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ANALYSIS OF GENETIC ARCHITECTURE OF HEAD YIELD AND BIOCHEMICAL TRAITS IN CABBAGE (*BRASSICA OLERACEA* VAR. *CAPITATA* L.) USING CYTOPLASMIC MALE STERILE LINES

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Abstract

The dearth of research on development of high quality cabbage hybrids in public sector by utilizing combining ability estimates, gene action and heterosis persuaded us to undertake this study. We made 30 F_1 hybrids between 15 cytoplasmic male-sterile lines and 2 testers during the summer of 2019 as per the line × tester design. The seedlings of all the parents and 30 F_1 hybrids along with two standard checks were transplanted during the Rabi season of 2019-2020 and evaluated using a randomized block design. Experimental results revealed that the parental lines II-105-CMS, III-M-CMS and SC 2008-09 were found to be good general combiners for most of the traits studied. Based on the mean performance, specific combining ability effects and heterosis three cross combinations viz., II-S-CMS × SC 2008-09, II-105-CMS × SC 2008-09 and II-105-CMS × E-1-3-1&2 were most outstanding. The proportional contribution of lines (5.77 – 62.12%) were found to be higher than the testers (0.04–11.93%) for all the traits studied. Further, the contribution of line × tester interactions (33.76 – 93.83%) was found to be higher than the individual contribution of lines and testers. This showed that interactions played a significant role in the expression of different characters in various cross-combinations. The dominance variances (σ^2D) were of higher magnitude for majority of the traits, indicating that non-additive gene effects were more important than additive effects. Hence, strong heterosis could be better displayed in yield and quality of cabbage heads.

Key words: *Brassica oleracea* var. *capitata*, Combining ability, Gene action, Heterosis.

Introduction

Cabbage (*Brassica oleracea* var. *capitata* L.) is one of the most economically important cole crops of *Brassicaceae* family, sharing a common chromosome number 2x=2n=18 (Bothmer *et al*., 1995) and probably the Western Mediterranean region is considered as its primary center of origin (Ji *et al*., 2020). It is mainly consumed for its nutritional values, i.e., vitamins especially A, C and B, and minerals, especially iron, calcium and potassium (Singh & Singh, 2010). Besides being nutritionally rich, cabbage has medicinal uses as well like, anticarcinogenic properties, anti-inflammatory potential due to the presence of chemical compounds like glucosinolates, glutathione, isothiocynates (Ghebramlak *et al*., 2004; Kopsell *et al*., 2004; Jamil *et al*., 2007; Singh *et al*., 2009a).

Till date, limited research work has been carried out in India to improve cabbage as only one hybrid KGMR-1 from public sector is available. Considering the importance and scope of cabbage as a commercial crop in our country, research efforts are required to develop high-yielding hybrids/varieties of cabbage. Being a cross pollinated crop, it shows the preponderance of non-additive gene action for most of the traits. Hence, heterosis breeding has turned out to be of more relevance in genetic improvement related to yield and quality traits (Singh *et al*., 2014). Heterosis breeding in cabbage is best done by employing CMS (cytoplasmic male sterility) system. The Ogura system of CMS has proved instrumental in commercialization of hybrid seed production in cabbage over traditionally used SI (self-incompatibility) and GMS (genetic male sterility) system because of its stability under the varying environmental conditions and producing 100 per cent pure hybrid seeds. Presently Ogura CMS is one of the extensively employed systems in cole crop hybrid breeding (Dey *et al*., 2013; Dey *et al*., 2017; Yu *et al*., 2020). Selection of superior parental lines is important for the development of hybrids. Estimates of general combining ability and specific combining ability are quite helpful in selecting the suitable parents for developing high-yielding hybrids, respectively. Therefore, the present study was undertaken to identify propitious parents and F_1 crosses based on combining ability, heterosis and gene action in order to recommend an appropriate breeding strategy for developing high-yielding hybrids in cabbage.

Materials and Methods

Experimental location, materials and layout: The present study was conducted at Experimental Farm of Department of Vegetable Science and Floriculture, CSK Himachal Pradesh Krishi Vishwavidyalaya, Palampur, India during 2019-20. The experimental farm is situated at 32° 6' N latitude, 76° 3' E longitude and at an altitude of 1290.80 m above mean sea level. Agro-climatically, the location falls under the mid hill zone (Zone-II) of Himachal Pradesh characterized by humid sub-temperate climate with high rainfall of 2500 mm per annum of which 80 per cent is received during June to September. The experimental material comprised 15 CMS lines (females) viz., I-105-CMS, I-S-CMS, I-M-CMS, II-105-CMS, II-S-CMS, II-M-CMS, III-105-CMS, III-M-CMS, Glory-I-S-CMS, Glory-I-M-CMS, Glory-7-S-CMS, Glory-7-M-CMS, GA (P)-105-CMS, GA (P)-S-CMS and GA (P)-M-CMS, and 2 testers (males) viz., SC 2008-09 and E-1-3-1&2, maintained at the Experimental farm, Palampur. Crosses were made during the summer season of 2019 (March-May) as per the line × tester design suggested by Kempthorne (1957). The 30 F_1 crosses, along with parents and standard checks, viz., Varun and KGMR-1, were planted in a randomized complete-block design in three replications during the Rabi season of 2019-2020. Inter-cultural operations were carried out as per the recommended package of practices (Sharma, 2003).

Observations recorded on field: The observations were recorded on five plants marked at random in each entry over the replications on different quantitative traits viz., days to harvest, plant spread (cm), stalk length (cm), number of non-wrapper leaves, gross weight (g), net weight of head (g), polar diameter of head (cm), equatorial diameter of head (cm), head shape index, compactness of head (g/cm^3), marketable heads per plot, heading per centage and marketable head yield (kg/plot).

Laboratory analysis: Total soluble solids (°B), ascorbic acid (mg/100 g), carotenoids (µg/100 g), iron content (mg/100 g), vitamin B_1 (µg/100 g) and dry matter (%) were measured in fresh marketable heads. TSS was measured with the help of hand refractometer. Ascorbic acid was estimated by colorimetric method given by Ranganna (2008) using 2, 6-dicholorophenol indophenol dye. Carotenoids were extracted in acetone solution and observations were recorded at 480, 663 and 645 nm OD via spectrophotometer. Iron content was estimated by the method elaborated by Ranganna (2008) where absorbance was measured at 480 nm and iron standards were used for the calibration curve. Vitamin B_1 was determined by a spectrophotometric method as described by Sadasivam & Manickam (2008). Dry matter was estimated as per procedure of Arora *et al*., (2008).

Statistical analysis

All the parents and their F_1 crosses were subjected to line × tester mating design given by Kempthorne (1957) and later on modified by Arunachalam (1974). Additive and dominance components of variance were computed by using the formula given by Singh & Chaudhary (1997) and Dabholkar (1992). Heterosis was estimated manually by using the formula given by Singh (1973).

Table 1. Analysis of variance (ANOVA) for head yield and related traits in cabbage.

Source of variation	Mean squares due to		
	Replication	Treatment	Error
Traits	2	48	96
Days to harvest	2.18	180.27*	2.19
Plant spread (cm)	0.34	26.35*	2.32
Stalk length (cm)	0.17	0.84*	0.11
Number of non-wrapper leaves	6.31	2.87*	0.80
Gross weight (g)	911.53	63973.21*	59.64
Net head weight (g)	133.19	39047.99*	39.32
Polar diameter (cm)	0.06	1.63*	0.05
Equatorial diameter (cm)	0.03	2.10*	0.04
Head shape index	0.00	0.008*	0.002
Head compactness (g/cm^3)	2.12	83.92*	0.65
Marketable heads per plot	0.33	1.64	0.57
Heading per centage	22.69	114.17	40.01
Marketable head yield per plot (kg)	0.05	5.42*	0.21
Ascorbic acid content (mg/100 g)	2.62	22.96*	1.12
Total soluble solids (°Brix)	2.27	1.73*	0.15
Carotenoids (µg/ 100 g)	15.37	18793.34*	53.25
Iron content (mg/ 100 g)	0.000	0.01*	0.000
Dry matter (%)	0.03	0.57*	0.09
Vitamin B_1 content (µg/100 g)	2.77	109.49*	1.87

