-0.50	-1.96	-2.31	0.12	0.02
17434	-4.19	-4.66	-1.70	2.36	-0.03	-0.20	0.05	0.05	-0.93	1.02	-0.01	-1.54	1.64	0.45	-0.02	0.08
17444	4.76	5.68	1.25	0.75	0.40	1.05	-0.91	0.49	-0.62	1.42	0.00	-0.17	1.90	-3.52	-0.11	-0.10
24566	-1.44	-4.53	-1.91	-0.14	1.03	-0.70	0.54	-0.18	-0.38	-0.56	0.02	-0.21	-1.28	2.47	0.08	0.02
24567	1.84	3.38	-0.06	-1.19	-0.63	0.12	0.23	-0.33	1.24	-0.88	0.02	2.43	-0.30	2.91	-0.07	-0.03
Standard error	1.14	0.86	0.29	0.35	0.17	0.89	0.35	0.19	0.97	0.32	0.00	0.57	0.24	0.37	0.04	0.00
Male parents																
24576	-0.28	-2.20	-0.02	0.67	-0.33	-0.58	-1.08	0.40	0.21	-1.96	-0.03	0.25	0.45	-4.15	-0.07	0.13
24581	1.87	-1.12	0.86	-0.82	0.32	1.38	0.98	-0.49	-0.38	1.79	0.01	1.33	-1.01	-0.51	0.12	-0.09
24582	-1.59	3.32	-0.84	0.15	0.01	-0.80	0.10	0.09	0.17	0.17	0.01	-1.57	0.56	4.66	-0.06	-0.04
Standard error	0.88	0.41	0.22	0.27	0.13	0.69	0.27	0.15	0.75	0.24	0.00	0.44	0.19	0.29	0.03	0.00

PH= Plant height, PFW= Plant fresh weight, PDW= Plant dry weight, LA= Leaf area, CC= Chlorophyll content, LT= Leaf temperature, NP/P= Number of pods/plant, NS/P= Number of seeds/pod, OC= Oil content, PC= Protein content, Pl.C= Proline content, EML= Electrolyte membrane leakage, DOM= Days to 50% maturity, DOF= Days to 50% flowering, NN/P= Number of nodes/plant, 100SW= 100 seed weight

Table 5. General combining ability effects of parents for maturity traits in soybean under treatment level T_2.

Accessions	PH	PFW	PDW	LA	CC	LT	NP/P	NS/P	OC	PC	Pl.C	EML	DOF	DOM	NN/P	100SW
Female parents																
17418	-0.86	0.14	2.31	1.83	-0.45	-0.05	0.00	-0.01	0.88	-1.39	-0.04	-8.02	-1.07	-2.22	-0.18	0.05
17434	-3.80	-4.67	-1.66	-0.87	-0.59	0.07	0.66	0.18	-0.34	1.08	-0.01	3.27	-1.86	-1.19	0.18	0.01
17444	4.20	5.61	1.14	-2.54	0.67	0.59	-1.21	0.44	0.36	1.24	0.00	4.17	2.87	-2.71	-0.10	-0.01
24566	-0.75	-4.22	-1.88	-1.21	0.69	-0.68	0.85	-0.34	-1.69	-0.42	0.02	3.60	-0.25	3.23	0.02	-0.07
24567	1.22	3.13	0.09	2.78	-0.32	0.06	-0.31	-0.27	0.79	-0.51	0.02	-3.03	0.32	2.89	0.08	0.02
Standard error	1.31	0.63	0.24	0.46	0.16	0.49	0.33	0.15	0.64	0.27	0.00	0.77	0.22	0.52	0.04	0.00
Males parents																
24576	0.51	-2.10	0.09	0.18	-0.47	-0.17	-1.46	0.47	0.15	-1.68	-0.03	1.45	1.02	-4.16	-0.25	-0.04
24581	1.62	-1.17	0.86	-0.95	0.20	0.87	1.39	-0.50	-0.24	1.20	0.01	-0.54	-0.34	-0.75	0.03	0.07
24582	-2.14	3.27	-0.94	0.77	0.27	-0.70	0.08	0.04	0.09	0.48	0.01	-0.91	-0.68	4.90	0.21	-0.03
Standard error	1.02	0.49	0.19	0.37	0.12	0.38	0.25	0.11	0.50	0.21	0.00	0.60	0.17	0.40	0.03	0.00

