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ESTIMATION OF COMBINING ABILITY AND HETEROSIS IN WHEAT

[1]Md. Abdus Sattar Karikor; [1]Md. Shahriar Kabir; [2]Md. Mukhtar Hossain*; [3]Md. Abul Kalam Azad; [4]Mohamed Ahmed Mohamud; [5]Md. Hafizur Rahman; [6]Nahar Shumsun; [7]Md. Aminul Hoque

[1]Md. Abdus Sattar Karikor, Student, Department of Agronomy and Agricultural Extension, Faculty of Agriculture, University of Rajshahi, Rajshahi, Bangladesh
[1]Md. Shahriar Kabir, Student, Department of Agronomy and Agricultural Extension, Faculty of Agriculture, University of Rajshahi, Rajshahi, Bangladesh
[2]Md. Mukhtar Hossain, Lecturer, Department of Crop Science and Technology, Faculty of Agriculture, Rajshahi University, Rajshahi, Bangladesh
[3]Md. Abul Kalam Azad Professor, Department of Crop Science and Technology, Faculty of Agriculture, Rajshahi University, Rajshahi, Bangladesh
[4]Mohamed Ahmed Mohamud, Campus Director, Zamzam University of Science and Technology, Mogadishu, Somalia
[5]Md. Hafizur Rahman, Professor, Department of Crop Science and Technology, Faculty of Agriculture, Rajshahi University, Rajshahi, Bangladesh
[6]Nahar Shumsun, Lecturer, Department of Crop Science and Technology, Faculty of Agriculture, Rajshahi University, Rajshahi, Bangladesh
[7]Md. Aminul Hoque, Professor, Department of Agronomy and Agricultural Extension University of Rajshahi Bangladesh

Email: mukhtar.gpb@gmail.com *

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Abstract:

The study used a half-diallel mating fashion to identify combining ability (GCA and SCA) and heterosis of six wheat (Triticum aestivum L.) genotypes and their 15 F1 hybrids for morpho-physiological, yield, and yield-contributing traits. The present study was carried out in a randomized complete block design with three replications. The studied characters are heading days, maturity days, chlorophyll content, Plant height, Effective tillers plant^{-1}, Total tillers plant^{-1}, Spikes plant^{-1}, Spike length, Filled spikelets spike^{-1}, Unfilled spikelets spike^{-1}, Grains spike^{-1}, Thousand grain weight, Grain yield plant^{-1}, Biological yield plant-1, and Harvest index Highly significant differences were observed among genotypes (parents and F_1 hybrids) for all characters studied. The results also showed that the mean squares due to general (GCA) and specific (SCA) combining abilities were highly significant for all studied characters except harvest index, indicating the magnitude of both additive and non-additive gene effects in governing these traits. GCA/SCA ratios were greater than one for all characters except filled spikelets spike-1 and harvests index, indicating the dominance of additive gene effects, which play important roles in the inheritance of these characters. While the non-additive effect of the gene predominated in the inheritance of filled spikelets (spike-1) and harvests index, The parent BARI GOM-30 emerged as the best general combiner for total tillers plant^{-1}, filled spikelets spike^{-1}, grains spike^{-1}, thousand-grain weight, grain yield plant-1, and harvest index. Bari Gom-28 was the best general combiner for heading days and maturity days, and Sourav was the best for effective tillers plant^{-1}, spikes plant-1, and biological yield plant^{-1}. The cross BARI GOM-30 SOURAV was the best specific combiner for effective tillers plant^{-1}, total tillers plant^{-1}, spikes plant-1, and PRODIP SOURAV for filled spikelets spike^{-1}. Bari GOM-33 Sourav emerged as the best specific combiner for grain yield plant^{-1} and Prodip Ayt-5 for grain spike^{-1}. Concerning heterotic effects in comparison to the midparent, the F_1 hybrid BARI GOM-28 BARI GOM-33 showed maximum significant positive heterosis for chlorophyll content and biological yield plant^{-1} and BARI GOM-33 SOURAV for effective tillers plant^{-1}, spikes plant-1, and grain yield plant^{-1}. These parents and cross combinations could be used for the breeding program of wheat for potential yield.

***Keywords*:** Heterosis, Wheat genotypes, Hybrid, Combining ability, Cross combination

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1. Introduction

Wheat (*Triticum aestivum* L.) is one of the most important cereal crops containing high protein content. Native to the arid lands of Asia Minor is the place where wheat developed from a type of wild grass (Dedaniya *et. al.*, 2018). Wheat is an incomparable gift of nature to mankind as it contains starch (60-68%), protein (6-21%), fat (1.5 2.0%), cellulose (2.0-2.5%), minerals (1.8%) and vitamins (Das, 2008).

According to the latest information, the total area under wheat crop has been estimated at 10,99,158 acres (4,44,805 hectares) obtaining the yield of 32.86 maunds per acre (3.031 metric tons per hectare) (BBS, 2015-2016). The total production of wheat during the year 2015-2016 has been recorded 13,48,186 metric tons which are 0.02% than the previous years (BBS, 2015-2016). The actual advancement of production in wheat is necessary not only to meet our increasing food requirement but also for earning foreign exchange by exporting it. The production of wheat must be increased to fulfill the increasing demand of the world population. Hybrid wheat is the desirable alternative option.

To start a breeding program to improve any crop variety, the breeders need to know the type of gene action and genetic system which govern the inheritance of the characters and also need to gain knowledge about the best breeding method to be utilized to develop them (Hossain *et al.*,2021 Ismail, 2015). The study of the genetic structure and trend of combining ability has great importance for the plant breeder for improvement in wheat yield. General and specific combining ability knowledge along with the mode of gene action in available breeding material is very important to start effective wheat breeding procedure.

In the wheat breeding program, the most important stage is the identification of desirable parents with the highest general combining ability (GCA) and specific combining ability (SCA) for yield and next to the exploitation of the heterosis process. Heterosis study has a great significance on the varietal improvement methodology and provides advantageous information about the effectiveness of the parents which are used in the breeding culture (Singh *et al*., 2012). Combining ability analysis is considered as one of the powerful tools to compare the performance of different parents in different hybrid combinations and help in selecting advantageous parents and crosses for the exploitation of heterosis (Rashid *et al.*, 2007 and Salgotra *et al.*, 2009). Combining ability researches are carried out by many plant breeders to select parents with efficient transferring preferable characters to the offspring (Madic *et al.*, 2005).

In the breeding procedure of wheat, some parents produce desirable progenies on crossing with others while some produce undesirable progenies. The parents which perform well in the combination procedure have great importance to the plant breeders. (Gami *et al*., 2010). Half-diallel fashion is one kind of mating system which aids plant breeders to estimate the general combining ability (GCA) and specific combining ability (SCA). The additive and non-additive genetic variances are estimated from the estimates (Khaled *et al.*, 2020). A genotype

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with additive gene expression is more responsive in selection than a genotype that contains high non-additive gene action. Heterosis reveals the percentage of increase or decrease in the mean value of the F_1 hybrids over their mid parents' value. Heterosis may be considered as a genetic expression of beneficial effects of hybridization (Khaled *et al.*, 2020).

For the evaluation of newly developed hybrid for their parental effectiveness, the heterosis studies are very important. The parents which produce the best cross combination with the highest expression of heterosis are determined by the help of the knowledge of heterosis. The great concern to the plant breeder is the choice of appropriate parents for developing better varieties or hybrids to improve the genetic yield potentials of the varieties. The best cross combinations that may produce preferable segregants from the advanced generations are identified by the nature and magnitude of heterosis. Heterosis breeding provides ways to exceed the yield barriers. The crosses showing the highest heterosis could be used for obtaining transgressive segregants for the advancement of yield and yield contributing characters (Dedaniya *et al.*, 2018).

Keeping in view of all the above facts, the present study was conducted to examine the heterosis as well as combining ability of six wheat genotypes and their fifteen possible cross combinations on morpho-physiological and yield and yield contributing characters. The main important objectives of the study are as follows:

i. To study the general combining ability (GCA) of the parental genotypes and specific combining ability (SCA) of the F_1 hybrids for morpho-physiological and yield and yield contributing characters.
ii. To study the heterotic effects of the F_1 hybrids for morpho-physiological and yield and yield contributing characters, and
iii. To study the relationship between heterosis and SCA effects of the F_1 hybrids for morpho-physiological and yield and yield contributing characters.

2. MATERIALS AND METHODS

2.1 Location and duration of the experiment

The experiment was conducted at the research field of the Department of Agronomy and Agricultural Extension, University of Rajshahi during the period of November, 2018 to March, 2020. There were two experiments, the first was conducted from November 2018 to March 2019 to complete the hybridization program and the second experiment was conducted to evaluate F_1 hybrids at the period of November 2019 to March 2020 to study the variability heterosis and combining ability in wheat.

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2.2 Experimental design

The experiment was set up in a randomized complete block design (RCBD) with three replications. The plot size was 5m long and genotypes were grown with 4 rows. The distance between the two plots was 50cm and the spacing between rows was 25cm and plant to plant was 5cm.

2.3 Recording of data

Data on fifteen morpho-physiological and yield and yield contributing characters were recorded for the study. From each plot, 10 sample plants were randomly selected for collecting post-harvest data. For statistical analysis, the average of the 10 plants for each character was used. Among the characters heading days (50%), days to maturity (90%) and chlorophyll content were recorded from the standing plants in the field. The above three characters were measured on the whole plot basis. On the other hand, the rest of the traits were measured on an individual plant basis in the laboratory after harvest. The characters were recorded as follows:

a) Heading days (50%)

The days required from sowing to a stage at which 50% of the spikes fully come out from the leaf sheath were recorded.

b) Maturity days (90%)

The days required from sowing to the date when 90% physiological maturity were recorded.

c) Chlorophyll content of flag leaf (SPAD)

From the fully expanded sunlit flag leaves, the trait was measured by a Minolta SPAD meter and expressed in the SPAD unit.

d) Plant height (cm)

The height of a plant was measured from the bottom to the top of the spike of the plant excluding awn and expressed in cm.

e) Effective tillers plant^{-1} (No.)

The tillers containing spikes at the top were counted from each of the sample plants and then expressed as effective tillers plant^{-1}.

f) Total tillers plant^{-1} (No.)

The number of all effective tillers and non-effective tillers from each plant was measured as total tillers plant^{-1}.

g) Spikes plant^{-1} (No.)

The number of spikes from each sample plant was counted and then expressed as spikes plant^{-1}.

h) Spike length (cm)

The length of the main spike was measured from the base to the top point of the spike excluding awn.

i) Filled spikelets spike^{-1} (No.)

Filled spikelets from the main spike of each sample plant were recorded and the average of filled spikelets per spike was taken.

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j) Unfilled spikelets spike^{-1} (No.)

The number of unfilled spikelets from the main spike of each sample plant was recorded and then the average of unfilled spikelets spike-1 was measured.

k) Grains spike^{-1} (No.)

The total number of grains from the main spike of each sample plant was recorded and then the average of grains spike^{-1} was taken.

k) 1000-grain weight (g)

It was recorded by weighing randomly selected two hundred clean and properly sundried grains. The grains were weighed in a digital balance in grams and then it was converted into 1000-grain weight.

l) Grain yield plant^{-1} (g)

It was measured by weighing the total grains of each sample plant and then the average of the grain yield per plant was taken in gram.

m) Biological yield plant^{-1} (g)

The biological yield was measured by weighing the sample plants including all spikes, leaves and stems after proper sun drying.

n) Harvest index (%)

It was calculated as the ratio of grain yield to the biological yield. It was expressed in percent. It was calculated according to the following formula.

$$\text{Harvest Index (\%)} = \frac{\text{Grain Yield}}{\text{Biological Yield}} \times 100$$

2.4 Statistical analysis of data

The data collected on morpho-physiological and yield and yield contributing characters were subjected to different analysis as follows-

2.4.1 Analysis of combining ability

Griffing's (1956 a) method 2 model 1 (fixed model) was used for general combining ability and specific combining ability analysis.

The mathematical model for the combining ability analysis is assumed to be:

$X_{ij} = \mu + g_i + g_j + s_{ij} + e$

Where,

Xij = Performance of the cross between the ith and jth parents

μ = Populations mean

gi = GCA effect of the ith parent

gj = GCA effect of the jth parent

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sij = SCA effect of the cross between ith and jth parents

e= Environmental influence peculiar to the cross

The sum of squares in the analysis of variance due to GCA and SCA effect was calculated using the following formula:

$$Sg = \frac{1}{P+2}\{\Sigma (Xi. + xii)^2 - \frac{4}{P}X^2..\}$$

$$Ss = \Sigma \Sigma Xij^2 - \frac{1}{P+2}\Sigma (Xi. + xii)^2 + \frac{2}{(P+1)(P+2)}X^2\ldots$$

Where,

Sg = Sum of squares due for gca

Ss = Sum of squares due to sca

P = Number of parents

Xi = Array total of the ith parent

Xii = Performance of the ith parent

X.. = Grand total of the diallel table

Xij = Performance of the cross between ith and jth parents.

GCA effects of the parents (gi) and SCA effects of the crosses (sij) were estimated using:

$$Gi = \frac{1}{P+2}[\Sigma (Xi. + xii) - \frac{2}{P}X\ldots]$$

$$sij = xij - \frac{1}{P+2}[Xi. + xii + X.j + xjj] + \frac{2}{(P+1)(P+2)}X^2\ldots$$

Where,

X.j. = Array total of the jth parent

Xjj = Performance of the jth parent

The effects were tested against zero by their respective standard errors (S.E.).

$$S.E.(gi) = [\frac{P-1}{P(P+2)}\sigma^2 e]^{1/2}$$

$$S.E.(sij) = [\frac{P(P-1)}{(P+1)(P+2)}\sigma^2 e]^{1/2}$$

Where,

$\sigma^2 e$ = Error variance obtained from analysis of variance for combining ability

2.4.2 Estimation of heterosis in F_1 hybrids

The values of heterosis were estimated by comparing the mean of F_1 hybrids over mid parental value according to the following formula (Fonseca & Patterson, 1968).

$$\text{Mid-parent heterosis (MP) \%} = \frac{\bar{F}_1 - MP}{MP} \times 100$$

Where,

$\bar{F}_1$ = Mean of the character of F_1 hybrids

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MP = Mid parental value of the character (The average of two parent mean)

The test of significance for heterosis was determined using the t-test.

$$t = \frac{\bar{F}_1 - MP}{SE}$$

$$SE = \sqrt{\frac{3EMS}{2r}}$$

Where,

SE = Standard error

EMS = Error mean square

r = Number of replications.

