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Heterosis for seed and seedling traits in papaya

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ABSTRACT

The current study aimed to explore the heterosis expressed in the seed and seedlings of 36 papaya hybrids originating from the 6 inbred lines. The results revealed that heterosis manifested in the papaya's seed and seedling stage. The cross combinations, P-9-5 × P-7-2, P-9-12 × PN and PN × P-9-5 exhibited positive average heterosis and heterobeltiosis for physical seed traits. The genotypes, P-9-5, P-9-12, P-9-5 × P-9-12 and P-9-12 × P-9-5 were observed with positive mid-parent heterosis and heterobeltiosis for the seedling traits. The hybrid, P-7-9 × PN and PS3 × P-7-9, showed positive average heterosis (5.89% and 9.91%) and heterobeltiosis (3.41% and 2.09%) for germination percentage, respectively. Whereas in case of seedling length and weight (fresh and dry), the hybrid combination, P-9-5 × P-9-12 exhibited positive heterosis. The heterosis effect estimate helped us to identify the superior performing hybrids like PN × P-7-2, PN × P-9-5, P-7-2 × PN, P-7-2 × P-7-9, P-7-9 × P-9-5, P-9-5 × P-7-2, P-9-5 × P-9-12, P-9-12 × PN, P-9-12 × P-7-2, P-9-12 × P-9-5and PS3 × P-7-9, in the initial stage of seedling development.

Keywords: *Carica papaya* L., Average heterosis, Germination, Heterobeltiosis.

INTRODUCTION

Papaya (*Carica papaya* L.)is a rich source of vitamin A and vitamin C, along with minerals like magnesium, potassium, and boron. It is commercially propagated through seeds, which play an important role in dissemination of genetic characteristics that are incorporated into improved varieties. Hence, seed and seedling traits in papaya are important for attempting any genetic improvement programme.

Seed quality and the seedling characteristics not only determine the success of seed germination and seedling growth, but also the final yield of the crop. Bigger and heavier seeds are considered to have more reserve food material than the smaller and lighter seeds. Various studies conducted for seed quality and seedling vigour in different crops revealed a positive correlation between the seed size, seedling vigour and seedling survival rate (Mengarda *et al.*, 9; Wulff 18; Tripathi and Khan 16; Moegenburg, 11). Studies conducted by also had similar observation regarding seed size and vigour in papaya.

The varieties which are largely cultivated in India are mostly inbreds like Pusa Nanha, Pusa Dwarf, Pusa Giant and some hybrids like Red Lady, Arka Surya and Arka Prabhath. The development of papaya inbreds and hybrids are gaining attention in the country due to their high agronomic potential. However, hybrids have several advantage over the inbreds in terms of yield, fruit quality and resistance to biotic and abiotic factors. Heterosis in papaya has been utilized by the breeders for the development of improved high yielding hybrid varieties (Singh *et al.*, 15). Heterosis in papaya has been analysed for vegetative, reproductive, yield and quality related traits, but not for seed and seedling related traits. However, there are few studies, which focus on the investigation of seed quality, germination and vigour characteristics of papaya seedlings (Macedo *et al.*, 6; Mengarda *et al.*, 9). Many morphological and physiological characteristics related to seeds have shown high heritability, indicating their utility in breeding programme (Mengarda *et al.*, 9). Various studies conducted on seed and seedlings of crop plants have revealed an increased vigour, manifested during embryo and early seedling development (Shull, 14), and the seed size, germination and vigour have been found to influence the final crop yield through both direct and indirect effects (Ellis, 1). So, it has become essential to study the magnitude of heterosis in the seed and seedling stage of papaya. Heterosis for seed and seedlings traits may also provide an insight for further increased heterosis for yield and other related traits.

MATERIALS AND METHODS

The present study was conducted in the Division of Fruits and Horticultural Technology, ICAR-IARI, New Delhi. The crosses between the six different papaya parents, namely, Pusa Nanha (PN), and five inbred lines i.e. P-7-2, P-7-9, P-9-5, P-9-12 and Pune Sel. 3 (PS3) were made at the Main Experimental Orchard during 2019-2020. The crosses were made

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in 6 × 6 full diallel mating design excluding the parental combinations. For the experiment, seeds of six parent papaya genotypes along with 30 hybrids, were used for the analysis of different seed and seedling traits. Three replicates each containing 25 seeds per treatment was used employing completely randomized design.