PH= Plant height, PFW= Plant fresh weight, PDW= Plant dry weight, LA= Leaf area, CC= Chlorophyll content, LT= Leaf temperature, NP/P= Number of pods/plant, NS/P= Number of seeds/pod, OC= Oil content, PC= Protein content, Pl.C= Proline content, EML= Electrolyte membrane leakage, DOM= Days to 50% maturity, DOF= Days to 50% flowering, NN/P= Number of nodes/plant, 100SW= 100 seed weight

Table 6. Specific combining ability effects of crosses for maturity traits in soybean under treatment level T_0

Crosses	PH	PFW	PDW	LA	CC	LT	NP/P	NS/P	OC	PC	Pl.C	EML	DOF	DOM	NN/P	100SW
17418×24576	5.78	3.44	2.27	1.52	-0.05	-1.03	0.15	0.07	0.44	-0.09	-0.04	-4.30	-0.37	-6.30	-0.15	-0.25
17434×24576	-5.78	-0.44	-0.32	3.59	1.82	-0.37	-1.88	0.27	-2.37	-1.27	0.10	0.65	-1.42	-0.68	0.36	0.27
17444×24576	-1.44	4.89	-2.62	-3.76	-2.15	-1.42	1.77	0.36	0.47	-0.48	-0.09	0.58	-0.48	4.54	-0.50	-0.07
24566×24576	-0.56	-5.11	-1.47	0.26	-0.15	-0.48	-1.04	-1.17	2.12	0.82	-0.02	0.99	3.30	1.12	-0.28	0.23
24567×24576	2.00	-2.79	2.14	-1.61	0.53	3.30	1.01	0.47	-0.66	1.02	0.06	2.08	1.50	1.32	0.57	-0.18
17418×24581	-4.69	-5.51	-0.33	0.19	0.37	1.50	-0.18	0.60	-1.36	-2.09	0.05	1.00	-4.83	4.19	0.01	0.35
17434×24581	5.42	-9.79	-0.16	-2.23	-2.27	-4.83	1.03	-0.34	3.14	0.85	0.01	-0.58	2.78	1.46	0.12	-0.12
17444×24581	2.76	4.35	2.93	2.91	1.66	2.78	-0.31	-1.01	-1.12	1.45	0.05	-0.98	3.56	-8.16	-0.16	0.03
24566×24581	1.98	9.18	-1.39	0.39	0.96	3.56	0.12	0.39	-1.94	1.85	-0.02	1.05	-3.00	1.22	0.19	-0.15
24567×24581	-5.47	1.77	-1.05	-1.27	-0.72	-3.00	-0.66	0.36	1.28	-2.06	-0.10	-0.49	-0.47	1.29	-0.16	-0.10
17418×24582	-1.09	2.07	-1.94	-1.71	-0.32	-0.47	0.03	-0.67	0.92	2.19	-0.01	3.30	5.20	2.11	0.14	-0.09
17434×24582	0.36	10.23	0.49	-1.36	0.45	5.20	0.85	0.06	-0.77	0.42	-0.11	-0.06	-1.36	-0.78	-0.48	-0.15
17444×24582	-1.31	-9.24	-0.31	0.85	0.49	-1.36	-1.46	0.65	0.65	-0.97	0.03	0.40	-3.08	3.61	0.66	0.04
24566×24582	-1.42	-4.07	2.86	-0.66	-0.81	-3.08	0.92	0.79	-0.18	-2.67	0.05	-2.05	-0.30	-2.34	0.08	-0.08
24567×24582	3.47	1.02	-1.10	2.88	0.19	-0.30	-0.34	-0.84	-0.62	1.04	0.04	-1.59	-1.03	-2.61	-0.40	0.28
Standard Error	2.61	1.44	0.91	0.97	0.39	1.00	0.84	0.45	2.84	0.83	0.00	0.84	0.75	0.75	0.05	-0.25

PH= Plant height, PFW= Plant fresh weight, PDW= Plant dry weight, LA= Leaf area, CC= Chlorophyll content, LT= Leaf temperature, NP/P= Number of pods/plant, NS/P= Number of seeds/pod, OC= Oil content, PC= Protein content, Pl.C= Proline content, EML= Electrolyte membrane leakage, DOM= Days to 50% maturity, DOF= Days to 50% flowering, NN/P= Number of nodes/plant, 100SW= 100 seed weight

Table 7. Specific combining ability effects of crosses for maturity traits in soybean under treatment level T_1.

