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Research Article

Elucidating the combining ability and gene action for direct and reciprocal crosses in chilli under North-Western Himalayas

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Abstract

Seven genetically diverse chilli lines were crossed in full diallel mating design to obtain 42 F1 cross combination including reciprocals. The hybrids along with parental lines and standard check were evaluated for sixteen characters in randomized complete block design in three replications at Dr. YSPUHF, Nauni Solan Himachal Pradesh, India to delineate the heterotic and combining ability effects to study the gene action involved in expression of various traits. The heterosis studies revealed hybrids P3 × P4, P3 × P1, P1 × P5 and P2 × P5 performed consistently better for majority of traits over both, better parent and standard check. The parental lines; P3 and P1 were superior based on their general combining ability effects hence, these parents can be used in multiple crosses while, in SCA, P3 × P4 and P1 × P5 performed best for majority of traits. The reciprocal specific combining ability effects were significant for all the characters studied and the crosses *viz*., P4 × P3 and P3 × P1 were good reciprocal specific combiners. Further, non-additive gene action was found to be predominant for the inheritance of majority characters thus, suggesting that breeding approaches such as heterosis breeding and recurrent selection can be employed for the improvement of yield and other desirable horticultural traits in chilli. Hence, these crosses may be helpful in isolating transgressive segregants and could be utilized for future chilli breeding programme.

Keywords: Diallel mating, combining ability, heterosis,gene action, reciprocals, chilli

INTRODUCTION

Capsicum annum L., commonly known as chilli, hot pepper or Wonder spice is a major spice-cum-vegetable crop mainly consumed for its fresh green and red dry fruits (Karim *et al*., 2021). Besides, native to South and Central American origin (Swamy, 2023), the crop is cultivated across the globe adapted to tropical and subtropical climates therefore, serving essential spice in every household enriching taste, colour, flavor and pungency (Sun *et al*., 2014). Beyond enciting colour and flavor, chillies supplement our diet with nutrients (magnesium, iron, potassium, zinc), vitamins complex (ascorbic acid, niacin, pyridoxine, riboflavin and thiamine), antioxidants curing various body ailments (Karim *et al*., 2021). In recent decades, processed products like pickles, sauces, dried powder, flakes are more dominant among consumers. Few quality parameters attributed to chilli being oleoresin, dry matter, capsaicinoids renders this as important trade crop of immense value. Chillies are endowded with characteristic quality of pungency owing to capsaicin and dihydrocapsaicin,major alkaloids, present in placenta of fruits giving spicy, burning taste to the palate (Aiswarya *et al*., 2020).Currently, chilli oleoresin is receiving focus due to its high export value (Singh *et al*., 2015). These constituents in chilli therefore can be exploited in food industry, curing body dysfunctioning, used in defense industry, pharmaceuticals, cosmetics products etc.

Chillies have been in cultivation in the past hundred years. Mexico, being centre of diversity with secondary at Gautemala, chillies spread globally. Its history in India dates back with its introduction in 1885 from Brazil by the Portugese. Major chilli producing countries being India, China, Korea, Japan, Spain, Nigeria, Pakistan Indonesia, Mexico etc. account for more than 85% of the world production. India stands as major producer, consumer and exporter of chilli in world dominating in the states of Karnataka, Andhra Pradesh, Telangana, Maharashtra, Orissa and Tamil Nadu accounting more than 70% acreage. The area under dry chillies cultivation accounts for 922'000ha with annual production 2693'000MT (Anonymous, 2025), while the export figures estimated out turned $41 million earnings in 2019. The dry chilli productivity has increased with the usage of high yielding hybrids in India. Moreover, the demand for hybrids is fast increasing as they are high yielding, highly adaptable, pest and disease resistant which can be accomplished through breeding programmes.

Chillies exhibit vast variability in terms of shape, size, colour, pungency etc. As the crop is often-cross pollinated, extent of outcrossing ranged between 7 to 90% in open field (Singh *et al*., 1994). Heterosis breeding thus, is a quick and convenient approach of combining desirable characters in F_1 hybrid production (Ramesh *et al*., 2013). In chilli, heterosis breeding was first reported by Deshpande (1993). Also heterosis breeeding is advantageous in chilli as the crop offers much scope of improvement with respect to quality and yield traits, which can further be utilized for development of desirable recombinants. In order to develop these hybrids, it becomes imperative for breeders to select good parental lines. Selection of parents based on their *per se* performance does not necessarily yields desirable combinations (Allard, 1960). Therefore, proper selection of parents based on combining ability generates information for effective transfer of desirable genes to the resultant progenies and also study the nature of gene action involved in the expression of various traits. Various biometrical techniques can be employed for analyzing combining ability and gene action. The approach of full diallel proposed by Griffing (1956) is based on estimates of combining ability variances and effects and also generates precise information of general combining abilities of parents and specific as well as reciprocal effects of hybrid combinations. Besides, it also determines the bases of inheritance of quantitative traits in bi-directional crosses. Sprague and Tatum (1942), firstly proposed the concepts of general combining ability (GCA) and specific combining ability (SCA). Griffing (1956) stated that the GCA includes the additive genetic portion, while SCA includes non-additive genetic portion of the total variation. Hayman (1958) found that in the absence of epistasis, GCA is composed of both additive and dominance while SCA involves mainly dominance effects. Besides this, additional information on the presence or absence of epistasis, average degree of dominance and distribution of dominant and recessive genes in the parents are also obtained using this approach (Nascimento *et al*., 2014). Thus, present investigation was dealt to delineate the performance of parents and hybrids based on heterosis, combining ability studies and also gene action studies that would assist plant breeders in formulating strategies for breeding populations, selection techniques, variety types and testing scope in chillies.

