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RESEARCH ARTICLE

Assessment of heterosis and combining ability for enhancing quantitative traits in pumpkin (*Cucurbita moschata*)

Akhil Kumar Chaudhary[1], C N Ram[1], Aastik Jha[1], D K Upadhyay[1*], V P Chaudhary[2] & Nimit Singh[1]

[1]Department of Vegetable Science, Acharya Narendra Deva University of Agriculture and Technology, Kumarganj 224 229, Ayodhya, Uttar Pradesh, India
[2]Department of Genetics and Plant Breeding, Acharya Narendra Deva University of Agriculture and Technology, Kumarganj 224 229, Ayodhya, Uttar Pradesh, India

*Correspondence email - dhananjay.gpb2011@gmail.com

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Abstract

The research aimed to examine the quantitative characteristics of pumpkin (*Cucurbita moschata* Duch. ex Poir) among different genotypes and hybrid combinations. The research took place during 2024 and 2025 at the Main Experimental Station, Department of Vegetable Science, Acharya Narendra Deva University of Agriculture and Technology, Ayodhya, Uttar Pradesh. The study analysed with 13 characters of F_1 hybrids and parents evaluated using a randomized complete block design with three replications half diallel mating design. Promising parent genotypes Narendra Upkar, NDPK-23-7 and VRPK-2362 were identified based on them per se performance. The hybrid combination VRPK-2362 x Narendra Agrim, VRPK-2307-02 x Narendra Upkar and NDPK-23-7 x Narendra Amrit exhibited exceptional results in terms of relative heterosis, heterobeltiosis and standard heterosis. Parents NDPK-23-7 followed by VRPK-2307-02, VRPK-2362 and VRPK-23303 demonstrated strong general combining ability for several traits. Notably, specific combining ability analysis identified hybrids such as VRPK-2362 x Narendra Agrim followed by VRPK-2372 x Narendra Upkar and VRPK-23303 x Narendra Agrim as promising for multiple traits. The study highlights the significance of quantitative in *Cucurbita moschata* Duch. ex Poir and explores practical approaches for enhancing these attributes through hybrid breeding techniques. It underscores the potential of genetic improvement in developing superior pumpkin varieties with improved health benefits and consumer appeal.

Keywords: combining ability; heterosis; hybrid breeding; pumpkin; quantitative traits

Introduction

India ranks as the world's second-largest vegetable producer, with an annual output of 204.6 million tons from 11.28 million hectares, achieving a productivity rate of 18.1 tons per hectare (1). Being fortunate to possess diverse agro-climatic zones with distinct seasons, enabling the cultivation of a wide range of vegetables (2).

Pumpkin (*Cucurbita moschata* Duch. ex Poir) is one of India's most crucial Cucurbitaceous vegetable crops. It has attracted increasing attention from scientists due to its high nutritional profile and has a higher commercial value, primarily attributed to shifts in consumer patterns. Moreover, it requires fewer inputs for production. Pumpkin's fruits are rich in antioxidants such as ascorbic acid and β-carotene, which make it a highly nutritious vegetable. In addition to several fruit-related nutrients, the seeds have high concentrations of simple proteins, calcium, iron, potassium, phosphorus, magnesium, zinc and beta-carotene. Furthermore, seeds contain unsaturated fatty acids and dietary fiber, both of which promote heart health (3).

Both the immature and mature fruits are used in cooking. However, immature fruits are generally preferred over mature ones. Despite being a widespread crop, most hybrids released in India have large fruits (4-5 kg), which an ideal family comprising up to four members may not find appealing. Furthermore, consumers prefer to purchase only medium-sized pumpkin fruits rather than cut pieces due to the rising trend of nuclear families. Also, it is much easier to pack and transport small-sized fruits without any bruising. Focused crop improvement work is required to create a hybrid of medium-sized fruits (1-2 kg) that would be ideal for a nuclear family, minimizing waste (4).

The proven way to increase productivity and quality in the shortest time is through heterosis breeding, which is feasible with this crop and crucial to crop improvement. In breeding, heterosis refers to the phenomenon in which a hybrid possesses a stronger genetic makeup than its parents despite having a homogeneous genetic background. Pumpkin is a cross-pollinated, monoecious crop that produces large amounts of seeds per pollination. Its cultivation offers an excellent opportunity to harness its genetic diversity and enhance overall quality by developing high-quality hybrids. In practical crop breeding, knowing the general combining ability (GCA) and specific combining ability (SCA) is helpful in choosing the parents and makes the mode of gene action clear in a hybridization program (5). Furthermore, minimal effort has been invested in improving the genetic makeup of this crop, particularly in terms

of quality traits. This could result from a lack of genetically distant genotype collections. Therefore, the breeder must understand the type and extent of variability in the genetic stocks. A significant limitation to its production is the absence of high-yielding F_1 hybrids with desirable agronomic traits. This crop exhibits considerable genetic variability among its cultivated landraces, which can be leveraged to its advantage. Thus, the goal of a breeder is to use selection to create high-yielding varieties, either from the segregates of a cross or existing genotypes. Furthermore, the growing demand for higher crop productivity underscores the need to develop improved cultivars with superior agronomic traits. This can be accomplished by leveraging heterosis and combining ability analysis of the best-yielding pumpkin genotypes that have been optimized in agroecology (6). A knowledge of general combining ability (gca) and specific combining ability (sca) helps to make choice of the parents for the development of hybrid and to determine the nature of gene action as a basis of choosing an effective breeding strategy. The present investigation therefore was undertaken to identify potential parental combinations to have superior hybrids.

Materials and Methods

The study was conducted at the Main Experimental Station, Department of Vegetable Science, Acharya Narendra Deva University of Agriculture and Technology, Ayodhya, Uttar Pradesh, during the Zaid seasons of 2024 and 2025. The F_1 hybrids and parents were evaluated using a randomized complete block design with three replications in line x tester mating fashion. The site, located in a humid subtropical climate at 113 m altitude, has sandy-loam soil with moderate fertility and a pH of 7.5–8.5. Geographically, the experimental site falls under a humid subtropical climate and is located between 24.47° and 26.56°N latitude and 82.12° and 83.58°E longitude.

