PLANT SCIENCE TODAY
Vol x(x): xx–xx
https://doi.org/10.14719/pst.9721

eISSN 2348-1900

RESEARCH ARTICLE

Identification of promising muskmelon parents and hybrids through combining ability and heterosis analysis in arid environments

Veeresh M Khapper[1], Pawan Kumar[2*], Balu Ram Choudhary[2], Anil Kumar Sharma[1] & Hardat Kaswan[3]

[1]Department of Genetics and Plant Breeding, Swami Keshwanand Rajasthan Agricultural University, Bikaner 334 006, Rajasthan, India
[2]ICAR-Central Institute for Arid Horticulture, Bikaner 334 006, Rajasthan, India
[3]Department of Horticulture, Swami Keshwanand Rajasthan Agricultural University, Bikaner 334 006, Rajasthan, India

*Correspondence email - pawanchoudhary2@gmail.com

Received: 30 May 2025; Accepted: 15 August 2025; Available online: Version 1.0: 22 October 2025

Cite this article: Khapper VM, Kumar P, Choudhary BR, Sharma AK, Kaswan H. Identification of promising muskmelon parents and hybrids through combining ability and heterosis analysis in arid environments. Plant Science Today (Early Access). https://doi.org/10.14719/pst.9721

Abstract

Despite the economic importance of muskmelon, there is limited information on the combining ability and heterotic potential of genetically diverse cultivars, highlighting the need for systematic evaluation of parental lines and hybrid combinations. Seven genetically diverse cultivars, including two inbred lines of muskmelon (*Cucumis melo* L.) were crossed in a half-diallel to generate 21 F_1 hybrids. These hybrids, along with the seven parental lines and commercial check, were evaluated in a randomized block design during summer-2024 at research farm, College of Agriculture, Swami Keshwanand Rajasthan Agriculture University, Bikaner, Rajasthan, India. The mean performance of parents revealed a wide range of variability for various characters within the parental line utilized in crossing programme. General combining ability (GCA) analysis indicated that the parents Thar Mahima, AHMM/BR-8, Punjab Sunehri, Hara Madhu and Durgapura Madhu exhibited the best GCA for yield and related traits. Specific combining ability (SCA) variance was greater than the GCA variance for all traits except some yield-contributing characters. Among the crosses AHMM/BR-8 × Punjab Sunehri, Thar Mahima × Durgapura Madhu, Thar Mahima × Hara Madhu and Durgapura Madhu × Hara Madhu showed superior SCA effects for yield and associates traits. Additionally, AHMM/BR-8 × Punjab Sunehri, Thar Mahima × Durgapura Madhu and Thar Mahima × Hara Madhu exhibited significant positive heterosis, making them promising candidates for future hybrid development in muskmelon.

Keywords: combining ability; correlation; fruit yield; heterosis; muskmelon

Introduction

The arid region is marked by low and erratic rainfall, frequent droughts, extreme temperatures, low humidity, nutrient-poor soils, high evapotranspiration rates and strong winds. Summer temperatures (March-June) reach 45-50 °C, while winter temperatures (November-February) range between 15-25 °C (1). Over 88 % of the annual rainfall, typically less than 25 cm, occurs during the monsoon season (July-October). The soil of the Thar Desert is sandy, comprising 60-90 % fine sand and 2-10 % silt-clay. It is low in organic matter and is characterized by shifting sand dunes. The soil contains low to moderate phosphorus content, medium to high potassium levels and a pH range of 7.6 to 8.5 (1).

Muskmelon (*Cucumis melo* L., 2n = 24) is an important cucurbitaceous crop, well suited to warm-season regions worldwide. India is one of the primary centres of *Cucumis* diversity. Several genetic diversity studies have been conducted on Indian accession of *cantalupensis, momordica* and *agrestris* plants (2, 3). Additionally, the Indian muskmelon germplasm serves as a reservoir of genes for distinctive traits related to fruit quality and tolerance to abiotic and biotic stresses, which can be effectively utilized in advanced muskmelon breeding strategies (4). Over the past two decades, India has experienced an increase in import of muskmelon cultivars. Most of these cultivars are not well suited to India's climatic conditions and necessitate highly input intensive cultivation practices. However, landrace-derived cultivars such as Hara Madhu, Punjab Sunhari and Durgapura Madhu continue to be popular in India (4, 5). Therefore, there is significant potential to combine high yield potential with enhanced shelf-life traits such as netting intensity, firmness and rind thickness, as well as quality parameters such as total soluble solids (TSS), sugar content and acidity, from Indian landraces (4). It is essential to assess combining ability potential and genetic parameter of newly developed and refined germplasm to develop locally adapted hybrid muskmelon cultivars.

Heterosis refers to the phenomenon that results in the superior performance of the F_1 progeny in comparison to genetically diverse parents (6). Heterosis breeding has been investigated and employed in muskmelon crop improvement programs (7, 8). Therefore, heterosis breeding can serve as an effective strategy for combining all desirable characteristics in muskmelon cultivars. Diallel analysis is used to estimate the combining ability of genotypes. It provides insight into GCA of parents and SCA of their F_1 hybrids (9). It enables the identification of parental lines with a higher frequency of favourable alleles through the GCA effect as well as the most promising hybrid combination through the SCA effect (10). It also provides an estimate of the gene action involved in determining the characteristics and the presence of heterosis (11, 12).

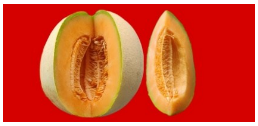
The primary objective of this study was to investigate the genetic architecture of yield and its component traits using diallel cross analysis, excluding reciprocals. The specific objective was to estimate combining abilities and identify potential parents, as well as heterotic parental combinations, for improved yield and fruit quality. Insight into the genetic control of horticultural traits will contribute to muskmelon breeding by facilitating the development of hybrid with higher yield and enhanced quality.

Materials and Methods

Experimental site and materials

The experiment was conducted at Research Farm, College of Agriculture, Swami Keshwanand Rajasthan Agricultural University (SKRAU), Bikaner, Rajasthan, India, during the summer season of 2024. The soil at the experimental site was sandy loam and the cropping season spanned from February to May 2024. Seven parental lines were chosen based on marketable fruit yield and fruit traits, including flesh thickness, TSS content and ascorbic acid content (Table 1).

