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Hybrid performance for yield and yield components in cardamom (*Elettaria cardamom* Maton)

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Abstract Cardamom is an important high value spice crop. Hybrid breeding is discussed for some time, but there is no information for cardamom. Eight genetically diverse cardamom lines were crossed in a diallel to evaluate the performance of hybrids and determine heterosis over mid-parent, better-parent and standard control for yield and yield components. The study was undertaken for a period of 3 years from 1988 to 2001 (Experiment I). Hybrids generally showed good overall performance for most of the characteristics compared with parents. Ten of the 56 hybrids significantly out-yielded the standard control (RR 1). Substantial mid-parent (MPH), better-parent (BPH) and standard (SH) heterosis were observed for the majority of the characteristics studied. Further evaluation of selected hybrids for yield and disease resistance during 2002–2007 (Experiment II) led to the identification of two cross combinations (CCS 1 × NKE 19 and RR 1 × NKE 12) with high yield and mosaic resistance. The study revealed that cardamom hybrids with high yield potential, desirable quality characteristics and mosaic resistance can be developed from appropriate parents through heterosis breeding. This is the first report of heterosis in cardamom for yield and yield contributing characteristics.

Keywords Cardamom · *Elettaria cardamom* · Hybrids · Heterosis · Yield · *Katte* disease

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Introduction

Cardamom (*Elettaria cardamomum* Maton), "Queen of spices" ($2n = 2x = 48$) is an important spice crop and is native of evergreen forests of Western Ghats of South India (Purseglove et al. 1981). In spite of its prominence in world trade from time immemorial, cardamom received attention for genetic upgradation only in the second half of this century. Three major types viz., Malabar, Mysore and Vazhukka are grown in the country. The Vazhukka is more important in terms of area and production. However, the average dry capsule production in India is only 142 kg ha^{-1} (Anonymous 2008). The low productivity is mainly due to low yielding local cultivars, which are susceptible to viral diseases especially mosaic or *katte* disease caused by *Cardamom mosaic virus* (CdMV) widely prevalent in all cardamom growing tracts of India with incidence ranging from 0.01 to 99% (Venugopal 2002).

Earlier studies on improvement of cardamom have mostly relied on selection of variants from open pollinated progenies (Venugopal and Prasath 2003).

Systematic studies on heterosis, a potent method for enhancing yield and disease resistance in cardamom are meagre. Heterosis is a genetic phenomenon resulting from heterozygosity (Kuroda et al. 1998), usually described as superior F_1 hybrid performance, i.e. hybrid vigour in relation to size or rate of growth of offspring over parents (Duvick 1999). Falconer and Mackay (1996) described heterosis as the difference between the hybrid and the mean of the two parents and is often expressed as a percentage of the mid-parent performance. Lamkey and Edwards (1999) suggested that high parent heterosis is the difference between the hybrid and the high parent, while the difference between the hybrid and the standard variety is termed as standard heterosis. From the plant breeding viewpoint, standard heterosis is of practical significance (Young and Virmani 1990). Exploitation of hybrid vigour in any crop depends on substantial heterosis for yield coupled with an economic and easy method of multiplication. Cardamom has the twin advantage of sexual and asexual reproduction, which offers good scope for exploitation of heterosis and multiplication of heterotic crosses through suckers (Padmini et al. 2000). Hence, the present long-term study was undertaken to determine the nature and magnitude of heterosis in order to develop high yielding disease resistant cardamom hybrids.

Materials and methods

Basic experimental materials

Eight diverse genotypes viz., CCS 1, RR 1 and six mosaic resistant lines (NKE 3, NKE 9, NKE 12, NKE 19, NKE 27 and NKE 34) comprised basic experimental materials and were crossed in diallel matting design (all possible combinations) to develop 56 F_1 hybrids. The details of parental lines are given in Table 1. Evaluation of hybrids was undertaken in two experiments (Experiment I and II).

Experiment I

All the 56 hybrids and 8 parents were evaluated in a randomised block design with three replications at Indian Institute of Spices Research, Cardamom Research Centre, Appangala, Karnataka, India (latitude 12°42′N, longitude 77°35′E and altitude 1,000 m amsl) during 1998–2001. Twelve plants were maintained in each plot with 2 × 2 m spacing. Standard package of practises (Venugopal et al. 2006) were followed to raise the crop. The observations were recorded on five quantitative characters viz., plant height (cm), total tiller per plant, bearing tillers per plant, number of panicles per plant and yield per plant (g) during cropping season 2000–2001.