*Significant at 5% level

Results and Discussion

Considerable amount of genetic variability was observed among treatments (parents and hybrids along with the standard checks) for all the traits studied and non-significant for marketable heads per plot and heading per centage (Tables 1 and 2). The partitioning of the mean squares into lines, testers and line × tester indicated significant differences among lines for all of the traits except number of non-wrapper leaves and significant differences among testers were observed for traits viz., plant spread, gross weight, net head weight, polar diameter, head compactness, TSS, dry matter and vitamin B_1. Mean square due to line × tester interaction was found significant for all the traits except marketable heads per plot and heading % (Table 3). In the present study, line I-105-CMS for polar diameter, head shape index, TSS, carotenoids, dry matter and iron content; line I-S-CMS for days to harvest, plant spread, stalk length and equatorial diameter; line I-M-CMS for gross weight, head compactness, ascorbic acid and dry matter; line II-105-CMS for days to harvest, plant spread, net head weight, gross weight, polar diameter, equatorial diameter, marketable head yield per plot, ascorbic acid, TSS, dry matter and vitamin B_1; line II-S-CMS for plant spread, gross weight, net head weight, polar and equatorial diameter; line II-M-CMS for ascorbic acid, TSS, carotenoids, iron content, dry matter and vitamin B_1; line III-105-CMS for stalk length, head shape index, head compactness, TSS and carotenoids; line III-M-CMS for days to harvest, plant spread, gross weight, net head weight, head shape index, head compactness, marketable heads per plot, marketable head yield, heading per centage, iron content and vitamin B_1; line GI-S-CMS for days to harvest, head compactness and carotenoids; line GI-M-CMS for gross weight, net head weight, polar diameter, head compactness, head shape index and marketable head yield per plot; line G7-S-CMS for gross weight, head compactness, TSS and carotenoids; line G7-M-CMS for stalk length, head compactness, marketable head yield per plot, carotenoids and vitamin B_1; line GA(P)-105-

CMS for plant spread, marketable head yield per plot, heading per centage, carotenoids, TSS, iron content, dry matter and vitamin B_1; line GA(P)-S-CMS for gross weight, net head weight, polar diameter, equatorial diameter, iron and ascorbic acid; and line GA(P)-M-CMS for stalk length, carotenoids, iron, dry matter, TSS and vitamin B_1 revealed significant and desirable GCA effects (Table 4). Tester SC 2008-09 for plant spread, gross weight, net head weight, polar diameter, TSS and dry matter and tester E-1-3-1&2 for head compactness and vitamin B_1 exhibited significant and desirable GCA effects. Thus, it may be concluded that parents viz., II-105-CMS, III-M-CMS and SC-2008-09 were good general combiners for most of the traits under study. The high GCA effects were observed primarily due to additive and additive × additive interactions which can be further exploited through hybridization and diallel selective mating/bi-parental mating and recurrent selection programmes. Different parental lines expressing significant positive and negative GCA effects had also been reported earlier by Solieman (2002), Chen *et al*., (2006), Cervenski *et al*., (2007), Singh *et al*., (2011) and Parkash *et al*., (2017).

From the present investigation, it was observed that no single cross could reveal significant SCA effects for all the traits (Table 5). Out of the 30 crosses studied, the promising hybrids/crosses exhibiting significant desirable SCA effects for most of the traits were II-105-CMS (good) × SC 2008-09 (average) for days to harvest, (good × good) for plant spread, (average × average) for stalk length, (average × average) for number of non-wrapper leaves, (good × good) for gross weight,(good × good) for net head weight, (poor × average) for carotenoids,(good × good) for polar and (good × average) for equatorial diameters; G7-S-CMS (poor) × E-1-3-1&2 (average) for days to harvest, (average × poor) for plant spread, (good × poor) for gross weight, (poor × poor) for net head weight, (poor × poor) for polar diameter, (average × average) for equatorial diameter, (average × average) for marketable head yield and (good × average) for carotenoids; II-S-CMS (average) × SC 2008-09 (average) for days to harvest, (good × good) for gross weight, (good × good) for net head weight, (good × good) for polar diameter, (average × average) for marketable head yield, (average × average) for number of non-wrapper leaves, (good × average) for equatorial diameter and (poor × average) for carotenoids; and GA(P)-S-CMS (average) × E-1-3-1&2 (average) for days to harvest, (good × poor) for gross weight, (good × poor) for net head weight, (good × poor) for polar diameter, (average × average) for marketable head yield, (poor × poor) plant spread, (poor × good) for head compactness and (poor × good) for vitamin B_1 . The combinations exhibiting high SCA effects derived from good general combiners will be of main interest as they certainly perform better for a particular character. However, Singh *et al*., (1985) were of the view that the best crosses involving at least one parent with good combining ability may produce transgressive segregants which are also possible in many of the crosses of the present study. In addition, high SCA effects were also shown by some cross-combinations involving poor general combiners which might be due to diverse genetic background of the parental lines involved in the crosses as well as might be attributable to high magnitude of non-additive gene action, especially complementary epistatic effects (Dey *et al*., 2014). Earlier workers have also reported significant SCA effects in their respective studies for different traits viz., net head weight, marketable head yield by Parkash *et al*., (2008); gross weight, net head weight, stalk length by Parkash *et al*., (2003); Iron content by Singh *et al*., (2012); ascorbic acid and carotenoids by Singh *et al*., (2018). The high SCA effects were observed primarily due to dominance and epistatic gene effects which can be further exploited through heterosis breeding and hybridization programme.

The perusal of data presented in Table 6 indicated that non-additive (dominance) component was larger than additive component for traits viz., days to harvest, plant spread, stalk length, number of non-wrapper leaves, gross weight, net head weight, polar and equatorial diameters of head, head shape index, head compactness, marketable heads per plot, heading per centage, marketable head yield, ascorbic acid, iron content and dry matter, revealing the degree of dominance in over-dominance range whereas, TSS, carotenoids and vitamin B_1, showed preponderance of additive gene action. The role of non-additive gene action in inheritance of different traits following line × tester design has also reported by (Singh *et al*., 2012; Pathak *et al*., 2007) for net head weight, heading per centage, head shape index and marketable head yield. In the present study, narrow sense of heritability was also computed which was low for plant spread, stalk length, number of non-wrapper leaves, gross weight, net head weight, polar diameter, equatorial diameter, head shape index, head compactness, marketable heads per plot, heading per centage, marketable head yield and dry matter. Medium for days to harvest, ascorbic acid and iron content whereas, high for TSS, carotenoids and vitamin B_1. Low heritability indicated predominantly non-additive gene action which could be exploited for the development of hybrids through heterosis breeding. Medium heritability suggested the involvement of both additive and non-additive gene action, which could be improved through recurrent reciprocal selection whereas, high heritability clearly reflected the role of additive gene action and thus high improvement could be expected from hybridization followed by selection.

The relative contribution of lines, testers and line × tester interactions revealed considerable variation among the expression of related traits (Table 6). The proportional contribution of lines ranged from 5.77 (vitamin B_1) to 62.12 (equatorial diameter). The contribution of testers varied from 0.04 (iron content) to 11.93 (days to harvest). The proportional contribution of line × tester interactions ranged from 33. 76 (equatorial diameter) to 93.83 (vitamin B_1). This signified that contribution of lines was higher than the corresponding testers for all the traits. Further, line × tester interaction was more than the individual contribution of lines and testers for all the traits except equatorial diameter, head shape index and head compactness. Again confirmed that non-additive gene action played a significant role and therefore, heterosis could be better exploited for the development of hybrids in cabbage.

Table 2. Mean performance of hybrids, parents and standard checks for head yield and related traits in cabbage.