Table 1. Details of the parental lines of muskmelon used in the diallel analysis

S. No.	Parental line	Descriptive features	Fruit image	Reference
1.	AHMM/BR-8 (IC-0599709)	Monoecious, TSS content: 10.8-11.3 %, flesh thickness: 3.4-4.0 cm, fruit weight: 800-1100 g and bear 3-4 fruits/ plant. Fruits are round with green sutures and salmon orange flesh.		(13)
2.	AHMM/BR-1	Developed by exercising single plant selection. It produced first harvesting in 75-80 days after sowing, TSS content: 11-11.8 %, average fruit weight: 0.7-0.8 kg, having light green flesh. Rind is red coloured with 10 green sutures.		(14)
3.	Punjab Sunehri	Vigorous growth, fruit shape: round, fruit weight: 400-500 g, flesh colour: orange red, fruit colour: greenish yellow, rind with netted surface. TSS content: 10-11 %, seed cavity: minimum, excellent transportability, tolerant to downey mildew.		(15)
4.	Thar Mahima (IC-0624305)	Fruits are round with netting on rind. Flesh colour: salmon orange, fruit weight: 780 to 900 g and become ready for first harvest in 75-80 DAS. Flesh thickness varied from 2.8-3.2 cm. TSS content: 11.58-11.80 %. rind: 0.30-0.48 cm thick, seed cavity: small.		(16)
5.	Durgapura Madhu	It is an early-maturing variety. Its fruits are oblong, weighting 500-600 g each; rind pale green; flesh yellowish green, non-juicy and very sweet, TSS content: 13-14 %, seed cavity: big.		(15)
6.	Hara Madhu	Fruit shape: round, fruit skin: pale green, yield: 127 q/ ha. It has attractive green flesh textured fruits with sweet taste and good aroma. Seeds are loosely packed in the seed cavity.		(15)
7.	Arka Siri	TSS content: 12-13 %, shelf life: 5-10 days under ambient conditions, 75-80 days maturity; fruits are elongated globe shaped with brownish yellow rind color, medium netting and musky, firm, juicy dark orange flesh.		(17)
8.	Muskan (Check)	This hybrid is vigorous and tolerant to virus. Fruit weight about 1.5 -1.8 kg. Rind is creamy tinged with light yellow colour and has sparse net. Flesh is light green, juicy, tasty and sweet with TSS content is 14 -16 %.		(18)

Production of F_1 hybrid and evaluation

The seven selected parental lines were planted in the open field in July 2023 and a total of 21 crosses were generated using a half diallel mating design. The F_1 hybrid, along with a commercial check (Muskan) and their corresponding parents was planted in the summer of 2024 for field evaluation. Each treatment consisted of a single row of ten vines accommodated in a bed of 8.0 m × 2.0 m bed. The vines were spaced 2.0 m between rows and 0.8 m within rows. The recommended agronomic practices for muskmelon crop production were followed to raise the experimental crop.

Vine length was recorded from the base of the plant to the tip of the main shoot at final harvest. Number of primary branches per vine was recorded at the final harvest of the crop. Days to 50 % female flowering was recorded from the date of sowing to the date when 50 % of the vines in the plot had produced female flowers. Fruit length was measured from the peduncle to the blossom end by cutting the fruit longitudinally into two halves. Fruit diameter was measured at the centre after cutting the fruit longitudinally into two halves. Flesh thickness (cm) was measured as the distance from the rind to the seed cavity after cutting the fruit longitudinally. The seed cavity length was measured longitudinally using a scale. The fruit seed cavity size was calculated from one starting point of the cavity to the end of another cavity. TSS were determined with a hand-held refractometer. Titratable acidity was worked out by titrating the pulp extract against 0.1N NaOH (sodium hydroxide) using phenolphthalein as an indicator and total sugar content was determined by the modified volumetric method (19). Ascorbic acid was extracted (20).

Statistical analysis

The averages were calculated from data recorded for each character on an individual vine basis, using five observational per replication. The mean values thus obtained were subjected to statistical analysis. The values of the seven parents and 21 F, hybrids from each replication were used for analysis of variance (ANOVA) (Table 2). The analysis of variance for GCA and SCA was performed using the method proposed (21). Heterosis was evaluated as the percentage improvement of F_1 performance in the desired direction compared to the better parent and standard check calculated using the Eqn. 1 and Eqn. 2, respectively.

$$\text{Heterobeltiosis (BPH \%)} = \frac{F_1 - BP}{BP} \times 100 \qquad \text{(Eqn. 1)}$$

$$\text{Standard heterosis (SDH \%)} = \frac{F_1 - SC}{SC} \times 100 \qquad \text{(Eqn. 2)}$$

Where, F_1 = F_1 mean performance, BP = better parent mean performance and SC = standard check mean performance

Results

Yield and yield components

The analysis of variance revealed significance differences among the parent and their F_1 hybrid for all the traits except seed cavity width (Table 2). The effects due to GCA (excluding fruit weight) and SCA (excluding flesh thickness and the number of primary branches per vine) were found to be highly significant for yield and its associated traits, indicating the relevance of both additive and non-additive factors in influencing these traits.

Table 2. Mean squares of the ANOVA for yield, its components and fruit quality traits and the ANOVA results of the half-diallel design analysis (general and specific combining abilities) of muskmelon

Source	df	Marketable fruit yield (q/ha)	Marketable fruit yield per vine (kg)	Fruit weight (g)	Flesh thickness (cm)	Vine length at last harvest (m)	Number of primary branches per vine	Days to 50 % female flowering	First female flower node	Days to first fruit harvest	Seed cavity width (cm)	TSS content (° Brix)	Total sugar content (%)	Acidity (%)	Ascorbic acid (mg/100 g)
Replications	2	81.13	0.07	0.52	0.24	0.06	0.02	0.16	0.45	0.01	0.06	0.11	0.62	0.34	0.18
Treatment	27	3145.47**	0.77**	0.05**	0.16**	0.13**	0.14**	5.55**	0.97**	20.08**	2.60**	0.24**	1.13**	0.85**	2.84**
Parent	6	1158.90**	0.30**	0.03*	0.18**	0.11*	0.21**	5.31**	0.28*	19.29**	10.06**	0.25**	1.80**	0.39**	3.50**
F_1	20	3598.40**	0.89**	0.06**	0.16**	0.13**	0.05**	5.37**	0.80**	18.22**	0.33	0.21**	0.95**	0.47**	2.77**
P vs F_1	1	6006.21**	1.21**	0.09**	0.13*	0.22**	1.58**	10.71**	8.65**	62.03**	3.30**	0.88**	0.50*	0.31*	0.25**
Error	54	12.27	0.01	0.33	0.31	0.01	0.02	0.19	0.07	0.10	0.04	0.01	0.19	0.01	0.01
GCA	6	2419.56**	0.62**	0.04	0.14**	0.15**	0.09**	5.26**	0.47**	18.36**	1.56**	0.17**	0.65**	1.64**	0.66**
SCA	21	656.76**	0.15**	0.09**	0.03	0.12**	0.05	0.88**	0.28**	3.36**	0.67**	0.06**	0.30**	0.58**	1.03**
Error	54	4.09	0.01	0.01	0.02	0.03	0.01	0.06	0.02	0.13	0.01	0.01	0.02	0.06	0.03

* and ** significance at 5 % and 1 % level, respectively.