3. RESULTS AND DISCUSSION

The present study was carried out to estimate combining ability and heterosis in different varieties of wheat for morpho-physiological and yield and yield contributing characters. The results of the present study consisting of general combining ability (GCA), specific combining ability (SCA), heterosis and relationship between heterosis and SCA effects for morpho-physiological and yield contributing characters in wheat are expressed and described under the following heads:

- 3.1 Performance of genotypes for morpho-physiological and yield contributing characters in wheat
- 3.2 General combining ability (GCA) and specific combining ability (SCA) for morpho-physiological and yield contributing characters in wheat
- 3.3 Heterosis of the crosses for morpho-physiological, yield and yield contributing characters in wheat
- 3.4 Relationship between heterosis and SCA effects of the crosses for morpho-physiological, yield and yield contributing characters in wheat

3.1 Performance of genotypes for morpho-physiological and yield contributing characters

The mean squares from analysis of variance (ANOVA) for genotypes are exhibited in Tables 1 and 2. The analysis of variance showed highly significant differences for all morpho-physiological and yield and yield contributing characters under study. Wide diversity among the genotypes is proved by the result.

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Table 1: Analysis of variance (MS) for morpho-physiological characters in a 6 × 6 diallel cross of wheat

SOV	DF	Mean square values					
		HD (50%)	MD (90%)	CC	PH (cm)	ETP^{-1} (No.)	TTP^{-1} (No.)
Replication	2	1.333	2.778	0.418	5.885	0.389	0.253
Genotype	20	29.605**	34.883**	31.782**	32.72**	2.738**	3.145**
Error	40	1.167	1.761	1.667	2.188	0.333	0.454

** indicate significant at 1% level of probability.

SOV = Source of variation; DF = Degrees of freedom; HD = Heading days; MD = Maturity days; CC = Chlorophyll content; PH = Plant height; ETP^{-1}= Effective tiller $plant^{-1}$; TTP^{-1} = Total Tiller $plant^{-1}$.

The results of the mean performance of six parental genotypes and fifteen F_1 hybrids are summarized in Tables 3 and 4 and discussed as follows:

3.1.1 Heading days

Performance of genotypes and F_1 hybrids demonstrated in Table 3 which expressed that the minimum heading days was noticed in two parental genotypes BARI GOM-30 (61.33 days) followed by BARI GOM-28 (62.67 days). Among the F_1 hybrids, BARI GOM-30 × BARI GOM-28 (58.67 days) displayed the minimum heading days. It was also found that the hybrids BARI GOM-28 × PRODIP (60.67 days) and BARI GOM-30 × SOURAV (62.00 days) exhibited earliness in heading.

3.1.2 Maturity days

The average performance of parental genotypes, along with cross combinations, is presented in Table 3 which revealed that the minimum maturity days were observed in the parental genotype BARI GOM-28 (106.67 days). The other two parental genotypes that showed earliness in maturity were BARI GOM-30 (107.67 days) and BARI GOM-33 (110.67 days) respectively. Extreme earliness in maturity was found in the F_1 hybrids BARI GOM-30 × BARI GOM-28 (104.33 days) followed by BARI GOM-28 × BARI GOM-33 (105.33 days) and BARI GOM-28 × PRODIP (106.00 days).

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Table 2: Analysis of variance (MS) for yield and yield contributing characters in a 6 × 6 diallel cross

SOV	DF	Mean square values								
		SP^{-1} (No.)	SL (cm)	FSS^{-1} (No.)	USS^{-1} (No.)	GS^{-1} (No.)	TGW (g)	GYP^{-1} (g)	BYP^{-1} (g)	HI (%)
Replication	2	0.389	1.231	0.794	0.058	2.336	0.873	0.802	3.498	1.830
Genotype	20	2.738**	7.41**	8.453**	0.746**	45.436**	28.873**	5.087**	20.564**	17.708**
Error	40	0.333	0.767	1.008	0.110	1.082	1.121	0.757	2.743	4.540

** indicate significant at 1% level of probability.

SOV = Source of variation; DF = Degrees of freedom; SP^{-1} = Spikes plant^{-1}; SL = Spike length; FSS^{-1} = Filled spikelet spike^{-1}; USS^{-1} = Unfilled spikelet spike^{-1}; GS^{-1} = Grains spike^{-1}; TGW = Thousand grain weight; GYP^{-1} = Grain yield

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Table 3: Mean performance of morpho-physiological characters of the parents and hybrids of wheat

Genotypes	HD (50%)	MD (90%)	CC (SPAD)	PH (cm)	ETP^{-1} (No.)
			Parents		
BARI GOM-30	61.33	107.67	25.87	97.39	7.47
BARI GOM-28	62.67	106.67	26.21	98.80	6.33
PRODIP	63.33	113.33	23.54	90.79	6.60
BARI GOM-33	64.67	110.67	29.23	93.79	5.47
SOURAV	68.33	112.00	24.84	93.17	7.30
AYT-5	70.33	114.00	22.06	92.03	6.50
			Hybrids		
BARI GOM-30 × BARI GOM-28	58.67	104.33	23.01	102.60	7.07
BARI GOM-30 × PRODIP	63.00	113.00	20.67	93.75	8.00
BARI GOM-30 × BARI GOM-33	64.33	114.00	25.41	92.80	6.57
BARI GOM-30 × SOURAV	62.00	110.33	22.13	92.32	9.13
BARI GOM-30 × AYT-5	68.33	111.33	26.34	91.41	5.37
BARI GOM-28 × PRODIP	60.67	106.00	22.56	93.94	6.53
BARI GOM-28 × BARI GOM-33	60.00	105.33	31.13	98.17	7.03
BARI GOM-28 × SOURAV	65.67	113.00	27.36	91.22	5.83
BARI GOM-28 × AYT-5	68.33	115.33	22.95	96.89	6.27
PRODIP × BARI GOM-33	66.33	111.67	19.16	92.03	6.00
PRODIP × SOURAV	64.33	114.00	19.27	88.82	7.13
PRODIP × AYT-5	68.67	113.00	23.85	90.92	7.77
BARI GOM-33 × SOURAV	65.67	115.00	28.77	91.83	8.23
BARI GOM-33 × AYT-5	66.00	111.33	27.58	96.33	5.67
SOURAV × AYT-5	63.33	115.67	21.54	93.87	6.83
Mean	64.57	111.32	24.45	93.95	6.81
SE(±)	0.882	1.084	1.054	1.208	0.471

HD = Heading days; MD = Maturity days; CC = Chlorophyll content; PH = Plant height; ETP^{-1}= Effective tiller $plant^{-1}$; TTP^{-1} = Total Tiller $plant^{-1}$.

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3.1.3 Chlorophyll content

The average efficiency of parental genotypes, along with cross combinations, is presented in Table 3 which expressed that the highest chlorophyll content was found in the parental genotype BARI GOM-33 (29.23). Among the F1 hybrids, the highest chlorophyll content was recorded in BARI GOM-28 × BARI GOM-33 (31.13) and followed by BARI GOM-33 × SOURAV (28.77), BARI GOM-33 × AYT-5 (27.58) and BARI GOM-28 × SOURAV (27.36).

3.1.4 Plant height

The mean performance of parents together with the F_1 hybrids is displayed in Table 3 which demonstrated that the tallest plant was found in parental genotypes BARI GOM-28 (98.80 cm) and BARI GOM-30 (97.39 cm). The shortest plant height was identified in the parental genotypes PRODIP (90.79 cm) followed by AYT-5 (92.03 cm). Among the crosses, BARI GOM-30 × BARI GOM-28 (102.60 cm), BARI GOM-28 × AYT-5 (96.89 cm), BARI GOM-28 × BARI GOM-33 (98.17 cm) and BARI GOM-33 × AYT-5 (96.33 cm) expressed the tallest plant height while, shortest plant height was observed in PRODIP × SOURAV (88.82 cm), PRODIP × AYT-5 (90.92 cm), BARI GOM-28 × SOURAV (91.22 cm), BARI GOM-30 × AYT-5 (91.41 cm) and BARI GOM-33 × SOURAV (91.83 cm).

3.1.5 Effective tillers plant^{-1}

The average performance of parents and cross combinations (Table 3) showed that the maximum number of effective tiller^{-1} was observed in the parent BARI GOM-30 (7.47) and SOURAV (7.30). The F_1 hybrid BARI GOM-30 × SOURAV (9.13) exhibited the maximum number of effective tiller plant^{-1}. It was also noticed that the crosses BARI GOM-33 × SOURAV (8.23) and BARI GOM-30 × PRODIP (8.00) respectively produced the maximum number of effective tiller plant^{-1}.

3.1.6 Total tillers plant^{-1}

The mean performance of F_1 hybrids together with their parental genotypes (Table 3) revealed that the maximum number of total tiller plant^{-1} was displayed by the parent BARI GOM-30 (9.40) and next to SOURAV (8.73). The hybrids BARI GOM-30 × SOURAV (9.67), SOURAV × AYT-5 (8.83), BARI GOM-33 × AYT-5 (8.07) and BARI GOM-30 × PRODIP (8.07) performed well for total tiller plant^{-1}.

3.1.7 Spikes plant^{-1}

In the case of spikes plant^{-1}, the average performance of parents, along with their crosses is listed in Table 4 which revealed that the parent BARI GOM-30 (7.47) and SOURAV (7.30) showed the maximum number of

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spikes plant^{-1}. Among the hybrids, the maximum number of spikes plant^{-1} was expressed by BARI GOM-30 × SOURAV (9.13), BARI GOM-33 × SOURAV (8.23) and BARI GOM-30 × PRODIP (8.00) respectively.

3.1.8 Spike length

Performance of genotypes and cross combinations is demonstrated in Table 4 which expressed that the parental genotype BARI GOM-30 (16.38 cm) produced maximum spike length followed by BARI GOM-33 (16.29 cm) and SOURAV (16.09 cm). Among the F_1 hybrids, BARI GOM-30 × PRODIP (17.37 cm), BARI GOM-33 × SOURAV (17.08 cm), PRODIP × BARI GOM-33 (16.95 cm), BARI GOM-30 × BARI GOM-28 (16.92 cm) and PRODIP × SOURAV (16.86 cm) performed maximum spike length.

Table 4: Mean performance of yield and yield contributing characters of the parents and hybrids of wheat

Genotypes	SP^{-1} (No.)	SL (cm)	FSS^{-1} (No.)	USS^{-1} (No.)	GS^{-1} (No.)	TGW (g)	GYP^{-1} (g)	BYP^{-1} (g)	HI (%)
Parents									
BARI GOM-30	7.47	16.38	18.27	2.60	48.20	49.19	13.06	49.87	26.20
BARI GOM-28	6.33	15.40	18.67	2.80	45.83	43.14	10.34	48.74	21.29
PRODIP	6.60	14.45	17.46	2.53	43.67	47.49	12.01	49.14	24.53
BARI GOM-33	5.47	16.29	18.40	2.23	47.33	41.23	10.05	49.92	20.15
SOURAV	7.30	16.09	18.47	2.10	46.40	43.39	11.31	50.98	22.19
AYT-5	6.50	13.87	17.60	2.67	39.07	39.18	11.13	44.14	25.36
Hybrids									
BARI GOM-30 × BARI GOM-28	7.07	16.92	19.27	2.83	41.80	43.47	11.35	46.96	24.21
BARI GOM-30 × PRODIP	8.00	17.37	17.43	1.87	48.93	40.14	12.23	48.59	25.16
BARI GOM-30 × BARI GOM-33	6.57	15.75	17.13	2.40	44.76	49.46	12.71	46.74	27.19
BARI GOM-30 × SOURAV	9.13	12.20	18.03	3.13	47.77	39.72	13.33	49.04	27.22
BARI GOM-30 × AYT-5	5.37	13.44	16.57	2.73	39.44	40.85	10.16	43.35	23.46
BARI GOM-28 × PRODIP	6.53	13.70	15.80	3.33	38.47	40.33	13.11	44.58	29.43
BARI GOM-28 × BARI GOM-33	7.03	14.84	17.53	2.70	45.18	39.90	12.46	51.89	24.02
BARI GOM-28 × SOURAV	5.83	15.84	14.60	4.00	46.91	43.07	12.62	47.80	26.40
BARI GOM-28 × AYT-5	6.27	14.00	16.30	2.37	42.63	42.56	10.14	43.57	23.30
PRODIP × BARI GOM-33	6.00	16.95	14.40	2.50	36.47	44.04	9.96	44.54	22.37
PRODIP × SOURAV	7.13	16.86	19.10	2.82	39.09	45.33	11.99	47.41	25.29
PRODIP × AYT-5	7.77	12.73	17.13	2.87	44.66	39.04	11.76	45.79	25.66
BARI GOM-33 × SOURAV	8.23	17.08	15.47	2.47	48.04	43.93	13.22	50.56	26.16
BARI GOM-33 × AYT-5	5.67	13.24	16.17	2.53	40.63	41.19	10.55	45.07	23.40
SOURAV × AYT-5	6.83	14.89	12.70	3.70	38.57	39.95	8.80	44.88	19.62
Mean	6.81	15.16	16.98	2.72	43.52	42.70	11.54	47.31	24.41
SE(±)	0.471	0.715	0.820	0.271	0.849	0.865	0.710	1.352	1.740

SP^{-1} = Spikes plant^{-1}; SL = Spike length; FSS^{-1} = Filled spikelet spike^{-1}; USS^{-1} = Unfilled spikelet spike^{-1}; GS^{-1} = Grains spike^{-1}; TGW = Thousand grain weight; GYP^{-1} = Grain yield plant^{-1}; BYP^{-1} = Biological yield plant^{-1}; HI = Harvest index.