Hybrids/Parents/Standard checks/Traits	Days to harvest	Plant spread (cm)	Stalk length (cm)	Number of non-wrapper leaves	Gross weight (g)	Net head weight (g)	Polar diameter (cm)	Equatorial diameter (cm)	Head shape index	Head compactness (g/cm^3)	Marketable head yield (kg/plot)	Ascorbic acid (mg/100g)	Total soluble solids (^{0}B)	Carotenoid content (µg/100 g	Iron content (mg/100g	Dry matter (%)	Vitamin B_1 content (µg/100g)
I-105-CMS× SC 2008-09	100.37	34.04	3.10	12.60	1047.00	669.67	12.61	11.32	1.11	39.11	6.25	11.3	7.36	828.43	0.87	8.37	45.26
I-105-CMS× E-1-3-1&2	109.81	36.59	3.46	11.17	749.34	556.34	12.71	12.18	1.04	28.90	5.75	14.04	7.49	823.14	1.01	8.64	45.13
I-S-CMS × SC 2008-09	86.63	27.47	2.98	9.24	735.67	545.00	11.30	11.82	0.95	35.31	5.26	10.11	5.31	628.09	0.75	7.97	32.91
I-S-CMS× E-1-3-1&2	108.62	33.72	2.77	10.10	995.34	639.34	11.68	12.52	0.94	36.39	6.4	8.05	5.44	729.00	0.79	7.27	33.45
I-M-CMS × SC 2008-09	102.78	37.79	3.41	11.15	1011.00	653.00	11.30	11.64	0.97	43.34	7.19	11.69	7.00	737.67	0.89	8.95	40.15
I-M-CMS × E-1-3-1&2	110.16	37.06	3.75	9.97	1006.67	612.34	11.38	11.78	0.96	39.43	6.33	16.23	6.61	733.59	0.87	8.54	45.27
II-105-CMS × SC 2008-09	86.55	26.63	2.95	10.41	1202.67	738.34	12.91	13.60	0.93	31.71	7.88	19.89	7.77	690.91	0.88	8.63	51.71
II-105-CMS × E-1-3-1&2	104.91	36.62	3.80	13.17	1030.34	749.67	11.91	11.80	1.01	45.03	8.00	21.29	7.90	664.92	0.83	8.51	49.38
II-S-CMS × SC 2008-09	91.76	31.53	4.04	8.14	1339.34	855.00	13.67	13.83	0.98	32.91	8.56	10.59	5.92	700.85	0.81	7.88	41.60
II-S-CMS × E-1-3-1&2	109.02	35.55	2.16	10.78	890.00	501.34	11.30	10.73	1.05	37.71	5.02	10.95	5.35	686.14	0.80	8.29	40.86
II-M-CMS × SC 2008-09	101.36	35.66	3.77	12.33	979.67	628.67	11.55	11.38	1.01	41.74	7.13	18.75	7.38	826.95	0.99	9.21	48.87
II-M-CMS × E-1-3-1&2	102.65	33.11	3.61	12.09	928.00	620.00	11.89	12.21	0.97	35.45	6.41	15.42	7.65	863.08	0.87	8.96	52.69
III-105-CMS × SC 2008-09	101.86	38.47	3.58	11.72	900.34	579.00	12.11	11.30	1.07	36.15	6.18	11.31	8.23	885.64	0.83	7.59	40.38
III-105-CMS × E-1-3-1&2	110.24	37.60	2.37	13.35	1040.67	614.34	11.18	11.29	0.99	43.47	5.94	12.93	7.61	804.66	0.87	8.28	44.75
III-M-CMS × SC 2008-09	94.27	32.01	3.41	10.39	1067.67	676.00	11.86	11.39	1.04	43.09	7.66	11.30	7.23	695.55	0.75	7.93	52.77
III-M-CMS × E-1-3-1&2	103.42	34.20	3.26	11.42	947.00	675.00	12.00	11.61	1.03	41.12	7.20	14.73	7.13	733.13	0.85	8.93	50.16
GI-S-CMS × SC 2008-09	94.09	35.85	3.60	9.70	886.00	591.00	11.08	11.58	0.96	40.64	5.12	9.21	5.83	786.96	0.75	8.15	36.19
GI-S-CMS × E-1-3-1&2	101.07	34.40	3.33	10.47	890.67	653.67	11.32	12.39	0.91	39.31	6.97	11.05	5.87	835.74	0.73	8.55	35.51
GI-M-CMS × SC 2008-09	99.12	38.55	3.89	12.15	1255.34	751.67	12.29	12.36	0.99	40.19	7.77	11.87	6.55	684.25	0.80	8.36	38.29
GI-M-CMS × E-1-3-1&2	103.45	34.41	3.43	10.39	1094.00	727.67	12.44	11.71	1.06	41.37	7.04	10.59	6.55	663.28	0.80	7.96	40.04
G7-S-CMS × SC 2008-09	115.32	37.45	3.43	12.16	981.34	559.00	10.87	11.39	0.95	40.56	5.59	9.65	7.82	831.28	0.84	8.71	41.06
G7-S-CMS × E-1-3-1&2	99.61	31.94	3.64	11.36	1079.67	643.34	11.61	11.9	0.97	39.66	6.65	9.87	6.87	868.94	0.87	7.60	39.29
G7-M-CMS × SC 2008-09	110.9	37.81	2.50	11.35	983.67	603.00	10.96	11.52	0.95	42.50	6.03	14.75	6.91	888.10	0.76	8.55	48.13
G7-M-CMS × E-1-3-1&2	113.06	35.55	2.80	11.47	846.00	521.00	11.44	10.78	1.06	38.01	5.21	11.94	6.47	900.88	0.73	8.36	48.88
GA(P)-105-CMS× SC 2008-09	102.97	31.97	3.57	12.84	951.00	601.34	11.35	12.81	0.89	34.18	6.62	11.91	8.12	802.67	1.04	8.81	54.76
GA(P)-105-CMS× E-1-3-1&2	106.09	33.97	3.97	10.44	961.00	556.34	11.83	10.89	1.08	38.02	6.12	12.40	7.47	843.66	0.91	8.35	49.92
GA(P)-S-CMS × SC 2008-09	106.41	40.97	3.27	10.43	979.67	591.67	12.19	13.07	0.93	29.40	5.13	15.53	6.83	731.87	0.86	8.55	35.55
GA(P)-S-CMS × E-1-3-1&2	94.91	36.24	3.41	11.04	1129.67	750.34	12.76	12.18	1.04	38.69	7.51	13.34	7.34	684.35	0.87	8.34	40.72
GA(P)-M-CMS × SC 2008-09	115.47	35.15	2.52	11.94	844.00	521.67	11.07	11.29	0.98	37.37	5.39	12.02	7.67	899.18	0.90	8.94	47.79
GA(P)-M-CMS × E-1-3-1&2	110.92	39.38	2.70	11.31	902.34	535.67	11.26	11.85	0.95	34.77	5.36	15.29	6.91	925.70	0.89	8.85	50.82
I-105-CMS	103.93	34.13	2.8	11.25	993.00	541.67	12.92	12.56	1.03	26.21	5.06	10.74	7.00	783.98	0.78	7.55	39.41
I-S-CMS	102.99	34.82	2.59	11.04	933.00	488.34	12.26	11.28	1.09	30.00	5.07	8.09	5.48	666.09	0.74	7.50	30.99
I-M-CMS	106.42	36.53	2.64	11.91	981.34	468.00	11.26	11.04	1.02	33.78	4.84	11.05	6.94	694.36	0.75	8.12	34.14
II-105-CMS	92.99	36.38	3.46	10.28	958.00	646.00	11.88	12.96	0.92	33.78	6.25	14.93	7.19	651.53	0.81	8.30	39.43
II-S-CMS	105.47	39.90	3.01	10.27	849.67	393.00	11.28	11.52	0.98	26.57	3.28	10.47	6.39	699.63	0.78	7.61	37.30
II-M-CMS	105.20	37.90	2.73	11.21	885.34	546.00	11.15	11.18	1.00	39.28	5.83	13.07	6.05	757.16	0.81	8.01	40.49
III-105-CMS	111.83	39.27	2.95	11.20	830.00	532.67	11.90	11.58	1.04	32.93	5.68	11.08	6.21	819.48	0.79	8.12	38.55
III-M-CMS	99.55	33.54	3.00	10.79	839.00	526.67	12.96	12.98	1.00	24.15	5.27	11.51	5.90	704.78	0.80	8.36	40.48
GI-S-CMS	98.08	38.62	3.19	10.11	850.34	479.67	11.28	11.31	1.00	33.33	4.48	10.30	6.04	744.21	0.81	7.94	34.09
GI-M-CMS	113.16	35.44	3.14	10.94	829.34	551.34	11.59	11.75	1.01	34.73	4.60	10.70	5.66	717.29	0.76	8.10	35.07
G7-S-CMS	118.23	34.09	2.61	11.38	758.00	378.34	10.37	9.94	1.05	36.18	3.28	10.49	5.94	853.40	0.80	7.95	38.26
G7-M-CMS	117.28	39.84	2.99	11.68	764.34	399.00	11.73	10.84	1.08	27.82	3.73	11.98	6.10	845.56	0.80	8.24	39.46
GA(P)-105-CMS	109.33	35.33	2.54	10.83	807.67	481.34	12.29	11.6	1.06	28.28	4.66	12.11	6.64	834.01	0.82	8.75	41.26
GA(P)-S-CMS	111.44	32.29	2.38	9.79	883.67	497.67	12.57	12.16	1.04	26.35	4.65	11.09	5.65	760.42	0.82	8.21	38.13
GA(P)-M-CMS	111.99	34.76	2.71	11.39	853.67	428.34	10.81	10.81	1.00	34.04	4.14	11.09	7.27	786.58	0.79	8.38	41.12
SC 2008-09	114.22	34.52	2.08	11.05	544.34	266.00	10.16	9.88	1.03	26.50	2.57	8.87	6.47	786.46	0.82	8.85	38.19
E-1-3-1&2	116.14	30.63	2.06	10.88	570.67	356.67	10.59	9.99	1.06	33.29	3.33	10.05	5.76	781.08	0.79	8.54	43.11
Varun	112.93	34.45	2.28	11.56	882.34	499.34	10.97	11.13	0.99	37.05	5.33	12.47	7.31	890.60	0.85	8.34	49.05
KGMR-1	111.84	38.11	2.34	11.45	955	620.34	12.58	11.9	1.05	34.21	6.83	14.18	6.45	854.27	0.87	8.68	48.74
CD (5%)	3.64	3.75	0.83	2.21	18.97	15.41	0.55	0.53	0.09	1.99	1.13	2.61	0.81	17.93	0.05	0.24	3.36

Table 3. Analysis of variance of combining ability for head yield and related traits in cabbage.