The genetic materials used in this study included 12 lines genotypes of pumpkin (*Cucurbita moschata* Duch. ex Poir) sown on *Ziad* 2023. The 12 parental lines *viz.*, VRPK-23302 (L1), VRPK-23303 (L2), VRPK- 2309 (L3), VRPK-2375 (L4), VRPK- 2301 (L5), VRPK- 2360 (L6), VRPK- 2322 (L7), VRPK-2372 (L8), VRPK- 2307-02 (L9), VRPK- 2362 (L10), VRPK- 2330 (L11) and NDPK-23-7 (L12) and the three testers *viz.*, Narendra Amrit (T1), Narendra Upkar (T2) and Narendra Agrim (T3) were crossed in a line x tester (L x T) mating design in the *Ziad* 2023 to obtain 36 F_1 hybrids. In 2 *Zaid* seasons of 2024 and 2025 seeds of the 12 parents, 3 testers and their 36 F_1 hybrids were evaluated with Anuj-VNR checks in the experimental design. for the study of heterobeltiosis and standard heterosis, combining ability effects and component of genetic variance among F_1's and parents for thirteen quantity parameters and yield attributing traits. All recommended package practices were followed.

Estimation of heterosis

The magnitude of heterosis was studied using information on various quantitative and fruit quality traits. Heterosis expressed as per cent increase or decrease in the mean values of F_1's (hybrid) over better-parent (heterobeltiosis) and standard variety (standard heterosis) (7). The formulas used for estimation of heterosis are as follows:

$$\text{Heterobeltiosis (\%)} = \frac{\overline{F}_1 - \overline{BP}}{\overline{BP}} \times 100$$

$$\text{Standard heterosis (\%)} = \frac{\overline{F}_1 - \overline{SV}}{\overline{SV}} \times 100$$

Whereas,

F_1 = Mean value of F_1

BP = Mean value of better parent

SV = Mean value of standard variety

The significance of heterosis was tested by 't' teat as given below:

$$\text{'t' (Heterobeltiosis)} = \frac{\overline{F}_1 - \overline{BP}}{SE}$$

$$\text{'t' (Standard heterosis)} = \frac{\overline{F}_1 - \overline{SV}}{SE}$$

SE of heterosis over better-parent and standard variety = $\sqrt{\frac{Me}{r}}$

Where,

Me = Error mean of square

r = Number of replications

SE = The standard error of the treatments mean and (t) is the table value of (t) at 5 % or 1 % level of significance at error of degree of freedom.

The calculated 't' value was compared with table value 't' at error d.f. at 5 % and 1 % level of probability for testing the significance of heterosis.

Combining ability variances and their effects

The combining ability analysis for different characters was carried out following the method 2 model 1 of (8), where parents and F_1's were included but not the reciprocals. Thus, the experimental material for this method comprises of n (n-1)/2 genotypes.

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

$$Y_{ij} = \mu + g_i + g_j + S_{ij} + \sum\sum e_{ijkl}$$

Where,

i, j = 1, 2, …, p (p = number of $\frac{1}{bc}$ parents involved in diallel)

K = 1, 2, ……, r (r = number of replications)

L = 1, 2, ……, c (c = number of observations taken in each plot)

μ = the population mean

gi, gj = gca effect of i^{th} and j^{th} parents, respectively

Sij = the interaction, *i.e.* the specific combining ability (sca) for the cross between i^{th} and j^{th} parents such that Sij = Sji.

eijkl = environmental effect associated with $ijkl^{th}$ observation

The restriction imposed on this mathematical model are:

$\sum_i g_i = 0$

$\sum_{ij} S_{ij} = 0$

Results and Discussion

Per se performance and heterosis (Table 1) results revealed significant and desirable variations in all the nutritional characteristics examined and the pooled mean value ranged between all the traits, viz. days to first staminate flower anthesis ranged from 40.65 to 45.70 for parents and 39.01 to 46.98 for hybrids. Days to first pistillate flower anthesis ranged from 45.12 to 49.05 for parents and 42.69 to 50.60 for hybrids. Node number to first staminate flower appearance ranged from 5.12 to 8.02 for parents and 4.73 to 8.72 for hybrids, while node number to first pistillate flower appearance ranged from 12.42 to 15.41 for parents and 10.07 to 16.45 for hybrids. Days to first fruit harvest ranged from 62.94 to 68.65 for parents and 60.31 to 71.90 for hybrids. Vine length (m) ranged from 3.95 to 4.42 for parents and 3.61 to 4.88 for hybrids. Number of primary branches per plant ranged from 4.16 to 22 for parents and 3.58 to 5.79 for hybrids. Fruit polar diameter (cm) ranged from 46.00 to 69.52 for parents and 44.74 to 62.71 for hybrids. Fruit equatorial circumference (cm) ranged from 46.89 to 55.02 for parents and 54.85 to 69.08 for hybrids. Average Fruit weight per plant (kg) ranged from 1.16 to 2.27 for parents and 1.45 to 2.73 for hybrids. Number of fruits per plant ranged from 3.41 to 4.54 for parents and 3.42 to 5.07 for hybrids. Flesh thickness (cm) ranged from 4.02 to 9.19 for parents and 4.94 to 13.84 for hybrids. Fruit yield per plant ranged from 4.02 to 9.19 kg for parents and 4.65 to 13.84 kg for hybrids.

Selecting parents solely based on their average performance does not yield optimal results. Therefore, we analyzed heterosis, combining ability and gene action for all the traits under investigation to identify the most superior parents (Table 2).

In the present study, the pooled mean data indicated varying degrees of heterosis (Table 2). The magnitude of heterobeltiosis for days to first staminate flower anthesis ranged from -10.72 (NDPK-23-7 x Narendra Amrit) to 9.61 % (VRPK-2307-02 x Narendra Agrim) over better parent while, for standard heterosis it varied from -09.63 (VRPK-23303 x Narendra Agrim) to 08.83 % (VRPK-2322 x Narendra Upkar). Out of 36 crosses, 10 crosses showed significant negative and 04 crosses showed positive heterosis over better parent whereas, 08 crosses showed significant negative and 06 crosses showed significant positive heterosis over standard variety. Among 36 crosses combination, best five crosses based on high negative value over better parent were NDPK-23-7 x Narendra Amrit (-10.72) followed by VRPK-2330 x Narendra Upkar (-8.78), VRPK-2307-02 x Narendra Amrit (-8.17), VRPK-2372 x Narendra Upkar (-7.45) and VRPK-2307-02 x Narendra Upkar (-7.43). Whereas, the best five crosses for negative heterosis over standard variety were VRPK-23303 x Narendra Agrim (-9.63) followed by NDPK-23-7 x Narendra Amrit (-8.32), VRPK-2362 x Narendra Agrim (-7.63), VRPK-2372 x Narendra Upkar (-7.54) and VRPK-2307-02 x Narendra Upkar (-7.52). F_1 hybrids outperformed their parental lines in terms of fruit number per plant, with observed ranges of 1.94 to 5.22 and 3.97 to 6.03, respectively. The variation in values across studies may be attributed to differences in the genetic makeup of the genotypes and the growing environments (9).