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3.1.9 Filled spikelets spike^{-1}

The average efficiency of parental genotypes, along with cross combinations (Table 4) expressed that the parent BARI GOM-28 (18.67) recorded the maximum number of filled spikelet spike^{-1}. It was also observed that the parent SOURAV (18.47), BARI GOM-33 (18.40) and BARI GOM-30 (18.27) showed the highest number of filled spikelet spike^{-1}. Being in a cross combination, BARI GOM-30 × BARI GOM-28 (19.27), PRODIP × SOURAV (19.10) and BARI GOM-30 × SOURAV (18.03) demonstrated the highest number of filled spikelet spike^{-1}.

3.1.10 Unfilled spikelets spike^{-1}

In the case of unfilled spikelet spike^{-1}, the average performance of parents, along with their crosses is listed in Table 4 which revealed that the parental genotype SOURAV (2.10) showed the minimum number of unfilled spikelets spike^{-1} and BARI GOM-28 (2.80) expressed maximum number of unfilled spikelet spike^{-1}. While among F1 hybrids, the lowest number of unfilled spikelets spike^{-1} was found in BARI GOM-30 × PRODIP (1.87). The maximum number of unfilled spikelets spike^{-1} was revealed by BARI GOM-28 × SOURAV (4.00), SOURAV × AYT-5 (3.70) and BARI GOM-28 × PRODIP (3.33) respectively.

3.1.11 Grains spike^{-1}

With the concern of grain yield, the mean performance of F_1 hybrids together with their parental genotypes (Table 4) revealed that the parent BARI GOM-33 (47.33) and BARI GOM-30 (48.20) gave the highest number of grains spike^{-1} while, in the F_1 hybrids, the maximum number of grains spike^{-1} was obtained from BARI GOM-30 × PRODIP (48.93) followed by BARI GOM-33 × SOURAV (48.04) and BARI GOM-30 × SOURAV (47.77).

3.1.12 1000-grain weight

In respect of thousand-grain weight, the average efficiency of parents, along with their crosses shown in Table 4 revealed that the highest 1000-grain weight was noticed from the parental genotype BARI GOM-30 (49.19 g) and next was PRODIP (47.49 g). While among crosses, the maximum 1000-grain weight was expressed with the hybrid BARI GOM-30 × BARI GOM-33 (49.46 g) and next to PRODIP × BARI GOM-33 (44.04). It is considered 1000-grain weight is the most sensitive yield contributing component. It was also noticed that BARI GOM-33 × SOURAV (43.93) and BARI GOM-30 × BARI GOM-28 (43.47) formed the maximum 1000-grain weight.

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3.1.13 Grain yield plant^{-1}

The mean performance of genotypes and cross combinations are listed in Table 4 which demonstrated that the parent BARI GOM-30 (13.06 g) displayed the maximum grain yield plant^{-1} and then PRODIP (12.01 g). Being in a cross combination, BARI GOM-30 × SOURAV (13.33 g), BARI GOM-33 × SOURAV (13.22 g) and BARI GOM-28 × PRODIP (13.11 g) showed maximum grain yield plant^{-1}.

3.1.14 Biological yield plant^{-1}

The average performance of parents, along with crosses (Table 4) displayed that the highest biological yield was identified in SOURAV (50.98 g) followed by BARI GOM-33 (49.92 g), BARI GOM-30 (49.87 g), PRODIP (49.14 g) and BARI GOM-28 (48.74 g). Among the F_1 hybrids BARI GOM-28 × BARI GOM-33 (51.89 g), BARI GOM-33 × SOURAV (50.56 g), BARI GOM-30 × SOURAV (49.04 g) and BARI GOM-30 × PRODIP (48.59 g) respectively formed the highest biological yield plant^{-1}.

3.1.15 Harvest index

The average efficiency of parental genotypes, along with F_1 hybrids (Table 4) showed that the highest harvest index was expressed with the parental genotype BARI GOM-30 (26.20%), and the next was AYT-5 (25.36%). Among the F_1 hybrids, the highest harvest index was noticed for BARI GOM-30 × SOURAV (27.22%) and BARI GOM-28 × PRODIP (29.43%).

3.2 General combining ability (GCA) and specific combining ability (SCA) for morpho-physiological and yield contributing characters in wheat

The present study was carried out to determine the general combining ability (GCA) and specific combining ability (SCA) for morpho-physiological and yield and yield contributing traits of the semi-diallelic crossings of the six wheat genotypes and crossings. The results of mean squares of analysis of variance for different characters are presented in Tables 5 & 6. The GCA effects of parents for morpho-physiological and yield and yield contributing traits are demonstrated in Tables 7 & 8 and the effects of SCA of cross combinations are presented in Tables 9 & 10 respectively.

The results of mean squares for both GCA and SCA from the analysis of variance (Tables 5 and 6) were highly significant for all the studied characters except harvest index. Harvest index exhibited only significant difference for GCA. The estimated results indicate the role of both additive and non-additive gene effects in governing these characters.

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The estimates of GCA/SCA (Ratio) values are summarized in Tables 5 and 6. For all studied characters the estimated values of the GCA/SCA ratios were more than unity except filled spikelets spike^{-1} and harvest index indicating these characters were governed by preponderance additive gene action. The results are in agreement with Attia *et al.* (2013), Khaled and Abd El-Dayem (2014), Murugan and Kannan (2017), Hussein & Okasha (2017), Hassan *et al.* (2018) who also reported mean squares due to GCA were greater than mean squares due to SCA. However, filled spikelets spike^{-1} and harvest index were predominantly governed by non-additive gene action. Similar findings were also achieved by Murugan and Kannan (2017)

Table 5: Analysis of variance (MS) of combining ability for morpho-physiological characters in a 6 × 6 diallel cross of wheat

SOV	DF	Mean square values					
		HD (50%)	MD (90%)	CC (SPAD)	PH (cm)	ETP^{-1} (No.)	TTP^{-1} (No.)
GCA	5	69.667**	76.944**	61.444**	81.621**	3.941**	4.109**
SCA	15	16.251**	20.862**	21.895**	16.419**	2.336**	2.824**
Error	40	1.167	1.761	1.667	2.188	0.333	0.454
GCA/SCA (Ratio)		4.287	3.688	2.806	4.971	1.687	1.455

** indicate significant at 1% level of probability.

SOV = Source of variation; DF = Degrees of freedom; GCA = General Combining Ability; SCA = Specific Combining Ability; HD = Heading days; MD = Maturity days; PH = Plant height; ETP^{-1}= Effective tiller plant^{-1};

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Table 6: Analysis of variance (MS) of combining ability for yield and yield contributing characters in a 6 × 6 diallel cross of wheat

SOV	DF	Mean square values								
		SP^{-1} (No.)	SL (cm)	FSS^{-1} (No.)	USS^{-1} (No.)	GS^{-1} (No.)	TGW (g)	GYP^{-1} (g)	BYP^{-1} (g)	HI (%)
GCA	5	3.941**	10.069**	5.259**	0.758**	62.176**	37.436**	6.672**	44.237**	14.654*
SCA	15	2.336**	6.524**	9.518**	0.742**	39.855**	26.019**	4.559**	12.673**	18.726**
Error	40	0.333	0.767	1.008	0.110	1.082	1.121	0.757	2.743	4.540
GCA/SCA (Ratio)		1.687	1.543	0.553	1.022	1.560	1.439	1.463	3.491	0.783

* and ** indicate significant at 5% and 1% level of probability respectively.

SOV = Source of variation; DF = Degrees of freedom; GCA = General Combining Ability; SCA = Specific Combining Ability; SP^{-1} = Spikes $plant^{-1}$; SL = Spike length; FSS^{-1} = Filled spikelet $spike^{-1}$; USS^{-1} = Unfilled spikelet $spike^{-1}$; GS^{-1} = Grains $spike^{-1}$; TGW = Thousand grain weight; GYP^{-1} = Grain yield $plant^{-1}$; BYP^{-1} = Biological yield $plant^{-1}$; HI = Harvest index.

The results concerning the general combining ability (GCA) effects and the specific combining ability (SCA) effects are presented and discussed character wise as follows-

3.2.1 Heading days

The estimates of GCA effects of the parental genotypes are summarized in Table 7. The highest significant negative GCA effect is preferable for heading days. Two parental genotypes BARI GOM-28 and BARI GOM-30 were identified to be the best general combiners with desirable significant and negative GCA values of -1.667 and -1.625, respectively. The parents SOURAV (.708) and AYT-5 (2.917) had the highest unwanted significant and positive GCA effects.

The SCA effects of the crosses for different characters in wheat are summarized in Table 8. Negative and significant SCA effects indicate earliness for days to heading. The hybrid SOURAV × AYT-5 gave the highest (-4.863) significant and negative effects for days to maturity followed by BARI GOM-28 × BARI GOM-33 (-2.863), BARI GOM-30 × BARI GOM-28 (-2.613), BARI GOM-28 × PRODIP (-1.946), BARI GOM-30 × SOURAV (-1.655) and BARI GOM-33 × AYT-5 (-1.446) respectively. However, the cross SOURAV × AYT-5 was considered as the best specific combiner.

The magnitude of significant negative GCA effects among parents and SCA effects among F_1 crosses for heading days was also reported by Kumar and Kerkhi (2015), Ahmad *et al.* (2017), Ingle *et al.* (2018) and Kaur *et al.* (2020).

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Table 7: Estimation of general combining ability (GCA) effects for morpho-physiological characters in a 6 × 6 diallel cross of wheat

Parents	HD (50%)	MD (90%)	CC (SPAD)	PH (cm)	ETP^{-1} (No.)	TTP^{-1} (No.)
BARI GOM-30	-1.625**	-1.361**	-0.232	1.253*	0.421*	0.454*
BARI GOM-28	-1.667**	-2.736**	1.035*	2.849**	-0.288*	-0.388*
PRODIP	-0.292	0.639*	-2.321**	-2.072**	0.117	0.083
BARI GOM-33	-0.042	-0.069	2.417**	0.14	-0.408*	-0.558*
SOURAV	0.708*	1.597**	-0.301	-1.654**	0.508*	0.425*
AYT-5	2.917**	1.931**	-0.598*	-0.517	-0.35*	-0.017
SE(gi)	0.201	0.247	0.241	0.276	0.107	0.126

* and ** indicate significant at 5% and 1% level of probability respectively.

HD = Heading days; MD = Maturity days; CC = Chlorophyll content; PH = Plant height; ETP^{-1}= Effective

Table 8: Estimation of specific combining ability (SCA) effects for morpho-physiological characters in a 6 × 6 diallel cross of wheat

Hybrids	HD (50%)	MD (90%)	CC (SPAD)	PH (cm)	ETP^{-1} (No.)	TTP^{-1} (No.)
BARI GOM-30 × BARI GOM-28	-2.613**	-2.887**	-2.247*	4.548**	0.119	0.214
BARI GOM-30 × PRODIP	0.345	2.405*	-1.225	0.619	0.648*	-0.157
BARI GOM-30 × BARI GOM-33	1.429*	4.113**	-1.23	-2.536*	-0.26	-0.282
BARI GOM-30 × SOURAV	-1.655*	-1.22	-1.792*	-1.225	1.39**	1.102*
BARI GOM-30 × AYT-5	2.47**	-0.554	2.722**	-3.273**	-1.518**	-2.49**
BARI GOM-28 × PRODIP	-1.946*	-3.22**	-0.605	-0.78	-0.11	0.452
BARI GOM-28 × BARI GOM-33	-2.863**	-3.179**	3.23**	1.235	0.915*	0.427
BARI GOM-28 × SOURAV	2.054*	2.821**	2.178*	-3.924**	-1.202*	-1.59**
BARI GOM-28 × AYT-5	2.512**	4.821**	-1.941*	0.611	0.09	0.318
PRODIP × BARI GOM-33	2.095*	-0.22	-5.388**	0.019	-0.523	0.623
PRODIP × SOURAV	-0.655	0.446	-2.556*	-1.4	-0.306	-0.461
PRODIP × AYT-5	1.47*	-0.887	2.314*	-0.438	1.186*	0.181
BARI GOM-33 × SOURAV	0.429	2.155*	2.199*	-0.605	1.319**	-0.186
BARI GOM-33 × AYT-5	-1.446*	-1.845*	1.306	2.764*	-0.389	0.956*
SOURAV × AYT-5	-4.863**	0.821	-2.009*	2.095*	-0.139	0.739*
SE(sij)	0.553	0.679	0.661	0.757	0.295	0.345

* and ** indicate significant at 5% and 1% level of probability respectively.

HD = Heading days; MD = Maturity days; CC = Chlorophyll content; PH = Plant height; ETP^{-1}= Effective tiller $plant^{-1}$; TTP^{-1} = Total tiller $plant^{-1}$.

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3.2.2 Maturity days

The results of GCA effects of the parental genotypes are displayed in Table 7. Negative and significant GCA effects are desirable for maturity days. BARI GOM-28 had the highest preferable significant and negative GCA effects (-2.736) among the parents followed by BARI GOM-30 (-1.361). The parents *viz;* AYT-5, SOURAV and PRODIP exhibited the highest undesirable significant and positive effects of GCA.

As for SCA effects, significant and negative effects of SCA are preferable for days to maturity. The hybrids BARI GOM-28 × PRODIP (-3.22), BARI GOM-28 × BARI GOM-33 (-3.179), BARI GOM-30 × BARI GOM-28 (-2.887) and BARI GOM-33 × AYT-5 (-1.845) exhibited significant and negative SCA effects (Table 8), however, BARI GOM-28 × PRODIP was noticed to be the best specific combiners for maturity days.

The results of the present study are in agreement with Ahmad *et al.* (2017), Din *et al.* (2020) and Kaur *et al.* (2020) who also stated the significant negative GCA effects for parents and SCA effects on the hybrids for the character maturity days.