Source of variation	Replication	Parent	Hybrid	Parent vs hybrid	Line	Tester	Line × Tester	Error
Traits df	**2**	**16**	**29**	**1**	**14**	**1**	**14**	**92**
Days to harvest	36.87	152.24*	176.07*	459.50*	141.19*	5.52	159.96*	22.78
Plant spread (cm)	0.24	21.06*	30.56*	16.31*	17.50*	22.69*	28.70*	2.36
Stalk length (cm)	0.16	0.42*	0.73*	8.97*	0.25*	0.08	0.70*	0.11
Number of non-wrapper leaves	6.14	0.94	4.13*	1.68	1.08	0.04	3.54*	0.83
Gross weight (g)	1072.47	45501.52*	52720.40*	804910.89*	15527.16*	1040.16*	50892.11*	55.68
Net head weight (g)	180.65	24849.95*	20953.41*	846190.27*	15375.75*	12330.66*	20656.12*	35.94
Polar diameter (cm)	0.07	2.13*	1.34*	1.38*	1.70*	0.28*	0.98*	0.05
Equatorial diameter (cm)	0.05	2.69*	1.67*	8.02*	2.06*	0.01	2.16*	0.04
Head shape index	0.01	0.05*	0.09*	0.02*	0.05*	0.01	0.09*	0.01
Head compactness (g/ cm^3)	3.23	55.95*	49.86*	1674.57*	58.40*	69.15*	58.34*	0.54
Marketable heads per plot	0.34	1.49*	1.27*	13.90*	1.68*	0.16	1.11	0.59
Heading (%)	24.15	103.48*	88.30*	965.28*	117.28*	11.56	77.46	41.22
Marketable head yield per plot (kg)	0.04	3.07*	2.91*	122.88*	2.27*	0.85	2.89*	0.21
Ascorbic acid (mg/100 g)	2.73	6.98*	29.73*	117.22*	6.62*	2.07	9.01*	1.17
Total soluble solids (0B)	1.06	0.94*	2.03*	14.97	1.01*	0.75*	0.28*	0.11
Carotenoid content (µg/ 100 g)	19.84	11454.23*	22191.51*	14746.05*	12764.85*	43.41	3010.17*	53.20
Iron content (mg/ 100 g)	0.01	0.02*	0.01*	0.10*	0.02*	0.01	0.08*	0.04
Dry matter (%)	0.03	0.43*	0.62*	2.06*	0.33*	0.14*	0.44*	0.09
Vitamin B_1 content (µg/100 g)	2.13	28.71*	117.11*	1122.49*	27.31*	36.40*	14.01*	1.89

*Significant at p≤0.05

Table 4. Estimates of general combining ability (GCA) effects of parents for head yield and related traits in cabbage.

Lines	Days to harvest	Plant spread	Stalk length	Gross weight	Net head weight	Polar diameter	Equatorial diameter	Head shape index	Head compactness	Marketable heads per plot	Heading per centage	Marketable head yield	Ascorbic acid	TSS	Carotenoid content	Iron content	Dry matter	Vitamin B_1
I-105-CMS	1.83	0.26	-0.07	-90.33*	-17.67*	0.86*	-0.12	0.08*	-4.17*	-0.38	-3.23	-0.45*	-0.26	0.47*	46.49*	0.09*	0.10*	1.11
I-S-CMS	-5.63*	-4.46*	-0.40*	-123.00*	-38.51*	-0.30*	0.30*	-0.04*	-2.33*	-0.38	-3.23	-0.62*	-3.85*	-1.57*	-100.73*	-0.07*	-0.77*	-10.89*
I-M-CMS	3.20	2.36*	0.29*	20.33*	1.98	-0.45*	-0.15	-0.02	3.20*	0.44	3.70	0.30	1.02*	-0.14	-43.65*	0.03*	0.34*	-1.37*
II-105-CMS	-7.53*	-3.43*	0.09	128.00*	113.32*	0.61*	0.83*	-0.02	0.18	0.44	3.70	1.48*	7.65*	0.88*	-101.37*	0.01	0.17*	6.46*
II-S-CMS	-2.87	-1.51*	-0.18	126.16*	47.48*	0.68*	0.41*	0.02	-2.87*	-0.22	-1.85	0.33	-2.16*	-1.31*	-85.78*	-0.04*	-0.31*	-2.84*
II-M-CMS	-1.25	-0.67	0.40*	-34.66*	-6.34*	-0.07	-0.07	0.00	0.40	0.61	5.09	0.31	4.15*	0.56*	65.72*	0.08*	0.68*	6.70*
III-105-CMS	2.79	2.97*	-0.30*	-18.00*	-34.01*	-0.15	-0.57*	0.03*	1.62*	-0.05	-0.46	-0.39*	-0.81	0.96*	65.86*	0.03	-0.46*	-1.51*
III-M-CMS	-4.41*	-1.95*	0.05	18.83*	44.82*	0.13	-0.37*	0.04*	3.91*	0.77*	6.48*	0.97*	0.08	0.23	-64.95*	0.04*	0.02	7.39*
GI-S-CMS	-5.67*	0.07	0.18	-100.16*	-8.34*	-0.59*	0.11	-0.05*	1.79*	-0.55	-4.62	-0.40*	-2.80*	-1.10*	32.06*	-0.10*	-0.05	-8.22*
GI-M-CMS	-1.97	1.42*	0.37*	186.16*	108.98*	0.57*	0.16	0.03*	2.59*	-0.22	-1.85	0.94*	-1.70*	-0.40*	-105.52*	-0.04*	-0.24*	-4.91*
G7-S-CMS	4.20*	-0.36	0.25	42.00*	-29.51*	-0.55*	-0.22*	-0.03	1.92*	-0.05	-0.46	-0.33	-3.17*	0.39*	70.82*	0.06	-0.24*	-3.90*
G7-M-CMS	8.71*	1.62	-0.63*	-73.66*	-68.67*	-0.59*	-0.72*	0.01	2.07*	-0.22	-1.85	0.83*	0.41	-0.26	115.19*	-0.10*	0.05	4.43*
GA(P)-105-CMS	1.27	-2.08*	0.49*	-32.50*	-51.84*	-0.20*	-0.02	-0.08	-2.08*	0.77*	6.48*	-0.08	-0.78	0.84*	43.87*	0.12*	0.18*	8.26*
GA(P)-S-CMS	-2.59	3.54*	0.05	66.16*	40.32*	0.68*	0.75*	-0.07	-4.13*	-0.88*	-7.40*	-0.13	1.50*	0.13	-71.17*	0.01*	0.04	-5.94*
GA(P)-M-CMS	9.93*	2.20*	-0.67*	-115.33*	-102.01*	-0.62*	-0.30*	-0.03	-2.11*	-0.05	-0.46	-1.07*	0.72	0.33*	133.15*	0.04*	0.49*	5.23*
SE (gi) ±	1.94	0.62	0.13	3.04	2.44	0.09	0.08	0.01	0.30	0.31	2.62	0.19	0.44	0.13	2.97	0.09	0.04	0.56
SE (gi-gi) ± CD	2.75	0.88	0.19	4.30	3.46	0.13	0.12	0.04	0.42	0.44	3.70	0.26	0.62	0.19	4.21	0.01	0.05	0.79
(5%)	5.51	1.77	0.38	8.62	6.92	0.26	0.25	0.04	0.85	0.89	7.42	0.53	1.25	0.38	8.42	0.02	0.11	1.59
Testers																		
SC 2008-09	-	-0.30*	-	22.45*	6.92*	0.01*	-	-	-0.30*	-	-	-	-	0.10*	-	-	0.03*	-0.38*
E-1-3-1&2	-	0.30*	-	-22.45*	-6.92*	-0.01*	-	-	0.30*	-	-	-	-	-0.10*	-	-	-0.03*	0.38*
SE (gi) ±	-	0.22	-	1.11	0.89	0.03	-	-	0.10	-	-	-	-	0.04	-	-	0.01	0.20
SE (gi-gi) ±	-	0.32	-	1.57	1.26	0.04	-	-	0.15	-	-	-	-	0.07	-	-	0.02	0.29
CD (5%)	-	0.64	-	3.14	2.53	0.09	-	-	0.31	-	-	-	-	0.14	-	-	0.04	0.58

*Significant at p≤0.05

Table 5. Estimates of specific combining ability (SCA) effects of different cross-combinations for head yield and related traits in cabbage.