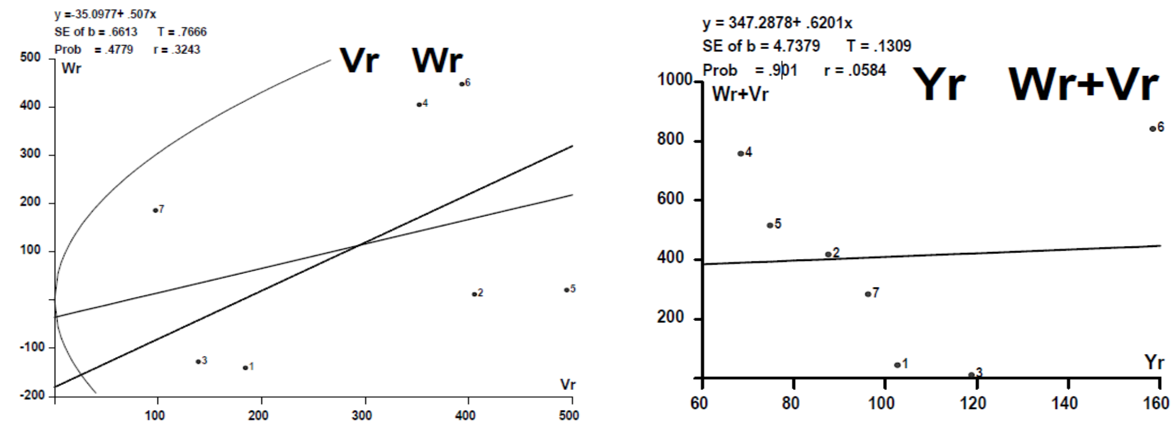
MATERIALS AND METHODS

The present investigation was carried out in the field and laboratory of Department of Vegetable Science, Dr. Y S Parmar University of Horticulture and Forestry, Nauni, Solan, Himachal Pradesh, during *Kharif* season, 2021 and 2022. The seven parents (**Table 1**) were crossed in all possible combinations that produced forty two F_1 hybrids (21 direct F_1's and 21 reciprocals) during *Kharif*, 2021. These F_1 hybrids along with reciprocals and standard check (DKC-8) were evaluated for various horticultural traits during *Kharif* 2022. The experiment was laid out in a Randomized Complete Block Design having plot size 1.8 × 1.8m^2 (3.24 m^2 area) with 45×45cm in three replications. The standard cultural practices as recommended for raising healthy crop were followed.

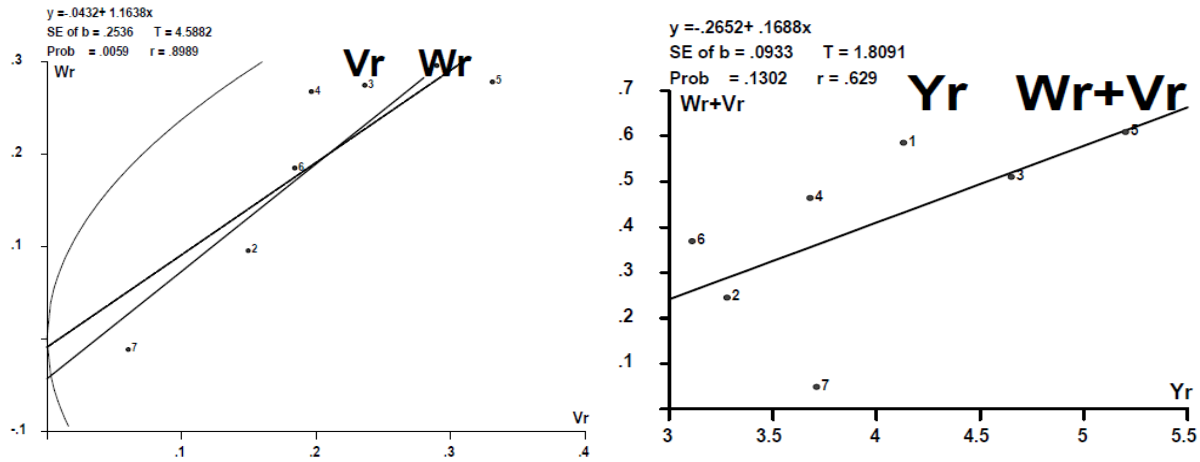
The data for growth, yield and biochemical traits were recorded at red ripe stage from ten randomly selected plants avoiding border plants. The sixteen different qualitative and quantitative traits recorded for evaluation were days to 50 per cent flowering, days to red ripe maturity, plant height (cm), fruit length (cm), fruit breadth (cm), number of fruits per plant, average fresh red fruit weight (g), fresh ripe fruit yield per plant (g), average dry fruit weight (g), dry fruit yield per plant (g), dry yield as percentage of fresh ripe fruits (%), number of seeds per fruit, thousand seed weight (g), oleoresin content (%), ascorbic acid content (mg/100g), capsaicin content (%).