Crosses	PH	PFW	PDW	LA	CC	LT	NP/P	NS/P	OC	PC	Pl.C	EML	DOF	DOM	NN/P	100SW
17418×24576	5.78	3.44	2.27	1.52	0.03	-1.04	-0.25	-0.04	-0.48	1.21	-0.04	-2.26	-2.25	-6.32	0.26	0.09
17434×24576	-5.78	-0.44	-0.32	3.59	1.58	-0.36	-1.31	0.49	-3.28	0.21	-0.04	-3.59	-1.38	0.09	-0.11	-0.03
17444×24576	-1.44	4.89	-2.62	-3.76	-2.09	-0.90	2.75	0.54	0.36	0.57	-0.04	5.45	-3.17	4.73	-0.19	-0.05
24566×24576	-0.56	-5.11	-1.47	0.26	-0.07	1.30	-2.14	-1.12	3.31	-0.91	0.08	-1.52	1.94	1.04	-0.11	-0.07
24567×24576	2.00	-2.79	2.14	-1.61	0.55	0.99	0.95	0.13	0.08	-1.09	0.04	1.91	4.86	0.46	0.15	0.06
17418×24581	-4.69	-5.51	-0.33	0.19	0.26	0.19	-0.58	0.89	-0.51	-1.23	-0.01	-1.71	4.94	5.22	-0.17	-0.04
17434×24581	5.42	-9.79	-0.16	-2.23	-1.84	0.28	0.35	-0.79	3.30	-0.10	0.05	3.40	-2.66	1.12	-0.04	0.03
17444×24581	2.76	4.35	2.93	2.91	1.38	-0.16	-0.99	-0.73	-1.85	1.20	0.03	-1.15	0.96	-8.25	0.25	-0.01
24566×24581	1.98	9.18	-1.39	0.39	0.94	1.41	1.42	0.60	-1.92	1.85	-0.05	1.32	-0.47	0.86	0.03	-0.04
24567×24581	-5.47	1.77	-1.05	-1.27	-0.74	-1.71	-0.20	0.02	0.98	-1.72	-0.01	-1.87	-2.78	1.05	-0.08	0.06
17418×24582	-1.09	2.07	-1.94	-1.71	-0.29	0.85	0.84	-0.86	0.99	0.02	0.05	3.96	-2.70	1.11	-0.09	-0.05
17434×24582	0.36	10.23	0.49	-1.36	0.26	0.08	0.96	0.30	-0.02	-0.12	-0.01	0.19	4.04	-1.21	0.14	0.00
17444×24582	-1.31	-9.24	-0.31	0.85	0.71	1.06	-1.76	0.19	1.49	-1.77	0.01	-4.30	2.22	3.52	-0.07	0.07
24566×24582	-1.42	-4.07	2.86	-0.66	-0.87	-2.71	0.72	0.52	-1.39	-0.94	-0.02	0.19	-1.47	-1.90	0.08	0.11
24567×24582	3.47	1.02	-1.10	2.88	0.19	0.72	-0.75	-0.16	-1.07	2.81	-0.03	-0.05	-2.09	-1.51	-0.07	-0.13
Standard Error	1.97	1.49	0.50	0.61	0.30	1.55	0.61	0.34	1.68	0.55	0.00	1.00	0.43	0.65	0.08	0.00

PH= Plant height, PFW= Plant fresh weight, PDW= Plant dry weight, LA= Leaf area, CC= Chlorophyll content, LT= Leaf temperature, NP/P= Number of pods/plant, NS/P= Number of seeds/pod, OC= Oil content, PC= Protein content, Pl.C= Proline content, EML= Electrolyte membrane leakage, DOM= Days to 50% maturity, DOF= Days to 50% flowering, NoN/P= Number of nodes/plant, 100SW= 100 seed weight

Table 8. Specific combining ability effects of crosses for maturity traits in soybean under treatment level T_2.

