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RESEARCH ARTICLE

Heterosis for morphological and yield contributing traits in tropical carrot (*Daucus carota* L.)

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Abstract

Carrot (*Daucus carota* L.) is one of the most important salad vegetable crops globally because of the nutrient richness, palatability and lower pesticide load. Heterosis breeding and hybrids has noteworthy role in boosting the productivity, better crop management and enhanced quality in many crops. Therefore, the field experiments were carried out during 2022-2024 to estimate the heterosis among CMS-based hybrids for growth and yield contributing traits in carrot. The significant differences of mean squares among parents and hybrids for various traits of economic importance indicated the presence of sufficient variation. Overall the hybrid mean of 48 cross-combinations is appreciably higher/desirable than parental mean for days to germination (13.2%), plant weight (41.5%), leaf length (15.0%), leaf weight (37.9%), root weight (42.7%), shoulder diameter (11.1%), core width (-24.2%) and marketable yield (42.5%) clearly indicates the presence of hybrid vigour and prospects for heterosis breeding in carrot. Overall, the superior hybrid-combinations namely VRCARH-23344, VRCARH-27244, VRCARH-23485, VRCARH-21185, VRCARH-212135, VRCARH-21244, VRCARH- 241199 and VRCARH-214206 have prospects for development of CMS-based potential heterotic hybrids in tropical carrot.

Keawords: Carrot, *Daucus carota*, Male sterility, CMS, Heterosis, Hybrid.

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Introduction

The cultivated carrot (*Daucus carota* L. subsp. *sativus* Hoffm., $2n = 2x = 18$), belongs to the family Apiaceae (formerly Umbelliferae) and is an important root vegetable crop in the world. It is descended by wild carrot or Queen Anne's lace (*Daucus carota* subsp. *carota*) and native to central Asia (Iorizzo et al., 2013). The genus *Daucus* contains 40 species and the wild forms grow mostly in Mediterranean region and south west Asia. Carrot is of Central Asian origin (Vavilov, 1951). Carrot is an important salad crop grown for its fleshy edible and colorful roots varying from white, yellow, orange, deep orange, red, purple to almost black; but orange, red and black carrots are of commercial importance worldwide which is in cultivation among all the climates ranging from temperate to tropics (Que et al., 2019; Singh et al., 2022). In India, red carrot is being grown predominantly in northern and central parts; while cultivation of orange carrot dominates in hilly and southern regions. Orange carrots are primarily used for table consumption, canning, drying and freezing; while red carrots are mainly used for table purpose, juice making, halwa preparation and making salted and pickled products. Globally, the production of carrot combined with turnip was 403 lakh t from 11.51 lakh ha area with China producing 45% of the world total (FAOSTAT, 2023).

However, in India, the production, area and productivity was recorded 18.93 lakh t, 1.09 lakh ha and 17.37 t/ha, respectively during 2018-19 (Anonymous, 2020). The productivity level of carrot in India is low because of predominance of open-pollinated varieties and lack of high yielding hybrids. Cultivated carrot has several categories varying in its root colour, shape & size, and need of vernalization to complete life cycle. Therefore, it is broadly classified on the basis of (1) presence of root pigments i.e. Carotenoid group (*D. carota* ssp. *sativus* var. *sativus*) and Anthocyanin or purple group (*D. carota* ssp. *sativus* var. *atrorubens*), and (2) need of vernalization i.e. Tropical or Eastern carrot (does not require vernalization & annual) and Temperate or Western/European carrot (requires vernalization & biennial). The majority of red/black and orange carrot cultivars grown in India are typically tropical and temperate in nature, respectively.

Carrot is a cross-pollinated crop (up to 95%), suffering with high inbreeding depression to the tune of 18-35% for root length, 40-55% for root weight and 62-82% for root yield while increasing the homogeneity by selfing of OP lines/varieties (Roth, 1981). Alternatively, the hybrids derived from unrelated/diverse lines exhibit both heterotic vigour and enhanced uniformity. Heterosis breeding provides opportunity to harness hybrid vigour for various traits of economic importance as well as increased homogeneity/uniformity. The use of F_1 hybrids of numerous vegetable crops has increased manifold during the past 3-5 decades in India and many countries (Behera et al., 2023). Heterosis is of direct interest for development and commercialization of F_1 hybrids in vegetable crops, including carrot which is being triggered by use of various types of CMS. The use of hybrids in vegetable crops has significantly increased in India, accounted for 79.4% share of the market in 2022 (Anonymous, 2024) over the past several decades and are driven by the benefits of higher yields, increased uniformity, improved quality, wide adaptability and better stress tolerance.