3.2.3 Chlorophyll content

The highest significant and positive GCA effect is preferable for chlorophyll content. The GCA effects of the parents summarized in Table 9 exhibited that the parental genotype BARI GOM-33 and BARI GOM-28 had significant and positive GCA effects of 2.417 and 1.035 respectively, proving they were the best general combiners. Thus, the parents could be used in the breeding program. As for SCA effects, five crosses showed significant and positive SCA effects (Table 8). The hybrids, BARI GOM-28 × BARI GOM-33, BARI GOM-30 × AYT-5, PRODIP × AYT-5, BARI GOM-33 × SOURAV and BARI GOM-28 × SOURAV recorded the significant positive SCA effects of about 3.23, 2.722, 2.314, 2.199 and 2.178 respectively. However, among the hybrids, the hybrid BARI GOM-28 × BARI GOM-33 recorded the highest significant and positive SCA effects (3.23) for chlorophyll content. Previous researchers Hussein & Okasha (2017) obtained significant positive GCA effects among parental genotypes and SCA effects among F_1 hybrids for this trait.

3.2.4 Plant height

In wheat, short growth plants are preferable because such plants are not susceptible to lodging. In the breeding program of wheat, plant height plays a vital role. Therefore, significant and negative GCA effects are advantageous for plant height because short growth plants are never logged and are more sensitive to fertilizers. The estimates of GCA presented in Table 7 revealed that the parent PRODIP had the highest GCA effects (-2.072) for plant height followed by the parent SOURAV (-1.654). These genotypes were considered the best general combiner for plant height due to their significant and negative GCA values and could be used for the development of varieties.

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Of the fifteen crosses of diallel, three crosses exhibited desirable significant and negative SCA effects. In this study the crosses *viz;* BARI GOM-28 × SOURAV, BARI GOM-30 × AYT-5 and BARI GOM-30 × BARI GOM-33 exhibited the preferable negative and significant SCA effects of -3.924, -3.273 and -2.536 respectively (Table 8). The unwanted positive and significant SCA effects were recorded for BARI GOM-30 × BARI GOM-28 followed by BARI GOM-33 × AYT-5 and SOURAV × AYT-5.

However, the hybrid BARI GOM-28 × SOURAV (-3.924) was the best specific combiner having the maximum negative SCA value for this trait. The hybrids with unwanted positive SCA effects were considered as the poor combiner and could not be used for the breeding purpose. The importance of significant negative GCA and SCA effects for plant height was also reported by Ahmed *et al.* (2015), Salam *et al.* (2019) and Junior de Pelegrin *et al.* (2020).

3.2.5 Effective tillers plant^{-1}

Effective tillers contain effective spikes which increase the grain yield. The highest positive and significant GCA effect is preferable for effective tillers plant^{-1}. With this concern, the highest positive and significant GCA effects were recorded in the parents SOURAV and BARI GOM-30 which were 0.508 and 0.421 respectively (Table 7). Therefore, these parental genotypes could be treated as the best concrete general combiner with the highest positive and significant GCA effects and could be used in the breeding program for the development of hybrid variety.

The estimates of SCA effects of the hybrids for different characters (Table 8) revealed that five cross combinations exhibited positive SCA effects for this trait effective tiller^{-1}. The cross combinations BARI GOM-30 × SOURAV, BARI GOM-33 × SOURAV, PRODIP × AYT-5, BARI GOM-28 × BARI GOM-33 and BARI GOM-30 × PRODIP recorded the significant positive SCA effects which were 1.39, 1.319, 1.186 0.915, and 0.648 respectively. However, the cross BARI GOM-30 × SOURAV (1.39) was considered as the concrete specific combiner with the highest and significant positive SCA effects among the hybrids for effective tillers plant^{-1}.

Other previous researchers like Ahmad *et al.* (2017), Parveen et al. (2019) and Junior de Pelegrin *et al.* (2020) reported negative GCA effects for parental genotypes and SCA effects for crosses for effective tillers plant^{-1}.

3.2.6 Total tillers plant^{-1}

The positive GCA effects is desirable for the expression of this trait. The results presented in the Table 7 showed that the parent, BARI GOM-30 and SOURAV gave the significant and positive GCA effects as 0.454 and 0.425 respectively. However, the parent BARI GOM-30 was shown to be best general combiner for total tiller plant^{-1} with largest value of 0.454 and could be utilized in hybridization and selection programme to improve total tiller plant^{-1} in wheat.

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While concerning the SCA effects of the cross combinations, it was noticed that three cross combinations showed maximum positive SCA effects (Table 8). The significant and positive SCA effects were observed in the cross combinations BARI GOM-30 × SOURAV (1.102), BARI GOM-33 × AYT-5 (0.956) and SOURAV × AYT-5 (0.739) respectively. The hybrid BARI GOM-30 × SOURAV had the maximum significant and positive SCA effects (1.102) for total tiller plant^{-1} and considered as good general combiner for total tiller plant^{-1} in the advancement of the breeding programme of wheat.

Comparable results were also achieved by Saeed *et al.* (2016), Saeed & Khalil (2017) and Farooq *et al.* (2019) who stated positive GCA and SCA effects for total tillers plant^{-1}.

3.2.7 Spikes plant^{-1}

The highest positive and significant GCA effects are preferable for spikes plant^{-1}. The results presented in Table 9 revealed that the parent SOURAV and BARI GOM-30showed the positive and significant GCA effects of 0.508 and 0.421 respectively. The parent SOURAV demonstrated the highest significant and positive GCA value of 0.508. So, the parental genotype SOURAV was considered as the best general combiner while for spikes plant^{-1}.

Among the fifteen crosses, five hybrids showed significant and positive effects of SCA (Table 10). The hybrids viz; BARI GOM-30 × SOURAV (1.39), BARI GOM-33 × SOURAV (1.319), PRODIP × AYT-5 (1.186), BARI GOM-28 × BARI GOM-33 (0.915) and BARI GOM-30 × PRODIP (0.648) showed the significant and positive effects of SCA. The cross BARI GOM-30 × SOURAV gave the maximum significant positive GCA effects (1.319) followed by BARI GOM-33 × SOURAV(1.319) and were considered as the best specific combiner for spikes plant^{-1}.

These findings are also confirmed by Kandil *et al.* (2016), Saeed & Khalil (2017) and Hassan *et al.* (2018) who reported that parents and F_1 hybrids manifested significant positive GCA and SCA effects for spikes plant^{-1} in their breeding programs.

3.2.8 Spike length

The estimates of GCA effects of the parents summarized in Table 9 showed that the parent BARI GOM-33 displayed the highest significant positive effect of GCA (0.544) for spike length.

As for SCA effects, among the fifteen hybrids, significant and positive SCA effects were recorded in five crosses (Table 10). The significant and positive SCA effects performed by BARI GOM-30 × PRODIP (1.869), BARI GOM-30 × BARI GOM-28 (1.47), PRODIP × SOURAV (1.28), PRODIP × BARI GOM-33(1.202) and BARI GOM-33 × SOURAV (1.008) respectively. The hybrid BARI GOM-30 × BARI GOM-33 was considered

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as the best specific combiner with the highest SCA effects (1.869) on spike length. This hybrid will be used in the next breeding program.

The results for spike length are in agreement with Nawara *et al.* (2016), Tiwari *et al.* (2017) and Din *et al.* (2020) who also obtained significant positive GCA effects among parents and SCA effects among F_1 hybrids for this trait.

3.2.9 Filled spikelets spike^{-1}

As for filled spikelet spike^{-1}, the highest significant and positive effects of GCA are preferable. One parental genotype out of six parental genotypes demonstrated the desirable significant positive GCA value (Table 9). The positive and significant GCA effect of 0.767 was noted in parent BARI GOM-30, implying that the parent was the best general combiner for the hybridization program.

Regarding the effects of SCA, out of fifteen cross combinations, two hybrids showed positive and significant SCA effects (Table 10). The maximum significant and positive SCA effects were noted in the two cross combinations *viz;* PRODIP × SOURAV (2.378) and BARI GOM-30 × BARI GOM-28 (1.274) respectively, proving that both combinations were the best concrete specific combiner and could be applied in the wheat breeding program.

Table 9: Estimation of general combining ability (GCA) effects for yield and yield contributing characters in a 6 × 6 diallel cross of wheat

Parents	SP^{-1} (No.)	SL (cm)	FSS^{-1} (No.)	USS^{-1} (No.)	GS^{-1} (No.)	TGW (g)	GYP^{-1} (g)	BYP^{-1} (g)	HI (%)
BARI GOM-30	0.42 1*	0.293	0.767*	-0.113	1.81**	1.643**	0.643*	0.404	1.095*
BARI GOM-28	-0.288*	0	0.25	0.221*	0.256	-0.407	-0.05	0.136	-0.116
PRODIP	0.117	0.051	-0.004	-0.075	-1.207*	0.624*	0.289	-0.25	0.763
BARI GOM-33	-0.408*	0.544*	-0.167	-0.25*	0.643*	0.265	-0.222	0.93*	-0.928
SOURAV	0.508*	0.368	-0.25	0.158	1.068*	-0.011	0.228	1.309*	-0.226
AYT-5	-0.35*	-1.256**	-0.596*	0.058	-2.569**	-2.115**	-0.888*	-2.529**	-0.588
SE(gi)	0.107	0.163	0.187	0.062	0.194	0.197	0.162	0.309	0.397

* and ** indicate significant at 5% and 1% level of probability respectively.

SP^{-1} = Spikes plant^{-1}; SL = Spike length; FSS^{-1} = Filled spikelet spike^{-1}; USS^{-1} = Unfilled spikelet spike^{-1}; GS^{-1} = Grains spike^{-1}; TGW = Thousand grain weight;

GYP^{-1} = Grain yield plant^{-1}; BYP^{-1} = Biological yield plant^{-1}; HI = Harvest index.

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Table 10: Estimation of specific combining ability (SCA) effects for yield and yield contributing characters in a 6 × 6 diallel cross of wheat

Hybrids	SP^{-1} (No.)	SL (cm)	FSS^{-1} (No.)	USS^{-1} (No.)	GS^{-1} (No.)	TGW (g)	GYP^{-1} (g)	BYP^{-1} (g)	HI (%)
BARI GOM-30 × BARI GOM-28	0.119	1.47*	1.274*	0.001	-3.783**	-0.459	-0.78	-0.892	-1.185
BARI GOM-30 × PRODIP	0.648*	1.869**	-0.305	-0.67*	4.813**	-4.827**	-0.24	1.127	-1.108
BARI GOM-30 × BARI GOM-33	-0.26	-0.243	-0.443	0.039	-1.204*	4.856**	0.748	-1.906	2.614*
BARI GOM-30 × SOURAV	1.39**	-3.621**	0.54	0.364*	1.371*	-4.608**	0.925	0.012	1.934
BARI GOM-30 × AYT-5	-1.518**	-0.75	-0.58	0.064	-3.324**	-1.371*	-1.132*	-1.834*	-1.457
BARI GOM-28 × PRODIP	-0.11	-1.512*	-1.422*	0.464*	-4.099**	-2.58**	1.33**	-2.622*	4.374*
BARI GOM-28 × BARI GOM-33	0.915*	-0.858	0.474	0.005	0.784	-2.654**	1.191*	3.512**	0.659
BARI GOM-28 × SOURAV	-1.202*	0.312	-2.376**	0.897**	2.059*	0.795	0.905	-0.954	2.326*
BARI GOM-28 × AYT-5	0.09	0.102	-0.33	-0.636*	1.43*	2.383**	-0.459	-1.349	-0.406
PRODIP × BARI GOM-33	-0.523	1.202*	-2.405**	0.101	-6.487**	0.458	-1.641**	-3.456**	-1.871
PRODIP × SOURAV	-0.306	1.288*	2.378**	0.026	-4.279**	2.018*	-0.065	-0.962	0.343
PRODIP × AYT-5	1.186*	-1.222*	0.757	0.16	4.926**	-2.168	0.821	1.259	1.075
BARI GOM-33 × SOURAV	1.319**	1.008*	-1.093	-0.165	2.805**	0.977	1.676**	1.006	2.904*
BARI GOM-33 × AYT-5	-0.389	-1.201*	-0.047	0.001	-0.958	0.348	0.119	-0.644	0.506
SOURAV × AYT-5	-0.139	0.625	-3.43**	0.76**	-3.449**	-0.62	-2.081**	-1.209	-3.976*
SE(sij)	0.295	0.448	0.514	0.170	0.532	0.542	0.445	0.848	1.090

* and ** indicate significant at 5% and 1% level of probability respectively.

SP^{-1} = Spikes $plant^{-1}$; SL = Spike length; FSS^{-1} = Filled spikelet $spike^{-1}$; USS^{-1} = Unfilled spikelet $spike^{-1}$; GS^{-1} = Grains $spike^{-1}$; TGW = Thousand grain weight; GYP^{-1} = Grain yield $plant^{-1}$; BYP^{-1}

The results of the present study are in further line with Ahmad *et al.* (2017), Junior de Pelegrin *et al.* (2020) and Din *et al.* (2020) who achieved significant positive GCA and SCA effects among parents and crosses for this trait.

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3.2.10 Unfilled spikelets spike^{-1}

As for GCA effects of unfilled spikelets per spike, maximum negative effects of GCA are preferable. In this regard, the results presented in Table 11 demonstrated that the parent BARI GOM-33 recorded maximum negative GCA effects of -0.25 proving that this parent was the concrete general combiner and could be used in the wheat breeding programme. The other parents with unwanted positive GCA effects were considered as the poor combiner for wheat breeding.

The results of SCA effects are summarized in Table 10 which revealed that the two cross combinations represented the maximum significant and negative SCA effects for the trait unfilled spikelets spike^{-1}. The best concrete specific combiners with maximum significant and negative SCA effects were BARI GOM-30 × PRODIP (-0.67) and BARI GOM-28 × AYT-5 (-0.636) respectively for unfilled spikelets per spike.