The magnitude of heterobeltiosis for days to first pistillate flower anthesis ranged from -11.29 (VRPK-2307-02 x Narendra Upkar) to 05.99 % (VRPK-23303 x Narendra Amrit) over better parent while, for standard heterosis it varied from -11.39 (VRPK-2307-02 x Narendra Upkar) to 5.03 % (VRPK-23303 x Narendra Amrit). Out of 36 crosses, 15 crosses showed significant negative and 6 crosses showed positive heterosis over better parent whereas, 15 crosses showed significant negative and 02 crosses showed significant positive heterosis over standard variety. Among 36 crosses combination, best five crosses based on high negative value over better parent were VRPK-2307-02 x Narendra Upkar (-11.29) followed by NDPK-23-7 x Narendra Amrit (-10.12), VRPK-2372 x Narendra Upkar (-09.60), VRPK-23303 x Narendra Agrim (-07.45) and VRPK-2360 x Narendra Agrim (-6.50). Whereas, the best five crosses for negative heterosis over standard variety were VRPK-2307-02 x Narendra Upkar (-11.39) followed by VRPK-23303 x Narendra Agrim (-10.64), NDPK-23-7 x Narendra Amrit (-09.79), VRPK- 2372 x Narendra Upkar (-09.70) and VRPK-2362 x Narendra Agrim (-09.55) (8).

The magnitude of heterobeltiosis for node number of first staminate flower appearance ranged from -40.98 (VRPK-2372 x Narendra Upkar) to 44.48 % (VRPK-2309 x Narendra Agrim) over better parent while, for standard heterosis it varied from -36.20 (VRPK-2372 x Narendra Upkar) to 17.51 % (VRPK-2309 x Narendra Agrim). Out of 36 crosses, 17 crosses showed significant negative and 10 crosses showed positive heterosis over better parent whereas, 16 crosses showed significant negative and 02 crosses showed significant positive heterosis over standard variety. Among 36 crosses combination, best five crosses based on high negative value over better parent were VRPK-2372 x Narendra Upkar (-40.98) followed by VRPK-2307-02 x Narendra Upkar (-31.63), VRPK-2301 x Narendra Upkar (-28.68), VRPK-23303 x Narendra Upkar (-25.64) and VRPK-2360 x Narendra Upkar (-25.60). whereas, the best five crosses for negative heterosis over standard variety were VRPK-2372 x Narendra Upkar (-36.20) followed by VRPK-2362 x Narendra Agrim (-32.87), VRPK-23303 x Narendra Agrim (-32.73), VRPK-2372 x Narendra Agrim (-29.81) and VRPK-2307-02 x Narendra Upkar (-26.09) (9).

The magnitude of heterobeltiosis for node number of first pistillate flower appearance ranged from -30.30 (VRPK-2372 x Narendra Upkar) to 15.32 % (VRPK-2307-02 x Narendra Agrim) over better parent while, for standard heterosis it varied from -20.49 (VRPK-2372 x Narendra Upkar) to 29.86 % (VRPK-2360 x Narendra Amrit). Out of 36 crosses, 16 crosses showed significant negative and 03 crosses showed positive heterosis over better parent whereas, 07crosses showed significant negative and 16 crosses showed significant positive heterosis over standard variety. Among 36 crosses combination, best five crosses based on high negative value over better parent were VRPK-2372 x Narendra Upkar (-30.30) followed by VRPK-2330 x Narendra Agrim (-28.16), NDPK-2322 x Narendra Upkar (-27.04), NDPK-23-7 x Narendra Amrit (-2228) and VRPK-2322 x Narendra Amrit (-20.30). Whereas the best five crosses for negative heterosis over standard variety were VRPK-2372 x Narendra Upkar (-20.49) followed by VRPK-2322 x Narendra Upkar (-15.14), VRPK-2362 x Narendra Agrim (-13.86), VRPK- 2330 x Narendra Agrim (-12.59) and VRPK-2360 x Narendra Agrim (-12.18) (9).

The magnitude of heterobeltiosis for days to first fruit harvest ranged from -09.29 (VRPK-2322 x Narendra Amrit) to 05.81 % (VRPK-2362 x Narendra Upkar) over better parent while, for standard heterosis it varied from -07.42 (VRPK-2372 x Narendra Upkar) to 10.38 % (VRPK-2301 x Narendra Agrim). Out

Table 1. Pooled per se performance of parents, hybrids and standard check for quantitative traits