In crops like carrot where hand-emasculation is challenging because of tiny flowers and very low seed-setting rates (1-2 seeds per flower pollination); the use of cytoplasmic male sterile (CMS) lines become crucial for hybrid breeding. This is because male sterility eliminates the need for the laborious and often ineffective hand-emasculation for controlled cross-pollination in hybrid breeding, which is essential for developing new hybrids. The first report of heterosis in carrot, observed from the crossing of two inbred lines, was made by Poole (1937). Moreover, Frimmel and Lauche (1938) were the first to recommend the breeding of F_1 carrot varieties, but the absence of a reliable system i.e. male sterility for producing hybrid seed in large quantities hindered the practical implementation of this approach. The cytoplasmic male sterility in carrot was discovered and analyzed by Thompson (1962), and Hanschke and Gabelman (1963) which is generally based on a complex interplay between maternally inherited mitochondrial and nuclear genetic information. There are various phenotypic forms of CMS known as brown anther CMS, petaloid-CMS, GUM-CMS, MAR-CMS and GAD-CMS (Kalia et al., 2023). Amongst the various male sterility systems, the petaloid-CMS is the most stable across a wide range of environmental conditions and is commercially being used in heterosis breeding programme of temperate and tropical carrot worldwide, including India. The petaloid-CMS is characterized by the replacement of the either stamens with petals or by the substitution of both stamens and petals with bract-like structures (Kitagawa et al., 1994).

The hybrid breeding in carrot is considered as best breeding approach to increase root yield and uniformity (Bunin and Yoshikawa, 1989; Duan et al., 1996; Suh et al., 1999; Simon and Strandberg, 1998; Chira et al., 2008; Jagosz, 2012; Turner et al., 2018), carotenoid content (Santos and Simon, 2006; Coelho et al., 2024), and resistance to *Alternaria* leaf blight (Simon and Strandberg, 1998). In India, despite the economic promise associated with carrots, the development of CMS lines of tropical carrot remains very limited and only two Public Sector Institutes developed CMS lines having various backgrounds (Kalia et al., 2019; Singh and Karmakar, 2021; Singh and Karmakar, 2023; Singh et al., 2023). However, Verma et al. (2002) and Gupta et al. (2006) have reported heterosis in temperate carrot. So far, the Indian Public Sector Institutes developed only two hybrids of tropical carrot i.e. Pusa Vasuda (developed by ICAR-IARI, Delhi and notified in 2016) and VRCARH-2 (developed by ICAR-IIVR, Varanasi and recommended in 2025). Keeping in view of the importance of hybrids in tropical carrot; the objective of present study, therefore, was to examine the magnitude and direction of heterosis for morphological traits of economic importance and identify the superior hybrids having better agronomical traits.

Materials and Methods

The present experiment was carried out at the research farm of the ICAR-IIVR Varanasi, UP during winter season of 2022-2023 and 2023-2024. The research form is located at 82.52 °E longitude and 25.10 °N latitude at an elevation of 128.93 m from mean sea level (MSL) having soil with silt-loam texture, pH 7.3 and electrical conductivity of 0.28 dSm^{-1}. The experimental materials for the present investigation comprised of 48 crosses developed by crossing eight lines (all CMS) i.e. VRCAR-212, VRCAR-213, VRCAR-214, VRCAR-211, VRCAR-272, VRCAR-233, VRCAR-234 & VRCAR-241, and six testers i.e. VRCAR-199, VRCAR-206, VRCAR-85, VRCAR-154, VRCAR-44 & VRCAR-135 along with one national check variety, Kashi Arun. The details of basic biological materials are summarized in Table 1. All the parental lines and a check variety were developed and maintained by the ICAR-IIVR, Varanasi, UP.

Table 1: Details of basic experimental materials of tropical carrot developed at ICAR-IIVR, Varanasi, UP

Genotype	*Leaf colour*	*Petiole colour*	*Root shape*	*Root colour*
Lines (All CMS)				
VRCAR-212	Green	Light green	Tapered	Red
VRCAR-213	Green	Light green	Tapered	Red
VRCAR-214	Green	Light green	Tapered	Red
VRCAR-211	Green	Light green	Tapered	Red
VRCAR-272	Green	Light green	Tapered	Yellow
VRCAR-233	Light green	Light green	Semi-blunt	Orange
VRCAR-234	Light green	Light green	Semi-blunt	Orange
VRCAR-241	Light green	Light green	Semi-blunt	Orange
Testers				
VRCAR-199	Green	Light green	Tapered	Red
VRCAR-206	Green	Light green	Tapered	Red
VRCAR-85	Green	Light green	Tapered	Red
VRCAR-154	Green	Light green	Tapered	Yellow
VRCAR-135	Light green	Light green	Semi-blunt	Orange
VRCAR-44	Light green	Light green	Semi-blunt	Orange

The parents were crossed in line × tester mating design during 2022-23 to obtain the adequate amount of F_1 hybrid seeds. The standard procedures for caging of CMS lines & tester pollen parents and pollination were followed to produce the seeds of 48 hybrids. The umbels were harvested about 60-70 days after pollination, air dried for 3-5 days and hand threshed individually. Finally, F_1 hybrid seeds were kept in moisture proof envelope. All the 63 genotypes, including 48 cross-combinations, 14 parents and a check variety were grown. Botanically schizocarp type carrot seeds were sown in double row of 7-8 cm apart and 25-28 cm wide ridge with the spacing of 65 cm between each pair of ridges. Each genotype comprises three ridges of 6 m long and replicated thrice for heterosis study. To get better root development, all the agronomic practices were carried out unvaryingly during both years of experimentations as described by Singh and Karmakar (2015).