3.2.11 Grains spike^{-1}

Grains per spike highly express grain yield and are more important for breeders as they play a vital role to develop high-yielding varieties, which helps to improve the economy of the farmer and the country. In this context, the positive effect of GCA is desirable for this trait. The GCA effects, summarized in Table 9 represented that the parent BARI GOM-30 (1.81), SOURAV (1.068) and BARI GOM-33 (0.643) showed significant and positive GCA effects. The parent BARI GOM-30 was considered as the best general combiner with the highest positive effects of GCA (1.81) while, the parental genotypes AYT-5 and PRODIP exhibited unwanted highest significant and negative GCA effects of -2.569 and -1.207 respectively and these varieties were considered as the poor general combiner.

With regards to the SCA effects, out of fifteen crosses, six hybrids showed significant and positive SCA effects for grains per spike (Table 10). The cross combinations PRODIP × AYT-5 (4.926), BARI GOM-30 × PRODIP (4.813), BARI GOM-33 × SOURAV (2.805), BARI GOM-28 × SOURAV (2.059), BARI GOM-28 × AYT-5 (1.43) and BARI GOM-30 × SOURAV (1.371) which expressed significant positive SCA values. Among these combiners, the hybrid PRODIP × AYT-5 was considered as the best specific combiner with the highest effects of SCA (4.926) for grains per spike. Similar results in regards to grains spike^{-1} for significant positive GCA effects among parent and SCA effects among F_1 hybrids were also reported by Saeed & Khalil (2017), Ahmed and Mustafa (2017) and Salam *et al.* (2019).

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3.2.12 1000-grain weight

There is a positive relationship between seed index and seed yield proving an increase in seed index per unit will simultaneously increase the seed yield amount. The results demonstrated in Table 9 showed that the parents BARI GOM-30 and PRODIP exhibited the maximum significant and positive effects of GCA 1.643 and 0.624 respectively, indicating that the parents were the best general combiner and could be used in hybridization program for the advancement of seed index.

As for SCA effects, of the fifteen crosses, three hybrids exhibited significant positive SCA effects (Table 10). The crosses viz; BARI GOM-30 × BARI GOM-33 (4.856), BARI GOM-28 × AYT-5 (2.383), BARI GOM-28 × AYT-5 (2.018) produced significant and positive effects of SCA. The best concrete specific combiner was BARI GOM-30 × PRODIP (4.856) which could be used for further breeding purposes. The magnitude of significant positive GCA and SCA effects was also achieved by Saeed & Khalil (2017), Ahmed *et al.* (2017), Ingle *et al.* (2018) and Din *et al.* (2020) in their breeding programs.

3.2.13 Grain yield plant^{-1}

Regarding the effects of GCA, the parent BARI GOM-30 showed maximum significant and positive GCA effects of 0.643 (Table 9). Thus, the parent BARI GOM-30 (0.643) was the best general combiner for grain yield per plant and could be recommended in the breeding program.

Regarding the effects of SCA, three hybrids out of fifteen crosses demonstrated significant and positive SCA effects (Table 10). The maximum significant and positive effects were observed in the hybrids BARI GOM-33 × SOURAV (1.676), BARI GOM-28 × PRODIP (1.33) and BARI GOM-28 × BARI GOM-33 (1.191). The significant positive SCA value 1.676 from the hybrid BARI GOM-33 × SOURAV proved that it was the best specific combiner and could be considered for the advancement of the hybrid program. The results of the present study are in harmony with Ahmad *et al.* (2017), Hassan *et al.* (2018) and Salam *et al.* (2019) who reported significant positive GCA effects among parental genotypes and SCA effects among F_1 hybrid for this trait.

3.2.14 Biological yield plant^{-1}

The effects of GCA of the parental genotypes for different characters presented in Table 9 demonstrated that the parents SOURAV and BARI GOM-33 had significant positive GCA effects of 1.309 and 0.93 respectively, indicating these parents were the best general combiner. The maximum significant and positive effect was noted in the parent SOURAV which was the best general combiner. With the concern of the SCA effects, one hybrid combination showed significant and positive SCA effects (Table 10). The best specific combiner with the maximum significant positive SCA effect of 3.512 was BARI GOM-28 × BARI GOM-33 and it could be

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applied in the breeding culture. Similar results were also obtained by many previous researchers such as Saeed & Khalil (2017), Din *et al.* (2020) and Kaur *et al.* (2020) who achieved significant positive GCA effects among parental genotypes and SCA effects among F_1 hybrids for this trait.

3.2.15 Harvest index

Concerning the impact of parents on the effects of GCA, the parent BARI GOM-30 expressed the highest positive GCA effects (Table 9). The parent BARI GOM-30 had the highest significant and positive GCA effects of 1.095, proving the best general combiner.

The estimates of the SCA effects of the crosses given in Table 10 displayed that the desirable significant positive effects of SCA were recorded in the four hybrids BARI GOM-28 × PRODIP (4.374), BARI GOM-33 × SOURAV (2.904), BARI GOM-30 × PRODIP (2.614) and BARI GOM-28 × SOURAV (2.326) respectively. The maximum positive SCA effects (4.374) from the hybrid BARI GOM-28 × PRODIP showed that it was the best specific combiner and could be considered for further hybrid cultures.

The results of the present study are in further line with Saeed & Khalil (2017) and Hama-Amin & Towfiq (2019) who obtained significant positive GCA effects among parents and SCA effects among the crosses for this trait.

3.3 Heterosis of the crosses for morpho-physiological, yield and yield contributing characters in wheat

The present study was conducted to estimate heterosis over mid parent in different varieties of wheat for morpho-physiological and yield and yield contributing characters. Fifteen possible F_1 hybrids were obtained from six parental varieties using half diallel mating fashion. The estimation of heterosis over mid parent for morpho-physiological and yield contributing characters over mid parent are presented in Tables 11 and 12.

The results regarding heterosis studies for morpho-physiological and yield and yield contributing traits are presented and described character-wise as follows:

3.3.1 Heading days

Heterosis for days to heading was presented in Table 13. The results revealed that out of fifteen crosses four hybrids expressed unwanted significant and positive heterosis over mid parent and six hybrids expressed preferable significant and negative mid parent heterosis. The undesirable positive mid parent heterosis was noticed in the hybrids BARI GOM-30 × AYT-5 (3.8%), BARI GOM-28 × AYT-5 (2.75%), PRODIP × BARI GOM-33 (3.64%) and PRODIP × AYT-5 (2.75%) while, six hybrids viz; BARI GOM-30 × BARI GOM-28, BARI GOM-30 × SOURAV, BARI GOM-28 × PRODIP, BARI GOM-28 × BARI GOM-33, PRODIP ×

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SOURAV, BARI GOM-33 × AYT-5 expressed desirable significant negative heterosis over mid parent which were -5.37%, -4.37%, -3.70%, -5.76%, -2.28% and -2.22% respectively.

Maximum significant and negative heterosis is desirable for days to heading. The maximum desirable negative mid parent heterosis was observed in BARI GOM-30 × BARI GOM-28 and BARI GOM-28 × BARI GOM-33. Thus, the hybrids, BARI GOM-30 × BARI GOM-28 and BARI GOM-28 × BARI GOM-33 were considered as desirable for days to heading and could be utilized in wheat hybrid advancement. The magnitude of negative heterosis for heading days was also reported by Motawea (2017b), Hussein & Okasha (2017), Hassan *et al.* (2018) and Jaiswal *et al.* (2018).

3.3.2 Maturity days

Heterosis results shown in Table 11 expressed six crosses displayed undesirable significant and positive heterosis over mid parent while only three crosses revealed advantageous significant and positive mid parent heterosis. The results expressed that undesirable positive heterosis was noticed in crosses BARI GOM-30 × PRODIP 2.26%, BARI GOM-30 × BARI GOM-33 4.42%, BARI GOM-28 × SOURAV 3.35%, BARI GOM-28 × AYT-5 4.53%, BARI GOM-33 × SOURAV 3.29% and SOURAV × AYT-52.36%. The preferable significant and negative heterosis was demonstrated in BARI GOM-30 × BARI GOM-28, BARI GOM-28 × PRODIP, BARI GOM-28 × BARI GOM-33 which were -2.65%, -3.64% and -3.07% respectively.

Negative mid parent heterosis was preferable for maturity days. With this regard, the desirable maximum negative and significant heterosis was obtained in the cross BARI GOM-28 × PRODIP (-3.64%). So, the hybrid BARI GOM-28 × PRODIP was considered the best F_1 hybrid for the character maturity days. Similar findings of the result for maturity days were stated by Ahmad *et al.* (2016), Thomas *et al.* (2017), Hassan *et al.* (2018) and Jaiswal *et al.* (2018) who found negative heterosis for maturity days.

3.3.3 Chlorophyll Content

Results concerning heterotic effects for chlorophyll content are demonstrated in Table 11. The results expressed that both positive and negative heterosis was found in the crosses. The desirable significant and positive heterosis was found in the crosses BARI GOM-30 × AYT-5 (9.91%), BARI GOM-28 × BARI GOM-33 (12.3%) and BARI GOM-33 × AYT-5 (7.55%). The results revealed that unwanted negative heterosis over mid parent was observed in the crosses BARI GOM-30 × BARI GOM-28 (-11.64%0, BARI GOM-30 × PRODIP (-16.33%), BARI GOM-30 × BARI GOM-33 (-7.77%), BARI GOM-30 × SOURAV (-12.72%), BARI GOM-28 × PRODIP (-9.31%), PRODIP × BARI GOM-33 (-27.38%), PRODIP × SOURAV (-20.34%) and SOURAV × AYT-5 (-8.14%). The hybrid BARI GOM-28 × BARI GOM-33 showed the highest positive heterosis 12.3% over mid parent and was considered as the best for chlorophyll content. The results are in agreement with

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Hussein & Okasha (2017) and Sharma & Kamaluddi (2020) who also stated the positive heterosis for chlorophyll content.

Table 11: Estimation of mid-parent heterosis for morpho-physiological characters in a 6 × 6 diallel cross of wheat

Hybrids	HD (50%)	MD (90%)	CC (SPAD)	PH (cm)	ETP^{-1} (No.)	TTP^{-1} (No.)
BARI GOM-30 × BARI GOM-28	-5.37**	-2.65**	-11.64**	4.59**	2.46	-2.8
BARI GOM-30 × PRODIP	1.07	2.26*	-16.33**	-0.36	13.72*	-4.67
BARI GOM-30 × BARI GOM-33	2.11	4.42**	-7.77*	-2.92*	1.55	-3.95
BARI GOM-30 × SOURAV	-4.37**	0.45	-12.72**	-3.11**	23.63**	6.67
BARI GOM-30 × AYT-5	3.8**	0.45	9.91*	-3.48**	-23.12**	-34.53**
BARI GOM-28 × PRODIP	-3.7**	-3.64**	-9.31*	-0.9	1.01	7.78
BARI GOM-28 × BARI GOM-33	-5.76**	-3.07**	12.3**	1.95	19.15**	12.03
BARI GOM-28 × SOURAV	0.26	3.35**	7.19	-4.96**	-14.45*	-22.06**
BARI GOM-28 × AYT-5	2.75**	4.53**	-4.91	1.55	-2.26	2.7
PRODIP × BARI GOM-33	3.64**	-0.29	-27.38**	-0.28	-0.58	17.48*
PRODIP × SOURAV	-2.28*	1.18	-20.34**	-3.44**	2.59	-4.92
PRODIP × AYT-5	2.75**	-0.59	4.61	-0.54	18.63**	3.46
BARI GOM-33 × SOURAV	-1.25	3.29**	6.42	-1.77	28.9**	1.45
BARI GOM-33 × AYT-5	-2.22*	-0.89	7.55*	3.68**	-5.26	18.68*
SOURAV × AYT-5	-8.65	2.36**	-8.14*	1.37	-1.01	6.84
SE(±)	0.764	0.938	0.913	1.046	0.408	0.476

* and ** indicate significant at 5% and 1% level of probability respectively.
HD = Heading days; MD = Maturity days; CC = Chlorophyll content; PH = Plant height; ETP^{-1}= Effective tiller $plant^{-1}$; TTP^{-1} = Total tiller $plant^{-1}$.

3.3.4 Plant height

The results of heterotic effects for plant height are demonstrated in Table 11. The results expressed that only two crosses BARI GOM-30 × BARI GOM-28 and BARI GOM-33 × AYT-5 exhibited undesirable significant positive heterosis over mid parent which were 4.59% and 3.68% while, the preferable significant and negative heterosis was recorded in the crosses BARI GOM-30 × BARI GOM-33, BARI GOM-30 × SOURAV, BARI GOM-30 × AYT-5, BARI GOM-28 × SOURAV, PRODIP × SOURAV which were -2.92%, -3.11%, -3.48% and -3.44% respectively.

The hybrid BARI GOM-28 × SOURAV (-4.96%) showed desirable largest negative mid parent heterosis followed by BARI GOM-30 × AYT-5 (-3.48%) and PRODIP × SOURAV (-3.44%). Negative heterosis is preferable for plant height. Therefore, these above-mentioned F_1 hybrids were considered as the best hybrid and could be applied in the breeding program for the character plant height. Other previous researchers like Kalhoro

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et al. (2015), Ahmad *et al.* (2016), Thomas *et al.* (2017) Hassan *et al.* (2018) and Jaiswal *et al.* (2018) reported negative mid parent heterosis for plant height.

3.3.5 Effective tillers plant $^{-1}$

Heterosis for effective tiller per plant is summarized in Table 11. The results revealed that five hybrids viz; BARI GOM-30 × PRODIP, BARI GOM-30 × SOURAV, BARI GOM-28 × BARI GOM-33, PRODIP × AYT-5 and BARI GOM-33 × SOURAV which showed advantageous and significant positive mid parent heterosis as 13.72%, 23.63%, 19.15%, 18.63% and 28.9% respectively while unwanted significant and negative heterosis was recorded in the hybrids BARI GOM-30 × AYT-5 and BARI GOM-28 × SOURAV which were -23.12% and -14.45%.