The average fruit yield of the hybrid ranged from 51.8 to 198.4 q ha^{-1}, while the parental lines exhibited yield between 47.57 and 97.6 q ha^{-1} (Table 3 & 4). Among the parental lines, the highest fruit yield was recorded in Thar Mahima (9.76 t ha^{-1}) followed by AHMM/BR-8 (9.54 t ha^{-1}). GCA effect value for fruit yield varied between -27.0 and 2.15 (Table 3). Thar Mahima exhibited the highest positive GCA contributing to a greater fruit yield while Arka Siri showed the lowest negative GCA. For average fruit weight the highest positive GCA effect was observed in Punjab Sunehri (0.08) while the lowest negative GCA was noted in Arka Siri (-0.10). Interestingly the highest GCA for marketable fruit yield per vine was recorded in Thar Mahima (0.34) and lowest in Arka Siri (-0.42). Thar Mahima also had the highest GCA fruit yield achieving the maximum fruit yield among all parental lines (Table 3). However, this trend was not consistent for traits such as flesh thickness (cm), vine length at the last harvest (m) and the highest mean value was recorded for fruit weight (640 g) and number of primary branches per vine (3.22), respectively.

SCA effect for fruit yield varied from -12.8 to 84.1 across the F_1 cross combination (Table 4). The highest SCA value for fruit yield was observed in the cross Thar Mahima × Durgapura Madhu (84.1). The magnitude of better parent heterosis and standard heterosis ranged from -10.8 to 103.3 % and 5.2 to 50.8 %, respectively. Based on *per se* performance, the best performing crosses are illustrated in Fig. 1. The highest magnitude of heterosis for fruit yield was observed in the cross Thar Mahima × Durgapura Madhu with a 103.3 % increase compared to both the better parent and the commercial check, Muskan. This suggests that this cross-hold potential for selection. Additionally, the highest SCA effect for fruit weight (970 g) was recorded in the cross Thar Mahima x Durgapura Madhu. Thus, the heterosis over commercial check variety (Muskan) for average fruit weight was observed in the cross Thar Mahima × Durgapura Madhu which also exhibited the highest SCA effect (0.34). The cross AHMM/BR-8 x Thar Mahima recorded the highest SCA value (0.2) for vine length at last harvest.

Fruit quality traits

The genotypes showed significant differences for all fruit quality traits (Table 2). Highly significant GCA and SCA effects (except for flesh thickness) were observed for all fruit traits indicating that both additive and non-additive effects govern these traits. The ANOVA revealed significant differences among the genotypes (parents and their crosses) for all the quality traits (Table 2). The variance due to GCA and SCA were highly significant for flesh thickness, TSS content, total sugar content and ascorbic acid highlighting the importance of both additive and dominance effects in controlling these traits.

The highest GCA value for flesh thickness was observed in AHMM/BR-8 (0.16) while the negative GCA was recorded for AHMM/BR-1 (-0.17) presented in the Table 3. Among the parental line Thar Mahima exhibited the thickest flesh (2.4 cm) whereas the thinnest flesh was found in Arka Siri (1.8 cm). The highest SCA value for flesh thickness was recorded in the cross Thar Mahima × Durgapura Madhu (Table 4). This cross showed the highest heterosis over better parent Thar Mahima (89.6 %) and exhibited SDH over commercial check, Muskan (74.5 %). Additionally, the cross combination AHMM/BR-8 × AHMM/BR-1, AHMM/BR-8 × Durgapura Madhu, AHMM/BR-8 × Hara Madhu and AHMM/BR-1 × Thar Mahima were also found to be promising for this trait.

Table 3. Least square means and estimates of the general combining ability (GCA) effects in a half-diallel analysis of 7 muskmelon parental lines

Parents	Marketable fruit yield (q/ha)		Marketable fruit yield per vine (kg)		Fruit weight (g)		Flesh thickness (cm)		Vine length at last harvest (m)		Number of primary branches per vine		Days to 50 % female flowering	
	Mean	GCA	Mean	GCA	Mean	GCA	Mean	GCA	Mean	GCA	Mean	GCA	Mean	GCA
AHMM/BR-8	95.49	13.58**	1.53	0.23**	530.4	0.02**	2.51	0.16**	2.16	0.27**	2.78	-0.01	39.22	0.13
AHMM/BR-1	58.40	-14.10**	0.93	-0.24**	421.1	-.08**	2.18	-.17**	1.88	0.03**	2.44	-0.07**	39.11	-0.07
Punjab Sunehri	79.52	1.73**	1.27	0.02	641.3	0.08**	2.39	0.03	1.73	-0.11**	2.78	-0.02	39.44	0.24**
Thar Mahima	97.60	21.25**	1.57	0.34**	522.4	0.07**	2.48	0.07**	1.67	-0.08**	3.22	0.21**	36.89	-1.60**
Durgapura Madhu	68.99	6.44**	1.10	0.10**	433.8	0.03**	2.00	-0.01	1.85	-0.01	2.78	0.01	39.67	0.06
Hara Madhu	55.76	-1.87**	0.90	-0.03	403.6	-0.02**	2.35	0.09**	1.85	-0.00	2.78	-0.01	41.44	0.82**
Arka Siri	47.57	-27.02**	0.76	-0.42**	381.7	-.10**	1.88	-0.16**	1.56	-0.09**	2.44	-0.11**	39.11	0.43**
Parents	First female flower node		Days to first fruit harvest		Seed cavity width (cm)		TSS content (°Brix)		Total sugar content (%)		Ascorbic acid (mg/100 g)			
	Mean	GCA	Mean	GCA	Mean	GCA	Mean	GCA	Mean	GCA	Mean	GCA		
AHMM/BR-8	5.89	0.09	78.22	1.40**	3.35	-0.09*	8.06	-0.08**	2.35	0.18**	4.97	0.40**		
AHMM/BR-1	5.33	0.09	76.00	-0.33**	3.40	-0.34**	7.71	-0.09**	2.94	0.07**	3.72	0.10**		
Punjab Sunehri	5.56	-0.32**	76.44	-0.05	5.70	0.25**	8.23	0.07**	2.83	0.34**	3.93	-0.24**		
Thar Mahima	5.22	-0.32**	72.11	-2.96**	6.65	0.53**	8.33	0.14**	1.90	0.11**	3.76	0.06**		
Durgapura Madhu	5.78	0.16**	78.67	0.41**	7.32	0.48**	8.27	-0.04*	2.81	-0.01	3.93	-0.31**		
Hara Madhu	5.89	0.05	80.00	0.96**	2.75	-0.41**	8.39	0.18**	0.77	-0.23**	6.63	0.24**		
Arka Siri	5.22	0.26**	77.34	0.57**	3.63	-0.42**	7.69	-0.19**	1.87	-0.46**	3.76	-0.24**		

* and ** significance at 5 % and 1 % level, respectively.