	Days to first staminate flower anthesis	Days to first pistillate flower anthesis	Node number to first staminate flower appearance	Node number to first pistillate flower appearance	Days to first fruit harvest	Vine length (m)	Number of primary branches per plant	Fruit polar diameter (cm)	Fruit equatorial circumference (cm)	Average Fruit weight per plant (kg)	Number of fruits per plant	Flesh thickness (cm)	Fruit yield/ plant (kg)
Range (Parents)	40.65 to 45.70	45.12 to 49.05	5.12 to 8.02	12.42 to 15.41	62.94 to 68.65	3.95 to 4.42	4.16 to 22	46.00 to 69.52	46.89 to 55.02	1.16 to 2.27	3.41 to 4.54	3.35 to 5.91	4.02 to 9.19
Mean	42.66	47.35	6.42	13.72	66.14	4.27	4.76	53.25	51.76	1.90	3.95	4.39	7.88
Parents (Best)	Narendra Agrim, VRPK-2307-02, NDPK-2372	Narendra Agrim, VRPK-2307-02, NDPK-2372	VRPK-2372, Narendra Agrim, VRPK-2307-02	VRPK-2372, VRPK-2362, VRPK-2307-02	VRPK-2307-02, VRPK-2372, VRPK-23303	Narendra Agrim, VRPK-23303, VRPK-2309	Narendra Agrim, VRPK-2307-02, VRPK-23303	VRPK-23303, NDPK-23-7, Narendra Agrim	VRPK-2362, VRPK-23303, VRPK-2307-02	VRPK-2322, VRPK-2375, VRPK-2362	VRPK-23303, VRPK-2309, VRPK-2307-2	Narendra Amrit, VRPK-2362, VRPK-2372	Narendra Upkar, NDPK-23-7, VRPK-2362
Range (Hybrids)	39.01 to 46.98	42.69 to 50.60	4.73 to 8.72	10.07 to 16.45	60.31 to 71.90	3.61 to 4.88	3.58 to 5.79	44.74 to 62.71	54.85 to 69.8, 5	1.45 to 2.73	3.42 to 5.07	3.62 to 5.36	4.94 to 13.84
Mean	43.07	47.09	6.71	13.33	66.32	4.29	4.75	53.36	58.26	1.92	4.14	4.62	8.26
Hybrid (Best)	VRPK-23303 x Narendra Agrim, NDPK-23-7 x Narendra Agrim, VRPK-2362 x Narendra Agrim	VRPK-2307-02 x Narendra Upkar, VRPK-23303 x Narendra Agrim, NDPK-23-7 x Narendra Amrit	VRPK-2372 x Narendra Upkar, VRPK-2362 x Narendra Agrim, VRPK-2372 x Narendra Agrim	VRPK-2372 x Narendra Upkar, VRPK-2322 x Narendra Upkar, VRPK-2362 x Narendra Agrim	VRPK-2372 x Narendra Upkar, VRPK-2362 x Narendra Agrim, NDPK-23-7 x Narendra Amrit	VRPK-2372 x Narendra Upkar, VRPK-2307-02 x Narendra Upkar, VRPK-2362 x Narendra Agrim	VRPK-2362 x Narendra Agrim, VRPK-2307-02 x Narendra Upkar, NDPK-23-7 x Narendra Amrit	NDPK-23-7 x Narendra Amrit, NDPK-23-7 x Narendra Upkar, NDPK-23-7 x Narendra Agrim	VRPK-2372 x Narendra Upkar, VRPK-2362 x Narendra Agrim, VRPK-23303 x Narendra Agrim	VRPK-2362 x Narendra Agrim, VRPK-2307-02 x Narendra Upkar, VRPK-2307-02 x Narendra Amrit	VRPK-2362 x Narendra Agrim, VRPK-23303 x Narendra Agrim, NDPK-23-7 x Narendra Amrit	VRPK-2372 x Narendra Upkar, VRPK-2307-02 x Narendra Upkar, NDPK-23-7 x Narendra Amrit	VRPK-2362 x Narendra Agrim, VRPK-2307-02 x Narendra Upkar, NDPK-23-7 x Narendra Amrit
Mean (Check)	42.95	47.17	6.62	13.44	66.26	4.37	4.52	52.10	59.48	1.77	4.28	4.69	8.98
SEM±	0.74	0.70	0.27	0.56	1.08	0.12	0.13	1.60	1.78	0.05	0.13	0.16	0.26
CD (5 %)	1.48	1.40	0.53	0.92	2.15	0.25	0.25	3.18	3.54	0.10	0.26	0.27	0.52

Table 2. Heterosis, top performing general and specific combiner for quantitative traits in pumpkin

	Days to first staminate flower anthesis	Days to first pistillate flower anthesis	Node number to first staminate flower appearance	Node number to first pistillate flower appearance	Days to first fruit harvest	Vine length (m)	Number of primary branches per plant	Fruit polar diameter (cm)	Fruit equatorial circumference (cm)	Average Fruit weight per plant (kg)	Number of fruits per plant	Flesh thickness (cm)	Fruit yield/ plant (kg)
Heterobeltiosis Range (%)	-10.72 to 9.61	-11.29 to 5.99	-40.98 to 44.48	-30.30 to 15.32	-9.29 to 5.81	-16.95 to 13.53	-30.08 to 10.98	-27.54 to 11.49	2.27 to 31.23	-35.60 to 30.00	-21.86 to 30.84	-26.39 to 16.60	-42.00 to 58.09
Heterobeltiosis (No.)	10	15	17	16	14	6	5	6	30	10	13	14	11
Hybrid (Best)	NDPK-23-7 x Narendra Amrit followed by VRPK-2330 x Narendra Upkar, VRPK-2307-02 x Narendra Amrit, VRPK-2372 x Narendra Upkar	VRPK-2307-02 x Narendra Upkar followed by NDPK-23-7 x Narendra Amrit, VRPK-2372 x Narendra Upkar, VRPK-23303 x Narendra Agrim and VRPK-2360 x Narendra Agrim	VRPK-2372 x Narendra Upkarfollowed by VRPK-2307-02 x Narendra Upkar, VRPK-2301 x Narendra Upkar, VRPK-23303 x Narendra Upkar and VRPK-2360 x Narendra Upkar	VRPK-2372 x Narendra Upkar followed by VRPK-2330 x Narendra Agrim, NDPK-2322 x Narendra Upkar, NDPK-23-7 x Narendra Amrit and VRPK-2322 x Narendra Amrit	VRPK-2322 x Narendra Amrit followed by VRPK-2360 x Narendra Upkar, NDPK-23-7 x Narendra Amrit, VRPK-2362 x Narendra Agrim and VRPK-2372 x Narendra Upkar	NDPK-23-7 x Narendra Amrit followed by VRPK-2307-02 x Narendra Upkar, VRPK-2372 x Narendra Upkar, VRPK-2362 x Narendra Agrim and VRPK-23303 x Narendra Agrim	VRPK-2362 x Narendra Agrim followed by NDPK-23-7 x Narendra Amrit, VRPK-2307-02 x Narendra Upkar, VRPK-2372 x Narendra Upkar and VRPK-23303 x Narendra Agrim	NDPK-23-7 x Narendra Amrit followed by VRPK-2307-02 x Narendra Upkar, VRPK-2330 x Narendra Amrit, NDPK-23-7 x Narendra Upkar and VRPK-2372 x Narendra Upkar	VRPK-2372 x Narendra Upkar followed by NDPK-23-7 x Narendra Amrit, VRPK-2301 x Narendra Agrim, VRPK-2322 x Narendra Agrim and VRPK-2322 x Narendra Amrit	VRPK-2362 x Narendra Agrim followed by NDPK-23-7 x Narendra Amrit, VRPK-2307-02x Narendra Upkar, VRPK-2307-02 x Narendra Amrit and VRPK-23303 x Narendra Agrim	NDPK-23-7 x Narendra Amrit followed by NDPK-2322 x Narendra Agrim, VRPK-2362 x Narendra Agrim, NDPK-23-7 x Narendra Agrim and VRPK-2372 x Narendra Upkar	VRPK-2330 x Narendra Agrim followed by VRPK-2372 x Narendra Upkar, VRPK-2307-02 x Narendra Upkar, VRPK-2322 x Narendra Agrim and VRPK-2322 x Narendra Upkar	VRPK-2362 x Narendra Agrim, VRPK-23303 x Narendra Agrim, NDPK-23-7 x Narendra Amrit
Standard heterosis Range (%)	-9.63 to 8.83	-11.39 to 5.03	-36.20 to 17.51	-20.49 to 29.86	-7.42 to 10.38	-17.30 to 11.87	-20.92 28.02	-14.12 to 20.37	-7.77 to 17.44	-17.91 to 54.24	-19.93 to 18.59	-30.91 to 14.31	-44.82 to 54.22
Standard heterosis (No.)	8	15	16	7	6	5	14	7	9	18	5	4	07