Fourteen growth related and yield contributing traits of economic importance were recorded such as days to germination (cm), plant height at 60 days after sowing (cm), days to harvest, gross plant weight (g), leaf length (cm), leaf weight (g), root weight (g), root length (cm), shoulder diameter (cm), core width (cm), number of leaf, harvest index (%), root colour uniformity (%) and marketable yield (q/ha). The data were subject to statistical analyses for ANOVA for parents and hybrids as per method given by Kempthorne (1957) later on modified by Arunachalam (1974), and better parent heterosis (BPH, %) and standard heterosis (SH, %) i.e. heterosis over check variety were estimated (Singh and Chaudhary, 1997).

Results and Discussion

The partitioning of mean squares due to parents, hybrids and parents vs. hybrids was observed to be highly significant for all morphological traits under study, i.e. days to germination, plant height at 60 DAS, days to harvest, plant weight, leaf length, leaf weight, number of leaf, root weight, root length, shoulder diameter, core width, harvest index, root colour uniformity and marketable yield; except days to harvest, number of leaf & harvest index for parents; and days to harvest & number of leaf for parents vs. hybrids (Table 2). The highly significant mean squares of parents, hybrids and parents vs. hybrids indicate the existence of sufficient variation and suggest the possibility of improvement in traits through population improvement and hybrid breeding. The hybrid effects, better parent heterosis (Heterobeltiosis) and standard heterosis were computed to find out the suitable hybrid combinations for various traits of growth and root related traits (Tables 3 and 4). The hybrid mean is appreciably higher (>10%) than parental mean for days to germination (13.2%), plant weight (41.5%), leaf length (15.0%), leaf weight (37.9%), root weight (42.7%), shoulder diameter (11.1%) and marketable yield (42.5%) which further gets the justification by positive sign of better parent heterosis for corresponding trait; indicating the presence of hybrid vigour and prospects for hybrid development and population improvement in carrot. Moreover, the negative value of hybrid mean for core width (-24.2%) along with negative better parent heterosis indicating the importance of heterosis breeding for narrow/smaller core, one of the important trait for consumers' preference. Singh et al. (2009) also reported negative and desirable heterosis for core length in cabbage.

Among 48 hybrid combinations; the better parent heterosis and standard heterosis in desirable direction for growth related traits (Table 3) were observed respectively in 1 & 3 hybrids for days to germination, 18 & 0 hybrids for plant height at 60 DAS, 15 & 11 combinations for days to harvest, 37 & 42 hybrids for plant weight, 7 & 2 combinations for leaf length, only 1 hybrid for leaf weight, and 15 & 32 for number of leaf. The higher numbers of desirable hybrid-combinations for majority of growth related traits is indicating the presences of heterosis for plant vigour related traits in tropical carrot. The significantly negative and desirable BPH and SH for days to germination was observed respectively only in one hybrid i.e. VRCARH-23385 (-12.00%), and three hybrids namely VRCARH-213199 (-16.37%), VRCARH-23385 (-16.37%) and VRCARH-23385 (-12.39%).

Table 2: ANOVA of morphological traits for parents and hybrids in tropical carrots

Source of variation	*df*	*Days to germination*	*Plant height 60 DAS (cm)*	*Days to harvest*	*Plant weight (g)*	*Leaf length (cm)*	*Leaf weight (g)*	*Root weight (g)*	*Root length (cm)*	*Shoulder diameter (cm)*	*Core width (cm)*	*No. of leaf*	*Harvest index (%)*	*Root colour uniformity (%)*	*Marketable yield (q/ha)*
Replication	2	0.07	9.61	0.70	390.77	22.42	77.28	313.70	0.40	0.826	0.006	0.121	36.47	1.20	408.08
Parents	13	0.34**	116.25**	1.09	534.70**	122.43**	52.10**	316.79**	54.58**	0.295**	0.151**	0.311	10.37	3.72**	2912.48**
Hybrids	47	0.99**	31.99**	23.22**	6252.74**	100.81**	970.04**	3021.63**	27.31**	1.011**	0.149**	4.609**	60.53**	7.85**	26907.97**
Hybrids vs. Parents	1	33.62**	342.15**	0.63	156996.2**	2453.63**	14523.8**	77629.97**	81.45**	5.748**	5.020**	0.728	40.66**	57.64**	718267.25**
Error	122	0.17	2.31	1.66	118.58	3.59	30.64	74.11	3.24	0.065	0.004	0.332	11.52	0.19	658.04
Total	185	0.57	19.77	7.08	2557.16	50.09	349.65	1261.80	13.35	0.360	0.079	1.417	24.32	2.70	11401.39