Table 4. Estimation of the mean, specific combining ability, better parent and standard heterosis (%) over the commercial check (Muskan F_1) for the marketable fruit yield, fruit weight and vine length at last harvest, flesh thickness, TSS content and total sugar content of muskmelon

Hybrid	Marketable fruit yield (q/ha)				Fruit weight (g)				Vine length at last harvest (m)			
	Mean	SCA	BPH	SDH	Mean	SCA	BPH	SDH	Mean	SCA	BPH	SDH
AHMM/BR-8 × AHMM/BR-1	86.78	0.76	6.82	2.06	452.4	-0.02**	5.36	3.51	2.22	0.02*	2.94**	13.07**
AHMM/BR-8 × Punjab Sunehri	140.62	38.76**	47.26**	6.87*	770.6	0.14**	20.94**	6.48	2.11	0.05**	4.37**	7.30**
AHMM/BR-8 × Thar Mahima	121.13	-0.24	24.11**	4.34	632.1	0.01	18.87**	11.64	2.29	0.20**	6.03**	1.09
AHMM/BR-8 × Duragapura Madhu	93.77	-2.80**	4.62	2.07	554.3	-.03**	3.77	3.28	2.27	0.10**	5.26**	15.62**
AHMM/BR-8 × Hara Madhu	115.51	17.25**	20.97**	3.43	563.5	0.03**	6.29**	11.90	2.25	0.08**	4.17**	0
AHMM/BR-8 × Arka Siri	65.82	-7.28**	2.34	0.06	442.7	-0.02*	5.64	2.14	2.20	0.12**	2.01**	12.05**
AHMM/BR-1 × Punjab Sunehri	82.50	8.32**	3.75	0.10	490	-.04**	3.56	14.52**	1.92	0.10**	2.31**	1.13
AHMM/BR-1 × Thar Mahima	82.60	-1.09**	0.03	0.01	453.2	-.07**	6.76	13.51	1.89	0.05**	0.89	1.20
AHMM/BR-1 × Durgapura Madhu	73.97	-4.92**	7.21	0.24	463.4	-0.02*	6.98*	16.78**	1.89	-.04**	0.53	16.47**
AHMM/BR-1 × Hara Madhu	70.21	-0.37	20.21**	3.64	441.4	0.01	4.76	13.46	1.91	-0.02	1.60*	2.31
AHMM/BR-1 × Arka Siri	52.60	7.18**	0.01	0.04	412.3	0.06**	2.46	6.48	1.87	0.04**	0.69	1.57
Punjab Sunehri × Thar Mahima	94.59	14.94**	0.06	0.08	674.5	-0.01	5.24**	4.68	1.64	-.06**	0.74	2.24
Punjab Sunehri × Durgapura Madhu	88.12	-6.61**	-10.82**	4.38	676.2	0.03**	5.24**	14.24**	1.69	-.09**	0.41	14.43**
Punjab Sunehri × Hara Madhu	91.27	4.85**	14.78**	-5.21**	654.3	0.05**	1.57	6.78	1.73	-.06**	0.09	2.56
Punjab Sunehri × Arka Siri	51.88	-9.38**	1.08	0.34	447.2	-.08**	4.62	3.65	1.65	0.05**	0.32	3.20
Thar Mahima × Durgapura Madhu	198.43	84.19**	103.30**	50.81**	974.2	0.34**	84.71**	15.68**	1.79	-0.02*	0.92	1.26
Thar Mahima × Hara Madhu	121.68	15.75**	24.66**	3.67	663.4	0.08**	26.11**	2.35	1.79	-0.02*	1.21	1.82
Thar Mahima × Arka Siri	70.00	-0.77**	9.43	1.46	435.1	0.07**	3.24	3.12	1.72	-0.00	3.20**	2.16
Durgapura Madhu × Hara Madhu	104.90	13.77**	52.04**	5.43	543.5	-0.00	25.58**	5.34	1.90	0.01	2.88**	2.58
Durgapura Madhu × Arka Siri	53.22	12.75**	13.61	4.82	454.3	-0.01	4.65	4.32	1.91	0.11**	3.24**	0
Hara Madhu × Arka Siri	60.51	2.85	8.52	3.54	435.2	0.02	6.61*	8.24	1.90	0.10**	2.89**	2.88

Hybrid	Flesh thickness (cm)				TSS content (°Brix)				Total sugar content (%)			
	Mean	SCA	BPH	SDH	Mean	SCA	BPH	SDH	Mean	SCA	BPH	SDH
AHMM/BR-8 × AHMM/BR-1	2.55	0.25**	1.59	42.64**	8.26	0.15*	2.48*	6.24*	2.70	0.10**	6.42	8.52*
AHMM/BR-8 × Punjab Sunehri	2.43	-0.07	0.04	35.94	8.54	0.28**	3.77**	4.35	3.29	0.43**	16.25**	-5.72
AHMM/BR-8 × Thar Mahima	2.43	-0.12*	1.62	35.75	8.45	0.11	1.36	2.34	3.18	0.54**	35.32**	-3.51
AHMM/BR-8 × Duragapura Madhu	2.50	0.03	-6.34*	39.66**	7.88	-.28**	1.72	1.27	2.25	-.27**	-3.52	-0.07
AHMM/BR-8 × Hara Madhu	2.73	0.16**	8.75**	52.70**	8.38	-0.01	1.46	0.15	3.16	0.87**	34.61**	24.81**
AHMM/BR-8 × Arka Siri	2.32	0.00	3.01	29.80	7.89	-0.12*	-0.07	0.07	1.12	-.95**	4.06	-2.82
AHMM/BR-1 × Punjab Sunehri	1.95	-.22**	5.82	9.12	8.39	0.13*	1.86	1.10	2.22	-.53**	-7.51	-3.76
AHMM/BR-1 × Thar Mahima	2.06	-.17**	7.38*	14.90**	8.55	0.22**	2.56*	3.51	2.69	0.17**	6.24	-4.51
AHMM/BR-1 × Durgapura Madhu	2.04	-0.10*	1.23	13.78	7.91	-.23**	0.01	2.62	1.79	-.62**	-3.52	-1.63
AHMM/BR-1 × Hara Madhu	2.14	-0.10*	4.12	19.74**	8.32	-0.04	2.04	3.42	2.25	0.07**	5.61	-3.57
AHMM/BR-1 × Arka Siri	1.92	-0.07	3.67	7.45	8.51	0.52**	10.33**	0.04	1.87	-.08**	7.53	-5.82
Punjab Sunehri × Thar Mahima	2.36	-0.07	1.58	31.66**	8.45	-0.04	1.36	11.20**	3.21	0.42**	13.31**	-8.64
Punjab Sunehri × Durgapura Madhu	2.52	0.19**	5.43	40.97	8.43	0.13*	2.02	5.21	2.48	-.19**	6.35	-1.45
Punjab Sunehri × Hara Madhu	2.53	0.09	5.85	41.53**	8.49	-0.04	1.19	3.52	2.64	0.19**	-8.16	1.72
Punjab Sunehri × Arka Siri	2.24	0.05	2.64	25.33	8.07	-0.09	-1.37	-4.30	2.27	0.05**	-6.37	-3.83
Thar Mahima × Durgapura Madhu	2.69	0.30**	18.19**	50.09**	8.53	0.16**	2.40*	0.04	2.56	0.11**	-2.46	-0.86
Thar Mahima × Hara Madhu	2.52	0.03	1.61	40.97**	8.83	0.23**	5.28**	0.53	2.54	0.31**	33.74**	-6.49
Thar Mahima × Arka Siri	2.22	-0.02	4.62	24.21	8.00	-.23**	0.03	1.52	1.78	-.21**	-4.67	-2.60
Durgapura Madhu × Hara Madhu	2.43	0.03	3.55	35.94**	8.47	0.05	0.91	6.24	2.35	0.25**	2.53	-1.62
Durgapura Madhu × Arka Siri	2.31	0.16**	15.39**	29.05	8.08	0.03	1.14	0.07	1.61	-.26**	-5.61	-3.72
Hara Madhu × Arka Siri	2.39	0.13**	1.70	33.52**	8.59	0.32**	2.38*	1.13	2.19	0.54**	17.32**	17.18**