Crosses	PH	PFW	PDW	LA	CC	LT	NP/P	NS/P	OC	PC	Pl.C	EML	DOF	DOM	NN/P	100SW
17418×24576	3.33	3.88	1.81	2.92	0.39	0.60	-0.85	-0.08	-0.61	0.72	-0.04	1.28	-3.67	-6.37	-0.10	0.02
17434×24576	-1.72	-0.58	-0.59	2.15	-0.05	-0.29	-0.51	0.23	-3.13	0.24	-0.04	0.44	1.99	1.60	0.40	0.03
17444×24576	-3.19	5.18	-2.26	-1.78	-1.90	-2.23	1.73	0.64	0.18	0.63	-0.04	-6.02	-4.34	4.08	-0.08	0.01
24566×24576	0.46	-5.32	-1.17	-2.77	0.74	0.03	-1.93	-0.91	4.33	-1.09	0.08	1.59	2.21	0.35	-0.13	-0.01
24567×24576	1.12	-3.15	2.20	-0.52	0.82	1.89	1.56	0.12	-0.76	-0.50	0.04	2.70	3.81	0.35	-0.10	-0.05
17418×24581	-4.91	-5.48	-1.12	-1.35	0.23	0.70	-0.50	0.79	-0.10	-0.67	-0.01	-2.62	4.89	5.24	-0.01	-0.14
17434×24581	3.10	-8.34	-0.32	1.15	-0.74	1.71	-0.26	-0.56	3.46	-0.26	0.05	8.10	-0.48	0.69	-0.28	0.02
17444×24581	3.70	1.05	2.68	1.85	1.38	0.83	-0.69	-0.88	-2.10	0.69	0.03	-1.55	0.42	-7.96	0.14	0.02
24566×24581	2.38	9.72	-0.97	-0.87	-0.19	-0.27	1.10	0.56	-2.39	1.90	-0.05	0.09	-1.86	0.37	0.12	0.05
24567×24581	-4.26	3.06	-0.27	-0.79	-0.67	-2.98	0.35	0.09	1.13	-1.66	-0.01	-4.02	-2.96	1.67	0.02	0.05
17418×24582	1.58	1.61	-0.69	-1.57	-0.61	-1.30	1.35	-0.71	0.72	-0.05	0.05	1.34	-1.23	1.13	0.11	0.11
17434×24582	-1.38	8.92	0.91	-3.31	0.79	-1.42	0.77	0.33	-0.33	0.02	-0.01	-8.54	-1.50	-2.29	-0.12	-0.05
17444×24582	-0.51	-6.22	-0.42	-0.07	0.53	1.40	-1.03	0.24	1.92	-1.32	0.01	7.56	3.93	3.89	-0.07	-0.03
24566×24582	-2.83	-4.39	2.13	3.64	-0.55	0.24	0.83	0.35	-1.94	-0.81	-0.02	-1.68	-0.35	-0.71	0.01	-0.04
24567×24582	3.14	0.09	-1.93	1.32	-0.15	1.09	-1.91	-0.21	-0.37	2.16	-0.03	1.31	-0.85	-2.01	0.08	0.00
Standard Error	2.28	1.09	0.43	0.84	0.27	0.85	0.57	0.26	1.12	0.47	0.00	1.34	0.39	0.90	0.08	0.00

PH= Plant height, PFW= Plant fresh weight, PDW= Plant dry weight, LA= Leaf area, CC= Chlorophyll content, LT= Leaf temperature, NP/P= Number of pods/plant, NS/P= Number of seeds/pod, OC= Oil content, PC= Protein content, Pl.C= Proline content, EML= Electrolyte membrane leakage, DOM= Days to 50% maturity, DOF= Days to 50% Flowering, NN/P= Number of nodes/plant, 100SW= 100 seed weight

Specific combining ability effects of crosses for maturity traits under T_2= Water level: 2 irrigations + Average weekly temperature = 29°C are presented in (Table 8). Crosses 17444×24581 had positive and significant specific combining ability effects for most of the traits followed by 17418×24576, 24567×24576, 17434×24581, 17444×24582 and 24566×24581. Cross 17444×24581 had positive and significant SCA effects for 100SW, PH, PDW, LA, CC, Pl.C, PC, DOF and NN/P. Positive and significant SCA effects were observed in cross 24567×24576 for PDW, CC, LT, NP/P, Pl.C, EML and DOF. Cross 24566×24581 had significant and positive SCA effects for 100SW, PH, PFW, NP/P, NS/P, PC and NN/P. Positive and significant SCA effects were observed in cross 17444×24582 for CC, LT, OC, Pl.C, EML, DOF and DOM. Cross 17434×24581 had positive and significant SCA effects for PH, LA, LT, 100SW, OC, Pl.C and EML. Cross 17418×24576 had positive and significant SCA effects for 100SW, PH, PFW, PDW, CC, LA and PC.

Selection of best general and specific combiners: Hence, on the basis of general combining ability effects of parents under various treatments of water and temperature at maturity stage, 17444, 24567 and 24581 were selected as best general combiners and crosses 17444×24581 and 24567×24576 were selected as best cross combiners.