The gross plant weight is an indicator for plant vigour. Among 48 hybrids, more than 82% cross-combinations namely, VRCARH-27244, VRCARH-23444, VRCARH-212135, VRCARH-234154, VRCARH-23485, VRCARH-23344 and VRCARH-241199 revealed significantly higher BPH and or SH ranging from 69.8-133.1% for plant weight among crosses of red, yellow and orange tropical carrots which indicating the presence of sufficient amount of heterosis. Among 48 cross-combinations, the substantial desirable negative heterosis for number of leaf was observed in 15 hybrids over better parent such as VRCARH-21485 (-39.39%), VRCARH-21144 (35.42%), VRCARH-21385 (-31.91%), VRCARH-21285 (-29.70%) & VRCARH-233206 (-26.37%), and 32 hybrids over standard check namely VRCARH-21485 (-45.45%), VRCARH-21144 (43.64%), VRCARH-21385 (-41.81%), VRCARH-212206 (-37.27%) & VRCARH-233135 (-36.36%). Similar findings were also reported by Janani (2019) and Reddy (2021) for number of leaf per plant.

The root and yield attributing traits also revealed desirable better parent heterosis and standard heterosis (Table 4), respectively in 40 & 36 hybrids for root weight, 9 & 3 hybrids for root length, 7 & 9 cross-combinations for shoulder diameter, 45 & 47 hybrids for core width, 5 combinations for harvest index, 2 & 1 cross-combination for root colour uniformity and 41 & 44 hybrids for marketable yield. The higher numbers of desirable hybrid-combinations for majority of yield contributing traits is indicating the presences of heterosis for root and yield contributing traits in tropical carrot. Among 48 hybrids evaluated, significantly positive heterosis was expressed for root weight in 40 hybrids over better parent namely VRCARH-23344 (92.62%), VRCARH-27244 (86.28%), VRCARH-23485 (78.70%), VRCARH-272199 (73.67%), VRCARH-21185 (69.60%); and 36 hybrids over standard check such as VRCARH-27244 (88.77%), VRCARH-23344 (88.37%), VRCARH-23485 (73.71%), VRCARH-272199 (67.31%), VRCARH-21185 (65.85%). Heterosis for root weight in carrot is also reported by Duan et al. (1996); Padmakara (1991) and Janani et al. (2023). Furthermore, substantial heterosis for root length over better parent and standard check were measured in 9 hybrids over better parent namely VRCARH-211154 (70.68%), VRCARH-213135 (48.18%), VRCARH-272154 (43.57%), VRCARH-21344 (25.86%), VRCARH-21285 (16.52%), and 3 hybrids over standard check such as VRCARH-211206 (14.80%), VRCARH-21285 (14.80%) and VRCARH-272154 (12.29%). Similar findings were also observed previously by Janani (2019) and Reddy (2021).

A small and narrow core is desirable in breeding programs with respect to greater cortex/flesh thickness, higher consumer preference and better post-harvest life. Out of 48 F_1 cross-combinations, significantly desirable negative heterosis over better parent was observed in 45 hybrids like VRCARH-233135 (-54.64%), VRCARH-21244 (-54.38%), VRCARH-21344 (-54.30%), VRCARH-214199

Table 3: Hybrid effects, better parent heterosis and standard heterosis for plant growth related traits in tropical carrot

Character	*Particular*	*DTG*	*PH at 60 DAS*	*DTH*	*PW*	*LL*	*LW*	*NL*
Parent	Range	7.00-8.33	40.73-61.33	89.13-91.07	138.73-177.80	46.27-67.93	46.67-59.73	5.40-6.73
	Mean	7.48	50.97	90.30	160.98	55.30	53.10	6.14
Hybrid effect	Range	7.00-9.00	48.00-60.80	83.20-94.40	156.67-390.07	52.60-80.40	41.40-132.95	4.00-9.27
	Mean	8.47	53.99	90.14	227.72	63.60	73.25	6.02
	No. of promising hybrids	6	0	11	42	2	1	-
	Promising hybrids along with hybrid effect	VRCARH-213199 (7.00), VRCARH-233206 (7.00), VRCARH-23385 (7.33), VRCARH-241199 (7.67), VRCARH-234206 (7.67)	0	VRCARH-241199 (83.20), VRCARH-233199 (83.93), VRCARH-234199 (84.13), VRCARH-24185 (86.47), VRCARH-233206 (86.60)	VRCARH-27244 (390.07) VRCARH-234154 (310.49), VRCARH-23344 (305.87), VRCARH-241199 (285.78), VRCARH-23485 (284.13)	VRCARH-21285 (52.60), VRCARH-211206 (52.87)	VRCARH -272199 (41.40)	-
Better Parent Heterosis (BPH)	Mean (%)	13.36	0.57	-0.33	36.69	11.60	40.54	–6.69
	No. of promising hybrids	1	18	15	37	7	1	15
	Promising hybrids along with heterosis (%)	VRCARH-23385 (-12.00%)	VRCARH-212206 (-20.11%), VRCARH-214199 (-16.52%), VRCARH-234206 (-12.07%), VRCARH-23485 (-11.66%) VRCARH-21244 (-10.76%)	VRCARH-241199 (-8.64%), VRCARH-233199 (-6.74%), VRCARH-234199 (-6.73%), VRCARH-211154 (-4.98%), VRCARH-233206 (-4.90%).	VRCARH-27244 (119.39%), VRCARH-23444 (89.67%), VRCARH-212135 (79.06%), VRCARH-234154 (74.63%), VRCARH-23485 (71.79%)	VRCARH-211206 (-22.18), VRCARH-214206 (18.94%), VRCARH-21285 (13.68%), VRCARH-212206 (11.97%), VRCARH-234199 (-10.99%)	VRCARH -233154 (-15.07%)	VRCARH-21485 (-39.39), VRCARH-21144 (-35.42%), VRCARH-21385 (-31.91%), VRCARH-21285 (-29.70%), VRCARH-233206 (-26.37%)
Standard Heterosis (SH)	Mean (%)	2.41	10.86	-0.22	36.11	15.44	38.05	–21.99
	No. of promising hybrids	3	-	11	42	2	1	32
	Promising hybrids along with heterosis (%)	VRCARH-213199 (-16.37), VRCARH-23385 (-16.37%), VRCARH-23385 (-12.39%)	-	VRCARH-241199 (-8.03%), VRCARH-233199 (-7.22%), VRCARH-234199 (-7.00%), VRCARH-24185 (-4.42%), VRCARH-272135 (-4.35%)	VRCARH-27244 (133.11), VRCARH-234154 (85.55%), VRCARH-23344 (82.79%), VRCARH-241199 (70.79%), VRCARH-23485 (69.80%)	VRCARH-21185 (-6.07%), VRCARH-211206 (-5.59%)	VRCARH -272199 (-20.49%)	VRCARH-21485 (-45.45%), VRCARH-21144 (43.64%), VRCARH-21385 (-41.81%), VRCARH-212206 (-37.27%), VRCARH-233135 (-36.36%)