***** and ****** significance at 5 % and 1 % level, respectively.

Fig. 1. Based on *per se* performance best F_1 hybrids among the crosses.

The highest GCA value for TSS content was recorded in Hara Madhu (0.18) while the most negative GCA was observed in Arka Siri (-0.19) (Table 3). Among the parental lines, Hara Madhu exhibited the highest TSS content (8.3 °Brix), while Arka Siri had the lowest TSS content (7.6 °Brix). The highest mean value for TSS content was observed in the cross Thar Mahima × Hara Madhu and highest SCA was recorded in the cross AHMM/BR-1 × Arka Siri (Table 4). The cross AHMM/BR-1 × Arka Siri exhibited the highest heterosis over the better parent AHMM/BR-1 (91.8 %) and superior over the commercial check, Muskan. Furthermore, the cross combination AHMM/BR-8 × AHMM/BR-1, AHMM/BR-8 × Punjab Sunehri, Punjab Sunehri × Durgapura Madhu and Thar Mahima × Hara Madhu was also identified as promising for this trait.

The highest positive and negative GCA value for total sugar content was recorded in Punjab Sunehri (0.34) and Arka Siri (-0.46) respectively (Table 3). Among the parental lines total sugar content ranged from 0.77 % to 2.94 %. The parent AHMM/BR-8 exhibited significantly higher total sugar content, while Hara Madhu showed lowest through still significantly lower total sugar content. For this cross combination total sugar content ranged from 1.12 % to 3.26 %. The cross AHMM/BR-8 × Punjab Sunehri exhibited significantly higher total sugar content while AHMM/BR-8 × Arka Siri showed the lowest but still significantly lower total sugar content (Table 4).

Correlation between parent performance, F_1 performance and heterosis

A correlation analysis was conducted between the performance of the parents and the crosses to explore the impact of parental traits on F_1 performance. The result revealed a significant positive correlation between parent and F_1 performance for marketable fruit yield, fruit weight, vine length at last harvest and TSS content. However, the correlation was non-significant for fruit flesh thickness and total sugar content. These findings suggest that parental performance may not serve as a reliable predictor for hybrid performance in these traits (Fig. 2).

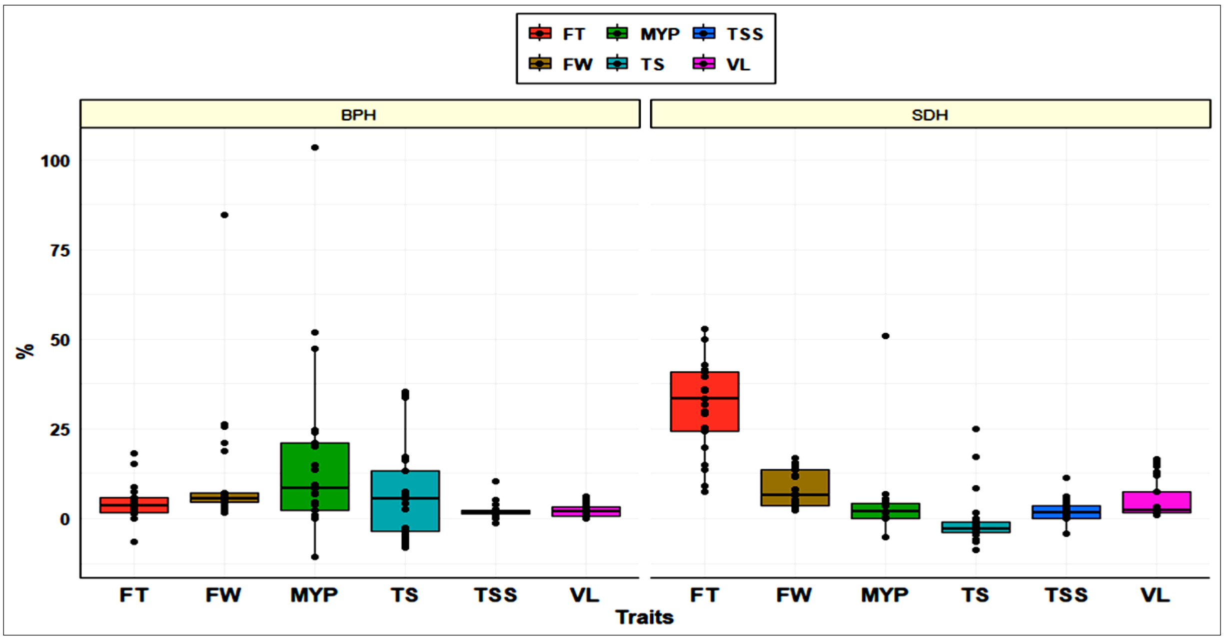


Fig. 2. Heterosis performance of F_1 hybrids along with boxplots showing better-parent (**BPH**) and standard check (**SDH**) for the studied traits. The black dots represent the mean of the hybrid mean per cross. **FT**: fruit flesh thickness (cm), **FW**: fruit weight (g), **MYP**: marketable fruit yield (q/ha), **TS**: total sugar content (%), **TSS**: TSS content (°Brix), **VL**: vine length at last harvest (m).