Discussion

Analysis of variance of our study showed that all soybean entries had significant differences for most of studied traits under various combinations of water and temperature treatments. Rima *et al.,* (2019) observed significant differences for plant height, total chlorophyll, proline content and total dry matter production of soybean under different temperature and water treatments respectively. Vegetative period of soybean from emergence to flowering including number of nodes, plant height, leaf area and juvenile period were significantly affected by temperature (Camara *et al*., 1997; Alsajri *el al.*, 2019). Previous studies revealed significant effect of climate warming and water stress conditions on different maturity traits in soybean i.e. number of pods/plant, number of seeds/pod and 100-seed weight (Shi *et al*., 2001; Sarkar *et al*., 2015; Zhang *et al*., 2016; Mimi *et al*., 2016). Present study showed that oil content had non-significant differences at treatment levels T_0 and T_1. Literature indicated that seed oil and protein concentrations of soybean were affected by both temperature and water stress (Foroud *et al*., 1993; Gibson & Mullen, 1996; Piper & Boote, 1999). Contradiction in results may be due to different environmental conditions and soybean accessions. Many plant scientists found significant effect of water and temperature stress on flowering and maturity in soybean (Major *et al*., 1975; Hadley *et al*., 1984; Cober *et al*., 2001; Agele *et al*., 2004; Han, 2007; Fei *et al*., 2009; Li *et al*., 2020). Soybean temperatures above 40°C have an adverse effect on the rate of growth, the rate of formation of the nodes and internode growth and floral initiation (Mamnabi *et al*., 2020). Szczerba *et al*., (2011) observed significant effect of temperature on electrolyte membrane leakage and plant weight in all studied soybean cultivars.

This revealed a high prevalence of genetic heterogeneity among soybean entries for most of the traits which could be useful in selection in subsequent generations of soybean breeding under different climatic conditions.

Estimates of specific and general combining ability (SCA and GCA) have been frequently used in crop improvement to select potential parents and crosses (Rukundo *et al*., 2017; Mwale *et al*., 2017). General combining ability effects in our study revealed that parents 17444, 24567 and 24581 and crosses 17444×24581 and 24567×24576 were best general and specific combiners respectively. These crosses obtained by crossing high × high and high × low general combiners respectively. Selected parents had significant and positive GCA values for most of the traits i.e. 17444 (PH, PFW, PDW, CC, LT, LA, EML, DOF, PC and NS/P), 24567 (PH, NP/P, OC, DOF PFW, LA, LT, Pl.C, EML and DOM) and 24581 (PH, PDW, CC, LT, NP/P, PC, Pl.C, EML, NN/P and 100SW) under various combinations of water and temperature treatments. Selected Crosses had significant and positive SCA values for most of the traits i.e. 17444×24581 (PH, NN/P, DOF, 100SW, PC, LA PFW, PDW, LT, CC and Pl.C) and 24567×24576 (PH, NN/P, DOF NP/P, 100SW, PC, PDW, LT, CC, EML, Pl.C and NS/P). High positive combining ability values for soybean cultivars for plant height, number of nodes, days to maturity and flowering were also reported in literature (Gavioli *et al*., 2008; Rialch & Sharma, 2019; Tesfaye *et al*., 2020). In literature, studied cultivars showed positive and significant GCA and SCA effects for number of pods/plant, number of seeds/pod and 100 seed weight (Rialch & Sharma, 2019; Tesfaye *et al*., 2020). Rialch *et al*., (2017) reported predominance of specific SCA effects over GCA effects for protein content and oil content. Dhanda & Munjal (2009) reported positive and significant GCA and SCA effects for electrolyte membrane leakage in eight wheat genotypes under different temperature treatments. Gopikannan & Ganesh (2013) found significant combining ability values among soybean crosses and parents for proline and chlorophyll content. In literature, plant fresh and dry weight of soybean had significant GCA and SCA effects under water-limited stress conditions (Chiipanthenga *et al*., 2021).

In present study, positive and significant GCA effects of parents (17444, 24567 and 24581) indicated the existence of favorable genes that were additive in nature and can be transmitted from parents to offspring. Cross 17444×24581 showed high SCA effects because of cross between high × high general combiners. In cross 24567×24576, male parent 24576 was a poor general combiner which indicated that significance of SCA effects is due to interaction of additive and non-additive genes (Cho & Scott, 2000; Friedrichs *et al*., 2016). Hence, combining ability analysis is helpful to evaluate the relative importance of effects due to non-additive (associated with SCA) as well as additive gene effects (expressed by GCA effects). This information is useful in establishing the best breeding strategy.

Conclusion

General combining ability effects suggested that 17444, 24567 and 24581 are best among parents and can be further used in selection for adaptation. Specific combining ability effects suggested that cross combinations 17444×24581 and 24567×24576 may be further evaluated under different climatic conditions to study their worth as potential crosses.

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