The highest positive heterosis over mid parent was recorded in BARI GOM-33 × SOURAV and the next high score was in BARI GOM-30 × SOURAV. Positive heterosis was advantageous for effective tiller per plant and therefore, above the two hybrids were found best among the hybrids for effective tiller plant^{-1} and could be used in the breeding program. The importance of positive heterosis for effective tillers plant^{-1} was reported by Patel (2015), Raiyani *et al.* (2016), Ahmad *et al.* (2016) and Kumar *et al.* (2017).

3.3.6 Total tillers plant^{-1}

The results of positive and negative heterosis over mid parent were recorded in hybrids that are expressed in Table 11. The results demonstrated that out of fifteen hybrids, only two hybrids viz. BARI GOM-33 × AYT-5 and PRODIP × BARI GOM-33 exhibited desirable significant and positive heterosis over mid parent which were 18.68% and 17.48% respectively. The results revealed that undesirable significant and negative heterosis was registered in BARI GOM-30 × AYT-5 (-34.53%) followed by BARI GOM-28 × SOURAV (-22.06%).

The highest advantageous significant and positive heterosis over mid parent was recorded in the hybrids BARI GOM-33 × AYT-5 followed by PRODIP × BARI GOM-33 and these hybrids emerged as the best hybrid for total tiller^{-1}. Negative heterosis for total tillers plant^{-1} was also reported by Kalhoro *et al.* (2015), Rahul (2017) and Jaiswal *et al.* (2018).

3.3.7 Spikes plant^{-1}

Heterotic effects in F_1 hybrids for spikes plant^{-1} are listed in Table 12. The results revealed that four F_1 hybrids BARI GOM-30 × PRODIP, BARI GOM-30 × SOURAV, PRODIP × AYT-5 and BARI GOM-33 × SOURAV showed desirable significant positive mid parent heterosis 13.72%, 23.63%, 18.63% and 28.9% respectively, while the unwanted significant negative heterosis was observed in BARI GOM-30 × AYT-5 (-23.12%) followed by BARI GOM-28 × SOURAV (-14.45%).

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The maximum preferable significant heterosis over mid parent was recorded in the hybrid BARI GOM-33 × SOURAV and the next high rank was in BARI GOM-30 × SOURAV. Positive heterosis is desirable for spikes plant^{-1}. With this regard, BARI GOM-33 × SOURAV and BARI GOM-30 × SOURAV were considered as the best hybrid for spikes plant^{-1}. The results of spikes plant^{-1} are in agreement with Motawea (2017a) who obtained positive heterosis for spikes plant^{-1}.

3.3.8 Spike length

The calculations of heterotic effects for spike length in F_1 hybrids are summarized in Table 12. Three cross combinations viz; BARI GOM-30 × PRODIP, PRODIP × BARI GOM-33, PRODIP × SOURAV showed desirable positive significant heterosis over mid parent which were 12.68%, 10.28% and 10.41% respectively while non-advantageous negative and significant mid parent heterosis was recorded in BARI GOM-30 × SOURAV, BARI GOM-30 × AYT-5, PRODIP × AYT-5, BARI GOM-33 × AYT-5 which were -24.85%, -11.14%, -10.1% and -12.2% respectively.

For mid parent heterosis, the best cross combination was BARI GOM-30 × PRODIP, which exhibited the highest significant positive heterosis. This cross was identified to be the best source for spike length, an important yield contributing trait. The magnitude of positive heterosis for spike length was also reported by previous researchers Ahmad *et al.* (2016), Kumar *et al.* (2017), Thomas *et al.* (2017), Ferrari *et al.* (2018) and Jaiswal *et al.* (2018).

3.3.9 Filled spikelet spike^{-1}

The heterotic effects in F_1 hybrids for filled spikelet spike^{-1} are listed in Table 12. The results showed that desirable significant positive heterosis was not found in any cross while, eight crosses viz. BARI GOM-30 × AYT-5, BARI GOM-28 × PRODIP, BARI GOM-28 × SOURAV, BARI GOM-28 × AYT-5, PRODIP × BARI GOM-33, BARI GOM-33 × SOURAV, BARI GOM-33 × AYT-5, SOURAV × AYT-5 showed undesirable significant and negative heterosis over mid parent which were -7.61%, -12.54%, -21.38%, -10.12%, -19.69%, -16.08%, -10.17% and -29.58% respectively.

The highest non-advantageous significant and negative heterosis was registered by SOURAV × AYT-5. None of these hybrids could be used for filled spikelet spike^{-1} in the breeding program. Positive heterosis for this trait was also achieved by Kumar *et al.* (2017), Jaiswal *et al.* (2018) and Ferrari *et al.* (2018).

3.3.10 Unfilled spikelets spike^{-1}

Heterotic effects concerning the unfilled spikelets spike^{-1} are displayed in Table 12. The results indicated that the significant but undesirable positive heterosis was recorded by five crosses viz; BARI GOM-30 × SOURAV (33.19%), BARI GOM-28 × PRODIP (24.95%), BARI GOM-28 × SOURAV (63.27%), PRODIP × SOURAV

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(21.81%), SOURAV × AYT-5 (55.14%). However, the most preferable significant and negative heterosis over mid parent was displayed by BARI GOM-30 × PRODIP (-27.1%). Therefore, the hybrid BARI GOM-30 × PRODIP was considered as the best for this trait unfilled spikelets spike^{-1} and could be used in the breeding program.

3.3.11 Grains spike^{-1}

The heterosis results for grains spike^{-1} over mid parent are summarized in Table 12. The results showed that out of fifteen cross combinations only two F_1 hybrids BARI GOM-30 × PRODIP and PRODIP × AYT-5 exhibited the most desirable significant and positive heterosis over mid parent which were 6.52% and 7.95% respectively while, the other seven cross combinations displayed significant but undesirable negative mid parent heterosis which were BARI GOM-30 × BARI GOM-28 (-11.09%), BARI GOM-30 × BARI GOM-33 (-6.29%), BARI GOM-30 × AYT-5 (-9.61%), BARI GOM-28 × PRODIP (-14.03%), PRODIP × BARI GOM-33 (-19.85%), PRODIP × SOURAV (-13.2%), BARI GOM-33 × AYT-5 (-5.95%) and SOURAV × AYT-5 (-9.75%) respectively. The highest positive and significant heterosis is desirable for the character grains spike^{-1}. With this context, the F_1 hybrid PRODIP × AYT-5 and BARI GOM-30 × PRODIP were considered as the best for grains spike^{-1}. Comparable results were also achieved by Brahim and Mohamed (2014), Kalhoro *et al.* (2015), Kumar *et al.* (2017), Hassan *et al.* (2018), Ferrari *et al.* (2018) and Jaiswal *et al.* (2018) who stated positive heterosis for Grains spike^{-1}.

3.3.12 1000-grain weight

Heterosis effects concerning thousand-grain weight are presented in Table 12. The results displayed that the most desirable positive mid parent heterosis was noticed in the hybrids BARI GOM-30 × BARI GOM-33 9.4% and BARI GOM-33 × SOURAV 3.83% while, seven hybrids *viz;* BARI GOM-30 × BARI GOM-28 (-5.84%), BARI GOM-30 × PRODIP (-16.96%), BARI GOM-30 × SOURAV (-14.19%), BARI GOM-30 × AYT-5 (7.55%), BARI GOM-28 × PRODIP (-11%), BARI GOM-28 × BARI GOM-33 (-5.42%) and PRODIP × AYT-5 (-9.91%) respectively exhibited unwanted significant negative mid parent heterosis.

The largest positive and significant heterosis over mid parent was measured in BARI GOM-30 × BARI GOM-33. Significant and positive heterosis is preferable. Therefore, BARI GOM-30 × BARI GOM-33 was the best cross for this trait thousand grain weight. The results for 1000-grain weight are in agreement with Kumar *et al.* (2017), Thomas *et al.* (2017), Ferrari *et al.* (2018) and Jaiswal *et al.* (2018) who also reported positive heterosis for 1000-grain weight.

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3.3.13 Grain yield plant^{-1}

Both Positive and negative significant mid parent heterosis for the character grain yield plant^{-1} are exhibited in Table 12. Out of fifteen crosses, four hybrids exhibited desirable significant positive heterosis over mid parent. The significant positive mid parent heterosis was noticed in BARI GOM-28 × PRODIP (17.32%) followed by BARI GOM-28 × BARI GOM-33 (22.22%), BARI GOM-28 × SOURAV (16.58%) and BARI GOM-33 × SOURAV (23.78%). The results expressed that undesirable significant and negative heterosis was recorded in the cross BARI GOM-30 × AYT-5 (-16%) and SOURAV × AYT-5 (-21.57%).The highest significant desirable positive heterosis was measured in the cross BARI GOM-33 × SOURAV, BARI GOM-28 × BARI GOM-33 and BARI GOM-28 × PRODIP. So, the crosses with positive heterosis were considered as the best for the character grain yield plant^{-1} and could be used in the breeding program. The magnitude of positive heterosis for grain yield plant-1 was also reported by previous researchers like Kalhoro *et al.* (2015), Thomas *et al.* (2017), Jaiswal *et al.* (2018), Hassan *et al.* (2018) and Sharma & Kamaluddi (2020).

3.3.14 Biological yield plant^{-1}

The heterotic effects in F_1 hybrids for the trait biological yield plant^{-1} are demonstrated in Table 12. The results expressed that only one F_1 hybrid revealed desirable significant and positive heterosis over mid parent and seven hybrids displayed unwanted significant negative heterosis. The significant positive heterosis was noticed in BARI GOM-28 × BARI GOM-33 (5.19%) while, the unwanted significant negative heterosis over mid parent was found in BARI GOM-30 × BARI GOM-33 (-6.32%) followed by BARI GOM-30 × AYT-5 (-7.78%), BARI GOM-28 × PRODIP (-8.91%), BARI GOM-28 × AYT-5 (-6.18%), PRODIP × BARI GOM-33 (-10.07%), PRODIP × SOURAV (-5.29%) and SOURAV × AYT-5 (-5.63%).

The highest significant and positive heterosis is preferable for the character biological yield plant^{-1}. With this concern, the most advantageous significant positive heterosis was recorded in BARI GOM-28 × BARI GOM-33 and therefore, this hybrid could be considered as the best for the advancement of the breeding program of wheat for this trait biological yield plant^{-1}. The present results are in similarity with Rahul (2017), Motawea (2017a), Kumar *et al.* (2017) and Jaiswal *et al.* (2018) who also reported positive heterosis for biological yield plant^{-1}.

3.3.15 Harvest index

The results of heterosis for the character harvest index are summarized in Table 12. The results revealed that desirable positive mid parent heterosis was observed in five hybrids while one hybrid expressed undesirable negative heterosis over mid parent. The crosses BARI GOM-30 × BARI GOM-33, BARI GOM-28 × PRODIP, BARI GOM-28 × BARI GOM-33, BARI GOM-28 × SOURAV and BARI GOM-33 × SOURAV expressed significant positive heterosis over mid parent which were 17.32%, 28.46%, 15.93%, 21.44% and 23.57%

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respectively. on the other hand, the unwanted significant and negative heterosis was noticed in SOURAV × AYT-5 (-17.48%).

The maximum significant positive heterosis was measured in crosses BARI GOM-28 × PRODIP, BARI GOM-33 × SOURAV and BARI GOM-28 × SOURAV respectively. Positive significant heterosis is desirable. So, the above-mentioned crosses were the best for the character harvest index and could be applied in the breeding program. Heterosis for harvest index is in agreement with the findings of Raiyani *et al.* (2016), Motawea (2017a), Rahul (2017), Kumar *et al.* (2017) and Ferrari *et al.* (2018).

3.4 Relationship between heterosis and SCA effects of the crosses for morpho-physiological, yield and yield contributing characters in wheat

In order to examine the heterosis and SCA relationship of the hybrids for morpho-physiological and yield and yield contributing characters were measured and results are displayed in Tables 13 and 14. The estimation of the relationship between heterosis and SCA effects are described character-wise as follows:

3.4.1 Heading days

Considering the relationship between SCA and heterotic effects results summarized in Table 13 showed that both significant positive heterosis and SCA effects were recorded for heading days in the hybrids viz. BARI GOM-30 × AYT-5, BARI GOM-28 × AYT-5, PRODIP × BARI GOM-33 and PRODIP × AYT-5.

On the other hand, the hybrids BARI GOM-30 × BARI GOM-28, BARI GOM-30 × SOURAV, BARI GOM-28 × PRODIP, BARI GOM-28 × BARI GOM-33 and BARI GOM-33 × AYT-5 showed both most desirable significant negative heterosis and SCA effects.

3.4.2 Maturity days

As for days to maturity, heterosis and SCA relationship are listed in Table 13. Out of fifteen hybrids, five crosses revealed both significant positive heterosis and SCA effects which were BARI GOM-30 × PRODIP, BARI GOM-30 × BARI GOM-33, BARI GOM-28 × SOURAV, BARI GOM-28 × AYT-5 and BARI GOM-33 × SOURAV while, only three hybrids exhibit both preferable significant negative heterosis and SCA effects for maturity days which were BARI GOM-30 × BARI GOM-28, BARI GOM-28 × PRODIP, BARI GOM-28 × BARI GOM-33.