The observed significant correlation between parent and F_1 performance suggest degree of heritability for traits. This suggests some traits may exhibit direct inheritance and be influenced by parental performance; others may be subject to dominance, epistasis or environmental effects that obscure direct inheritance pattern. However, non-significant correlations suggest the transmission of these traits from the parental generation to the F_1 generation may not follow a straightforward pattern of direct inheritance. The performance of parents exhibited a negative correlation with BPH for most of the traits examined.

Specifically, for fruit flesh thickness, TSS content and total sugar content the correlation between parental performance and BPH value showed a significant negative association. This suggests that lower performing parents tend to produce hybrid with higher heterosis for these traits. For fruit weight no significant correlation was found between parent performance and BPH. The absence of a significant correlation for fruit weight indicates that parental performance may not serve as a reliable predictor of hybrid vigor for this trait.

The correlation analysis between parental performance and SDH revealed significantly positive correlations for marketable fruit yield, vine length at last harvest and TSS content illustrated in Fig. 3. This positive correlation suggests that selecting high performing parents for these traits could result in hybrid with improved performance, highlighting potential targets for breeding programme focused on enhancing these characteristics.

Discussion

Significant differences were observed among both parental lines and their hybrids for fruit yield and quality traits (Table 2). Significant variations were observed among different parental lines and their crosses for fruit yield and related traits in Indian muskmelons (7, 22, 23). The significance of both GCA and SCA variance highlighted the importance of both additive and non-additive gene effects in controlling these traits. Similar findings have been reported in earlier studies in muskmelon, wheat, barley and mustard, where both gene actions influenced traits (23 -28).

However, dominant gene action predominately governs yield related traits, such as fruit weight (29, 30). Additionally, the role of additive gene action in controlling yield per hill, fruits per hill and fruit weight has been discussed in earlier works (31, 32). The parents Nahavand and Tashkandi exhibited significant positive GCA effects for yield-related traits and parent Rish-baba displayed significant positive GCA effects for total yield, while Ananasi showed significant positive GCA effects for fruit weight and number of fruits per plant (23, 33).

The significant SCA effects for fruit yield and its components align with finding, suggesting that hybrid cultivar development could be a promising strategy for yield improvement (33). The highest better parent heterosis for fruit yield was observed in the cross Thar Mahima × Durgapura Madhu. Similarly, this cross also exhibited the highest SCA and BPH for fruit weight, while AHMM/BR-8 × Thar Mahima showed the highest SCA and BPH for vine length at the last harvest (Table 4). Similarly, inbred line KP4HM-15 and MM-916 were found to be the best general combiner for the number of fruits per vine and TSS (34). The best cross combination for fruit yield (ha^{-1}) and TSS MS-1 × M-610 and Kajri × MM-904, respectively.

The highest significant BPH for average fruit weight and total yield in the crosses Ananasi × Mashhadi and Abasali × Hose-sirkh respectively (23). Garmak × Rish-baba was the best specific combiner for total yield and the number of fruits per plant, while Saveh × Garmak was the best performer for fruit weight (33). Additionally, cross EC-3 × GP-211 exhibited significant SCA effects, leading to higher fruit weight, fruit yield and shelf life (32). Several researchers have also reported that crosses derived from low × high general combiner parents exhibited the highest SCA effects and heterosis for yield in muskmelon (22).

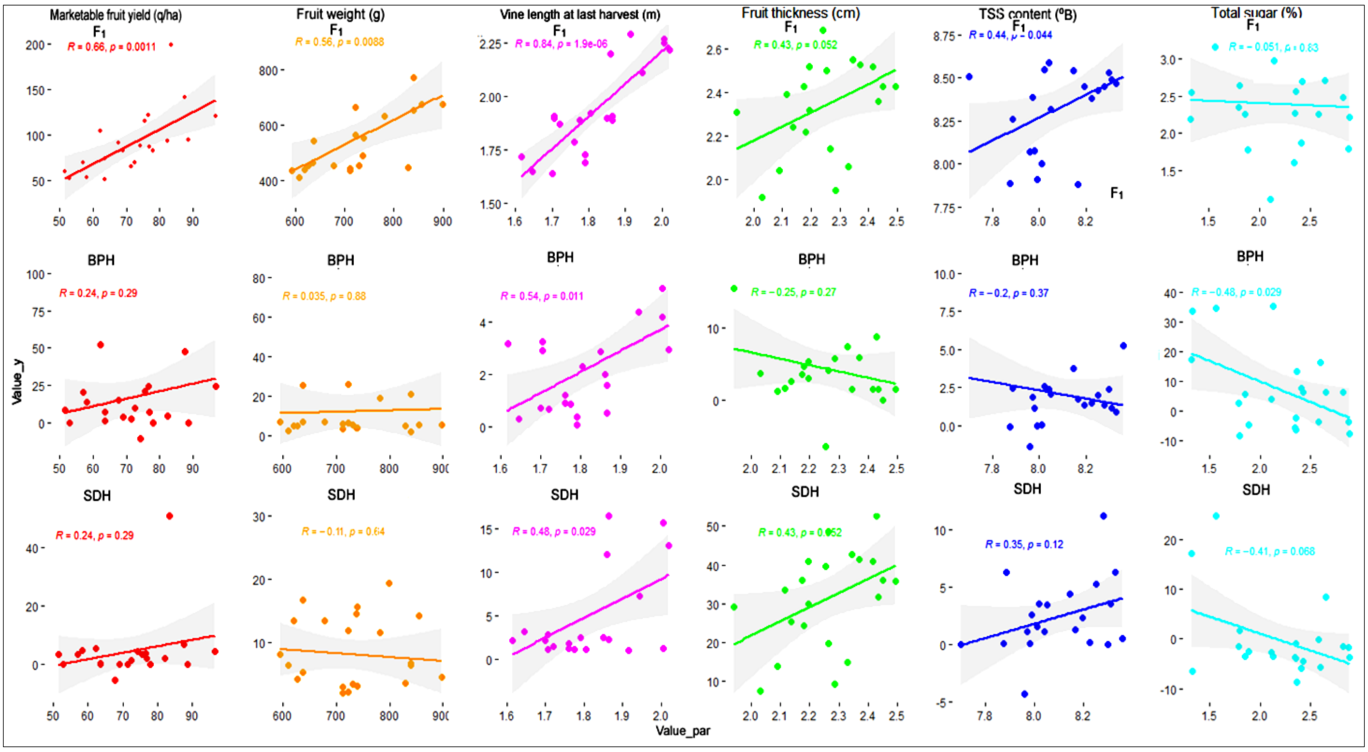


Fig. 3. Correlation matrix showing the relationships among parental performance, F_1 performance and heterosis for key traits: marketable fruit yield (q/ha), fruit weight (g), vine length at last harvest (m), fruit flesh thickness (cm), TSS content (°Brix) and total sugar content (%).