DTG: Days to germination, PH at 60 DAS: Plant height at 60 days after sowing (cm), DTH: Days to harvest, PH: Plant weight (cm), LL: Leaf length (cm), LW: Leaf weight (g), NL: Number of leaf

Table 4: Hybrid effects, better parent heterosis and standard heterosis for root and yield related traits in tropical carrot

Character	*Particular*	*RW*	*RL*	*SD*	*CW*	*HI*	*RCU*	*MY*
Parent	Range	88.93-118.47	13.93-25.50	3.24-4.09	1.26-1.94	63.56-69.53	96.77-99.67	269.26-358.71
	Mean	107.61	19.37	3.70	1.53	66.83	98.21	325.98
Hybrid effect	Range	101.40-216.33	15.00-27.40	3.19-6.29	0.83-1.98	55.77-81.09	93.50-99.53	307.24-625.05
	Mean	153.61	21.02	4.11	1.16	68.00	96.95	464.62
	No. of promising hybrids	37	3	-	-	3	-	48
	Promising hybrids along with hybrid effect	VRCARH-27244 (216.33), VRCARH-23344 (215.87), VRCARH-23385 (199.07), VRCARH-272199 (191.73), VRCARH-21185 (190.07)	VRCARH-211206 (27.40), VRCARH-21285 (26.80), VRCARH-272154 (26.80)	-	-	VRCARH-272199 (81.09), VRCARH-211199 (76.83), VRCARH-212206 (75.64)	-	VRCARH-27244 (625.05), VRCARH-23344 (624.38), VRCARH-23485 (603.17), VRCARH-21185 (575.90), VRCARH-21244 (568.13)
Better Parent Heterosis (BPH)	Mean (%)	40.76	-7.46	5.18	-35.30	-0.96	-2.74	31.64
	No. of promising hybrids	40	9	7	45	5	2	41
	Promising hybrids along with heterosis (%)	VRCARH-23344 (92.62%), VRCARH-27244 (86.28%), VRCARH-23485 (78.70%), VRCARH-272199 (73.67%), VRCARH-21185 (69.60%)	VRCARH-211154 (70.68%), VRCARH-213135 (48.18%), VRCARH-272154 (43.57%), VRCARH-21344 (25.86%), VRCARH-21285 (16.52%)	VRCARH-234199 (-22.15%), VRCARH-233135 (-18.43%), VRCARH-272135 (-18.20%), VRCARH-234135 (-17.92%) VRCARH-241154 (-14.60%)	VRCARH-233135 (-54.64%), VRCARH-21244 (-54.38%), VRCARH-21344 (-54.30%), VRCARH-214199 (-48.91%), VRCARH-211154 (-47.77%)	VRCARH-272199 (16.63%), VRCARH-212206 (12.85%), VRCARH-211199 (11.46%), VRCARH-21485 (9.50%), VRCARH-214135 (8.87%)	VRCARH-24144 (1.07%), VRCARH-214199 (1.01%)	VRCARH-23344 (83.88%), VRCARH-27244 (77.63%), VRCARH-23485 (78.70%), VRCARH-21185 (69.60%), VRCARH-212135 (68.59%)
Standard Heterosis (SH)	Mean (%)	42.42	-13.99	-5.02	-47.06	-1.80	-2.87	48.93
	No. of promising hybrids	36	3	9	47	5	1	44
	Promising hybrids along with heterosis (%)	VRCARH-27244 (88.77%), VRCARH-23344 (88.37%), VRCARH-23485 (73.71%), VRCARH-272199 (67.31%), VRCARH-21185 (65.85%)	VRCARH-211206 (14.80%), VRCARH-21285 (14.80%), VRCARH-272154 (12.29%)	VRCARH-234199 (-22.78%), VRCARH-234135 (-22.29%), VRCARH-272135 (-20.84%), VRCARH-233135 (-19.24%), VRCARH-272199 (-19.07%)	VRCARH-21244 (-57.22%), VRCARH-233135 (-54.80%), VRCARH-21344 (-54.44%), VRCARH-234135 (-54.13%), VRCARH-21444 (-52.75%)	VRCARH-272199 (18.24%), VRCARH-211199 (12.02%), VRCARH-212206 (10.29%), VRCARH-214199 (7.11%)	VRCARH-214199 (0.93%)	VRCARH-27244 (99.21%), VRCARH-23344 (98.99%), VRCARH-23485 (92.23%), VRCARH-21185 (83.54%), VRCARH-21244 (81.06%)