Hybrid (Best)	VRPK-23303 x Narendra Agrim followed by NDPK-23-7 x Narendra Amrit, VRPK-2362 x Narendra Agrim,VRPK-2372 x Narendra Upkar and VRPK-2307-02 x Narendra Upkar	VRPK-2307-02 x Narendra Upkar followed by VRPK-23303 x Narendra Agrim, NDPK-23-7 x Narendra Amrit,VRPK-2372 x Narendra Upkar and VRPK-2362 x Narendra Agrim	VRPK-2372 x Narendra Upkar followed by VRPK-2362 x Narendra Agrim, VRPK-23303 x Narendra Agrim,VRPK-2372 x Narendra Agrim and VRPK-2307-02 x Narendra Upkar	VRPK-2372 x Narendra Upkar followed by VRPK-2322 x Narendra Upkar, VRPK-2362 x Narendra Agrim, VRPK-2330 x Narendra Agrim and VRPK-2360 x Narendra Agrim	VRPK-2372 x Narendra Upkar followed by VRPK- 2362 x Narendra Agrim, NDPK-23-7 x Narendra Agrim, VRPK-2322 x Narendra Amrit and VRPK-23303 x Narendra Agrim	VRPK-2307-02 x Narendra Upkar followed by VRPK-2372 x Narendra Upkar, VRPK-2362 x Narendra Agrim, VRPK-23303 x Narendra Agrim and NDPK-23-7 x Narendra Amrit	VRPK-2362 x Narendra Agrim followed by VRPK-2307-02 x Narendra Upkar, NDPK-23-7 x Narendra Amrit, VRPK-2372 x Narendra Upkar and VRPK-23303 x Narendra Agrim	NDPK-23-7 x Narendra Amrit followed by NDPK-23-7 x Narendra Upkar, NDPK-23-7 x Narendra Agrim, VRPK-2372 x Narendra Upkar and VRPK-2307-02 x Narendra Upkar	VRPK-2372 x Narendra Upkar followed by VRPK-2362 x Narendra Agrim, VRPK-23303 x Narendra Agrim, NDPK-23-7 x Narendra Amrit and VRPK-2307-02 x Narendra Upkar	VRPK-2362 x Narendra Agrim followed by VRPK-2307-02 x Narendra Upkar, NDPK-23-7 x Narendra Amrit, VRPK-23303 x Narendra Agrim and VRPK-2372 x Narendra Upkar	VRPK-2362x Narendra Agrim followed by VRPK-23303 x Narendra Agrim, NDPK-23-7 x Narendra Amrit, VRPK-2307-02 x Narendra Upkar and VRPK-2372 x Narendra Upkar	VRPK-2372 x Narendra Upkar followed by VRPK-2307-02 x Narendra Upkar, NDPK-23-7 x Narendra Amrit and VRPK-2362 x Narendra Agrim	VRPK-2362 x Narendra Agrim, VRPK-2307-02 x Narendra Upkar, NDPK-23-7 x Narendra Amrit
GCA effects Parents (No.)	2	2	5	4	3	2	5	1	3	5	4	4	05
Parents (Best)	NDPK-23-7, VRPK-2307-02	VRPK-2372, NDPK-23-7	NDPK-2372, VRPK-2330, NDPK-23-7, VRPK-23303, VRPK-2360	VRPK-2372, VRPK-2322, VRPK-2330, VRPK-2375	VRPK-2307-02, VRPK-2360, NDPK-23-7	VRPK-2372, NDPK-23-7	VRPK-2307-02, NDPK-23-7, VRPK-2372, VRPK-23303, VRPK-2362	NDPK-23-7	VRPK-23303, VRPK-2372, VRPK-2322	NDPK-23-7, VRPK-2362, VRPK-2307-02, VRPK-23303, VRPK -2322	VRPK-2307-02, NDPK-23-7, VRPK-2362, VRPK-2322	VRPK-2307-02, NDPK-23-7, VRPK-2372 VRPK-2362	VRPK-23303, VRPK- 2322, VRPK- 2307-02, VRPK- 2362
SCA effects Hybrids (No.)	7	6	12	11	11	9	10	5	5	12	8	3	10
Hybrids (Best)	VRPK-23303 X NARENDRA AGRIM, VRPK-2372 X NARENDRA UPKAR, VRPK-2362 X NARENDRA AGRIM	NDPK-23-7 X NARENDRA AMRIT VRPK-23303 X NARENDRA AGRIM VRPK-2307-02 X NARENDRA UPKAR	VRPK-2362 X NARENDRA AGRIM VRPK-23302 X NARENDRA AMRIT NDPK-23-7 X NARENDRA AMRIT	VRPK-2360 X NARENDRA AGRIM VRPK-2307-02 X NARENDRA UPKAR NDPK-23-7 X NARENDRA AMRIT	VRPK-2372 X NARENDRA UPKAR VRPK-2322 X NARENDRA AMRIT VRPK-2362 X NARENDRA AGRIM	VRPK-2307-02 X NARENDRA UPKAR VRPK-2362 X NARENDRA AGRIM VRPK-23302 X NARENDRA AMRIT	VRPK-2362 X NARENDRA AGRIM NDPK-23-7 X NARENDRA AMRIT VRPK-23303 X NARENDRA AGRIM	VRPK-2372 X NARENDRA AGRIM VRPK-2307-02 X NARENDRA UPKAR VRPK-2372 X NARENDRA AMRIT	NDPK-23-7 X NARENDRA AMRIT VRPK-2362 X NARENDRA AGRIM VRPK-2307-02 X NARENDRA UPKAR	VRPK-2362 X NARENDRA AGRIM VRPK-2372 X NARENDRA UPKAR VRPK-2360 X NARENDRA AMRIT	VRPK-23303 X NARENDRA AGRIM VRPK-2362 X NARENDRA AGRIM NDPK-23-7 X NARENDRA AMRIT	NDPK-23-7 X NARENDRA AMRIT VRPK-2309 X NARENDRA UPKAR VRPK-2372 X NARENDRA UPKAR	VRPK-23302 X N. AGRIM, VRPK-23303 X N. AGRIM VRPK-2309 X N. AMRIT