Cr posses	Days to harvest	Plant spread	Stalk length	Number of non-wrapper leaves	Gross weight	Net head weight	Polar diameter	Equatorial diameter	Head compactness
I-105-CMS× SC 2008-09	-2.11	-0.97	-0.23	0.78	126.37*	49.74*	-0.06	-0.58*	5.41*
I-105-CMS× E-1-3-1&2	2.11	0.97	0.23	- 0.78	-126.37*	-49.74*	0.06	0.58*	-5.41*
I-S-CMS × SC 2008-09	-8.39*	-2.82*	0.05	-0.36	-152.28*	-54.08*	-0.20	-0.49*	-0.23
I-S-CMS× E-1-3-1&2	8.39*	2.82*	-0.05	0.36	152.28*	54.08*	0.20	0.49*	0.23
I-M-CMS × SC 2008-09	-1.08	0.66	-0.22	0.65	-20.28*	13.41*	-0.05	-0.21	2.25*
I-M-CMS × E-1-3-1&2	1.08	-0.66	0.22	-0.65	20.28*	-13.41*	0.05	0.21	-2.25*
II-105-CMS × SC 2008-09	-6.57*	-4.69*	-0.47*	-1.31*	63.71*	12.58*	0.48*	0.75*	-6.35*
II-105-CMS × E-1-3-1&2	6.57*	4.69*	0.47*	1.31*	-63.71*	-12.58*	-0.48*	-0.75*	6.35*
II-S-CMS × SC 2008-09	-6.02*	-1.71	0.89*	-1.25*	202.21*	169.91*	1.16*	1.40*	-2.09*
II-S-CMS × E-1-3-1&2	6.02*	1.71	-0.89*	1.25*	-202.21*	-169.91*	-1.16*	-1.40*	2.09*
II-M-CMS × SC 2008-09	1.95	1.57	0.03	0.18	3.37	-2.58	-0.18	-0.56*	3.44*
II-M-CMS × E-1-3-1&2	-1.95	-1.57	-0.03	-0.18	-3.37	2.58	0.18	0.56*	-3.44*
III-105-CMS × SC 2008-09	-1.58	0.73	0.55*	-0.74	-92.62*	-24.58*	0.45*	-0.14	-3.35*
III-105-CMS × E-1-3-1&2	1.58	-0.73	-0.55*	0.74	92.62*	24.58*	-0.45*	0.14	3.35*
III-M-CMS × SC 2008-09	-1.97	-0.79	0.02	-0.45	37.87*	-6.42	-0.08	-0.25*	1.28*
III-M-CMS × E-1-3-1&2	1.97	0.79	-0.02	0.45	-37.87*	6.42	0.08	0.25*	-1.28*
GI-S-CMS × SC 2008-09	-0.88	1.02	0.08	-0.31	-24.78*	38.25*	-0.13	-0.55*	0.96*
GI-S-CMS × E-1-3-1&2	0.88	-1.02	-0.08	0.31	24.78*	-38.25*	0.13	0.55*	-0.96*
GI-M-CMS × SC 2008-09	0.44	2.37*	0.18	0.94	58.21*	5.07	-0.08	0.17	-0.28
GI-M-CMS × E-1-3-1&2	-0.44	-2.37*	-0.18	-0.94	-58.21*	-5.07	0.08	- 0.17	0.28
G7-S-CMS × SC 2008-09	10.45*	3.05*	-0.15	0.46	-71.62*	-49.08*	-0.38*	-0.40*	0.75
G7-S-CMS × E-1-3-1&2	-10. 45*	-3.05*	0.15	-0.46	71.62*	49.08*	0.38*	0.40*	-0.75
G7-M-CMS × SC 2008-09	1.52	1.42	-0.20	0.05	46.37*	34.07*	-0.25	0.21	2.54*
G7-M-CMS × E-1-3-1&2	-1.52	-1.42	0.20	-0.05	-46.37*	-34.07*	0.25	-0.21	-2.54*
GA(P)-105-CMS× SC 2008-09	1.04	-0.69	-0.25	1.26*	-27.45*	15.57*	-0.25	0.81*	-1.61*
GA(P)-105-CMS× E-1-3-1&2	-1.04	0.69	0.25	-1.26*	27.45*	-15.57*	0.25	-0.81*	1.61*
GA(P)-S-CMS × SC 2008-09	8.34*	2.66*	-0.12	-0.23	-97.45*	-86.25*	-0.30*	0.29*	-4.34*
GA(P)-S-CMS × E-1-3-1&2	-8.34*	-2.66*	0.12	0.23	97.45*	86.25*	0.30*	-0.29*	4.34*
GA(P)-M-CMS × SC 2008-09	4.87	-1.81*	-0.14	0.38	-51.62*	13.92*	-0.10	-0.43*	1.60*
GA(P)-M-CMS × E-1-3-1&2	-4.87	1.81*	0.14	-0.38	51.62*	-13.92*	0.10	0.43*	-1.60*
SE (Sij)±	2.75	0.88	0.19	0.52	4.30	3.46	0.13	0.12	0.42
SE (Sij-Skl) ±	3.89	1.25	0.27	0.74	6.09	4.89	0.18	0.17	0.60
SE (Sij-Sik) ±	11.02	3.55	0.77	2.10	17.23	13.84	0.52	0.50	1.69
CD (5%)$_{Sij}$	5.51	1.77	0.38	1.05	8.62	6.92	0.26	0.25	0.85
CD (5%)$_{Sij-Skl}$	7.80	2.51	0.54	1.49	12.19	9.79	0.37	0.35	1.20
CD (5%)$_{Sij-Sik}$	22.06	7.10	1.55	4.22	34.49	27.71	1.04	1.07	3.40

Table 5. (Cont'd.).

Cr posses	Days to harvest	Plant spread	Stalk length	Number of non-wrapper leaves	Gross weight	Net head weight	Polar diameter	Equatorial diameter	Head compactness
I-105-CMS × SC 2008-09	0.19	0.04*	-0.47	-3.98	-1.09	7.37	-0.070*	-0.177*	0.44
I-105-CMS × E-1-3-1&2	-0.19	-0.04*	0.47	3.98	1.09	-7.37	0.070*	0.177*	-0.44
I-S-CMS × SC 2008-09	-0.63*	0.02	-0.14	-1.20	1.30*	-45.72*	-0.020	0.313*	0.11
I-S-CMS× E-1-3-1&2	0.63*	-0.02	0.14	1.20	-1.30*	45.72*	0.020	-0.313*	-0.11
I-M-CMS × SC 2008-09	0.36	0.01	0.35	2.96	-1.99*	6.76	0.01	0.16*	-2.17*
I-M-CMS × E-1-3-1&2	-0.36	-0.01	-0.35	-2.96	1.99*	-6.76	-0.01	-0.16*	2.17*
II-105-CMS × SC 2008-09	-0.12	-0.02	0.02	0.18	-0.42	17.72*	0.02	0.02	1.54
II-105-CMS × -1-3-1&2	0.12	0.02	-0.02	-0.18	0.42	-17.72*	-0.02	-0.02	-1.54
II-S-CMS × SC 2008-09	1.70*	-0.02	0.02	0.18	0.09	12.08*	0.05	-0.24*	0.75
II-S-CMS × E-1-3-1&2	-1.70*	0.02	-0.02	-0.18	-0.09	-12.08*	-0.05	0.24*	-0.75
II-M-CMS × SC 2008-09	0.29	0.03	0.52	4.35	1.94*	-13.34*	0.05*	0.08	-1.52
II-M-CMS × E-1-3-1&2	-0.29	-0.03	-0.52	-4.35	-1.94*	13.34*	-0.05*	-0.08	1.52
III-105-CMS × SC 2008-09	0.05	0.05*	0.52	4.35	-0.53	45.21*	-0.01	-0.38*	-1.80*
III-105-CMS × E-1-3-1&2	-0.05	-0.05*	-0.52	-4.35	0.53	-45.21*	0.01	0.38*	1.80*
III-M-CMS × SC 2008-09	0.16	0.01	0.35	2.96	-1.44*	-14.06*	-0.05*	-0.53*	1.68*
III-M-CMS × E-1-3-1&2	-0.16	-0.01	-0.35	-2.96	1.44*	14.06*	0.05*	0.53*	-1.68*
GI-S-CMS × SC 2008-09	-0.98*	0.03	-0.97*	-8.14*	-0.64	-19.66*	0.01	-0.23*	0.72
GI-S-CMS × E-1-3-1&2	0.98*	-0.03	0.97*	8.14*	0.64	19.66*	-0.01	0.23*	-0.72
GI-M-CMS × SC 2008-09	0.30	-0.022	0.35	2.96	0.91	15.20*	0.02	0.16*	-0.49
GI-M-CMS × E-1-3-1&2	-0.30	0.02	-0.35	-2.96	-0.91	-15.20*	-0.02	-0.16*	0.49
G7-S-CMS × SC 2008-09	-0.59*	0.00	-0.14	-1.20	0.16	-14.10*	-0.01	0.51*	1.26
G7-S-CMS × E-1-3-1&2	0.59*	0.00	0.14	1.20	-0.16	14.10*	0.01	-0.51*	-1.26
G7-M-CMS × SC 2008-09	0.35	-0.04	0.02	0.18	1.67*	-1.66	0.02	0.05	0.08
G7-M-CMS × E-1-3-1&2	-0.35	0.04	-0.02	-0.18	-1.67*	1.66	-0.02	-0.05	-0.08
GA(P)-105-CMS× SC 2008-09	0.18	-0.08*	0.02	0.18	0.02	-15.76*	0.06*	0.19*	2.80*
GA(P)-105-CMS× E-1-3-1&2	-0.18	0.08*	-0.02	-0.18	-0.02	15.76*	-0.06*	-0.19*	-2.80*
GA(P)-S-CMS × SC 2008-09	-1.24*	-0.04	-0.64	-5.37	1.37*	28.48*	-0.01	0.07	-2.20*
GA(P)-S-CMS × E-1-3-1&2	1.24*	0.04	0.64	5.37	-1.37*	-28.48*	0.01	-0.07	2.20*
GA(P)-M-CMS × SC 2008-09	-0.04	0.02	0.18	1.57	-1.35*	-8.52*	0.00	0.03	1.13
GA(P)-M-CMS × E-1-3-1&2	0.04	-0.02	-0.18	-1.57	1.35*	8.52*	0.00	-0.03	-1.13
SE (Sij)±	0.26	0.02	0.44	3.70	0.62	4.21	0.01	0.05	0.79
SE (Sij-Skl) ±	0.38	0.03	0.62	5.24	0.88	5.95	0.01	0.08	1.12
SE (Sij-Sik) ±	1.07	0.09	1.77	14.82	2.50	16.84	0.05	0.22	3.18
CD $(5\%)_{Sij}$	0.53	0.04	0.89	7.42	1.25	8.42	0.02	0.11	1.59
CD $(5\%)_{Sij-Skl}$	0.76	0.06	1.25	10.49	1.77	11.92	0.03	0.16	2.25
CD $(5\%)_{Sij-Sik}$	2.15	0.18	3.56	29.68	5.08	33.71	0.10	0.45	6.36