RW: Root weight (g), RL: Root length (cm), SD: Shoulder diameter (cm), CW: Core width (cm), HI: Harvest index (%), RCU: Root colour uniformity (%), MY: Marketable yield (q/ha)

(48.91%), VRCARH-211154 (-47.77%); and standard heterosis in 47 hybrids namely VRCARH-21244 (-57.22%), VRCARH-233135 (54.80%), VRCARH-21344 (-54.44%), VRCARH-234135 (-54.13%) and VRCARH-21444 (-52.75%). The result for core size is in accordance with the finding of Janani (2019). The negative heterosis for core width indicates that core size could be reduced, a most desirable trait, through heterosis breeding in carrot. The marketable yield in carrot refers to the amount of root that is suitable for sale or consumption, and it's generally considered the most valuable part of the total harvest. Appreciably higher better parent heterosis for marketable yield was realized 41 hybrids i.e. VRCARH-23344 (83.88%), VRCARH-27244 (77.63%), VRCARH-23485 (78.70%), VRCARH-21185 (69.60%), VRCARH-212135 (68.59%), VRCARH-241199 (62.19%) & VRCARH- 214206 (61.40%); and standard heterosis found in 44 hybrids such as VRCARH-27244 (99.21%), VRCARH-23344 (98.99%), VRCARH-23485 (92.23%), VRCARH-21185 (83.54%), VRCARH-21244 (81.06%), VRCARH-241199 (79.28%) & VRCARH-214206 (79.53%) among red, yellow and orange tropical carrots. The result is in conformity with the findings of Kravtsova (1979), Jagosz (2011), Janani (2019) and Reddy (2021). The presence of higher magnitude of heterosis over better parent and standard variety among carotenoid carrot hybrids enlightening that there is enough scope to increase the productivity of tropical carrot.

In conclusion, the significant differences of mean squares among parents and hybrids for various traits of economic importance indicated the presence of sufficient variation. Further, the hybrid mean of 48 cross-combinations is appreciably higher/desirable than parental mean for days to germination (13.2%), plant weight (41.5%), leaf length (15.0%), leaf weight (37.9%), root weight (42.7%), shoulder diameter (11.1%), core width (-24.2%) and marketable yield (42.5%) evidently demonstrating the presence of hybrid vigour and prospects for development of CMS-based potential heterotic hybrids in tropical carrot.

References

Anonymous (2020). NHB Database for Horticulture Crops (2018-19). National Horticulture Board, Government of India, Gurugram, Haryana, India.

Anonymous (2024). India Vegetable Seed Market Analysis. https://www.mordorintelligence.com/industry-reports/vegetable-seed-market-india.

Arunachalam, V. (1974). The fallacy behind the use of a modified line × tester design. Indian Journal of Genetics and Plant Breeding, 34: 280–287.

Behera, T. K, Devi, J., Tiwari, J. K. & Singh, B. K. (2023). Vegetable breeding: Status and strategies. Vegetable Science, 50(Special Issue), 131-145. doi.org/10.61180/vegsci.2023.v50.spl.01

Bunin, M. S., & Yoshikawa, H. (1989). Heterosis breeding in carrot in USSR and Japan. Japanese Journal of Breeding, 39(2), 235-241.

Chira, E., Sbirciog, G. & Badea, R. (2008). Manifestation intensity of the heterosis phenomenon for some chemical contents in some F_1 carrot hybrids (*Daucus carota* L.). *Bulletin of the University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca Horticulture,* 65(1), 465.