of 36 crosses, 14 crosses showed significant negative and 07 crosses showed positive heterosis over better parent whereas, 06 crosses showed significant negative and 15 crosses showed significant positive heterosis over standard variety. Among 36 crosses combination, best five crosses based on high negative value over better parent were VRPK-2322 x Narendra Amrit (-09.29) followed by VRPK-2360 x Narendra Upkar (-09.01), NDPK-23-7 x Narendra Amrit (-07.52), VRPK-2362 x Narendra Agrim (-07.39) and VRPK-2372 x Narendra Upkar (-07.00) whereas, the best five crosses for negative heterosis over standard variety were VRPK-2372 x Narendra Upkar (-07.42) followed by VRPK-2362 x Narendra Agrim (-05.66), NDPK-23-7 x Narendra Agrim (-05.63), VRPK-2322 x Narendra Amrit (-05.50) and VRPK-23303 x Narendra Agrim (-05.28) (9-12).

The magnitude of heterobeltiosis for vine length ranged from -16.95 (VRPK-2301 x Narendra Upkar) to 13.53 % (NDPK-23-7 x Narendra Amrit) over better parent while, for standard heterosis it varied from -17.30 (VRPK-2301 x Narendra Upkar) to 11.87 % (VRPK-2307-02 x Narendra Upkar). Out of 36 crosses, 9 crosses showed significant negative and 6 crosses showed positive heterosis over better parent whereas, 6 crosses showed significant negative and 05 crosses showed significant positive heterosis over standard variety. Among 36 crosses combination, best five crosses based on high positive value over better parent were NDPK-23-7 x Narendra Amrit (13.53) followed by VRPK-2307 -02 x Narendra Upkar (12.43), VRPK-2372 x Narendra Upkar (11.85), VRPK-2362 x Narendra Agrim (10.04) and VRPK-23303 x Narendra Agrim (08.23) whereas, the best five crosses for positive heterosis over standard variety were VRPK-2307-02 x Narendra Upkar (11.87) followed by VRPK-2372 x Narendra Upkar (11.73), VRPK-2362 x Narendra Agrim (11.34), VRPK-23303 x Narendra Agrim (9.51) and NDPK-23-7 x Narendra Amrit (9.58) (8).

The magnitude of heterobeltiosis for number of primary branches per plant ranged from -30.01 (VRPK-2360 x Narendra Amrit) to 10.98 % (VRPK-2362 x Narendra Agrim) over better parent while, for standard heterosis it varied from -20.92 (VRPK-2360 x Narendra Amrit) to 28.08 % (VRPK-2362 x Narendra Agrim). Out of 36 crosses, 23 crosses showed significant negative and 5 crosses showed positive heterosis over better parent whereas, 3 crosses showed significant negative and 14 crosses showed significant positive heterosis over standard variety. Among 36 crosses combination, best five crosses based on high positive value over better parent were VRPK-2362 x Narendra Agrim (10.98) followed by NDPK-23-7 x Narendra Amrit (10.96), VRPK-2307-02 x Narendra Upkar (9.15), VRPK-2372 x Narendra Upkar (7.21) and VRPK-23303 x Narendra Agrim (6.13) whereas, the best five crosses for positive heterosis over standard variety were VRPK-2362 x Narendra Agrim (28.08) followed by VRPK-2307-02 x Narendra Upkar (25.64), NDPK-23-7 x Narendra Amrit (25.36), VRPK-2372 x Narendra Upkar (22.70) and VRPK-23303 x Narendra Agrim (22.48) (9).

The magnitude of heterobeltiosis for fruit polar diameter ranged from -27.54 (VRPK-23303 x Narendra Amrit) to 11.49 % (NDPK-23-7 x Narendra Amrit) over better parent while, for standard heterosis it varied from -14.12 (VRPK-2372 x Narendra Agrim) to 20.37 % (VRPK-23-7 x Narendra Amrit). Out of 36 crosses, 14 crosses showed significant negative and 6 crosses showed positive heterosis over better parent whereas, 2 crosses showed significant negative and 7 crosses showed significant positive heterosis over standard variety. Among 36 crosses combination, best five crosses based on high positive value over better parent were NDPK-23-7 x Narendra Amrit (11.49) followed by VRPK-2307-02 x Narendra Upkar(8.72), VRPK-2330 x Narendra Amrit (8.42), NDPK-23-7 x Narendra Upkar (7.39) and VRPK-2372 x Narendra Upkar (6.63) whereas, the best crosses for positive heterosis over standard variety were NDPK-23-7 x Narendra Amrit (20.37) followed by NDPK-23-7 x Narendra Upkar (15.94), NDPK-23-7 x Narendra Agrim (14.35), VRPK-2372 x Narendra Upkar (12.17) and VRPK-2307-02 x Narendra Upkar (10.24) (9).