The physical traits considered for the study were seed length, seed diameter, seed weight and seed moisture. The seed size including the length and diameter were measured using a vernier caliper. The seed weight was measured using 100 seeds in each genotypes. For the estimation of seed moisture, initially weight of the well dried seeds was determined and then the seeds were dried at 105 ± 3ºC for 24 h in hot-air oven (Mengarda *et al*., 9) and then the difference was taken as the moisture content in the seed. The data on other traits include seed germination percentage, first count of germination (FCG), second count (SCG), third count (TCG), mean germination time (MGT), speed of germination index (SGI), the shoot length (SL), root length (RL), fresh mass (FM) and dry mass (DM) of seedlings, which were recorded over the span of 30 days. For the germination test, the seeds were distributed evenly over the germi-test paper, with prior soaking in double-distilled water, and placed in a BOD incubator with alternating temperature of 20-30ºC with the photoperiod of 16/8 h light and dark period at optimum relative humidity. The following assessment were made during the seed germination period: number of germinating seeds (G); first count of germination (FCG) was recorded at 10 days, the second count (SCG) was observed at 20 days, and the third count (TCG) was noted at 30 days, andthe number of germinating seeds were later expressed in terms of percentage. The speed of germination index (SGI) was calculated by the formula given by Maguire (7); and mean germination time (MGT) which was calculated based on the formula given by Labouriau (5). The shoot (SL) and root length (RL) were measured after 30 days of the initiation of the experiment. The fresh mass (FM) and dry mass (DM) of seedlings were also weighed on an analytical balance (0.0001 g) after 30 days of the experiment. For dry mass estimation, the seedlings were kept in an oven of forced air circulation at 70ºC for 72 h (Mengarda *et al*., 9). The data obtained were analysed online using OP Stat software (Sheoran *et al*., 13).

RESULTS AND DISCUSSION

The data of mean performance of parents and crosses for seed and seedlings traits are given in Table 1 and 2. The highest value of mean seed length was recorded in the hybrid, P-9-12 × PN (7.64 mm), and the lowest was found in the hybrid, P-7-2 × PS3 (3.38 mm). In case of seed diameter, the genotype P-7-9 (5.12 mm) was observed with the highest value, and it was lowest in P-7-2 × PS3 (2.60 mm). The genotypes, P-9-12 and P-9-12 × P-7-2 had the highest 100-seed weight (1.63 g in each), while the hybrid, P-7-2 × P-9-12 had the lowest 100-seed weight. In the study conducted by Mengarda *et al*. (9), the data revealed that seed dimension and seed weight hada positive correlation with seed vigour. The average seed moisture ranged from 4.47% in PS3 × P-9-5 to 8.20% in P-9-5 × P-7-2. Study conducted by Mengarda *et al*. (9) in papaya revealed that the water content of the dried seeds are adequate for the maintenance of seed viability during storage and also supports seed germination under congenial environment.

The genotypes P-9-5, P-9-12 and P-9-12 × P-9-5 tended to show the highest seed germination (92.00% in each), while hybrid PS3 × P-9-5 had the lowest germination (58.67%).Few studies on papaya revealed that higher moisture content of the seeds also had positive relation with the vigour and germination of seeds (Mengarda *et al*., 9), and a similar trend was also observed in this study as the seed containing moisture content above 6% were more vigorous as compared to the seeds with lower moisture (5% or less).The first count germination values ranged from 1.33 to 37.33% in the genotypes PS3 × PN and P-7-2, respectively. After 20 days of germination, the hybrid P-9-12 × P-9-5 (92.00%) showed the highest seed germination, while hybrid P-7-2 × PS3 (24.00%) showed the lowest germination. On third count germination at 30 days, genotypes P-9-12 and P-9-12 × P-9-5 (92.00%) were observed with highest seed germination, whereas PS3 × P-9-5 (56.00%) was observed with lowest seed germination. Speed of germination index was highest in the hybrid P-9-12 × P-9-5 (3.65), while lowest (1.28) was noticed in hybrid PN × PS3. Mean germination time was recorded earliest (14.17 days) in PS3 × P-9-5, while it was most delayed in hybrid P-9-12 × P-9-5 (30.33). The above results suggests that the seeds with greater seed size and higher moisture content showed the maximum germination along with highest germination rate, as also earlier reported by Mengarda *et al.*(9). Improvement in seed germination and survival and seedlings growth are largely attributed to large seed size (Tripathi and Khan,16).

The hybrid PS3 × P-7-9 tended to show the highest shoot length (10.93 cm), root length (3.17 cm) and fresh weight (93.10 mg) of papaya seedlings, while the lowest shoot length (5.07 cm) and root

Table 1. Performance of papaya parent and hybrid genotypes for seed traits.