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Table 12: Estimation of mid-parent heterosis for yield and yield contributing characters in a 6 × 6 diallel cross of

Hybrids	SP^{-1} (No.)	SL (cm)	FSS^{-1} (No.)	USS^{-1} (No.)	GS^{-1} (No.)	TGW (g)	GYP^{-1} (g)	BYP^{-1} (g)	HI (%)
BARI GOM-30 × BARI GOM-28	2.46	6.48	4.33	4.81	-11.09**	-5.84**	-2.99	-4.76	1.96
BARI GOM-30 × PRODIP	13.72*	12.68**	-2.43	-27.1**	6.52**	-16.96**	-2.43	-1.85	-0.81
BARI GOM-30 × BARI GOM-33	1.55	-3.58	-6.57	-0.62	-6.29**	9.4**	10	-6.32*	17.32*
BARI GOM-30 × SOURAV	23.63**	-24.85**	-1.85	33.19**	0.99	-14.19**	9.4	-2.75	12.5
BARI GOM-30 × AYT-5	-23.12**	-11.14**	-7.61*	3.61	-9.61**	-7.55**	-16**	-7.78**	-9.0
BARI GOM-28 × PRODIP	1.01	-8.21	-12.54**	24.95**	-14.03**	-11**	17.32**	-8.91**	28.46**
BARI GOM-28 × BARI GOM-33	19.15	-6.34	-5.42	7.36	-3.01	-5.42**	22.22**	5.19*	15.93*
BARI GOM-28 × SOURAV	-14.45*	0.6	-21.38**	63.27**	1.72	-0.45	16.58**	-4.13	21.44**
BARI GOM-28 × AYT-5	-2.26	-4.34	-10.12*	-13.35	0.42	3.4	-5.54	-6.18*	-0.11
PRODIP × BARI GOM-33	-0.58	10.28*	-19.69**	5.04	-19.85**	-0.72	-9.7	-10.07**	0.13
PRODIP × SOURAV	2.59	10.41*	6.32	21.81*	-13.2**	-0.24	2.83	-5.29*	8.26
PRODIP × AYT-5	18.63**	-10.1*	-2.28	10.38	7.95**	-9.91**	1.64	-1.82	2.87
BARI GOM-33 × SOURAV	28.9**	5.5	-16.08**	14.09	2.51	3.83*	23.78**	0.22	23.57**
BARI GOM-33 × AYT-5	-5.26	-12.2**	-10.17**	3.27	-5.95**	2.45	-0.38	-4.17	2.83
SOURAV × AYT-5	-1.01	-0.6	-29.58**	55.14**	-9.75**	-3.23	-21.57**	-5.63*	-17.48**
SE(±)	0.408	0.619	0.71	0.235	0.736	0.749	0.615	1.171	1.507

* and ** indicate significant at 5% and 1% level of probability respectively.

SP^{-1} = Spike plant^{-1}; SL = Spike length; FSS^{-1} = Filled spikelet spike^{-1}; USS^{-1} = Unfilled spikelet spike^{-1}; GS^{-1} = Grains spike^{-1}; TGW = Thousand grain weight; GYP^{-1} = Grain yield plant^{-1}; BYP^{-1} = Biological yield plant^{-1}; HI = Harvest index.

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Table 13: Estimation of the relationship between heterosis and SCA effects of the hybrids for morpho-physiological characters in a 6 × 6 diallel cross of wheat

Hybrids	HD (50%)		MD (90%)	
	Heterosis	SCA	Heterosis	SCA
BARI GOM-30 × BARI GOM-28	-5.37**	-2.613**	-2.65**	-2.887**
BARI GOM-30 × PRODIP	1.07	0.345	2.26*	2.405*
BARI GOM-30 × BARI GOM-33	2.11	1.429*	4.42**	4.113**
BARI GOM-30 × SOURAV	-4.37**	-1.655*	0.45	-1.22
BARI GOM-30 × AYT-5	3.8**	2.47**	0.45	-0.554
BARI GOM-28 × PRODIP	-3.7**	-1.946*	-3.64**	-3.22**
BARI GOM-28 × BARI GOM-33	-5.76**	-2.863**	-3.07**	-3.179**
BARI GOM-28 × SOURAV	0.26	2.054*	3.35**	2.821**
BARI GOM-28 × AYT-5	2.75**	2.512**	4.53**	4.821**
PRODIP × BARI GOM-33	3.64**	2.095*	-0.29	-0.22
PRODIP × SOURAV	-2.28*	-0.655	1.18	0.446
PRODIP × AYT-5	2.75**	1.47*	-0.59	-0.887
BARI GOM-33 × SOURAV	-1.25	0.429	3.29**	2.155*
BARI GOM-33 × AYT-5	-2.22*	-1.446*	-0.89	-1.845*
SOURAV × AYT-5	-8.65	-4.863**	2.36**	0.821

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Table 13: Contd.

Hybrids	PH (cm)		ETP^{-1} (No.)		TTP^{-1} (No.)	
	Heterosis	SCA	Heterosis	SCA	Heterosis	SCA
BARI GOM-30 × BARI GOM-28	4.59**	4.548**	2.46	0.119	-2.8	0.214
BARI GOM-30 × PRODIP	-0.36	0.619	13.72*	0.648*	-4.67	-0.157
BARI GOM-30 × BARI GOM-33	-2.92*	-2.536*	1.55	-0.26	-3.95	-0.282
BARI GOM-30 × SOURAV	-3.11**	-1.225	23.63**	1.39**	6.67	1.102*
BARI GOM-30 × AYT-5	-3.48**	-3.273**	-23.12**	-1.518**	-34.53**	-2.49**
BARI GOM-28 × PRODIP	-0.9	-0.78	1.01	-0.11	7.78	0.452
BARI GOM-28 × BARI GOM-33	1.95	1.235	19.15**	0.915*	12.03	0.427
BARI GOM-28 × SOURAV	-4.96**	-3.924**	-14.45*	-1.202*	-22.06**	-1.59**
BARI GOM-28 × AYT-5	1.55	0.611	-2.26	0.09	2.7	0.318
PRODIP × BARI GOM-33	-0.28	0.019	-0.58	-0.523	17.48*	0.623
PRODIP × SOURAV	-3.44**	-1.4	2.59	-0.306	-4.92	-0.461
PRODIP × AYT-5	-0.54	-0.438	18.63**	1.186*	3.46	0.181
BARI GOM-33 × SOURAV	-1.77	-0.605	28.9**	1.319**	1.45	-0.186
BARI GOM-33 × AYT-5	3.68**	2.764*	-5.26	-0.389	18.68*	0.956*
SOURAV × AYT-5	1.37	2.095*	-1.01	-0.139	6.84	0.739*

* and ** indicate significant at 5% and 1% level of probability respectively.

HD = Heading days; MD = Maturity days; CC = Chlorophyll content

3.4.3 Chlorophyll content

The relationship between heterotic effects and SCA effects displayed in Table 13 revealed that most desirable both significant positive heterosis and SCA effects for the character chlorophyll content was performed by only two hybrids BARI GOM-30 × AYT-5 and BARI GOM-28 × BARI GOM-33.

BARI GOM-30 × BARI GOM-28, BARI GOM-30 × SOURAV, PRODIP × BARI GOM-33 and PRODIP × SOURAV displayed undesirable both significant negative heterosis and SCA effects for chlorophyll content.

3.4.4 Plant height

The relationship between heterosis and SCA effects shown in Table 13 revealed that BARI GOM-30 × BARI GOM-28 and BARI GOM-33 × AYT-5 displayed non-advantageous both significant positive heterosis and SCA for the trait plant height while BARI GOM-30 × BARI GOM-33, BARI GOM-30 × AYT-5 and BARI GOM-28 × SOURAV exhibited the most desirable both significant negative heterosis and SCA effects for plant height.

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Table 14: Estimation of the relationship between heterosis and SCA effects of the hybrids for yield and yield contributing characters in a 6 × 6 diallel cross of wheat

Hybrids	SP^{-1} (No.)		SL (cm)		FSS^{-1} (No.)		USS^{-1} (No.)		GS^{-1} (No.)	
	Heterosis	SCA	Heterosis	SCA	Heterosis	SCA	Heterosis	SCA	Heterosis	SCA
BARI GOM-30 × BARI GOM-28	2.46	0.119	6.48	1.47*	4.33	1.274*	4.81	0.001	-11.09**	-3.783**
BARI GOM-30 × PRODIP	13.72*	0.648*	12.68**	1.869**	-2.43	-0.305	-27.1**	-0.67*	6.52**	4.813**
BARI GOM-30 × BARI GOM-33	1.55	-0.26	-3.58	-0.243	-6.57	-0.443	-0.62	0.039	-6.29**	-1.204*
BARI GOM-30 × SOURAV	23.63**	1.39**	-24.85**	-3.621**	-1.85	0.54	33.19**	0.364*	0.99	1.371*
BARI GOM-30 × AYT-5	-23.12**	-1.518**	-11.14**	-0.75	-7.61*	-0.58	3.61	0.064	-9.61**	-3.324**
BARI GOM-28 × PRODIP	1.01	-0.11	-8.21	-1.512*	-12.54**	-1.422*	24.95**	0.464*	-14.03**	-4.099**
BARI GOM-28 × BARI GOM-33	19.15	0.915*	-6.34	-0.858	-5.42	0.474	7.36	0.005	-3.01	0.784
BARI GOM-28 × SOURAV	-14.45*	-1.202*	0.6	0.312	-21.38**	-2.376**	63.27**	0.897**	1.72	2.059*
BARI GOM-28 × AYT-5	-2.26	0.09	-4.34	0.102	-10.12*	-0.33	-13.35	-0.636*	0.42	1.43*
PRODIP × BARI GOM-33	-0.58	-0.523	10.28*	1.202*	-19.69**	-2.405**	5.04	0.101	-19.85**	-6.487**
PRODIP × SOURAV	2.59	-0.306	10.41*	1.288*	6.32	2.378**	21.81*	0.026	-13.2**	-4.279**
PRODIP × AYT-5	18.63**	1.186*	-10.1*	-1.222*	-2.28	0.757	10.38	0.16	7.95**	4.926**
BARI GOM-33 × SOURAV	28.9**	1.319**	5.5	1.008*	-16.08**	-1.093	14.09	-0.165	2.51	2.805**
BARI GOM-33 × AYT-5	-5.26	-0.389	-12.2**	-1.201*	-10.17**	-0.047	3.27	0.001	-5.95**	-0.958
SOURAV × AYT-5	-1.01	-0.139	-0.6	0.625	-29.58**	-3.43**	55.14**	0.76**	-9.75**	-3.449**

* and ** indicate significant at 5% and 1% level of probability respectively.

SP^{-1} = Spikes $plant^{-1}$; SL = Spike length; FSS^{-1} = Filled spikelet $spike^{-1}$; USS^{-1} = Unfilled spikelet $spike^{-1}$; GS^{-1} = Grains $spike^{-1}$.

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Table 14: Contd.

Hybrids	TGW (g)		GYP^{-1} (g)		BYP^{-1} (g)		HI (%)	
	Heterosis	SCA	Heterosis	SCA	Heterosis	SCA	Heterosis	SCA
BARI GOM-30 × BARI GOM-28	-5.84**	-0.459	-2.99	-0.78	-4.76	-0.892	1.96	-1.185
BARI GOM-30 × PRODIP	-16.96**	-4.827**	-2.43	-0.24	-1.85	1.127	-0.81	-1.108
BARI GOM-30 × BARI GOM-33	9.4**	4.856**	10	0.748	-6.32*	-1.906	17.32*	2.614*
BARI GOM-30 × SOURAV	-14.19**	-4.608**	9.4	0.925	-2.75	0.012	12.5	1.934
BARI GOM-30 × AYT-5	-7.55**	-1.371*	-16**	-1.132*	-7.78**	-1.834*	-9.0	-1.457
BARI GOM-28 × PRODIP	-11**	-2.58**	17.32**	1.33**	-8.91**	-2.622*	28.46**	4.374*
BARI GOM-28 × BARI GOM-33	-5.42**	-2.654**	22.22**	1.191*	5.19*	3.512**	15.93*	0.659
BARI GOM-28 × SOURAV	-0.45	0.795	16.58**	0.905	-4.13	-0.954	21.44**	2.326*
BARI GOM-28 × AYT-5	3.4	2.383**	-5.54	-0.459	-6.18*	-1.349	-0.11	-0.406
PRODIP × BARI GOM-33	-0.72	0.458	-9.7	-1.641**	-10.07**	-3.456**	0.13	-1.871
PRODIP × SOURAV	-0.24	2.018*	2.83	-0.065	-5.29*	-0.962	8.26	0.343
PRODIP × AYT-5	-9.91**	-2.168	1.64	0.821	-1.82	1.259	2.87	1.075
BARI GOM-33 × SOURAV	3.83*	0.977	23.78**	1.676**	0.22	1.006	23.57**	2.904*
BARI GOM-33 × AYT-5	2.45	0.348	-0.38	0.119	-4.17	-0.644	2.83	0.506
SOURAV × AYT-5	-3.23	-0.62	-21.57**	-2.081***	-5.63*	-1.209	-17.48**	-3.976*

* and ** indicate significant at 5% and 1% level of probability respectively.

SP^{-1} = Spikes $plant^{-1}$; SL = Spike length; FSS^{-1} = Filled spikelet $spike^{-1}$; USS^{-1} = Unfilled spikelet $spike^{-1}$; GS^{-1} = Grains $spike^{-1}$.

3.4.5 Effective tillers $plant^{-1}$

The relationship between heterotic effects and SCA effects of F_1 hybrids (Table 13) showed that out of fifteen F_1 hybrids, five hybrids expressed most preferable both significant positive heterosis and SCA effects which were BARI GOM-30 × PRODIP, BARI GOM-30 × SOURAV, BARI GOM-28 × BARI GOM-33, PRODIP × AYT-5 and BARI GOM-33 × SOURAV respectively.

On the other hand, only two crosses demonstrated unwanted both significant negative heterosis and SCA effects which were BARI GOM-30 × AYT-5 and BARI GOM-28 × SOURAV respectively.

3.4.6 Total tillers $plant^{-1}$

Heterosis and SCA effects for total tillers $plant^{-1}$ of F_1 hybrids are presented in Table 13. Both significant positive heterosis and SCA effects for total tiller $plant^{-1}$ were found in cross BARI GOM-33 × AYT-5.

In the case of both significant negative heterosis and SCA effects for total tillers $plant^{-1}$, only two hybrids were identified which were BARI GOM-30 × AYT-5 and BARI GOM-28 × SOURAV.