*Significant at $p \leq 0.05$

Table 6. Estimates of genetic parameters for head yield and related traits and proportional contribution of lines, testers and their interactions in cabbage

Traits	σ^2A	σ^2D	$(H/D)^{1/2}$	h^2ns	Contribution (%) due to		
					Lines	Testers	Line x Tester
Days to harvest	28.437	45.726	1.268	34.781	43.859	11.936	44.204
Plant spread (cm)	1.467	8.780	2.447	13.293	45.339	0.915	53.746
Stalk length (cm)	0.032	0.196	2.459	12.182	45.851	1.132	53.016
Number of non-wrapper leaves	0.146	0.903	2.488	10.995	41.365	0.329	58.306
Gross weight (g)	3935.064	16945.470	2.075	18.829	46.601	2.968	50.430
Net weight (g)	1046.275	6873.391	2.563	13.191	47.590	0.709	51.699
Polar diameter (cm)	0.067	0.312	2.155	16.957	35.438	0.049	64.512
Equatorial diameter (cm)	0.121	0.704	2.415	14.365	62.125	4.110	33.764
Head shape index	0.001	0.003	1.910	18.637	48.503	4.526	46.969
Head compactness (g/ cm^3)	2.023	19.267	3.086	9.422	56.481	0.574	42.944
Marketable heads per plot	0.015	0.174	3.451	3.779	42.349	0.120	57.530
Heading (%)	1.015	12.081	3.450	3.782	42.348	0.121	57.531
Marketable head yield per plot (kg)	0.119	0.892	2.742	10.449	47.937	0.405	51.657
Ascorbic acid content (mg/100 g)	2.217	2.612	1.085	42.474	14.628	0.788	84.583
Total soluble solids (^{0}Brix)	0.18	0.06	0.55	66.20	6.687	1.792	91.521
Carotenoid content (μg/ 100 g)	1753.70	985.65	0.75	63.60	6.548	0.313	93.139
Iron content (mg/ 100 g)	0.01	0.02	1.43	31.33	20.088	0.041	79.871
Dry matter (%)	0.04	0.15	1.98	19.96	34.658	0.737	64.604
Vitamin B_1 content (μg/100 g)	9.29	4.03	0.66	66.54	5.777	0.385	93.838

*Significant at $p\leq0.05$

σ^2A = Additive variance, σ^2D = Dominance variance, $(H/D)^{1/2}$ = Degree of dominance, h^2ns= Narrow sense heritability; high (> 50), medium (30-50) and low (< 30)

A high and significant heterosis over better parent (BP) and Standard checks Varun (SC_1) and KGMR-I (SC_2) in both positive and negative directions were estimated for all the traits (Table 7) except marketable heads per plot and heading percentage. In the present study, 19, 25 and 23 hybrids for days to harvest and 4, 3 and 6 hybrids for plant spread recorded significant, desirable negative estimates over BP, SC_1 and SC_2, respectively. Two hybrids II-S-CMS×SC 2008-09 (-20.74%) and I-S-CMS×SC 2008-09 (-16.28%) over BP and three crosses II-S-CMS×SC 2008-09 (-29.54% and -28.89%), I-S-CMS×SC 2008-09 (-20.05% and -19.31%) and GI-S-CMS×SC 2008-09 (-16.10% and -15.32%) each over SC_1 and SC_2 showed significant desirable negative heterosis for number of non-wrapper leaves. For stalk length, none of the hybrids exhibited significant negative heterosis. The number of heterotic hybrids in the positive direction over BP, SC_1 and SC_2 for gross weight and net head weight were 27, 23, 17 and 30, 29 and 12, respectively. Among the 30 hybrids, 9,20,1 and 16, 19, 7 cross combinations showed heterosis in the desirable positive direction over BP, SC_1 and SC_2 for polar and equatorial diameters, respectively. Hybrid combinations for head shape index (1, 4, 0), head compactness (26, 16, 23) and marketable head yield (23, 19, 5) exhibited significant positive estimates of heterobeltiosis and standard heterosis. The most outstanding cross combinations for quality traits viz., ascorbic acid (12, 9, 4); TSS (14, 3 14); carotenoids (11, 1, 6); iron content (14, 7, 4); dry matter (4, 15, 6) and vitamin B_1 (15, 4, 4) exhibited significant positive estimates of heterosis over BP, SC_1 and SC_2, respectively. Significant heterosis for different traits in cabbage had also been reported earlier by Parkash & Verma (2004), Singh *et al.*, (2009b), Parkash *et al.*, (2015), Kibar *et al.*, (2015), Raygade (2015) and Parkash *et al.*, (2017). Therefore, heterosis studies revealed that the hybrids II-S-CMS × SC 2008-09, II-105-CMS × E-1-3-1&2 and II-105-CMS × SC 2008-09 had significantly higher heterotic values for marketable head yield and most of the other horticultural traits. Hence, heterosis breeding can be utilized in enhancing yield and quality in cabbage for commercial exploitation.

Conclusion

The presence of sufficient and significant variation among parents and hybrids for head yield and other traits signified the possibility of developing quality rich and high yielding hybrids in cabbage through heterosis breeding. From the present study, we concluded that parental lines II-105-CMS, III-M-CMS and SC 2008-09 were good general combiners for most of the quantitative and qualitative traits studied. Due to the presence of high magnitude of dominance variance indicated that non-additive gene action governed most of the traits in cabbage. Based on the mean performance, SCA effects and heterosis, three hybrid combinations viz., II-S-CMS × SC 2008-09, II-105-CMS × E-1-3-1&2 and II-105-CMS × SC 2008-09, were most promising for majority of the traits under study.

Table 7. Estimation of heterosis (%) over better parent (BP) and standard checks (SC_1 and SC_2) for head yield and related traits in cabbage.