Table 1 Description of parental lines used in the diallel cross

Parents	Yield level	Mosaic resistance
CCS 1 (APG 296)	Moderate	Susceptible
RR 1 (APG 298)	Moderate	Susceptible
NKE 3 (APG 328)	Low	Resistant
NKE 9 (APG 307)	Low	Resistant
NKE 12 (APG 306)	Low	Resistant
NKE 19 (APG 310)	Low	Resistant
NKE 27 (APG 308)	Low	Resistant
NKE 34 (APG 305)	Low	Resistant

Experiment II (performance of selected hybrids)

In the second experiment, ten promising hybrids (from experiment I) along with standard checks were studied during 2002–2007. The experiment was also arranged in a randomised block design (RBD) with three replicates. Twelve plants were maintained in each plot with 2 × 2 m spacing. Recommended package of practises (Venugopal et al. 2006) were followed and observations were recorded during 2004, 2005 and 2006 crop seasons on various yield and yield contributing characters viz., plant height (cm), tillers per plant, panicles per plant, capsules per plant and dry yield (kg/ha).

Screening hybrids against mosaic disease

The clones of hybrids and checks were established in pots under screen house and screening was carried out during 2005–2006. Three clones of each genotype were inoculated with viruliferous aphids (*Pentalonia nigronervosa* f. *caladii*) carrying local severe isolate of mosaic virus. In each microplot, two leaves of actively growing tillers were rolled to make the leaf funnels and aphids were released at 5 per tiller. The inoculants were assessed for symptoms up to

45–50 days and the screening was repeated twice at an interval of 50 days (Venugopal 1999).

Quality evaluation

Dried cardamom capsules (20 g per genotype per replication) of promising hybrids and checks were crushed and the seeds were separated and weighed. The decorticated seeds were subjected to hydro distillation in a Clevenger-type apparatus for 3 h and the volatile oil yield was recorded. The oil was dried over anhydrous sodium sulphate and kept in refrigerator until the analysis was carried out [American Spice Trade Association (ASTA) 1997].

The oil was analysed using a Shimadzu GC-2010 Gas chromatograph equipped with QP 2010 mass spectrometer. RTX—5 column (30 m × 0.25 mm, film thickness 0.25 µm) coated with polyethylene glycol was used. Helium was used as the carrier gas at a flow rate of 1.67 ml/min. The injection port was maintained at 220°C, the detector temperature was 250°C. Oven temperature was programmed as stated above. The split ratio was 1:40 and ionisation voltage was maintained at 70 eV. 0.1 µl sample was injected. The compounds were identified by a combination of retention indices, co-injection of the authentic standards purchased from Fluka chemicals and also by matching the mass spectrum of individual compounds with that of NIST and Wiley library. The concentration of each compound was determined by area normalisation.

Statistical analyses

All statistical analyses were performed using Statistica 5.1 (Statsoft 1997). Heterosis in F_1 hybrids was estimated for each trait based on the criteria using the three mean values as detailed below (Gowen 1952).

Mid-parent heterosis (MPH) i.e. percentage of deviation of the F_1 hybrid from the respective mid-parental value = (F_1 − MP/MP) × 100. Better-parent heterosis (BPH) i.e. percentage of deviation of the F_1 hybrid from the better parent = (F_1 − BP/BP) × 100. Standard heterosis (SH) i.e. percentage of deviation of the F_1 hybrid from the best parent for each trait = (F_1 − SP/SP) × 100, where F_1 = mean value of the F_1 hybrid, MP = mid parental value $(P_1 + P_2)/2$ where, P_1 and P_2 are the mean values of the first and second parent, respectively. BP = mean value of the better of the two parents used in the respective cross combination and SP = mean value of the standard parent.

The standard error values for testing significance of heterosis were calculated as suggested by Snedecor and Cockhran (1967). $SE_{MP} = (3EMS/2r)^{1/2}$ $SE_{HP\ or\ VP} = (2EMS/r)^{1/2}$ where, EMS = error mean square obtained in the combined analysis for parents and the crosses and r = number of replications.

The '*t*' value was worked out as the deviation of F_1 from the mid parent or better parent or the best parent by standard error and tested against the table '*t*' value at error degrees of freedom for 5 and 1% levels of probability.

Results

The analysis of variance for the experiment revealed significant differences due to genotypes (parents and F_1s) for all the five traits viz., plant height, total tillers, panicles, capsules and yield per plant, suggesting the existence of substantial genetic variability. The total variation due to genotypes was divided into three components viz., variation due to parents, F_1s and parents versus F_1s. The parents and hybrids differed significantly among themselves for all the traits.

Evaluation of diallel hybrids

The performance of yield and yield components averaged across 56 hybrids compared with their parents in the first experiment from 1998 to 2001 are summarised in Table 2. The parents used in this experiment differed significantly for all the characters. The parent RR 1 had the highest yield, panicles per plant and total tillers per plant. CCS 1 was the second best for yield per plant and panicles per plant. The maximum plant height and bearing tillers per plant were recorded in CCS 1 and NKE 19, respectively. Hybrids showed superiority over their parents for various characteristics. Yield per plant of crosses ranged from 283.66 to 1186.38 g with an average yield of 604.40 g. Some of the best yielding crosses were RR 1 × NKE 34, CCS 1 × NKE 19, NKE 9 × CCS 1 and NKE 27 × NKE 3. Higher mean capsules per plant was also observed in most of the hybrids, the highest being between RR 1 × NKE 34 and CCS 1 × NKE 19. Although no hybrids showed increase for all the characteristics, there were significant differences between means for all measured characteristics.