Table 1. List of parents used in hybridation programme along with their sources

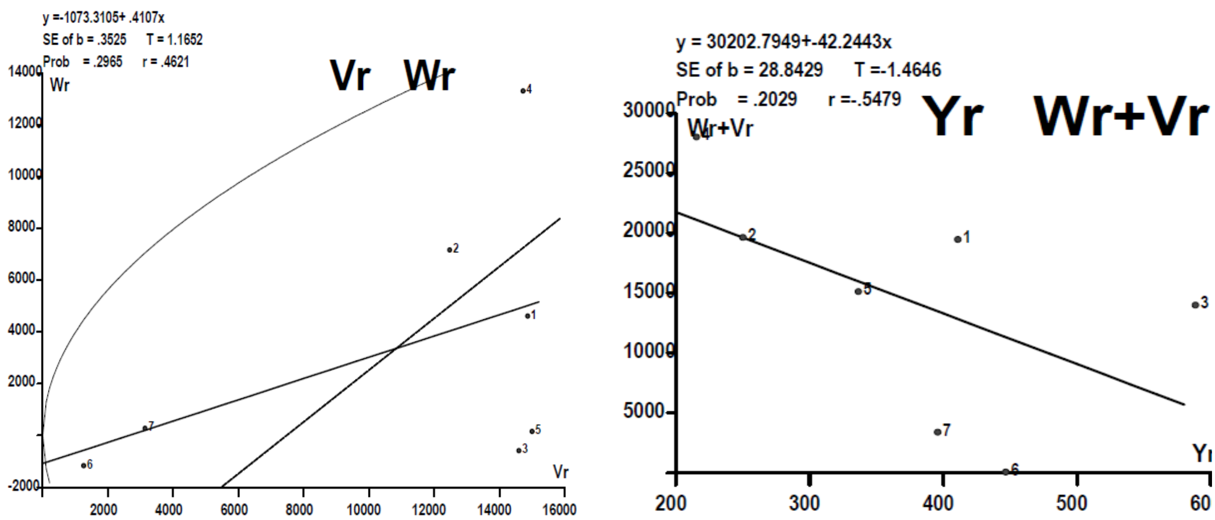
S.No.	Parents	Notation	Source
1	UHF-Selection-14	P1	Dr YSP UHF, Nauni, Solan (HP)
2	UHF-Selection-1	P2	Dr YSP UHF, Nauni, Solan (HP)
3	UHF-Selection-2	P3	Dr YSP UHF, Nauni, Solan (HP)
4	UHF-CHI-17	P4	Dr YSP UHF, Nauni, Solan (HP)
5	UHF-CHI-11	P5	Dr YSP UHF, Nauni, Solan (HP)
6	UHF-CHI-13	P6	Dr YSP UHF, Nauni, Solan (HP)
7	UHF-CHI-5	P7	Dr YSP UHF, Nauni, Solan (HP)
Standard check			
	DKC-8		Dr YSP UHF, Nauni, Solan (HP)



1. Number of fruits per plant



2. Average fresh red fruit weight



3. Fresh ripe fruit yield per plant

Fig.1. Coefficient of correlation (r) between the parental order of dominance (Wr+Vr) and parental measurements (Yr) i.e. r (Wr+Vr,Yr) for different traits in chilli

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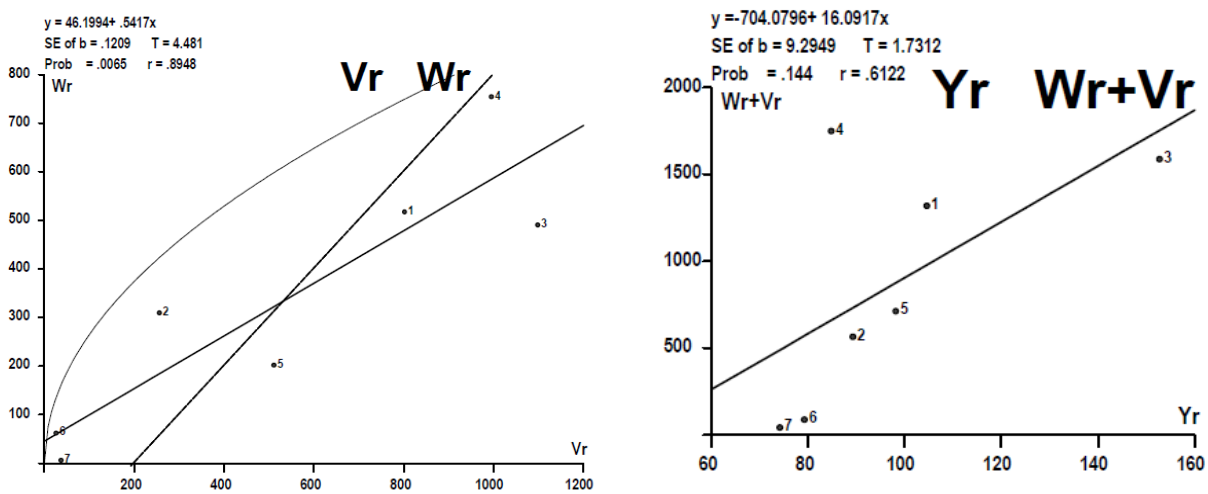

4. Dry fruit yield per plant

Fig.1. Coefficient of correlation (r) between the parental order of dominance (Wr+Vr) and parental measurements (Yr) i.e. r (Wr+Vr,Yr) for different traits in chilli

Statistical analysis: The analysis of variance (ANOVA) for full diallel analysis was done according to the model by Griffing and Hayman's numerical approaches. GCA, SCA, RCA, additive and dominance components of variances were calculated. The heterobeltiosis and standard heterosis was estimated and significance of heterosis, 't' calculated value for heterosis were compared with 't' tabulated values at error degree of freedom ($P \leq .05$). The analysis was done using computer software 'WINDOSTAT version 9.3' (from INDOSTAT services Ltd, Hyderabad, India). The R Package version 0.7.0[28] was used to plot graph of coefficient of correlation (r) between the parental order of dominance (Wr+Vr) and parental measurements (Yr) i.e. r (Wr+Vr,Yr) (**Fig. 1**) for yield contributing traits in chilli.