Coelho, F. G. T., Maciel, G. M., Siquieroli, A. C. S., de Oliveira, C. S., Parrella, N. N. L. D., da Silva, A. F., Luz, J. M. Q., Nogueira, A. P. O. (2024). Analysis of combining ability to obtain tropical carrot hybrids for production traits. Horticulturae, 10, 442. https://doi.org/10.3390/horticulturae10050442

Duan, Y., Wang, Y., Ren, X. & Du, G. (1996). Analysis of heterosis and combining ability for main yield characteristics in carrot. *China Vegetables*, 2, 13-15.

FAOSTAT (2023). https://www.fao.org/faostat/en/#data/QCL.

Frimmel, F. & Lauche, K. (1938). Heterosis— Versuehe an Karotten. Z Pflanzenzuchtg, 22, 469-481.

Gupta, A. J., Verma, T. S., Sethi, S. & Singh, G. (2006). Evaluation of European carrot genotypes including F_1 hybrids for their root quality, yield and nutritive characters. Indian Journal of Horticulture, 63(1), 48-52.

Hansche, P. E. & Gabelman, W. H. (1963). Digenic control of male sterility in carrots, *Daucus carota* L. Crop Science, 3, 383-386.

Iorizzo, M. (2013). Genetic structure and domestication of carrot (*Daucus carota* subsp. *sativus*) (Apiaceae). *American Journal of Botany,* 100, 930–938.

Jagosz, B. (2011). The relationship between heterosis and genetic distances based on RAPD and AFLP markers in carrot. Plant Breeding, 130(5), 574-579.

Jagosz, B. (2012). Combining ability of carrot (*Daucus carota* L.) lines and heritability of yield and its quality components. Folia Horticulturae, 24, 115.

Janani, R. (2019). *Heterosis and combining ability analysis using petaloid cytoplasmic male sterility in tropical carrot (Daucus carota L.)*. Master's thesis, ICAR-Indian Agricultural Research Institute, Pusa, New Delhi.

Janani, R., Sureja, A. K., Dey, S. S., Krishnan, S. G., Bhardwaj, R., Rudra, S. G., & Tomar, B. S. (2023). Selection of inbreds with better combining ability is instrumental in developing CMS-based heterotic hybrids in tropical carrot (*Daucus carota* L.). Plant Genetic Resources, 21(3), 237-247.

Kalia, P., Mangal, M., Singh, S., Chugh, C., Mishra, S. & Chaudhary, S. (2019). Morphological and molecular changes on cytoplasmic male sterility (CMS) introgression in Asiatic carrot (*Daucus carota* L.). Planta, 250, 507–518.

Kalia, P., Singh, B. K., Bhuvaneswari, S., Patel, V. & Selvakumar R. (2023). Carrot: Breeding and genomics. Vegetable Science, 50(Special Issue), 221-230. doi.org/10.61180/vegsci.2023.v50.spl.08

Kempthorne, O. (1957). An Introduction to Genetic Statistics. John Wiley and Sons, New York, pp. 468-471.

Kitagawa, J., Gerrath, J., Posluszny, U. & Wolyn, D. J. (1994). Developmental and morphological analysis of homeotic cytoplasmic male sterile and fertile carrot flowers. Sexual Plant Reproduction, 7, 41-50.

Kravtsova, M. V. (1979). Breeding carrot in Moldavia. Bulletin VIR, 90, 65-68.

Padmakara, S. (1991). Heterosis and combining ability studies in carrot (*Daucus carota* L.). PhD Thesis, University of Agricultural Sciences, Bangalore, Karnataka.

Poole, C. F. (1937). Improving the Root Vegetables. USDA Yearbook, pp 300-325.

Que, F., Hou, X. L., Wang, G. L., Xu, Tan, G. F., Li, T., Wang, Y. H., Khadr, A., & Xiong, A. S. (2019). Advances in research on the carrot, an important root vegetable in the Apiaceae family. Horticultural Research, 6, 69.

Reddy, D. J. (2021). *Assessment of combining ability and heterosis for yield and quality traits utilizing petaloid CMS inbreds in tropical carrot (Daucus carota L.).* Master's thesis, ICAR-Indian Agricultural Research Institute, Pusa, New Delhi.

Roth, E. (1981). Zur Problematik der Inzuchtwirkung bei Ausgangslinien der Speisemohre (*Daucus carota* L.). Tag.-Ber. Akad. Landwirtsch.-wiss. DDR Berlin, 191, 41-44.

Santos, C. A. F. & Simon, P. W. (2006). Heritabilities and minimum gene number estimates of carrot carotenoids. Euphytica, 151(1), 79-86.

Simon, P. W. & Strandberg, J. O. (1998). Diallel analysis of resistance in carrot to *Alternaria* leaf blight. Journal of American Society of Horticultural Science, 123, 412–415.

Singh, B. K. & Karmakar, P. (2015). Improved production technology for root crops. In: Improved Production Technologies in Vegetable Crops (Singh, N., Roy, S., Karmakar, P., Chaurasia, S. N. S., Gupta, S. & Singh, B. Eds.). IIVR Training Manual No. 59, ICAR-Indian Institute of Vegetable Research, Varanasi, pp. 120-133.