The heterosis, measured as departure from the averaged mid-parent, better-parent and standard parent for plant height, tillers, panicles, capsules and yield per plant of 56 F_1s is summarised in Table 2. The highest mid-parent yield heterosis was observed in NKE 9 × NKE 34. Many of the F_1 hybrids also out-yielded the better-parent. Nine of the 56 crosses showed standard heterosis ranging from 5.61 to 37.06% for yield. RR 1 × NKE 34, CCS 1 × NKE 19 and NKE 9 × CCS 1 were among the best hybrids that showed highest significant SH for yield per plant.

For plant height, of the total hybrids, twelve and nine crosses showed significant positive heterosis over mid-parent and better-parent, respectively, and three crosses showed significant positive heterosis over the check. RR 1 × NKE 9, CCS 1 × NKE 9 and CCS 1 × NKE 19 were some of the hybrids that showed higher plant height. However, the crosses CCS 1 × NKE 3, NKE 12 × RR 1 and NKE 19 × RR 1, in general, showed low heterosis for this character. The SH for total tillers ranged from −59.73% for hybrid NKE 34 × NKE 27 to 34.45% for hybrid CCS 1 × NKE 19 with mean performance ranging from 12.00 to 40.07 tiller per plant. Many crosses also showed high MPH, BPH and SH for panicles per plant; the highest SH was recorded in the hybrid NKE 19 × CCS 1. Twenty, twelve and five of the 56 crosses showed significant high percentages of MPH, BPH and SH, respectively, for number of capsules per plant.

Evaluation of short listed hybrids

Of the 56 F_1s produced in the first experiment, ten promising high heterotic cross combinations were used for evaluation of yield performance, *katte* disease incidence and essential oil content as part of the second experiment. The analysis of variance for the experiment revealed significant differences due to genotypes for all the traits studied suggesting the existence of substantial genetic variability. The performance of yield and yield components averaged across 10 hybrids with the five checks in the second experiment from 2002 to 2006 are summarised in Table 3. The plant height of hybrids ranged from 187.20 to 323.10 cm and the difference was significant among genotypes. Maximum tillers and panicles per plant were observed in RR 1 × NKE 12. The cross, CCS 1 × NKE 19 recorded the maximum capsules per plant (3142.7) followed by CCS 1 × NKE 9 (2345.3) and NKE 27 × NKE 3 (2035.0).

The yield (dry) over 3 years varied from 156.65 kg/ha (NKE 19) to 975.51 kg/ha (CCS 1 × NKE 19) and among the checks, highest yield (dry) of 585.70 kg/ha was recorded in IISR Avinash followed by MB 3 (420.15 kg/ha). Among the 10 hybrids, three hybrids viz., CCS 1 × NKE 19, CCS 1 × NKE 9 and RR 1 × NKE 12 out yielded checks over the cumulative yield of three cropping seasons. The hybrid CCS 1 × NKE 19 recorded significantly high yield of 975.51 kg/ha compared to IISR Avinash (585.70 kg/ha).

Discussion

Heterosis for yield and yield components

The commercial exploitation of the phenomenon of heterosis is one of the most important contributions to plant breeding. The extent of heterotic response of the F_1 hybrid largely depends on the breeding values and genetic diversity of the parents included in the crosses (Knobel et al. 1997; Jordaan 1999). Cultivars are known to differ in their ability to combine with others when they are crossed. Therefore, identification of these specific combinations of parents is essential while exploitation of heterosis in agricultural crops (Jordaan 1999).

Large number of hybrids showed superiority over their parents for various characteristics, revealing substantial heterosis in the hybrids. The magnitude of heterosis for different characters varied in different crosses. Some of them manifested significant positive heterosis while others exhibited low positive or negative heterosis, which resulted mainly due to the varying extent of genetic diversity among parents of different crosses for the component characters. Yield per plant was high in the hybrids compared with parental lines. As expected, crosses that involved the moderate yielders as one of their parents in general gave higher panicles, capsules and yield per plant.

Table 2 Mean performance and percentage of heterosis of eight parents and 56 crosses for various characters