RESULTS AND DISCUSSION

Heterosis: Early flowering and fruiting aid farmers to fetch early profits and make the land available for next growing season. The heterosis studies revealed that the most heterotic crosses for earliness i.e., days to 50% flowering and days to red ripe maturity were P5 × P2 and P4 × P1 over better parent, respectively, while heterotic combinations over standard check were P3 × P4 for both days to 50% flowering and days to red ripe maturity. Supporting evidences in these aspects were available from results of Prasath and Ponnuswami (2008) in chilli.

The extent of negative heterosis for plant height was found to be more prominent over better parent. The cross combination *viz*., P1 × P2 showed positive significant heterotic effect over better parent. All the forty-two hybrids exhibited significant positive heterosis over the standard check, as the check itself was the shortest in the whole population. The highest standard heterosis was possessed by the hybrid, P2 × P3. The information on difference in plant height in chilli was noted to be available from the studies of Prasath and Ponnuswami (2008) and Rao *et al*. (2017). For fruit length, P3× P4 exhibited the highest significant positive heterosis. The hybrid P2× P1exhibited maximum positive heterosis over DKC-8. The present results are in conformity with the findings of Rao *et al*. (2017) in chilli.

The magnitude of heterosis over better parent was more prominent in negative direction for fruit breadth. The highest positive significant heterosis was exhibited by P3 × P4. The standard heterosis over DKC-8 showed that nineteen hybrids showed significant positive standard heterosis with the highest positive significant heterosis recorded by P1× P6. Similar results for this trait were observed by Nagaraja *et al.* (2016) in studies of chilli. For fruits per plant, hybrid P4× P5 showed highest positive significant heterosis. Heterosis over standard check was observed maximum in P3 × P4 cross combination. The present results are in concurrence with the findings of Rekha *et al*. (2016) in chilli. The heterobeltiosis for average red fruit weight showed the highest significant positive heterosis recorded in P6× P2. The highest heterosis over standard check was recorded by P4× P5 hybrid. The results are in conformity with Payakhapaab *et al*. (2012) findings in chilli research.

The cross P4 × P5 showed maximum heterosis over better parent whereas, crosses P3 × P4, showed maximum heterosis over standard check for both fresh ripe fruit yield per plant as well as dry fruit yield per plant. The superior hybrids based on *per se* peformance and heterosis is illustrated in **Table 3**. The increased fruit yield of first generation hybrids obtained in the present study also correlates with the findings of Kaur *et al*. (2017). For oleoresin and ascorbic acid content, hybrids having the highest heterobeltiosis were P4 × P5 and P2 × P4 respectively, while, hybrids exhibiting heterosis over

Table 2. Analysis of variance for combining ability analysis in respect of yield and yield component characters in chilli

S.No.	Notation	Characters	GCA	SCA	RCA	Error
			6	21	21	96
1	T1	Days to fifty percent flowering	90.5450*	4.1883*	5.1561*	1.4345
2	T2	Days to red ripe maturity	371.5079*	16.1630*	16.0503*	1.9458
3	T3	Plant height	191.0529*	8.6530*	21.2419*	1.7770
4	T4	Fruit length	3.3716*	1.3244*	0.6677*	0.0149
5	T5	Fruit breadth	3.3848*	1.1891*	1.7955*	0.0168
6	T6	Number of fruits per plant	547.3783*	512.3975*	174.1654*	3.7023
7	T7	Average fresh red fruit weight	1.3609*	0.2193*	0.2567*	0.0050
8	T8	Fresh ripe fruit yield per plant	49950.0469*	14581.5918*	10977.1494*	58.6882
9	T9	Average dry fruit weight	0.0971*	0.0227*	0.0247*	0.0001
10	T10	Dry fruit yield per plant	3150.8047*	613.9023*	784.9194*	3.0597
11	T11	Dry yield as percentage of fresh ripe fruits	42.4512*	1.7247*	4.1798*	0.1202
12	T12	Number of seeds per fruit	242.4393*	124.2115*	106.4357*	1.7620
13	T13	1000-seed weight	2.4453*	0.7117*	0.3203*	0.0121
14	T14	Oleoresin content	24.2886*	4.2229*	3.4061*	0.0357
15	T15	Ascorbic acid content	2629.5442*	521.9716*	132.6815*	6.1847
16	T16	Capsaicin content	0.0096*	0.0027*	0.0012*	0.0000

standard check were P2 × P6, and P2 × P7, respectively. Similar results were obtained from the studies of Jindal *et al*. (2015) for ascorbic acid and oleoresin content. For capsaicin, the major contributor of pungency, only five hybrids showed hetreobeltiosis in desired direction with P2× P7(19.77%) being the highest, while none of the hybrid surpassed the performance of standard check.

Yield is a complex trait governed by many factors. Early flowering yields early fruits ultimately outstretch the market in advance generating more gains. As deducing, P3× P4 was earl for both traits and can be used in breeding programmes for improvement of this trait. As inference from the studies that fruit length, fruit width, fruit weight, fruit count per plant are directly correlated with the plant yield and merely influenced by environmental factors. Also the consumers preference and demands of processing industry decides its fate. For instance, green long fruits for salad, thicker fruits for pickle making,, fruits with red thick pericarp for drying and processing industry. P3× P4, P3× P5, P4× P5 performed well for these traits contributing to high yield. The capsaicin content was notably high in hybrids P6× P1, P1× P6, P3× P4 but none surpassed the check performance.