Singh, B. K. & Karmakar, P. (2021). Introgression of cytoplasmic male sterility (CMS) in tropical carrots (*Daucus carota* subsp. *sativus* Schubl. & Martens). Vegetable Science, 48(2), 203-208. doi.org/10.61180/vegsci.2021.v48.i2.12

Singh, B. K. & Karmakar, P. (2023). VRCAR-252 (INGR22088): Anthocyanin rich petaloid-CMS line of black carrot. Vegetable Science, 50(1), 129-130 doi.org/10.61180/vegsci.2023.v50.i1.20

Singh, B. K., Karmakar, P. & Bhuvaneswari, S. (2023). VRCAR-214 (INGR22160): A petaloid-CMS line of red coloured tropical carrot. Vegetable Science, 50(2), 289-291. doi.org/10.61180/vegsci.2023.v50.i2.19

Singh, B. K., Karmakar, P., Singh, P. M. & Singh, J. (2022). Exploring the phytochemical potential of purple carrot (*Daucus carota* L. subsp. *sativus* var. *atrorubens* Alef.) developed at ICAR-IIVR, Varanasi, UP. Vegetable Science, 49(2), 133-144. doi.org/10.61180/vegsci.2022.v49.i2.02

Singh, B. K., Sharma, S. R. & Singh, B. (2009). Heterosis for antioxidants and horticultural traits in single cross hybrids of cabbage (*Brassica oleracea* var. *capitata* L). Indian Journal of Agricultural Sciences, 79(9), 703-708.

Singh, R. K. & Chaudhary, B. D. (1997). Line × tester analysis. In: Biometrical Methods in Quantitative Genetic Analysis, Kalyani Publishers, Ludhiana, pp. 191-200.

Suh, Y. A., Arnold, R. S., Lassegue, B., Shi, J., Xu, X., Sorescu, D., & Lambeth, J. D. (1999). Cell transformation by the superoxide-generating oxidase Mox1. Nature, 401(6748), 79-82.

Thompson, D. J. (1962). Studies on the inheritance of male-sterility in the carrot, *Daucus carota* L. Proceedings of the American Society for Horticultural Science, 78, 332-338.

Turner, S. D., Maurizio, P. L., Valdar, W., Yandell, B. S. & Simon, P. W. (2018). Dissecting the genetic architecture of shoot growth in carrot using a diallel mating design. Genes Genomes Genetics, 8, 411-426.

Vavilov, N. I. (1951). The origin, variation, immunity, and breeding of cultivated plants. Chronica Botanica, 13, 1-366.

Verma, T. S., Sharma, S. C., & Lal, H. (2002). Heterosis in temperate carrot. Vegetable Science, 29(2), 119-122.

सारांश

गाजर विष्व स्तर पर सबसे महत्वपूर्ण सलाद सब्जियों में से एक है, क्योंकि यह पोशक तत्वों से भरपूर, स्वाद में रुचिकर और कीटनाषकों का कम प्रयोग होता है। हेटरोसिस प्रजनन और संकर किस्मों की खेती ने कई फसलों में उत्पादकता बढ़ाने, बेहतर फसल प्रबंधन और गुणवत्ता सुधारने में उल्लेखनीय भूमिका निभाई है। अतः गाजर में वृद्धि और उपज से संबंधित गुणों में नर-वन्ध्यता आधारित संकर किस्मों के बीच हेटरोसिस का आकलन करने के लिए 2022-2024 के दौरान क्षेत्रीय प्रयोग किए गए। आर्थिक दृश्टि से महत्वपूर्ण विभिन्न गुणों के लिए जनक संततियों और संकर किस्मों के बीच महत्वपूर्ण अंतर ने पर्याप्तद विविधता की उपस्थिति को दर्षाया। कुल मिलाकर 48 क्रॉस-संयोजनों का संकर औसत एवं जनक संततियों के औसत की तुलना में अंकुरण के दिनों (13.2ः), पौधे का वजन (41.5ः), पत्तियों की लंबाई (15.0ः), पत्तियों का वजन (37.9ः), जड़ का वजन (42.7ः), जड़ का व्यास (11.1ः), कोर की चौड़ाई (-24.2ः) और विपणन योग्य उपज (42.5ः) जैसे गुणों में उल्लेखनीय रूप से अधिकध्इच्छित पाया गया। यह स्पश्ट रूप से संकर-ओज की उपस्थिति और गाजर में ओज-प्रजनन की प्रकल्पनाओं को दर्षाता है। कुल मिलाकर, निम्नलिखित श्रेश्ठ संकर.संयोजनों जैसे VRCARH-23344, VRCARH-27244, VRCARH-23485, VRCARH-21185, VRCARH-212135, VRCARH-21244, VRCARH- 241199, VRCARH-214206 इत्यादि श्रेश्ठ पाए गए, तथा इस अध्ययन से यह निश्कर्श निकलता है कि उश्णकटिबंधीय गाजर में नरवन्ध्यता-आधारित उत्कृश्ट संकर किस्मों की विकास की अपार संभावनाएं हैं।