Genotype	Plant height (cm)				Total tillers				Panicles per plant			
	Mean	MPH	BPH	SH	Mean	MPH	BPH	SH	Mean	MPH	BPH	SH
NKE 3 (P1)	146.33				19.20				20.00			
NKE 9 (P2)	142.67				23.13				21.67			
NKE 12 (P3)	152.00				24.00				25.33			
NKE 19 (P4)	200.00				29.27				28.33			
NKE 27 (P5)	151.17				28.85				21.33			
NKE 34 (P6)	140.56				22.00				23.33			
RR 1 (P7)	233.00				29.75				31.67			
CCS 1 (P8)	221.67				29.80				31.00			
Parental mean	173.42				25.75				25.33			
Standard error	13.56				1.47				1.60			
P1 × P2	135.67	−6.11	−7.29	−41.77**	19.33	−8.66	−16.43	−35.12**	23.33	12.00	7.69	−26.32**
P1 × P3	154.33	3.46	1.54	−33.76**	29.47	36.42**	22.78*	−1.12	33.33	47.06**	31.58**	5.26
P1 × P4	149.00	−13.96*	−25.50**	−36.05**	22.00	−9.22	−24.83**	−26.17**	19.67	−18.62	−30.59**	−37.89**
P1 × P5	143.42	−3.59	−5.13	−38.45**	20.00	−16.75	−30.68**	−32.89**	22.00	6.45	3.12	−30.53**
P1 × P6	181.00	26.18**	23.69**	−22.32**	26.80	30.10*	21.82	−10.07	19.67	−9.23	−15.71	−37.89**
P1 × P7	167.00	−11.95*	−28.33**	−28.33**	27.67	13.04	−7.00	−7.16	20.00	−22.58*	−36.84**	−36.84**
P1 × P8	188.33	2.36	−15.04**	−19.17**	24.93	1.77	−16.33	−16.33	20.00	−21.57*	−35.48**	−36.84**
P2 × P1	165.67	14.65	13.21	−28.90**	28.53	34.80**	23.34*	−4.25	39.33	88.80**	81.54**	24.21**
P2 × P3	171.67	16.52*	12.94	−26.32**	25.83	9.62	7.64	−13.31	25.33	7.80	0	−20.00*
P2 × P4	225.33	31.52**	12.67*	−3.29	36.93	40.97**	26.20**	23.94**	36.00	44.00**	27.06**	13.68
P2 × P5	186.67	27.06**	23.48**	−19.89**	30.73	18.24	6.53	3.13	26.67	24.03	23.08	−15.79
P2 × P6	216.67	53.00**	51.87**	−7.01	33.07	46.53**	42.94**	10.96	35.00	55.56**	50.00**	10.53
P2 × P7	243.67	29.72**	4.58	4.58	35.13	32.87**	18.10*	17.90	35.00	31.25**	10.53	10.53
P2 × P8	157.00	−13.82*	−29.17**	−32.62**	24.27	−8.31	−18.57*	−18.57*	38.33	45.57**	23.66**	21.05*
P3 × P1	173.33	16.20*	14.04	−25.61**	21.07	−2.47	−12.22	−29.31**	24.67	8.82	−2.63	−22.11**
P3 × P2	143.00	−2.94	−5.92	−38.63**	14.00	−40.59**	−41.67**	−53.02**	24.67	4.96	−2.63	−22.11**
P3 × P4	132.00	−25.00**	−34.00**	−43.35**	18.33	−31.16**	−37.36**	−38.48**	24.67	−8.07	−12.94	−22.11**
P3 × P5	189.33	24.90**	24.56**	−18.74**	36.67	38.76**	27.09**	23.04*	36.67	57.14**	44.74**	15.79
P3 × P6	148.33	1.40	−2.41	−36.34**	19.60	−14.78	−18.33	−34.23**	21.00	−13.70	−17.11	−33.68**
P3 × P7	125.00	−35.06**	−46.35**	−46.35**	18.33	−31.78**	−38.38**	−38.48**	24.00	−15.79	−24.21**	−24.21**
P3 × P8	166.67	−10.79	−24.81**	−28.47**	26.00	−3.35	−12.75	−12.75	28.00	−0.59	−9.68	−11.58