Combining ability effects: Theparents with high *per se* performance may not alwaysbe able to transmit their superior traits into hybrids andso assessment of combining ability is most needed. General combining ability (GCA) of a parent is a factorthat predicts the performance of a parent over a seriesof cross combinations. The ANOVA for the full diallel mating design (**Table 2**) revealed significant mean sum of squares for most of the yield contributing traits studied, indicating the availability of sufficient genetic variation within the germplasm.

General combining ability (GCA) effects of the parents: For earliness traits, those parents are good combiners exhibiting significant negative combining ability effects (**Table 4**). P3 was good combiner for earliness traits *viz.*, days to 50 percent flowering (-3.86) and days to red ripe fruit maturity (-7.85). Besides this also, parent P3 was the best with highest GCA effect in positive direction for fruit length (0.89), average fresh red fruit weight (0.35), fresh ripe fruit yield per plant (78.53), dry fruit yield per plant (21.36), number of seeds per fruit (4.60), thousand seed weight (0.73), ascorbic acid content (14.26). The parent P6had high general combining ability effects for plant height (2.22); P1 for fruit breadth (0.95), number of fruits per plant (6.44); P5 for average dry fruit weight (0.12); dry yield as percentage of fresh ripe (2.23) ; P6 for oleoresin content (1.20). The favourable gene for pungency, a key quality component of chilli, was exhibited by the parent P4 (0.04) ((**Table 4**). The overall GCA status from present studies exemplifies that parents P3 and P1performed as best parents corresponding to high estimates of GCA under effect of additive genes which would further prove worthy in hybridization programme in enhancing yield and attributing traits of the superior hybrid combinations. Patel *et al*. (2003) in chilli studies reported significant positive GCA effects for plant height, fruit breadth and fresh red fruit weight. The results were in conformity with the findings of Jagtap *et al.* (2015) for days to fifty percent to flowering in chilli. The results of Chakrabarty *et al*. (2019) for fruit length, number of fruits per plant, fruit yield per plant, dry fruit weight and seed count;

Table 3. Top five promising hybrids based on *per se performance* and hetrosis for fruit yield and contributing traits in chilli

Top five promising hybrids	Based on	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16
P3 × P4	*Per se*	44.00	9300	88.15	9.83	11.02	148.69	5.18	718.69	1.24	238.46	21.10	94.27	7.73	12.74	185.10	0.40
	BPH	2.33	-0.36	-13.68*	-9.82*	31.19*	25.17*	11.40	22.10	80.58*	56.15*	-18.94*	5.45	-4.64*	-22.25*	-14.51*	-2.46*
	SH	-28.65*	-15.97*	1.77*	41.44*	33.90*	77.01*	35.60*	191.97*	103.28*	142.43*	5.76*	52.03*	44.55*	-1.06	1.32	-11.85*
P3 × P1	*Per se*	45.00	100.33	95.27	9.13	9.84	137.10	4.99	702.52	0.94	156.28	26.46	52.38	6.64	15.63	171.91	0.25
	BPH	4.65	7.50*	-6.70*	-16.24*	-15.99*	15.42*	7.248	19.35*	37.38*	2.34*	1.64*	-45.71*	-18.13*	-4.64*	-20.61*	-19.35*
	SH	-27.03*	-9.34*	1.92*	31.37*	19.56*	63.22*	30.54*	185.40*	54.64*	58.89*	32.61*	-15.54*	24.11*	21.35*	-5.90*	-44.44*
P4 × P5	*Per se*	52.33	120.33	86.54	6.53	10.14	122.57	5.65	678.89	1.28	162.11	22.16	83.11	7.24	16.89	158.38	0.31
	BPH	0.64	7.12*	1.69	-41.36*	8.22	63.86*	8.65*	101.76*	18.83*	65.10*	-18.28*	-1.42	12.47*	33.66*	-10.59*	-23.58*
	SH	-15.14*	8.73*	1.74*	-6.09*	23.21*	45.91*	47.91*	175.80*	110.38*	64.81*	11.09*	34.03*	35.39*	31.13*	-13.30*	-30.37*
P1 × P5	*Per se*	56.33	105.33	96.16	7.59	8.55	146.27	4.53	656.38	0.89	158.02	24.20	93.16	6.79	12.78	176.42	0.35
	BPH	10.46*	0.00	3.36	-31.81*	-26.99*	42.51*	-12.88	59.75*	-17.59*	51.04*	-10.77*	-3.44*	1.85	-10.75*	-0.40	11.83
	SH	-8.65*	-4.82*	1.93*	9.21*	3.89	74.13*	18.59*	166.66*	45.90*	60.65*	21.30*	50.23*	26.98*	-0.78	-3.43	-22.96*
P1 × P6	*Per se*	55.67	110.67	94.54	9.40	12.01	128.64	4.37	570.81	0.85	102.47	19.81	72.93	6.12	11.84	196.12	0.40
	BPH	9.15*	5.06*	1.62	6.46	2.56*	-18.78*	5.89	27.76*	24.39*	-2.06*	-15.12	-24.41*	-8.25*	-22.94*	-6.63*	3.42*
	SH	-9.73*	0.00	1.90*	35.25*	45.93*	53.14*	14.49*	131.90*	39.34*	4.18	-0.70	17.61*	14.39*	-8.10*	7.35*	-10.37*

* Significant at 5% level of significance ; BPH: Better parent heterosis SH: Standard heterosis

Table 4. Top promising hybrids based on *GCA, SCA* and *RCA* for fruit yield and contributing traits in chilli