Hybrids	Days to harvest			Quantitative traits						Number of non	wrapper leaves	
				Plant spread			Stalk length					
	BP	SC_1	SC_2	BP	SC_1	SC_2	BP	SC_1	SC_2	BP	SC_1	SC_2
I-105-CMS× SC 2008-09	-3.43*	-11.12*	-10.26*	-0.26	-1.17	-10.68*	48.96 *	36.07*	32.38*	14.03*	9.06	10.08
I-105-CMS× E-1-3-1&2	5.65*	-2.77*	-1.82*	19.47 *	6.22	-4.00	68.18 *	51.91*	47.79*	2.63	-3.35	-2.45
I-S-CMS × SC 2008-09	-15.89 *	-23.29*	-22.55*	-20.43 *	-20.27*	-27.94*	43.18 *	30.79*	27.25*	-16.28*	-20.05*	-19.31*
I-S-CMS× E-1-3-1&2	5.46*	-3.82*	-2.89*	10.10 *	-2.11	-11.53*	34.90 *	21.85	18.54	-7.17	-12.58	-11.76
I-M-CMS × SC 2008-09	-3.43*	-8.99*	-8.11*	9.48 *	9.71*	-0.85	63.88 *	49.71*	45.65*	0.87	-3.52	-2.62
I-M-CMS × E-1-3-1&2	3.51*	-2.46*	-1.51	21.00 *	7.58*	-2.77	82.31 *	64.66*	60.20*	-8.36	-13.70*	-12.90
II-105-CMS × SC 2008-09	-6.93*	-23.37*	-22.62*	-22.86 *	-22.70*	-30.14*	42.05 *	29.77*	26.25*	1.23	-9.92	-9.09
II-105-CMS × E-1-3-1&2	12.81 *	-7.10*	-6.20*	19.58 *	6.32	-3.91	84.90 *	67.01*	62.48*	28.05*	13.94*	15.00*
II-S-CMS × SC 2008-09	-13.00 *	-18.75*	-17.96*	-8.66 *	-8.48*	-17.28*	94.54 *	77.71*	72.90*	-20.74*	-29.54*	-28.89*
II-S-CMS × E-1-3-1&2	3.37*	-3.47*	-2.52*	16.09 *	3.21	-6.72*	5.03	-5.13	-7.70	4.93	-6.72	-5.85
II-M-CMS × SC 2008-09	-3.65*	-10.25*	-9.37*	3.30	3.51	-6.45	81.54 *	65.84*	61.34*	11.55	6.69	7.69
II-M-CMS × E-1-3-1&2	-2.43*	-9.11*	-8.22*	8.12	-3.87	-13.12*	75.49 *	58.50*	54.21*	11.06	4.59	5.56
III-105-CMS × SC 2008-09	-8.92 *	-9.81*	-8.93*	11.45 *	11.68*	0.94	72.39 *	57.48*	53.21*	6.06	1.44	2.39
III-105-CMS × E-1-3-1&2	-1.42	-2.38*	-1.43	22.76 *	9.15*	-1.36	15.42	4.25	1.43	22.64 *	15.49*	16.57*
III-M-CMS × SC 2008-09	-5.31*	-16.53*	-15.72*	-4.56	-7.07	-16.02*	64.21 *	50.00*	45.93*	-3.71	-10.13	-9.29
III-M-CMS × E-1-3-1&2	3.88*	-8.43*	-7.53*	11.66 *	-0.73	-10.28*	58.77 *	43.40*	39.51*	5.90	-1.15	-0.23
GI-S-CMS × SC 2008-09	-4.06*	-16.69*	-15.87*	3.86	4.07	-5.94	73.35 *	58.36*	54.07*	-4.12	-16.10*	-15.32*
GI-S-CMS × E-1-3-1&2	3.05*	-10.51*	-9.63*	12.33 *	-0.13	-9.73*	62.18 *	46.48*	42.51*	3.49	-9.43	-8.59
GI-M-CMS × SC 2008-09	-12.40 *	-12.23*	-11.37*	11.70 *	11.92*	1.15	87.16 *	70.97*	66.33*	11.03	5.11	6.09
GI-M-CMS × E-1-3-1&2	-8.58 *	-8.40*	-7.51*	12.37 *	-0.10	-9.71*	66.72 *	50.59*	46.50*	-4.53	-10.10	-9.26
G7-S-CMS × SC 2008-09	0.96	2.11*	3.11*	9.88 *	8.73*	-1.73	65.01 *	50.73*	46.65*	9.98	5.19	6.17
G7-S-CMS × E-1-3-1&2	-14.13 *	-11.80*	-10.94*	4.29	-7.28	-16.20*	77.27 *	60.12*	55.78*	4.38	-1.70	-0.79
G7-M-CMS × SC 2008-09	-2.90*	-1.80	-0.84	9.53 *	9.76*	-0.80	20.39	9.97	6.99	2.65	-1.82	-0.90
G7-M-CMS × E-1-3-1&2	-2.65*	0.11	1.08	16.09 *	3.21	-6.72*	36.20 *	23.02	19.69	5.39	-0.75	0.17
GA(P)-105-CMS× SC 2008-09	-5.82*	-8.82*	-7.93*	-7.37 *	-7.18	-16.11*	71.91 *	57.04*	52.78*	18.53 *	11.08	12.11
GA(P)-105-CMS× E-1-3-1&2	-2.96*	-6.06*	-5.14*	10.92 *	-1.38	-10.87*	93.34 *	74.63*	69.90*	-3.57	-9.64	-8.79
GA(P)-S-CMS × SC 2008-09	-4.52*	-5.78*	-4.86*	26.88 *	18.94*	7.50*	57.14 *	43.55*	39.66*	6.54	-9.72	-8.88
GA(P)-S-CMS × E-1-3-1&2	-14.83 *	-15.96*	-15.14*	18.32 *	5.20	-4.92	66.07 *	50.00*	45.93*	12.77	-4.44	-3.55
GA(P)-M-CMS × SC 2008-09	3.10*	2.25*	3.24 *	1.83	2.03	-7.78*	21.03	10.56	7.56	8.05	3.35	4.31
GA(P)-M-CMS × E-1-3-1&2	-0.96	-1.78	-0.83	28.58 *	14.32*	3.32	31.49 *	18.77	15.55	3.92	-2.14	-1.22
I-105-CMS× SC 2008-09	5.44*	18.66*	9.63*	23.63*	34.11*	7.95*	-2.37	14.95*	0.27	-9.90*	1.68	-4.90*
I-105-CMS× E-1-3-1&2	-24.54*	-15.07*	-21.54*	2.71*	11.42*	-10.32*	-1.65	15.80*	1.01	-3.03*	9.43*	2.35
I-S-CMS × SC 2008-09	-21.15*	-16.62*	-22.97*	11.60*	9.15*	-12.14*	-7.81*	2.98	-10.18*	4.85*	6.20*	-0.67
I-S-CMS× E-1-3-1&2	6.68*	12.81*	4.22*	30.92*	28.04*	3.06*	-4.73*	6.41*	-7.18*	11.06*	12.49*	5.21*
I-M-CMS × SC 2008-09	3.02*	14.58*	5.86*	39.53*	30.77*	5.27*	0.33	2.95	-10.20*	5.43*	4.58	-2.18
I-M-CMS × E-1-3-1&2	2.58*	14.09*	5.41*	30.84*	22.63*	-1.29	1.10	3.74*	-9.51*	6.70*	5.84*	-1.01
II-105-CMS × SC 2008-09	25.54*	36.31*	25.93*	14.29*	47.86*	19.02*	8.73*	17.68*	2.65	4.99*	22.19*	14.29*
II-105-CMS × E-1-3-1&2	7.55*	16.77*	7.89*	16.05*	50.13*	20.85*	0.25	8.51*	-5.35*	-8.90*	6.02*	-0.84
II-S-CMS × SC 2008-09	57.63*	51.79*	40.24*	117.56*	71.23*	37.83*	21.16*	24.55*	8.64*	20.12*	24.26*	16.22*
II-S-CMS × E-1-3-1&2	4.75*	0.87	-6.81*	27.57*	0.40	-19.18*	0.18	2.98	-10.18*	-6.83*	-3.62*	-9.86*
II-M-CMS × SC 2008-09	10.66*	11.03*	2.58*	15.14*	25.90*	1.34	3.56*	5.26*	-8.19*	1.85	2.25	-4.37*
II-M-CMS × E-1-3-1&2	4.82*	5.18*	-2.83*	13.55*	24.17*	-0.05	6.61*	8.36*	-5.49*	9.28*	9.70*	2.61
III-105-CMS × SC 2008-09	8.47*	2.04*	-5.72*	8.70*	15.95*	-6.66*	1.77	10.36*	-3.74*	-2.45	1.50	-5.07*
III-105-CMS × E-1-3-1&2	25.38*	17.94*	8.97*	15.33*	23.03*	-0.97	-6.08*	1.85	-11.16*	-2.53	1.41	-5.15*
III-M-CMS × SC 2008-09	27.25*	21.00*	11.80*	28.35*	35.38*	8.97*	-8.49*	8.08*	-5.72*	- 12.28*	2.31	-4.31*
III-M-CMS × E-1-3-1&2	12.87*	7.33*	-0.84	28.16*	35.18*	8.81*	-7.44*	9.33*	-4.64*	-10.61*	4.25*	-2.49

Table 7. (Cont'd.).