Table 2 continued

Genotype	Plant height (cm)				Total tillers				Panicles per plant			
	Mean	MPH	BPH	SH	Mean	MPH	BPH	SH	Mean	MPH	BPH	SH
P4 × P1	141.83	−18.09**	−29.08**	−39.13**	23.30	−3.85	−20.39*	−21.81*	21.33	−11.72	−24.71**	−32.63**
P4 × P2	153.33	−10.51	−23.33**	−34.19**	25.53	−2.54	−12.76	−14.32	29.33	17.33	3.53	−7.37
P4 × P3	189.33	7.58	−5.33	−18.74**	37.87	42.18**	29.38**	27.07**	34.33	27.95**	21.18*	8.42
P4 × P5	168.33	−4.13	−15.83**	−27.75**	34.33	18.15	17.31	15.21	26.33	6.04	−7.06	−16.84*
P4 × P6	176.00	3.36	−12.00*	−24.46**	32.40	26.40*	10.71	8.72	35.33	36.77**	24.71**	11.58
P4 × P7	150.67	−30.41**	−35.34**	−35.34**	26.73	−9.40	−10.14	−10.29	35.00	16.67	10.53	10.53
P4 × P8	194.75	−7.63	−12.14*	−16.42**	34.13	15.58	14.54	14.54	44.00	48.31**	41.94**	38.95**
P5 × P1	213.67	43.64**	41.35**	−8.30	38.00	58.17**	31.72**	27.52**	35.33	70.97**	65.62**	11.58
P5 × P2	164.35	11.87	8.72	−29.46**	26.40	1.57	−8.49	−11.41	23.00	6.98	6.15	−27.37**
P5 × P3	171.67	13.25	12.94	−26.32**	26.67	0.91	−7.57	−10.51	28.00	20.00	10.53	−11.58
P5 × P4	179.00	1.95	−10.50	−23.18**	25.67	−11.67	−12.30	−13.87	27.67	11.41	−2.35	−12.63
P5 × P6	165.00	13.12	9.15	−29.18**	25.13	−1.15	−12.88	−15.66	38.00	70.15**	62.86**	20.00*
P5 × P7	150.36	−21.72**	−35.47**	−35.47**	24.13	−17.63	−18.88*	−19.02*	24.33	−8.18	−23.16**	−23.16**
P5 × P8	173.67	−6.84	−21.65**	−25.46**	27.60	−5.88	−7.38	−7.38	42.00	60.51**	35.48**	32.63**
P6 × P1	146.67	2.25	0.23	−37.05**	15.67	−23.95	−28.79*	−47.43**	25.33	16.92	8.57	−20.00*
P6 × P2	121.00	−14.56	−15.19*	−48.07**	13.80	−38.85**	−40.35**	−53.69**	20.33	−9.63	−12.86	−35.79**
P6 × P3	167.00	14.17	9.87	−28.33**	25.03	8.84	4.31	−16.00	32.00	31.51**	26.32*	1.05
P6 × P4	153.67	−9.76	−23.17**	−34.05**	21.20	−17.30	−27.56**	−28.86**	20.67	−20.00	−27.06**	−34.74**
P6 × P5	122.00	−16.36*	−19.29**	−47.64**	12.00	−52.80**	−58.41**	−59.73**	21.00	−5.97	−10.00	−33.68**
P6 × P7	163.00	−12.73*	−30.04**	−30.04**	25.87	−0.03	−13.05	−13.20	28.67	4.24	−9.47	−9.47
P6 × P8	140.17	−22.61**	−36.77**	−39.84**	22.58	−12.81	−24.22**	−24.22**	20.67	−23.93*	−33.33**	−34.74**
P7 × P1	203.33	7.21	−12.73**	−12.73**	21.00	−14.20	−29.41**	−29.53**	21.00	−18.71	−33.68**	−33.68**
P7 × P2	292.00	55.46**	25.32**	25.32**	36.67	38.67**	23.25*	23.04*	34.00	27.50**	7.37	7.37
P7 × P3	211.00	9.61	−9.44*	−9.44*	33.53	24.78*	12.72	12.53	39.33	38.01**	24.21**	24.21**
P7 × P4	168.33	−22.25**	−27.75**	−27.75**	24.33	−17.54	−18.21*	−18.34*	20.00	−33.33**	−36.84**	−36.84**
P7 × P5	164.00	−14.62*	−29.61**	−29.61**	14.00	−52.22**	−52.94**	−53.02**	18.67	−29.56**	−41.05**	−41.05**
P7 × P6	170.33	−8.80	−26.90**	−26.90**	28.93	11.82	−2.75	−2.91	33.33	21.21*	5.26	5.26
P7 × P8	171.00	−24.78**	−26.61**	−26.61**	18.07	−39.32**	−39.37**	−39.37**	22.67	−27.66**	−28.42**	−28.42**
P8 × P1	114.00	−38.04**	−48.57**	−51.07**	13.13	−46.39**	−55.93**	−55.93**	18.00	−29.41**	−41.94**	−43.16**
P8 × P2	284.00	55.90**	28.12**	21.89**	37.40	41.31**	25.50**	25.50**	39.67	50.63**	27.96**	25.26**
P8 × P3	184.43	−1.28	−16.80**	−20.84**	24.33	−9.54	−18.34*	−18.34*	35.67	26.63**	15.05	12.63

Table 2 continued

Genotype	Plant height (cm)				Total tillers				Panicles per plant			
	Mean	MPH	BPH	SH	Mean	MPH	BPH	SH	Mean	MPH	BPH	SH
P8 × P4	285.00	35.18**	28.57**	22.32**	40.07	35.67**	34.45**	34.45**	35.00	17.98*	12.90	10.53
P8 × P5	187.33	0.49	−15.49**	−19.60**	23.20	−20.89*	−22.15*	−22.15*	32.67	24.84*	5.38	3.16
P8 × P6	170.33	−5.95	−23.16**	−26.90**	24.60	−5.02	−17.45	−17.45	20.33	−25.15*	−34.41**	−35.79**
P8 × P7	170.33	− 25.07**	−26.90**	−26.90**	22.07	−25.89**	−25.95**	−25.95**	26.67	−14.89	−15.79	−15.79
Hybrid mean	174.00				25.79				28.34			
Standard error	5.01				0.94				0.96			
Overall mean	173.93				25.78				27.96			
Standard error	4.66				0.84				0.87			