Characters	GCA	SCA	RSCA
T1	P1 (-3.86) P7 (-1.31) P2 (-1.17)	P3 × P4 (-2.73) P2 × P5 (-2.52) P4 × P6 (-1.50)	P6 × P1 (-2.33) P6 × P5 (-2.17) P7 × P6 (-2.00)
T2	P3 (-7.85) P7 (-3.06) P1 (-2.47)	P3 × P4 (-6.46) P1 × P4 (-4.01) P1 × P5 (-3.08)	P7 × P6 (-5.17) P6 × P1 (-4.33) P5 × P3 (-4.33)
T3	P6 (2.22) P1 (1.76)	P4 × P7 (2.74) P1 × P5 (2.68) P4 × P5 (2.15)	P3 × P2 (7.38) P5 × P1 (6.55) P6 × P2 (5.66)
T4	P3 (0.89) P1 (0.23) P2 (0.22)	P1 × P6 (1.20) P2 × P4 (0.83) P1 × P2 (0.45)	P4 × P3 (0.87) P7 × P5 (0.82) P5 × P2 (0.77)
T5	P1 (0.95) P3 (0.13)	P3 × P4 (0.86) P1 × P6 (0.84) P4 × P5 (0.78)	P6 × P1 (2.15) P4 × P3 (1.50) P7 × P5 (1.43)
T6	P1 (6.44) P6 (5.77) P3 (5.20)	P2 × P5 (25.87) P1 × P5 (24.65) P3 × P4 (14.56)	P4 × P3 (22.50) P6 × P1 (18.11) P5 × P4 (15.73)
T7	P3 (0.35) P4 (0.04)	P2 × P6 (0.64) P1 × P3 (0.50) P4 × P7 (0.35)	P6 × P5 (0.61) P4 × P3 (0.53) P6 × P1 (0.31)
T8	P3 (78.53) P1 (44.47) P51 (33.78)	P1 × P5 (147.00) P2 × P5 (105.45) P3 × P4 (104.76)	P5 × P4 (193.93) P6 × P1 (148.66) P4 × P3 (125.23)
T9	P5 (0.12) P3 (0.07) P4 (0.03)	P3 × P4 (0.21) P2 × P6 (0.14) P4 × P5 (0.13)	P5 × P4 (0.30) P4 × P3 (0.23) P6 × P5 (0.19)
T10	P3 (21.36) P5 (10.81) P1 (6.43)	P3 × P4 (43.48) P1 × P5 (34.01) P6 × P7 (16.15)	P4 × P3 (70.12) P5 × P4 (39.86) P5 × P3 (15.46)
T11	P5 (2.23) P3 (1.78) P1 (0.40)	P2 × P5(1.05) P1 × P3 (0.99) P3 × P7 (0.98)	P7 × P2 (2.09) P7 × P6 (1.86) P3 × P2 (1.63)
T12	P3 (4.60) P1 (3.56) P2 (1.09)	P3 × P6 (16.14) P1 × P2 (13.08) P1 × P5 (9.78)	P3 × P1 (14.37) P7 × P5 (12.43) P4 × P1 (11.55)
T13	P3 (0.73) P2 (0.28) P1 (0.14)	P1 × P7 (1.17) P3 × P6 (0.99) P4 × P5 (0.89)	P7 × P5 (0.61) P5 × P2 (0.59) P4 × P3 (0.55)
T14	P6 (1.20) P3 (0.62) P4 (0.52)	P4 × P5 (2.37) P6 × P7 (1.79) P2 × P6 (1.47)	P6 × P2 (2.55) P5 × P2 (2.16) P4 × P1 (1.92)
T15	P3 (14.26) P7 (11.80) P6 (10.08)	P2 × P4 (32.72) P1 × P5 (19.94) P1 × P6 (13.70)	P7 × P2 (18.28) P6 × P1 (15.39) P4 × P2 (14.40)
T16	P4 (0.04) P6 (0.03) P1 (0.01)	P3 × P4 (0.08) P1 × P6 (0.06) P2 × P5 (0.05)	P7 × P3 (0.07) P7 × P2 (0.04) P3 × P2 (0.04)

Navhale *et al*. (2014) for fruit breadth, fruits per plant, fruit yield; Aiswarya *et al*. (2020) for plant height, number of seeds per fruit, oleoresin content and ascorbic acid content in chilli were in consonance with the present findings.

*Specific combining ability (SCA) effects of the hybrids:*The hybrids derived from all possible combinations of parents exhibited good, average and poor GCA effects. The parents possessing significant SCA effects in the negative direction are good specific combiners for earliness traits (**Table 4**). The hybrid P3× P4 was best performer for both earliness traits viz., days to 50 percent flowering (-2.73) and days to red ripe maturity (-6.46) which was the outcome of good × poor GCA effects of their respective parents. The SCA effect of this hybrid was superior in