Flesh thickness, TSS and total sugar levels are the key determinants of muskmelon fruit quality, playing a crucial role in its marketability (4). This study investigated the genetic regulation of both fruit yield and quality traits in muskmelon accession. GCA to SCA variance ratio for TSS and total sugar indicate that genetic enhancement of these trades through selection is highly achievable. Several studies have previously documented additive gene action for flesh thickness and rind thickness (11, 12). However, the dominance gene action for fruit flesh thickness was observed (30).

The advanced line AHMM/BR-8 showed the highest mean fruit flesh thickness and a significant GCA for this trait (Table 3). Therefore, AHMM/BR-8 holds potential for the genetic enhancement of Indian muskmelon. Given the significance of additive effects in regulating flesh thickness, TSS content and total sugar content selecting for desirable texture and transportability is feasible within this population. The inbreed line Meloa exhibited a significant GCA effect for flesh thickness (11). The hybrids AHMM/BR-8 × Hara Madhu, AHMM/BR-8 × Arka Siri and AHMM/BR-8 × Hara Madhu showed the highest SCA effects for flesh thickness, TSS content and total sugar content, respectively (Table 4).

Similarly, the cross-combination MS-1 × M-610 and Kajri × MM-904 displayed significant SCA value for flesh thickness and rind thickness, respectively (34). Additionally, notable SCA effects and desirable BPH for flesh thickness (23, 32). The Thar Mahima and Durgapura Madhu crosses exhibited the highest BPH and SDH compared to the commercial check, Muskan.

For selecting superior parents, we recommend AHMM/BR-8 and Thar Mahima, as they exhibited the highest significant GCA in a desirable direction for yield and related traits. The cross AHMM/BR-8 × Thar Mahima demonstrated high heterosis for marketable fruit yield, fruit weight and vine length at the final harvest, making it a promising parent for achieving higher yield and larger fruits. Additionally, the cross Punjab Sunehri × Thar Mahima exhibited favourable heterosis over better parent for TSS content and total sugar content. These finding highlight the potential for developing superior muskmelon hybrids.

When selecting superior parents for future breeding crosses, it is crucial to consider trait correlations, as both positive and negative associations can indicate potential trade-offs. Understanding the relationship helps to optimize breeding strategies by effectively balancing desirable trait. In this context, index selection has been recognized as a valuable approach for simultaneously improving multiple traits, as reported in the recent studies (14, 35, 36). Integrating biochemical and molecular tools with traditional breeding offer a compressive approach to muskmelon improvement, enhancing the efficiency of hybrid development. While preliminary evaluation of F_1 hybrids is informative, further assessment of these crosses in subsequent segregation generations could provide valuable insight into trait segregation and recombination, ultimately contributing to the development of improved muskmelon varieties.

Conclusion

The study investigated GCA and SCA effects on yield and fruit traits in muskmelon under arid conditions in Western India. The findings support the development of high-potential muskmelon cultivars to enhance global production sustainability. Parental lines Thar Mahima, AHMM/BR-8 and Hara Madhu showed strong GCA for early maturity and yield traits, making them valuable for breeding programs. Promising hybrids such as Thar Mahima × Durgapura Madhu, AHMM/BR-8 × Punjab Sunehri, AHMM/BR-1 × Thar Mahima and Thar Mahima × Hara Madhu showed potential as F_1 hybrids, pending multi-location performance validation. These results provide useful direction for selecting superior genotypes and hybrids.

Acknowledgements

We are indebted to Director, ICAR-Central Institute for Arid Horticulture (CIAH), Bikaner, India for providing necessary facility and support to conduct the experiment.

Authors' contributions

The conceptualization of the study was carried out by VMK, PK and BRC. The methodology was designed by VMK, PK, AKS and BRC, while the implementation of experiments in the field was undertaken by VMK, PK, AKS and BRC. Statistical analysis was performed by VMK, PK and HK. The original draft of the manuscript was prepared by VMK, PK and HK, whereas PK, BRC, AKS and HK contributed to writing, reviewing and editing the final version of the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

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

Ethical issues: None

References

1. Saroj PL, Ram C, Kumar K. Arid horticultural crops: Status and opportunities under changing climatic conditions. Indian J Plant Genet Resour. 2020;33(1):17–31.
2. Fergany M, Kaur B, Monforte AJ, Pitrat M, Rys C, Lecoq H, et al. Variation in muskmelon (*Cucumis melo*) landraces adapted to the humid tropics of southern India. Genet Resour Crop Evol. 2011;58:225–43.
3. Gonzalo MJ, Díaz A, Dhillon NPS, Reddy UK, Pico B, Monforte AJ. Re-evaluation of the role of Indian germplasm as centre of muskmelon diversification based on genotyping-by-sequencing analysis. BMC Genomics. 2019;20:1–13. https://doi.org/10.1186/s12864-019-5636-2
4. Singh M, Sharma SP, Sarao NK, Kaur S, Chhuneja P. Molecular mapping of nuclear male-sterility gene ms-1 in muskmelon (*Cucumis melo* L.). J Hortic Sci Biotechnol. 2020;95:162–68. https://doi.org/10.1080/14620316.2019.1690892
5. Pandey S, Rai M, Prasanna HC, Kalloo G. "Kashi Madhu": A new muskmelon cultivar with high total soluble solids. Hort Sci. 2008;43:245–46.
6. Rehman A, Dang T, Qamar S, Ilyas A, Fatema R. Revisiting plant heterosis-from field scale to molecules. Genes. 2021;12:1688. https://doi.org/10.3390/genes12111688
7. Choudhary BR, Dhaka RS, Fageria MS. Heterosis for yield and yield related attributes in muskmelon (*Cucumis melo* L.). Indian J Genet. 2003;63:91–92.
8. Kamer A, Yousry M. Heterosis and heritability studies for fruit characters and yield in muskmelon (*Cucumis melo* L.). Middle East J Appl Sci. 2015;5:262–73.

9. Griffing B. Concept of general and specific combining ability in relation to diallel crossing systems. Austr J Biol Sci. 1956;9:463.