The magnitude of heterobeltiosis for fruit equatorial circumference ranged from 2.27 (VRPK-2307-02 x Narendra Agrim) to 31.23 % (VRPK-2372 x Narendra Upkar) over better parent while, for standard heterosis it varied from -7.77 (NDPK-23 -7 x Narendra Agrim) to 17.44 % (VRPK-2372 x Narendra Upkar). Out of 36 crosses, 0 crosses showed significant negative and 30 crosses showed positive heterosis over better parent whereas, 4 crosses showed significant negative and 09 crosses showed significant positive heterosis over standard variety. Among 36 crosses combination, best five crosses based on high positive value over better parent were VRPK-2372 x Narendra Upkar (31.23) followed by NDPK-23-7 x Narendra Amrit (29.52), VRPK-2301 x Narendra Agrim (25.19), VRPK-2322 x Narendra Agrim (23.88) and VRPK-2322 x Narendra Amrit (23.79) whereas, the best five crosses for positive heterosis over standard variety were VRPK-2372 x Narendra Upkar (17.44) followed by VRPK-2362 x Narendra Agrim (13.28), VRPK-23303 x Narendra Agrim (13.23), NDPK-23-7 x Narendra Amrit (13.07) and VRPK-2307-02 x Narendra Upkar (12.55) (9).

The magnitude of heterobeltiosis for average fruit weight per plant ranged from -35.60 (VRPK-2375x Narendra Amrit) to 30.00 % (VRPK-2362 x Narendra Agrim) over better parent while, for standard heterosis it varied from -17.91 (NDPK-2375 x Narendra Amrit) to 54.24 % (VRPK-2362 x Narendra Agrim). Out of 36 crosses, 21 crosses showed significant negative and 10 crosses showed positive heterosis over better parent whereas, 8 crosses showed significant negative and 18 crosses showed significant positive heterosis over standard variety. Among 36 crosses combination, best five crosses based on high positive value over better parent were VRPK-2362 x Narendra Agrim (30.00) followed by NDPK-23-7 x Narendra Amrit (26.04), VRPK-2307-02x Narendra Upkar (24.54), VRPK-2307-02 x Narendra Amrit (21.30) and VRPK-23303 x Narendra Agrim (19.40) whereas, the best five crosses for positive heterosis over standard variety were VRPK-2362 x Narendra Agrim (54.24) followed by VRPK-2307-02 x Narendra Upkar (45.20), NDPK-23-7 x Narendra Amrit (36.72), VRPK-23303 x Narendra Agrim (34.46) and VRPK-2372 x Narendra Upkar (32.37). The fruit number per plant provides a more reliable estimate of potential yield and modifying this trait can lead to direct yield improvement. Hence, selection should emphasize fruit quantity over fruit size to achieve enhanced productivity (9, 13).

The magnitude of heterobeltiosis for number of fruits per plant ranged from -21.86(VRPK-23303 x Narendra Upkar) to 30.84 % (NDPK-23-7 x Narendra Amrit) over better parent while, for standard heterosis it varied from -19.93 (VRPK-2375 x Narendra Amrit) to 18.59 % (VRPK-2362 x Narendra Agrim). Out of 36 crosses, 06 crosses showed significant negative and 13 crosses showed positive heterosis over better parent whereas, 11 crosses

showed significant negative and 05 crosses showed significant positive heterosis over standard variety. Among 36 crosses combination, best five crosses based on high positive value over better parent were NDPK-23-7 x Narendra Amrit (30.84) followed by NDPK-2322 x Narendra Agrim (24.14), VRPK-2362 x Narendra Agrim (20.52), NDPK-23-7 x Narendra Agrim (17.26) and VRPK-2372 x Narendra Upkar (16.61) whereas, the best five crosses for positive heterosis over standard variety were VRPK-2362x Narendra Agrim (18.59) followed by VRPK-23303 x Narendra Agrim (17.82), NDPK-23-7 x Narendra Amrit (16.09), VRPK-2307-02 x Narendra Upkar (14.15) and VRPK-2372 x Narendra Upkar (12.21) (9, 14).

The magnitude of heterobeltiosis for flesh thickness ranged from -26.39 (VRPK-2309 x Narendra Amrit) to 16.60 % (VRPK-2330 x Narendra Agrim) over better parent while, for standard heterosis it varied from -22.91 (VRPK-2309 x Narendra Amrit) to 14.31 % (VRPK-2372 x Narendra Upkar). Out of 36 crosses, 06 crosses showed significant negative and 14 crosses showed positive heterosis over better parent whereas, 02 crosses showed significant negative and 04 crosses showed significant positive heterosis over standard variety. Among 36 crosses combination, best crosses based on high positive value over better parent were VRPK-2330 x Narendra Agrim (16.60) followed by VRPK-2372 x Narendra Upkar (13.87), VRPK-2307-02 x Narendra Upkar (13.71), VRPK-2322 x Narendra Agrim (12.69) and VRPK-2322 x Narendra Upkar (08.18) (16 & 24). The best crosses for positive heterosis over standard variety were VRPK-2372 x Narendra Upkar (14.31) followed by VRPK-2307-02 x Narendra Upkar (12.54), NDPK-23-7 x Narendra Amrit (11.96) and VRPK-2362 x Narendra Agrim (11.42) (9, 14).

The magnitude of heterobeltiosis for fruit yield per plant ranged from -42.00 (VRPK-2375 x Narendra Amrit) to 58.09 % (VRPK-2362 x Narendra Agrim) over better parent while, for standard heterosis it varied from -44.82 (VRPK-2375 x Narendra Amrit) to 54.22 % (VRPK-2362 x Narendra Agrim). Among 36 crosses combination, best five crosses based on high positive value over better parent were VRPK-2362 x Narendra Agrim (58.09) followed by VRPK-23303 x Narendra Agrim (38.05), NDPK-23-7 x Narendra Amrit (37.28), VRPK-2307-02 x Narendra Upkar (36.62) and VRPK-2372 x Narendra Upkar (22.12) whereas, the best five crosses for positive heterosis over standard variety were VRPK-2362 x Narendra Agrim (54.22) followed by VRPK-2307-02 x Narendra Upkar (39.93), NDPK-23-7 x Narendra Amrit (34.84), VRPK-23303 x Narendra Agrim (33.39) and VRPK-2372 x Narendra Upkar (25.08). Significant heterosis in pumpkins relative to standard and superior parents for yield per plant, dry matter content, average fruit weight, flesh thickness and fruit number. heterosis for fruit yield and the number of fruits per plant is often positively correlated, reinforcing the conclusion that fruit weight, size and number are major contributors to overall yield (15-17). The extent of heterosis observed is strongly influenced by both the genetic composition of the parental lines and environmental interactions (5, 9, 13, 14, 18-26).