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the desirable direction for fruit breadth (0.86), average dry fruit weight (0.21), dry fruit yield per plant (43.48) and also capsaicin content (0.08) that involved parents with good × poor, good × good, good × good, poor × good general combiners. The fresh ripe fruit yield per plant was positive and significant in the crosses, P1× P5(147.00), P2× P5(105.45), P3× P4(104.76) with good × good, poor × good, good × poor GCA effects of corresponding parents. The hybrid, P2 × P5showed highest SCA effects for number of fruits per plant (25.87) and dry yield as percentage of fresh ripe (1.05) which were outcome of average × poor and poor × good combiners. Also, P1 × P5 (24.65), P3 × P4 (14.56) were promising hybrids for fruits number per plant based on SCA effects. For average fresh red fruit weight hybrids *viz*., P2 × P6 (0.64) and P1 × P3 (0.50) were top specific combiners with poor × poor and average × good combiners. The cross combination P3 × P6(16.14) had high SCA effect for seeds count per fruit (good × poor); P4 × P5(2.37) for 1000-seed weight (poor × poor); P4 × P5(2.37) for oleoresin content (good × poor) and P2 × P4(32.72) for ascorbic acid content (good × poor). In most of the cases, the parents involved in crosses were either both good combiners or good and poor combiners. Singh (2001) found good × average, poor × poor/average, good × poor, and good × good GCA combiners that resulted higher SCA effects for fruit number, fruit width, fruit weight and plant height, respectively. Rohini *et al*. (2017) reported superior hybrids $P_1 \times P_3$ and $P_2 \times P_3$ based on their SCA effects for dry pod yield per plant which were result of low × low, and high × low GCA combiners. The findings of Janki *et al*. (2017) resulted in negative significant SCA effects in crosses LCA 466 × G4 and LCA 466 × LCA 678 that were outcome of poor × good and good × average GCA combiners for fifty percent flowering and days to maturity respectively in chilli. Navhale *et al*. (2014) noted highest sca effect for red fruit yield per plant-1 in the reciprocal crosses of BC-28 × Konkan kirti, Selection-2 × PANT-C-3 and Selection-2 × Konkan Kirti in chilli studies.

Reciprocal combining ability (RCA) effects of the hybrids The reciprocal cross, P6 × P1(-2.33) and P7 × P6 (-5.17) had high significant reciprocal combining ability for days to fifty percent flowering and days to red ripe fruit maturity respectively in desirable direction (**Table 4**). Good reciprocal combiners were P4 × P3 (22.50 and 70.12) for number of fruits per plant and dry fruit yield per plant respectively, P6 × P5 (0.61),P4× P3(0.53), P6 × P1(0.31) for average fresh red fruit weight and P5 × P4 (193.93), P6× P1(148.66), P4 × P3(125.23) for fresh ripe fruit yield per plant. For fruit length and fruit breadth, significant RCA effect in the desirable direction was exhibited by the crosses P4× P3(0.87) and P6 × P1(2.15) respectively. The maximum reciprocal effect for capsaicin content was revealed by P7 × P3(0.07), for ascorbic acid P7 × P2(18.28) and P6 × P2(2.55) for oleoresin content. Rohini *et al.* (2017) reported reciprocal crosses *viz*., $P_6 \times P_2$ and $P_6 \times P_5$ had the low × high GCA combination with high positive significant RCA effects suggesting dominant × additive gene interaction.

Gene action studies: The diallel analysis proves worthy in estimating general combining ability effects of parents and specific combining ability and reciprocal effects of the

Table 5. Components of variance for various characters in chilli

Components of Variance	V_{GCA}	V_{SCA}	$V_{Reciprocal}$	V_{GCA}/V_{SCA}	V_A	V_D	V_A/V_D
T1	6.37	2.75	1.86	2.31	12.73	2.75	4.62
T2	26.4	14.22	7.05	1.86	52.79	14.22	3.71
T3	13.52	6.88	9.73	1.97	27.04	6.88	3.93
T4	0.24	1.31	0.33	0.18	0.48	1.31	0.37
T5	0.24	1.17	0.89	0.21	0.48	1.17	0.41
T6	38.83	508.7	85.23	0.08	77.67	508.7	0.15
T7	0.1	0.21	0.13	0.45	0.19	0.21	0.9
T8	3563.67	14522.9	5459.23	0.25	7127.34	14522.9	0.49
T9	0.01	0.02	0.01	0.31	0.01	0.02	0.61
T10	224.84	610.84	390.93	0.37	449.68	610.84	0.74
T11	3.02	1.6	2.03	1.88	6.05	1.6	3.77
T12	0.17	0.7	0.15	0.25	0.35	0.7	0.5
T13	17.19	122.45	52.34	0.14	34.38	122.45	0.28
T14	1.73	4.19	1.69	0.41	3.46	4.19	0.83
T15	187.38	515.79	63.25	0.36	374.77	515.79	0.73
T16	0.0007	0.0027	0.0006	0.2593	0.0014	0.0027	0.5185

V_g= Variance due to GCA, V_s = Variance due to SCA V_r = Variance due to reciprocal effects
V_A= Additive variance = $2V_g$; V_D = Non - additive variance = V_s

Table 6. Estimates and ratios of components of genetic variance for different characters in chilli