10. Valerio IP, Iraja F, De Carvalho F, De Oliveira AC, De Souza VQ. Combining ability of wheat genotypes in two models of diallel analyses. Crop Breed Appl Biotechnol. 2009;9:100–107. https://doi.org/10.12702/1984-7033.v09n01a15

11. De Araújo Barros AK, de Sousa Nunes GH, de Queiróz MA, Pereira EWL, Costa Filho JH. Diallel analysis of yield and quality traits of muskmelon fruits. Crop Breed Appl Biotechnol. 2011;11:313–19. https://doi.org/10.1590/S1984-70332011000400006

12. Costa IJN, de Normandes Valadares R, Nóbrega DA, Mendes AQ, Silva FS, Menezes D. Heterosis and combining ability of muskmelon genotypes of momordica group. J Exp Agric Int. 2019;30:1–9. https://doi.org/10.9734/jeai/2019/v30i330120

13. Choudhary BR, Haldhar SM, Maheshwari SK, Bhargava R, Sharma SK. AHMM/BR-8 (IC0599709; INGR 14043), a muskmelon (*Cucumis melo* L.) germplasm with monoecious sex form. Indian J Plant Genet Resour. 2015;28(3):357–58.

14. Choudhary BR, Singh D, Saroj PL. Development and characterization of intraspecific hybrids derived from *Cucumis melo* L. Bangladesh J Bot. 2019;48(2):359–66.

15. Bhowmick BC, Dutta SK, Puzari NN, Goswami J, Saud RK, Ray BK. Package of practices for horticultural crops, fisheries and home science. Department of Agriculture, Assam. 2015; p. 81.

16. Choudhary BR, Maheshwari SK, Haldhar SM, Ram C, Singh D. Thar Mahima: An improved cultivar of muskmelon identified for arid region. Indian J Arid Hortic. 2024;3(1&2):13-17. https://doi.org/10.48165/ijah.2021.3.1.3

17. Yogesh M, Vidya, Kavya DO, Kishorkumar GK, Pramod BS. Advances in production technology of muskmelon. In: Yadav A, Rajbhar R, Kumar R, Prasad L, Luthra CNRS, editors. Advances in vegetable production. PK Publishers and Distributors, New Delhi; 2023. p. 112.

18. Kaur A, Sharma M, Manan J, Bindu. Comparative performance of muskmelon (*Cucumis melo*) hybrids at farmers' field in district Kapurthala. J Krishi Vigyan. 2017;6(1):24-31. https://doi.org/10.5958/2349-4433.2017.00043.5

19. Ranganna S. Manual of analysis of fruit and vegetable products. New York: McGraw-Hill; 1977.

20. Heinze PH, Kanapaux MS, Wade BL, Grimball PC, Foster RLAAC. Ascorbic acid contents of 39 varieties of snap bean. Food Res. 1944;9:19–26.

21. Tomar RS, Bhalala MK. Heterosis studies in muskmelon (*Cucumis melo* L.). J Hortic Sci. 2006;1:144–47.

22. Singh V, Vashisht VK. Heterosis and combining ability for yield in muskmelon (*Cucumis melo* L.). Int J Curr Microbiol Appl Sci. 2018;7:2996–3006. https://doi.org/10.20546/ijcmas.2018.708.319

23. Feyzian E, Dehghani H, Rezai AM, Javaran MJ. Diallel cross analysis for maturity and yield-related traits in muskmelon (*Cucumis melo* L.). Euphytica. 2009;168:215–23. https://doi.org/10.1007/s10681-009-9938-0

24. Kumar P, Singh H, Lal C, Sharma SR. Combining ability analysis in bread wheat (*Triticum aestivum*) over environments. Indian J Agric Sci. 2020;90(6):1093–96. https://doi.org/10.56093/ijas.v90i6.104773

25. Kumar P, Singh H, Choudhary R, Lal C. Heterosis analysis for yield and its component traits in bread wheat (*Triticum aestivum* L.) over different environment. J Environ Biol. 2021;42(2):438–44. http://dx.doi.org/10.22438/jeb/42/2(SI)/SI-251

26. Lal C, Shekhawat AS, Singh J, Rajput SS, Sharma SR, Kumar P. Heterosis studies in 6-rowed barley (*Hordeum vulgare*) under different sowing condition. Indian J Agric Sci. 2020;90(7):1306–309. https://doi.org/10.56093/ijas.v90i7.105600

27. Lal C, Shekhawat AS, Singh J, Kumar P. Combining ability analysis in six-rowed barley under different date of sowing conditions. Ann Agric Sci. 2021;42(4):1–6.

28. Barupal HL, Sharma AK, Shekhawat HS, Kumar P, Kumar M. Heterosis studies in Indian mustard (*Brassica juncea*). Int J Agric Innov Res. 2017;5:960–66.

29. Saha K, Mishra S, Choudhary H, Mahapatra S. Estimates of genetic component of variation in muskmelon (*Cucumis melo* L.). Int J Curr Microbiol Appl Sci. 2018;7:1144–51.

30. Badami K, Daryono BS, Amzeri A, Khoiri S. Combining ability and heterotic studies on hybrid muskmelon (*Cucumis melo* L.) populations for fruit yield and quality traits. SABRAO J Breed Genet. 2020;52:402–17.

31. Mohammadi R, Dehghani H, Karimzadeh G. Genetic analysis of yield components, early maturity and total soluble solids in cantaloupe (*Cucumis melo* L. subsp. *melo* var. *cantalupensis* Naudin). Yuzuncu Yil Univ Tarim Bilim. 2014;24(1):79–86. https://doi.org/10.29133/yyutbd.235919

32. Rolania S, Fageria MS. Heterosis and combining ability evaluation for yield, quality and fruit fly resistance in muskmelon. Int J Curr Microbiol Appl Sci. 2018;7:902–15.

33. Pouyesh A, Lotfi M, Ramshini H, Karami E, Shamsitabar A, Armiyoun E. Genetic analysis of yield and fruit traits in cantaloupe cultivars. Plant Breeding. 2017;136:569–77.

34. Kaur S, Sharma SP, Sarao NK, Deol JK, Gill R, Abd-Elsalam KA, et al. Heterosis and combining ability for fruit yield, sweetness, β-carotene, ascorbic acid, firmness and *Fusarium* wilt resistance in muskmelon (*Cucumis melo* L.) involving genetic male sterile lines. Horticulturae. 2022;8:82. https://doi.org/10.3390/horticulturae8010082

35. Gomes DA, Alves IM, Maciel GM, Siquieroli ACS, Peixoto JVM, Pires PS, et al. Genetic dissimilarity, selection index and correlation estimation in a muskmelon germplasm. Hortic Brasileira. 2021;39:46–51.

36. Adewumi AS, Asare PA, Adejumobi II, Adu MO, Taah KJ, Adewale S, et al. Multi-trait selection index for superior agronomic and tuber quality traits in bush yam (*Dioscorea praehensilis* Benth.). Agronomy. 2023;13:682.

Additional information

Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

Reprints & permissions information is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

Publisher's Note: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Indexing: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

Publisher information: Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.