Genotype	Capsules per plant				Yield per plant (g)			
	Mean	MPH	BPH	SH	Mean	MPH	BPH	SH
NKE 3	423.00				356.17			
NKE 9	479.33				402.46			
NKE 12	393.67				335.53			
NKE 19	543.00				457.21			
NKE 27	702.33				591.36			
NKE 34	426.00				358.69			
RR 1	970.67				817.30			
CCS 1	1028.00				865.58			
Parental mean	620.75				523.04			
Standard error	89.60				75.29			
P1 × P2	416.00	−7.79	−13.21	−59.53**	375.73	−0.94	−6.63	−56.59**
P1 × P3	652.33	59.76**	54.22**	−36.54**	549.26	58.82**	54.22**	−36.54**
P1 × P4	452.33	−6.35	−16.7	−56.00**	380.86	−6.35	−16.70	−56.00**
P1 × P5	493.33	−12.32	−29.76*	−52.01**	419.77	−11.39	−29.01*	−51.50**
P1 × P6	545.33	28.46	28.01	−46.95**	459.17	28.46	28.00	−46.95**
P1 × P7	687.33	−1.36	−29.19**	−33.14**	578.73	−1.36	−29.19**	−33.14**
P1 × P8	449.33	−38.07**	−56.29**	−56.29**	405.02	−33.70**	−53.21**	−53.21**
P2 × P1	958.67	112.49**	100.00**	−6.74	810.10	113.58**	101.30**	−6.41
P2 × P3	622.00	42.50*	29.76	−39.49**	523.72	41.94*	30.14	−39.49**
P2 × P4	803.33	57.16**	47.94**	−21.85*	723.02	68.22**	58.14**	−16.47*

Table 2 continued

Genotype	Capsules per plant				Yield per plant (g)			
	Mean	MPH	BPH	SH	Mean	MPH	BPH	SH
P2 × P5	614.33	3.98	−12.53	−40.24**	517.27	4.10	−12.53	−40.24**
P2 × P6	1073.33	137.11**	123.92**	4.41	949.47	149.48**	135.93**	9.69
P2 × P7	966.33	33.29**	−0.45	−6.00	833.05	36.59**	1.93	−3.76
P2 × P8	1280.00	69.84**	24.51**	24.51**	1077.76	69.99**	24.51**	24.51**
P3 × P1	584.33	43.10*	38.14	−43.16**	492.01	42.27*	38.15	−43.16**
P3 × P2	451.67	3.47	−5.77	−56.06**	380.30	3.08	−5.49	−56.06**
P3 × P4	330.00	−29.54	−39.23*	−67.90**	319.04	−19.5	−30.21*	−63.14**
P3 × P5	1105.00	101.64**	57.33**	7.49	921.80	98.90**	55.88**	6.49
P3 × P6	466.00	13.7	9.39	−54.67**	392.37	13.03	9.38	−54.67**
P3 × P7	496.33	−27.24*	−48.87**	−51.72**	417.91	−27.49*	−48.86**	−51.72**
P3 × P8	659.67	−7.20	−35.83**	−35.83**	555.44	−7.51	−35.83**	−35.83**
P4 × P1	512.00	6.00	−5.71	−50.19**	431.10	6.00	−5.72	−50.20**
P4 × P2	740.00	44.77**	36.28*	−28.02**	623.08	44.96**	36.28*	−28.02**
P4 × P3	588.67	25.69	8.41	−42.74**	592.67	49.52**	29.63	−31.53**
P4 × P5	749.67	20.4	6.74	−27.08**	631.22	20.40	6.74	−27.08**
P4 × P6	692.67	42.97*	27.56	−32.62**	713.33	74.85**	56.02**	−17.59*
P4 × P7	570.67	−24.60*	−41.21**	−44.49**	480.50	−24.60*	−41.21**	−44.49**
P4 × P8	901.67	14.79	−12.29	−12.29	759.20	14.79	−12.29	−12.29
P5 × P1	1249.33	122.04**	77.88**	21.53*	1068.75	125.58**	80.72**	23.47**
P5 × P2	598.67	1.33	−14.76	−41.76**	504.08	1.45	−14.76	−41.76**
P5 × P3	666.67	21.65	−5.08	−35.15**	561.33	21.12	−5.08	−35.15**
P5 × P4	730.00	17.24	3.94	−28.99**	614.66	17.23	3.93	−28.99**
P5 × P6	772.67	36.96*	10.01	−24.84**	650.59	36.95*	10.01	−24.84**
P5 × P7	659.67	−21.14*	−32.04**	−35.83**	555.44	−21.15*	−32.04**	−35.84**
P5 × P8	542.33	−37.31**	−47.24**	−47.24**	456.64	−37.32**	−47.25**	−47.25**
P6 × P1	551.67	29.96	29.5	−46.34**	464.50	29.96	29.49	−46.33**
P6 × P2	432.67	−4.42	−9.74	−57.91**	364.31	−4.28	−9.48	−57.91**
P6 × P3	1053.33	157.02**	147.26**	2.46	856.49	146.74**	138.76**	−1.05
P6 × P4	481.67	−0.58	−11.3	−53.15**	405.56	−0.60	−11.3	−53.15**
P6 × P5	373.67	−33.77*	−46.80**	−63.65**	314.63	−33.78*	−46.80**	−63.66**
P6 × P7	924.00	32.32*	−4.81	−10.12	778.01	32.31**	−4.81	−10.12