	D	H_1	H_2	F	h^2	E	$(H_1/D)^{0.5}$	$H_2/4H_1$	KD/KR	h^2/H_2	h^2_{ns}	Coefficient of correlation (r) between (Wr+Vr)Yr	t2	b	SE(b)	1-b/SE(b)
T1	23.14*	5.36*	-0.40*	-2.5	-0.4	1.41*	0.48	0.25	0.79	-0.07	10.96	0.09	0	0.96	0.12	0.29
T2	86.03*	31.30*	28.49*	-16.73	0.39	1.92	0.6	0.22	0.72	0.01	12.26	-0.05	3.91	0.7	0.11	2.64
T3	70.75*	16.73*	13.70*	19.68*	6.81*	1.78*	0.48	0.2	1.8	0.49	53.91	0.72	2.12	1.19	0.25	-0.75
T4	2.34*	3.83*	2.61*	2.60*	2.45*	0.01	1.28	0.17	2.53	0.93	12.83	0.71	0.08	0.93	0.22	0.28
T5	2.55*	3.21*	2.34*	2.46*	0.17	0.01	1.12	0.18	2.5	0.07	13.63	0.42	2.77	1.07	0.61	-0.12
T6	923.61*	1640.04*	1017.42*	1390.92*	392.07	3.69	1.32	0.15	3.59	0.38	45.1	0.05	1.19	0.5	0.66	0.74
T7	0.55*	0.58*	0.42*	0.32*	0.02	0.01	1.02	0.18	1.79	0.06	30.92	0.62	1.77	1.16	0.25	-0.64
T8	15775.72*	45565.95*	29048.62*	18038.44	6202.68	57.57	1.69	0.15	2.01	0.21	32.98	-0.54	0.08	0.41	0.35	1.67
T9	0.03*	0.06*	0.04*	0.02*	0.01	0.01	1.29	0.17	1.81	0.06	25.93	0.44	2.27	0.7	0.13	2.17
T10	697.01*	1482.12*	1221.46*	58.33	17.83	3.16	1.45	0.2	1.05	0.01	55.28	0.61	6.86	0.54	0.12	3.79
T11	15.96*	3.67*	3.20*	4.34*	0.04	0.12	0.47	0.21	1.79	0.01	50.04	-0.4	3.77	1.27	0.22	-1.22
T12	119.68*	271.18*	244.94*	77.16	23.87	1.74	1.5	0.22	1.54	0.09	19.9	0.24	0.02	0.29	0.43	1.6
T13	0.76*	1.46*	1.39*	0.13	-0.01	0.01	1.38	0.23	1.13	-0.01	41.87	0.1	0.32	0.98	0.25	0.06
T14	7.68*	11.47*	8.37*	3.86	0.53	0.03	1.22	0.18	1.51	0.06	36.77	0.16	1.02	1.05	0.33	-0.17
T15	865.81*	1088.85*	1031.588	173.47	371.89*	6.15	1.12	0.23	1.19	0.36	46.49	0.77	0.23	0.73	0.22	1.2
T16	0.0036*	0.0056*	0.0053*	0.0011	0.0002*	0	1.2385	0.23	1.28	0.032	35.95	-0.12	0.09	0.98	0.15	0.09

* Significant at 5% level. ** Significant at 1% level

Where, D=Additive effect ; H_1= Dominance effect; H_2= Proportion of dominance due to positive and negative effect of genes; F= Fr mean; h^2= F1 deviation from the average parent; E= Environment; $(H_1/D)^{0.5}$= Mean degree of dominance; $H_2/4H_1$= Proportion of genes with +ve and -ve effects in the parents; KD/KR= Proportion of dominant and recessive genes in the parents; h^2/H_2= number of groups which control character and exhibit dominance; h^2_{ns}= Narrow-sense heritability possible cross combinations generated. This is effective in predicting additive and dominant effects of a population which can be used to predict the genetic variability and heritability. GCA effects caused by the additive type of gene action and SCA effects are due to non-additive (dominant or epistatic) gene action.

The gene action involved in expression of trait and its inheritance determine the breeding methodology for the genetic improvement of that particular trait. The genetic components of variance (**Table 5**) showed that the ratio V_{GCA}/V_{SCA} was more than unity for days to 50% flowering (2.31), days to red ripe maturity (1.86), plant height (1.97) and dry yield as percentage of fresh ripe (1.88) which indicated preponderance of additive gene action, while non-additive gene effects were predominant for the remaining characters as the ratio V_{GCA}/V_{SCA} was less than unity.

The additive effects (D) was higher in days to 50% flowering, days to red ripe maturity, plant height and dry yield as percentage of red ripe while remaining exhibited high dominance effect (H_1 and H_2). Preponderance of additive gene action due to additive effects depicts that hybridization followed by selection in segregating generations is advocated for improving these traits. On the contrary, heterosis breeding would prove effective for the triats governed by non- additive gene action. The proportion of positive genes was observed from the values of H_1 against H_2 and the higher values of H_1 than H_2 showed that more positive genes were involved in determining the character. Mean degree of dominance $(H_1/D)^{0.5}$ was less than unity for days to 50% flowering, days to red ripe maturity, plant height and dry yield as percentage of red ripe showing partial dominance, while remaining traits had value more than unity indicating over-dominance. The dominant genes were higher in proportion than recessive genes (KD/KR ratio >1) was observed for all characters except days to 50% flowering and days to red ripe maturity. Therefore, dominant genes enable rapid expression of desirable traits, promoting hybrid vigour, simplifying selection and minimizing harmful recessive traits.The effective factors (gene or gene group) exhibiting dominance (h^2/H_2 ratio) was less than unity for all the traits, indicating all characters were controlled by one major gene group (**Table 6**).

The present studies reported additive as well as non additive variances in governing the trait. Sitaresmi *et al*. (2010) deduced both additive and non-additive gene effects in controlling fruit weight. Singh *et al*. (2014) opined in studies additive variance were predominant for expression of days to flowering and non-additive variance for total fruit yield per plant plant. While contradictory results were obtained for additive effects governing fruit width, average fruit weight and fruit length. The h^2/H_2 ratio less than one suggested that, at least one gene group was operating the inheritance of all the traits which were in conformity with the findings of Chakrabarty *et al*. (2019) in chilli.

In conclusion, the present study inferred the sufficient diversity present among parents and hybrid combination obtained. Heterosis studies revealed that P3×P4, P3 × P1 hybrids performed consistently better over both the estimates of heterosis for majority of traits. The estimates of combining ability aid in selection of good parents and the best hybrid for the yield and various contributing traits in chilli. The parents P3 and P1 were identified as good combiners while, the crosses P3× P4 and P1× P5 were promising hybrids based on specific combining ability effects. Based on reciprocal effects, the reciprocal crosses *viz*., P4 × P3and P3 × P1 were as good reciprocal specific combiners for majority of yield and its contributing traits. The predominance of additive and non-additive gene action governing various traits helps to decide the breeding strategies to be employed for the chilli improvement program.

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