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3.4.7 Spikes plant^{-1}

Relationship regarding heterotic and SCA effects for spike plant^{-1} shown in Table 14 displayed that hybrid *viz;* BARI GOM-30 × PRODIP, BARI GOM-30 × SOURAV, PRODIP × AYT-5 and BARI GOM-33 × SOURAV were identified for both desirable significant positive heterosis and SCA effects for spike plant^{-1}.

Only two hybrids *viz;* BARI GOM-30 × AYT-5 and BARI GOM-28 × SOURAV revealed unwanted both significant negative heterosis and SCA effects for this trait spike plant^{-1}.

3.4.8 Spike length

The relationship between heterotic and SCA effects regarding spike length displayed in Table14 revealed that advantageous both positive significant heterosis and SCA effects for spike length were displayed by only three crosses which were BARI GOM-30 × PRODIP, PRODIP × BARI GOM-33 and PRODIP × SOURAV respectively.

Unwanted both significant negative heterosis and SCA effects were performed by BARI GOM-30 × SOURAV, PRODIP × AYT-5 and BARI GOM-33 × AYT-5.

3.4.9 Filled spikelets spike^{-1}

Both heterosis and SCA effects relationship are summarized in Table 14. The results expressed that both significant positive heterosis and SCA effects were not found in any cross combination for filled spikelet spike^{-1} but, four crosses viz; BARI GOM-28 × PRODIP, BARI GOM-28 × SOURAV, PRODIP × BARI GOM-33 and SOURAV × AYT-5 showed unwanted both significant positive heterosis and SCA effects for this trait filled spikelet spike^{-1}.

3.4.10 Unfilled spikelets spike^{-1}

Heterosis and SCA effects relationship for unfilled spikelet spike-1 were estimated and the results are given in Table 14. Non-advantageous both significant positive heterosis and SCA effects were exhibited by the crosses *viz;* BARI GOM-30 × SOURAV, BARI GOM-28 × PRODIP, BARI GOM-28 × SOURAV and SOURAV × AYT-5 respectively, but most desirable both significant negative heterosis and SCA effects were identified in the cross BARI GOM-30 × PRODIP.

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3.4.11 Grains spike^{-1}

For the character grains spike^{-1}, both heterosis and SCA effects relationship were summarized in Table 14. Only two crosses *viz;* BARI GOM-30 × PRODIP and PRODIP × AYT-5 exhibited desirable both significant positive heterosis and SCA effects. Concerning the relationship between heterosis and SCA, the hybrids BARI GOM-30 × BARI GOM-28, BARI GOM-30 × BARI GOM-33, BARI GOM-30 × AYT-5, BARI GOM-28 × PRODIP, PRODIP × BARI GOM-33, PRODIP × SOURAV, PRODIP × AYT-5, BARI GOM-33 × AYT-5 and SOURAV × AYT-5 showed undesirable both significant negative heterosis and SCA effects for this trait.

3.4.12 1000-grain weight

The relationship between heterotic effects and SCA effects for the character thousand-grain weight shown in Table 14 revealed that out of fifteen hybrids, only one hybrid BARI GOM-30 × BARI GOM-33 showed desirable both significant negative heterosis and SCA effects. The results revealed that the five hybrids BARI GOM-30 × PRODIP, BARI GOM-30 × SOURAV, BARI GOM-30 × AYT-5, BARI GOM-28 × PRODIP and BARI GOM-28 × BARI GOM-33 showed unwanted both significant positive heterosis and SCA effects.

3.4.13 Grain yield pant^{-1}

The relationship between heterotic and SCA effects concerning the character grain yield plant^{-1} was calculated and is listed in Table 14. Advantageous both significant positive heterosis and SCA effects were obtained from the following crosses i.e., BARI GOM-28 × PRODIP, BARI GOM-28 × BARI GOM-33 and BARI GOM-33 × SOURAV. The data on the grain yield plant^{-1} indicated that the unwanted both significant positive heterotic and SCA effects were found in the crosses BARI GOM-30 × AYT-5 and SOURAV × AYT-5.

3.4.14 Biological yield plant^{-1}

For the character biological yield plant^{-1}, both heterosis and SCA effect relationship is presented in Table 14. Only one F_1 hybrid BARI GOM-28 × BARI GOM-33 showed useful both significant positive estimates of heterotic and SCA effects for biological yield plant^{-1} while, BARI GOM-30 × AYT-5, BARI GOM-28 × PRODIP and PRODIP × BARI GOM-33 showed undesirable both significant negative heterosis and SCA effects.

3.4.15 Harvest index

Results regarding heterosis and SCA effects for harvest index are demonstrated in Table 14. Results indicated that the hybrids BARI GOM-30 × BARI GOM-33, BARI GOM-28 × PRODIP, BARI GOM-28 × SOURAV and BARI GOM-33 × SOURAV revealed advantageous both significant positive heterosis and SCA effects for harvest index. On the other hand, only, one hybrid SOURAV × AYT-5 expressed unwanted significant negative estimates of both heterosis and SCA effects for this trait harvest index.

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4. SUMMARY

The present study was carried out to estimate heterosis and combining ability for morpho-physiological and yield and yield contributing characters with a view to obtain and analyze genetic information about the studied characters of wheat using the half diallel fashion of mating. The experiment was conducted at the experimental field of the Department of Agronomy and Agricultural Extension, University of Rajshahi from November, 2018 to April, 2020 using randomized complete block design (RCBD) with three replications.

Six parental genotypes used in the present investigation were BARI GOM-30, BARI GOM-28, PRODIP, BARI GOM-33, SOURAV, AYT-5. Observations were estimated on randomly selected plants for fifteen morpho-physiological and yield and yield contributing characters which were Heading days, Maturity days, Chlorophyll content, Plant height, Effective tillers plant^{-1}, Total tillers plant^{-1}, Spikes plant^{-1}, Spike length, Filled spikelet spike^{-1}, Unfilled spikelet spike^{-1}, Grains spike^{-1}, Thousand-grain weight, Grain yield plant^{-1}, Biological yield plant^{-1} and Harvest index.

The results of the present study are summarized and described as follows:

4.1 Performance of genotypes for morpho-physiological and yield contributing characters

The analysis of variance revealed all the genotypes showed significant differences for all the characters under study. Parental genotype BARI GOM-30 took the lowest days for heading and among the F_1 hybrids, minimum heading days were observed in BARI GOM-30 × BARI GOM-28. The parental genotypes BARI GOM-28 and the cross BARI GOM-30 × BARI GOM-28 required minimum days to maturity. The highest chlorophyll content was measured in parent BARI GOM-33 and the cross BARI GOM-28 × BARI GOM-33 gave the highest chlorophyll content. Parent PRODIP and the cross PRODIP × SOURAV showed the shortest plant height. The parent BARI GOM-30 and the cross GOM-30 × SOURAV produced the highest number of effective tiller plant^{-1}. The highest number of total tillers plant^{-1} were produced by the parental genotype BARI GOM-30 and the cross-combination SOURAV × AYT-5.

BARI GOM-30 showed the maximum number of spikes plant^{-1} and the crosses BARI GOM-30 × SOURAV gave similar results. Parental genotype BARI GOM-30 and the hybrid BARI GOM-30 × PRODIP produced the longest spike. The parent SOURAV and the cross BARI GOM-30 × BARI GOM-28 produced the highest number of filled spikelets spike^{-1}. The lowest number of unfilled spikelets spike^{-1} was found in parent SOURAV and cross BARI GOM-30 × PRODIP. The parent BARI GOM-33 and the cross BARI GOM-30 × PRODIP produced the maximum number of grains spike^{-1}. The highest 1000-grain weight was measured by the parent BARI GOM-30 and the cross BARI GOM-30 × BARI GOM-33. The parent BARI GOM-30 displayed the maximum grain yield plant^{-1} and the cross-combination BARI GOM-30 × SOURAV gave the result of maximum grain yield plant^{-1}. The parent SOURAV and the cross GOM-28 × BARI GOM-33 produced the

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highest biological yield plant^{-1}. The highest harvest index was noticed in parent BARI GOM-30 and in cross BARI GOM-30 × SOURAV.

4.2 General combining ability (GCA) and specific combining ability (SCA) for morpho-physiological and yield contributing characters in wheat

The estimates of mean squares due to GCA and SCA revealed that all studied characters were highly significant for GCA and SCA except harvest index. The only significant difference was noticed in the harvest index for GCA variance. The results showed both additive and non-additive gene actions were responsible for the expression of the characters studied.

For all studied characters except filled spikelets spike^{-1} and harvest index, the GCA/SCA ratios indicated the involvement of additive gene action for the expression of these traits. Filled spikelets spike^{-1} and harvest index were governed by predominance non-additive gene action.

The results of GCA effects showed that among the parents, the parent BARI GOM-30 emerged as the best general combiner for total tillers plant^{-1}, filled spikelet spike^{-1}, grains spike^{-1}, thousand-grain weight, grain yield plant^{-1}, harvest index. BARI GOM-28 was the best general combiner for heading days and maturity days. The parent PRODIP for plant height and BARI GOM-33 was the best general combiner for chlorophyll content, spike length, unfilled spikelet spike^{-1}. The parental genotype SOURAV was the best general combiner for effective tillers plant^{-1}, Spikes plant^{-1}, biological yield plant^{-1}. These parents may be utilized for the advancement of the breeding program.

The above-mentioned results revealed that no single parental genotype showed all the studied desirable characters. However, the results of GCA effects demonstrated that BARI GOM-30 was the best general combiner and could be applied in the hybridization program in yield improvement.

The estimates of SCA effects of the hybrids for morpho-physiological and yield and yield contributing characters revealed that the hybrid BARI GOM-30 × SOURAV was the best specific combiner for effective tillers plant^{-1}, total tillers plant^{-1}, spikes plant^{-1}. The cross BARI GOM-30 ×PRODIP emerged as the best specific combiner for the character spike length and unfilled spikelets spike^{-1}. The cross BARI GOM-28 × BARI GOM-33 was the best specific combiner for maturity days and chlorophyll content and BARI GOM-28 × PRODIP for harvest index. The cross SOURAV × AYT-5 appeared to be the best specific combiner for heading days. BARI GOM-28 × SOURAV was the best specific combiner for plant height. The hybrid BARI GOM-30 × BARI GOM-33 appeared to be the best specific combiner for thousand-grain weight. The cross PRODIP × SOURAV was the best specific combiner for filled spikelet spike^{-1} and PRODIP × AYT-5 for grains spike^{-1}. The cross BARI GOM-33 × SOURAV emerged as the best specific combiner for the character grain yield plant^{-1}.

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4.3 Heterosis of the crosses for morpho-physiological, yield and yield contributing characters in wheat

The results for mid-parent heterosis revealed that among the F_1 hybrids, the cross BARI GOM-28 × BARI GOM-33 showed desirable significant negative heterosis for heading days. The hybrid BARI GOM-28 × PRODIP exhibited maximum significant negative heterosis for maturity days. BARI GOM-28 × BARI GOM-33 showed maximum significant positive heterosis for chlorophyll content. Maximum significant negative heterosis for plant height was displayed by BARI GOM-28 × SOURAV. BARI GOM-33 × SOURAV exhibited maximum significant positive heterosis for effective tillers plant^{-1}. The highest significant positive heterosis was expressed by BARI GOM-33 × AYT-5 for total tillers plant^{-1}.

The hybrid BARI GOM-33 × SOURAV showed the highest significant positive heterosis for spikes plant^{-1}. BARI GOM-30 × PRODIP exhibited the highest significant positive heterosis for spike length. For the trait, filled spikelets spike^{-1}, significant positive heterosis was not found in any crosses. Maximum negative significant heterosis for unfilled spikelets spike^{-1} was noticed in the cross BARI GOM-30 × PRODIP. The F_1 hybrid PRODIP × AYT-5 displayed the highest significant heterosis for grains spike^{-1}. The highest significant positive heterosis for thousand-grain weight was recorded by the cross BARI GOM-30 × BARI GOM-33. The hybrid BARI GOM-33 × SOURAV recorded the highest significant positive heterosis for grain yield plant^{-1}. BARI GOM-28 × BARI GOM-33 exhibited maximum significant heterosis for biological yield plant^{-1}. The F_1 hybrid BARI GOM-28 × PRODIP exhibited maximum significant heterosis for harvest index.

The above-mentioned hybrids expressed good opportunities for their use of heterosis in the breeding culture.

4.4 Relationship between heterosis and SCA effects of the crosses for morpho-physiological, yield and yield contributing characters in wheat

The results of the relationship between heterosis and SCA effects revealed that the crosses *viz;* BARI GOM-30 × BARI GOM-28, BARI GOM-28 × PRODIP and BARI GOM-28 × BARI GOM-33 exhibited significant negative heterosis and SCA for heading days and maturity days. The cross-combination BARI GOM-30 × PRODIP showed significant positive heterosis and SCA for effective tillers plant^{-1}, spikes plant^{-1}, spike length and grains spike^{-1}. The hybrid BARI GOM-30 × BARI GOM-33 showed significant positive heterosis and SCA effects for thousand-grain weight and harvest index. The cross BARI GOM-30 × SOURAV recorded positive heterosis and SCA effects for effective tillers plant^{-1}, spikes plant^{-1}. The hybrid BARI GOM-28 × BARI GOM-33 showed positive heterosis and SCA effects for chlorophyll content, effective tiller plant^{-1}, grain yield plant^{-1} and biological yield plant^{-1}. The cross BARI GOM-33 × SOURAV showed positive heterosis and SCA effects for effective tiller plant^{-1}, spike length, grain yield plant^{-1} and harvest index.

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5. Conclusion:

i. The results of GCA effects showed that among the parents, the parent BARI GOM-30 emerged as the best general combiner for total tillers per plant and filled spikelets per spike.

ii. The estimates of SCA effects of the hybrids for morpho-physiological traits and yield and contributing characters revealed the hybrid SOURAV was the best specific combiner.

iii. The results for mid-parent heterosis revealed that the cross BARI GOM-28 showed desirable significant negative heterosis for heading days among the F1 hybrids. Significant positive heterosis was not found in any crosses for the trait filled spikelets per Spike.

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