Table 2 continued

Genotype	Capsules per plant				Yield per plant (g)			
	Mean	MPH	BPH	SH	Mean	MPH	BPH	SH
P6 × P8	502.00	−30.95*	−51.17**	−51.17**	422.68	−30.95**	−51.17**	−51.17**
P7 × P1	633.33	−9.11	−34.75**	−38.39**	533.27	−9.11	−34.75**	−38.39**
P7 × P2	1085.67	49.75**	11.85	5.61	963.35	57.96**	17.87*	11.29
P7 × P3	1205.33	76.69**	24.18**	17.25*	1014.89	76.07**	24.18**	17.25*
P7 × P4	495.00	−34.60**	−49.00**	−51.85**	417.40	−34.50**	−48.93**	−51.78**
P7 × P5	372.00	−55.53**	−61.68**	−63.81**	318.02	−54.85**	−61.09**	−63.26**
P7 × P6	1409.00	101.77**	45.16**	37.06**	1186.38	101.76**	45.16**	37.06**
P7 × P8	423.33	−57.64**	−58.82**	−58.82**	356.45	−57.64**	−58.82**	−58.82**
P8 × P1	333.33	−54.05**	−67.57**	−67.57**	283.66	−53.56**	−67.23**	−67.23**
P8 × P2	1085.67	44.05**	5.61	5.61	914.13	44.19**	5.61	5.61
P8 × P3	852.33	19.91	−17.09*	−17.09*	717.66	19.50	−17.09*	−17.09*
P8 × P4	1315.67	67.49**	27.98**	27.98**	1107.79	67.49**	27.98**	27.98**
P8 × P5	742.67	−14.16	−27.76**	−27.76**	625.33	−14.16	−27.76**	−27.76**
P8 × P6	521.00	−28.34*	−49.32**	−49.32**	446.14	−27.12*	−48.46**	−48.46**
P8 × P7	749.67	−24.98**	−27.08**	−27.08**	631.22	−24.98**	−27.08**	−27.08**
Hybrid mean	707.58				604.40			
Standard error	36.74				31.05			
Over all mean	696.73				594.23			
Standard error	34.00				28.75			

*, ** Significant at 5 and 1% level, respectively

Table 3 Evaluation of promising hybrids for different characters

Entries	Plant height (cm)	Tillers per plant	Panicles per plant	Capsules per plant	Dry yield (kg/ha)			
					2004–2005	2005–2006	2006–2007	Mean
RR 1 × NKE 12	267.13	45.33	65.00	1844.7	463.59	857.69	1004.37	775.22
CCS 1 × NKE 9	323.10	38.33	47.00	2345.3	515.19	1193.37	745.69	818.08
NKE 27 × NKE 3	262.13	40.67	58.33	2035.0	238.50	819.71	579.19	545.80
RR 1 × NKE 9	323.60	33.67	48.00	1328.3	252.77	487.39	598.83	446.33
NKE 9 × NKE 34	235.13	32.33	47.67	1223.3	49.22	516.15	354.33	306.57
NKE 9 × NKE 19	260.50	26.00	31.00	662.3	50.00	278.59	324.86	217.82
NKE 19 × NKE 12	191.67	39.00	33.00	679.0	176.82	335.51	304.83	272.39
NKE 9 × RR 1	260.30	38.33	42.33	1021.3	210.85	465.79	371.41	349.35
NKE 19 × NKE 34	187.20	33.33	34.00	685.3	115.35	306.28	466.98	296.20
CCS 1 × NKE 19	297.13	31.67	51.67	3142.7	699.83	1498.18	728.52	975.51
MB 3	208.60	26.00	30.00	1119.7	296.65	519.22	444.58	420.15
IISR Avinash	301.97	34.00	44.67	2091.3	403.35	957.53	396.23	585.70
Green Gold	283.67	29.00	32.00	1123.7	211.73	526.79	290.64	343.05
SKP 14	266.70	44.33	63.33	1459.3	210.02	486.71	225.55	307.43
NKE 19	201.90	29.33	29.00	468.3	97.60	165.63	206.71	156.65
Mean	267.77	35.23	44.42	1441.72	298.67	629.96	482.51	
SEd	27.52	5.15	10.81	529.86	56.14	236.34	74.86	
CV (%)	12.59	17.89	29.80	45.01	18.65	45.95	19.00	
CD ($P = 0.005$)	55.23	10.33	21.69	1063.25	132.45	474.26	150.21	

The highest percentage of SH of 37.06 and 27.98% for yield per plant were observed in hybrids between RR 1 × NKE 34 and CCS 1 × NKE 19. Earlier reports by Madhusoodanan et al. (1999) and Kuruvilla et al. (2006) also indicate superior yield performance of cardamom hybrids. The significant average heterosis for various characteristics indicates the importance of dominant genetic effects in the inheritance of these characteristics. Krishnamurthy (1989) also observed vigorous diallel cross combinations when compared to the parental lines. The wide range in relative yield heterosis indicates cardamom's potential for further increasing hybrid yield by a systematic search for parents for their combining ability.