Combining ability

In case of pooled, among lines significant and negative gca effects were observed for NDPK-23-7 (-1.45) and VRPK-2307-02 (-1.34) for days to first staminate flower anthesis. Lines significant and negative gca effects were observed for VRPK-2372 (-1.09) and NDPK- 2307 (-0.75). Thus, among the parents Narendra Agrim (-0.67) and Narendra Upkar (-0.36) were found good general combiner for days to first female flower anthesis. The lines significant and negative gca effects were recorded for NDBG - 25(-1.08) followed by VRPK- 2372 (-0.85) followed by VRPK-2330 (-0.66), NDPK- 2307 (-0.56), VRPK-23303(-0.44) and VRPK-2360 (-0.43). However, two parent among testers Narendra Agrim (-0.29) and Narendra Upkar (-0.17) exhibited significant and negative gca effects for node number to first staminate flower appearance. Among lines VRPK-2372 (-1.55) followed by VRPK-2322 (-1.43), VRPK-2330(-0.77) and VRPK-2375(-0.51) exhibited significant and negative gca effects for node number to first pistillate flower appearance. However, one parent among testers Narendra Agrim (-0.40) exhibited significant and negative gca effects for node number to first pistillate flower appearance. The lines VRPK-2307-02 (-2.08), VRPK-2360 (-2.06) and NDPK-23-7 (-1.35) exhibited significant and negative gca effects for days to first harvest. However, one parent among testers Narendra Agrim (-0.56) exhibited significant and negative gca effects for days to first harvest. Among lines VRPK-2372 (0.27) followed by NDPK 23-7 (0.27) exhibited significant and positive gca effects for vine length (m). The lines VRPK-2307-02 (0.51) followed by NDPK 23-7 (0.48), VRPK-2372 (0.36), VRPK -23303 (0.24) and VRPK-2362 (0.24) exhibited significant and positive gca effects for number of primary branches per plant. However, two parents among testers Narendra Agrim (0.10) and Narendra Upkar (0.10) exhibited significant and positive gca effects for primary branches per plant. Among lines NDPK-23-7 (8.05) exhibited significant and positive gca effects for fruit polar diameter (cm). among lines VRPK-23303 (4.14) followed by VRPK-2372 (3.43) and VRPK-2322 (2.15) exhibited significant and positive gca effects for fruit equatorial circumference (cm). Among lines NDPK 23-7 (0.40) followed by VRPK-2362 (0.27), VRPK-2307-02 (0.25), VRPK -23303 (0.18) and VRPK-2322 (0.12) exhibited significant and positive gca effects for average fruit weight per plant (Kg). However, one parent among testers Narendra Upkar (0.04) exhibited significant and positive gca effects for average fruit weight per plant (Kg). Among lines VRPK 2307-02 (0.52) followed by NDPK-23-7 (0.34), VRPK-2362 and VRPK-2322 (0.17) exhibited significant and positive gca effects number fruit per plant. However, one parent among testers Narendra Agrim (0.09) exhibited significant and positive gca effects for number fruit per plant. Lines VRPK 2307-02 (0.28) followed by NDPK-23-7 (0.26), VRPK -2372 (0.24) and VRPK-2362 (0.20) exhibited significant and positive gca effects flesh thickness. However, one parent among testers Narendra Upkar (0.10) exhibited significant and positive gca effects for flesh thickness (21-24)

In pooled, out of thirty-six cross combinations ten showed significant and positive sca effects. Based on magnitude of sca effects best cross combinations VRPK-2362 x Narendra Agrim (3.70) followed by VRPK-2372 x Narendra Upkar (2.99), VRPK-23303 x Narendra Agrim (2.51), VRPK-2307-02 x Narendra Upkar (2.49) and NDPK-23-7 x Narendra Amrit (1.78). Fifteen crosses exhibited negative and significant sca effects for fruit yield per plant (Kg). These combinations, particularly those involving high × high general combiners, suggest additive × additive gene action. The observed SCA in various combinations, whether high × high, high × low, or low × low, points to a mix of additive, dominant and epistatic genetic interactions. This genetic complexity is also influenced by the degree of heterozygosity in parental lines. Both positive and negative

heterosis over better parent for yield contributing characters (17). Involvement of at least one good general combiner parent for expression of high heterotic responses for yield (5). Improvement in number of female flowers per plant, equatorial and polar circumferences of fruit and yield per plant through hybridization in pumpkin (26).

Conclusion

The research successfully evaluated the quantitative traits of *Cucurbita moschata* across various genotypes and hybrid combinations. Promising parental lines such as Narendra Upkar, NDPK-23-7 and VRPK-2362 were identified based on their superior performance. Hybrids like VRPK-2362 × Narendra Agrim and VRPK-2307-02 × Narendra Upkar exhibited high levels of heterosis. Both relative and standard heterosis were significant in key hybrid combinations, indicating strong hybrid vigour. General combining ability analysis revealed NDPK-23-7 and VRPK-2307-02 as excellent combiners for yield-related traits. Specific combining ability effects identified hybrids with superior trait expression. Improved hybrids could contribute to higher yield and better quality in pumpkin cultivation. Overall, the study advances strategic hybrid development in *Cucurbita moschata*. Overall, the findings underscore the importance of both GCA and SCA in selecting parental lines and hybrids. The identification of superior parents and high-performing hybrids lays a strong foundation for future breeding strategies aimed at improving yield, earliness, fruit quality and other economically important traits in pumpkin.

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Authors' contributions

AKC designed the experiments, conducted the field study and drafted the manuscript. AKC and CNR conceptualized the research. AJ and DKU analysed the data and contributed to its interpretation. AKC, CNR, AJ and DKU prepared the final manuscript. All authors read and approved the final version of the manuscript.

Compliance with ethical standards

Conflict of interest: The Authors do not have any conflict of interest to declare.

Ethical issues: None

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