Hybrids	Days to harvest			Quantitative traits						Number of non wrapper leaves		
				Plant spread			Stalk length					
	BP	SC_1	SC_2	BP	SC_1	SC_2	BP	SC_1	SC_2	BP	SC_1	SC_2
GI-S-CMS × SC 2008-09	4.19*	0.42	-7.23*	23.21*	18.36*	-4.73*	-1.77	1.00	-11.90*	2.45	4.04*	-2.69
GI-S-CMS × E-1-3-1&2	4.74*	0.94	-6.74*	36.28*	30.91*	5.37*	0.30	3.13	-10.05*	9.55*	11.26*	4.06*
GI-M-CMS × SC 2008-09	51.37*	42.27*	31.45*	36.34*	50.53*	21.17*	6.07*	12.03*	-2.28	5.19*	10.99*	3.81*
GI-M-CMS × E-1-3-1&2	31.91*	23.99*	14.55*	31.98*	45.73*	17.30*	7.34*	13.37*	-1.11	-0.28	5.21*	-1.60
G7-S-CMS × SC 2008-09	29.46*	11.22*	2.76*	47.75*	11.95*	-9.89*	4.86*	-0.94	-13.60*	14.63*	2.34	-4.06*
G7-S-CMS × E-1-3-1&2	42.44*	22.36*	13.05*	70.04*	28.84*	3.71	9.63*	5.80*	-7.71*	19.09*	6.86*	-0.06
G7-M-CMS × SC 2008-09	28.70*	11.48*	3.00*	5 1.13*	20.76*	-2.79*	-6.51*	-0.09	-12.85*	6.28*	3.44*	-3.25*
G7-M-CMS × E-1-3-1&2	10.68*	-4.12*	-11.41*	30.58*	4.34*	-16.01*	-2.45	4.25*	-9.06*	-0.49	-3.14	-9.41*
GA(P)-105-CMS× SC 2008-09	17.75*	7.78*	-0.42	24.93*	20.43*	-3.06*	-7.65*	3.40*	-9.81*	10.41*	15.03*	7.59*
GA(P)-105-CMS× E-1-3-1&2	18.98*	8.92*	0.63	15.58*	11.42*	-10.32*	-3.74*	7.78*	-5.99*	-6.15*	-2.22	-8.54*
GA(P)-S-CMS × SC 2008-09	10.86*	11.03*	2.58*	18.89*	18.49*	-4.62*	-3.02*	11.09*	-3.10*	7.46*	17.37*	9.78*
GA(P)-S-CMS × E-1-3-1&2	27.84*	28.03*	18.29*	50.77*	50.27*	20.96*	1.54	16.32*	1.46	0.19	9.43*	2.35
GA(P)-M-CMS × SC 2008-09	-1.13	-4.34*	-11.62*	21.79*	4.47*	-15.91*	2.41	0.91	-11.98*	4.38*	1.38	-5.18*
GA(P)-M-CMS × E-1-3-1&2	5.70*	2.27*	-5.51*	25.06*	7.28*	-13.65*	4.13*	2.61	-10.50*	9.59*	6.44*	-0.45
I-105-CMS× SC 2008-09	6.10*	2.76	0.77	-5.50*	0.32	-3.61*	14.84*	-7.73*	-7.15*			
I-105-CMS× E-1-3-1&2	27.43*	18.90*	16.60*	1.21	3.64*	-0.42	4.67	-7.99*	-7.42*			
I-S-CMS × SC 2008-09	-8.54*	-11.42*	-13.13*	-9.94*	-4.40*	-8.14*	-13.82*	-32.90*	-32.49*			
I-S-CMS× E-1-3-1&2	-0.42	-7.09*	-8.88*	-14.88*	-12.83*	-16.25*	-22.42*	-31.80*	-31.38			
I-M-CMS × SC 2008-09	8.13*	4.72*	2.70	1.05	7.28*	3.07*	5.13	-18.15*	-17.64*			
I-M-CMS × E-1-3-1&2	9.28*	1.97	0.00	0.04	2.44*	-1.58	4.99	-7.71*	-7.13*			
II-105-CMS × SC 2008-09	7.32*	3.94	1.93	-2.52*	3.48*	-0.58	31.14*	5.42*	6.08*			
II-105-CMS × E-1-3-1&2	2.90	-2.36	-4.25*	-0.31	2.08*	-1.92*	14.53*	0.67	1.30			
I-S-CMS × SC 2008-09	-1.63	-4.72*	-6.56*	-11.04	-5.56*	-9.26*	8.94*	-15.18*	-14.66*			
II-S-CMS × E-1-3-1&2	0.42	-6.30*	- 8.11*	-2.97*	-0.64	-4.53*	-5.23*	-16.70*	-16.18*			
II-M-CMS × SC 2008-09	20.73*	16.93*	14.67*	3.99*	10.40*	6.07*	20.72*	-0.35	0.27			
II-M-CMS × E-1-3-1&2	8.30*	2.76	0.77	4.92*	7.44*	3.23*	22.22*	7.44*	8.10*			
III-105-CMS × SC 2008-09	1.22	-1.97	-3.86	-14.24*	-8.96*	-12.52*	4.75	-17.66*	-17.15*			
III-105-CMS × E-1-3-1&2	9.28*	1.97	0.00	-3.08*	-0.76	-4.65*	3.79	-8.77*	-8.20*			
III-M-CMS × SC 2008-09	-9.35*	-12.20*	-13.90*	-10.43*	-4.92*	-8.64*	30.37*	7.60*	8.27*			
III-M-CMS × E-1-3-1&2	5.83*	0.00	-1.93	4.53*	7.04*	2.84*	16.35*	2.27	2.91			
GI-S-CMS × SC 2008-09	-8.94*	-11.81*	-13.51*	-7.95*	-2.28*	-6.11*	-5.22	-26.21*	-25.75*			
GI-S-CMS × E-1-3-1&2	-9.96*	-14.57*	-16.22*	0.12	2.52*	-1.50	-17.63*	-27.59*	-27.14*			
GI-M-CMS × SC 2008-09	-2.44	-5.51*	-7.34*	-5.61*	0.20	-3.73*	0.27	-21.93*	-21.45*			
GI-M-CMS × E-1-3-1&2	0.42	-6.30*	-8.11*	-6.79*	-4.56*	-8.30*	-7.12*	-18.36*	-17.85*			
G7-S-CMS × SC 2008-09	1.63	-1.57	-3.47	-1.62	4.44*	0.35	7.31*	-16.28*	-15.76*			
G7-S-CMS × E-1-3-1&2	8.33*	2.36	0.39	-10.97*	-8.84*	-12.41*	-8.88*	-19.90*	-19.40*			
G7-M-CMS × SC 2008-09	-7.72*	-10.63*	-12.36*	-3.43*	2.52*	-1.50	21.99*	-1.86	-1.25			
G7-M-CMS × E-1-3-1&2	-8.37*	-13.78*	-15.44*	-2.07*	0.28	-3.65*	13.38*	-0.34	0.28			
GA(P)-105-CMS× SC 2008-09	26.83*	22.83*	20.46*	-0.45	5.68*	1.54	32.73*	11.65*	12.34*			
GA(P)-105-CMS× E-1-3-1&2	11.07*	6.69*	4.63*	-4.61*	0.12	-3.80*	15.79*	1.78	2.41			
GA(P)-S-CMS × SC 2008-09	4.07	0.79	-1.16	-3.39*	2.56*	-1.46	-6.90*	-27.51*	-27.06*			
GA(P)-S-CMS × E-1-3-1&2	6.53*	2.76	0.77	-2.38*	-0.04	-3.96*	-5.55*	-16.98*	-16.46*			
GA(P)-M-CMS × SC 2008-09	8.94*	5.51*	3.47	0.94	7.16*	2.96*	16.22*	-2.56	-1.96			
GA(P)-M-CMS × E-1-3-1&2	12.66*	5.12*	3.09	3.67*	6.16*	2.00*	17.88*	3.62	4.27			

*Significant at 5% level

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Contribution

A. Jabeen conduct the whole experiment and get the data, S. Chadha supervised the experiment, S.H. Wani produce the idea and write the manuscript, M.S. Zaheer, Y. Niaz and H.F. Alharby write the dissection section and improve the technical language of the paper, S.A. Alghamdi and H.H. Ali review the whole paper and improve English language. A. Alasmari and M.I. Sakran write the results and discussion.

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