In the present investigation, high MPH, HPH and SH were also observed for plant height, tillers and capsules per plant. Padmini et al. (2001) also observed high positive significant heterosis in seedlings of cardamom with respect to plant height, number of leaves per plant, leaf length and breadth. The cross between RR 1 × NKE 34, CCS 1 × NKE 19 and RR 1 × NKE 12 had the highest mean number of panicles per plant. Some crosses, although they involved high-panicle parental lines, demonstrated low heterosis for this character. Morgan et al. (1989) found that heterosis for wheat grain yield was less where the parents were higher yielding because the parental lines already had many of the genes beneficial for yield in the homozygous state and so were unable to show much heterosis.

Performance of short listed hybrids for yield and *katte* resistance

The mean dry yield per hectare ranged from a lowest of 217.82 kg/ha to a highest 975.51 kg/ha in the hybrids tested. Three hybrids out of ten out yielded the check IISR Avinash, a released variety. Previous report has shown superiority of cardamom hybrids for yield over other selections (Kuruvilla et al. 2006). Commercial acceptance of hybrids will also be decisively determined by percentage yield increase over local cultivars or varieties. In our experiment, the best F_1 hybrid (CCS 1 × NKE 19) out yielded its best check by 389.91 kg/ha (39.97%). High yield combined with *katte* resistance in hybrids is highly desirable for sustainable cardamom production. Among the high yielding hybrids screened both under field and artificial conditions, CCS 1 × NKE 19 (Fig. 1) and RR 1 × NKE 12 recorded resistance to *katte* disease under both the conditions (Table 4). In relation to disease resistance F_1 hybrids can show distinct advantages depending on the mode of inheritance (Johnson and Lupton 1987). For *katte* disease resistance, the cross combinations tested resulted in resistant F_1's if any one of the parents had resistance.

Fig. 1 High yielding mosaic resistant cardamom hybrid (CCS1 × NKE19)

Table 4 Mosaic incidence among hybrids and released varieties

Entries	Field reaction	Artificial screening
RR 1 × NKE 12	R	R
CCS 1 × NKE 9	S	S
NKE 27 × NKE 3	R	R
RR 1 × NKE 9	R	S
NKE 9 × NKE 34	R	R
NKE 9 × NKE 19	R	R
NKE 19 × NKE 12	R	R
NKE 9 × RR 1	R	S
NKE 19 × NKE 34	R	R
CCS 1 × NKE 19	R	R
MB 3	S	S
IISR Avinash	R	S
IISR Suvasini	S	S
Green Gold	S	S
SKP 14	S	S
NKE 19	R	R

Table 5 Quality attributes of promising hybrids

Entries	Oil (%)	α-Terpinyl acetate	1,8-Cineloe
CCS 1 × NKE 19	5.75	40.32	29.53
CCS 1 × NKE 9	5.50	39.30	29.52
RR 1 × NKE 12	5.00	39.12	33.07
IISR Avinash	6.00	38.94	31.95
CCS 1	5.50	37.30	29.10
NKE 19	5.00	38.51	26.02
Green Gold	6.00	39.94	29.89

The highest oil yield (6.00%) was obtained in IISR Avinash and the lowest (5.00%) was recorded in RR 1 × NKE 12 (Table 5). This is in accordance with previously reported result in Karnataka, India (Sreekrishna Bhat and Sudharshan 2006). Among the constituents in the cardamom volatile oil, 1,8-cineole and α-terpinyl acetate are the major components and the basic cardamom aroma is produced by a combination of α-terpinyl acetate and 1,8-cineole. The major chemical constituent that impart sweet flavour to the oil is α-terpinyl acetate while 1,8-cineole imparts harsh camphory note (Sarath Kumara et al. 1985). In the present study, among the seven genotypes α-terpinyl acetate was high compared to 1, 8-cineole. Highest α-terpinyl acetate content was recorded in CCS 1 × NKE 19 followed by Green Gold. This quality attribute is added advantage in this hybrid besides high yield and *katte* resistance.

In the present study, the high heterosis among the parental lines for most of the characteristics studied indicates that considerable potential exists in these accessions for developing hybrids. From the study, it was observed that F_1 cardamom hybrids did not only have high yield potential and overall plant performance but could also increase productivity on account of their mosaic resistance. Therefore, yield, yield components, quality, resistance, and overall plant performance can be effectively improved in cardamom. Cardamom breeding programmes should aim to produce new F_1 hybrids for sustainability.

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