Genotype	Seed length (mm)	Seed diameter (mm)	100-seed weight (g)	Seed moisture (%)	Germination (%)	First count germination (%)	Second count germination (%)
PN	6.00	4.97	1.23	7.16	84.00	24.00	50.67
PN × PS3	5.71	4.24	1.06	6.45	62.67	2.67	25.33
PN × P-7-2	6.14	4.52	1.28	7.68	84.67	16.00	52.00
PN × P-7-9	6.02	4.43	1.05	5.74	77.33	8.00	50.67
PN × P-9-5	7.26	4.79	1.30	7.90	84.00	14.67	53.33
PN × P-9-12	5.59	3.91	1.08	5.44	88.00	9.33	52.00
P-7-2	4.84	3.87	1.07	6.36	90.67	37.33	65.33
P-7-2 × PS3	3.38	2.60	0.68	5.07	61.33	8.00	24.00
P-7-2 × PN	5.80	4.64	1.08	7.19	82.67	30.67	46.67
P-7-2 × P-7-9	5.26	4.03	0.90	6.81	73.33	20.00	45.33
P-7-2 × P-9-5	6.08	4.55	0.87	7.42	85.33	22.67	62.67
P-7-2 × P-9-12	4.76	3.31	0.66	5.04	86.67	32.00	76.00
P-7-9	6.49	5.12	1.19	6.72	80.00	17.33	56.00
P-7-9 × PS3	4.45	2.65	0.81	5.77	62.67	2.67	28.00
P-7-9 × PN	6.56	5.02	0.97	5.88	86.67	24.00	72.00
P-7-9 × P-7-2	6.05	4.07	0.88	5.64	77.33	18.67	62.67
P-7-9 × P-9-5	6.09	4.37	1.42	7.86	85.33	20.00	73.33
P-7-9 × P-9-12	6.47	4.55	1.17	6.54	90.67	26.67	80.00
P-9-5	6.70	4.55	1.38	7.48	92.00	21.33	57.33
P-9-5 × PS3	5.34	3.12	1.25	6.75	72.00	5.33	34.67
P-9-5 × PN	6.07	3.90	1.28	6.86	84.00	20.00	58.67
P-9-5 × P-7-2	6.91	4.64	1.52	8.20	82.67	21.33	52.00
P-9-5 × P-7-9	6.66	4.50	1.44	7.34	84.00	14.67	53.33
P-9-5 × P-9-12	6.22	3.99	1.25	6.76	90.67	21.33	57.33
P-9-12	6.99	4.83	1.63	7.74	92.00	21.33	76.00
P-9-12 × PS3	4.17	2.80	0.75	5.70	76.00	6.67	45.33
P-9-12 × PN	7.64	4.82	1.55	7.76	90.67	17.33	89.33
P-9-12 × P-7-2	7.19	4.35	1.63	7.82	78.67	9.33	52.00
P-9-12 × P-7-9	6.07	4.18	1.24	6.66	84.00	16.00	49.33
P-9-12 × P-9-5	6.14	4.37	1.50	7.90	92.00	25.33	92.00
PS3	4.44	3.57	0.82	5.23	68.00	9.33	38.67
PS3 × PN	5.24	4.65	1.03	6.19	70.67	1.33	50.67
PS3 × P-7-2	5.46	4.74	1.05	6.67	61.33	5.33	30.67
PS3 × P-7-9	5.30	4.63	1.09	7.29	81.33	17.33	37.33
PS3 × P-9-5	4.93	3.98	0.79	4.47	58.67	8.00	25.33
PS3 × P-9-12	5.19	4.27	0.95	5.18	60.00	10.67	30.67
C.D.	0.38	0.36	0.13	0.26	6.40	5.79	5.24
SE (m)	0.13	0.13	0.05	0.09	2.26	2.05	1.86
SE (d)	0.19	0.18	0.07	0.13	3.20	2.90	2.63
C.V.	3.99	5.27	7.15	2.38	4.93	21.78	6.07

Table 2. Performance of papaya parent and hybrid genotypes for seed and seedling traits.

Genotype	Third count germination (%)	Speed of germination index	Mean germination time (days)	Shoot length (cm)	Root length (cm)	Fresh weight (mg)	Dry weight (mg)
PN	84.00	2.76	23.58	7.23	0.97	84.17	3.93
PN × PS3	61.33	1.28	14.83	5.07	0.77	52.83	3.10
PN × P-7-2	85.33	2.52	23.50	8.53	1.47	78.87	4.07
PN × P-7-9	76.00	2.10	21.08	8.20	1.53	78.63	3.73
PN × P-9-5	84.00	2.48	23.33	7.33	1.37	71.93	3.57
PN × P-9-12	86.67	2.29	23.33	7.93	1.40	73.60	3.37
P-7-2	90.67	3.58	27.50	8.03	1.47	73.67	2.90
P-7-2 × PS3	57.33	1.40	14.25	5.23	0.90	57.53	3.53
P-7-2 × PN	81.33	2.90	23.00	5.53	1.53	65.83	3.13
P-7-2 × P-7-9	72.00	2.38	20.42	8.77	1.50	83.97	2.37
P-7-2 × P-9-5	81.33	2.90	24.50	8.10	1.43	75.53	2.47
P-7-2 × P-9-12	86.67	3.53	27.75	8.43	1.70	80.30	3.03
P-7-9	78.67	2.56	22.83	8.93	2.17	87.87	3.07
P-7-9 × PS3	60.00	1.31	14.92	6.33	0.70	49.47	2.73
P-7-9 × PN	86.67	3.17	26.75	7.43	1.03	69.90	3.93
P-7-9 × P-7-2	74.67	2.67	23.00	8.50	1.53	80.83	3.10
P-7-9 × P-9-5	81.33	2.99	25.67	8.87	1.87	84.60	2.23
P-7-9 × P-9-12	90.67	3.46	28.67	9.13	1.97	87.13	2.93
P-9-5	90.67	2.86	25.50	7.37	1.13	65.80	3.70
P-9-5 × PS3	70.67	1.65	17.92	6.13	0.63	54.20	3.70
P-9-5 × PN	82.67	2.74	24.08	6.57	1.40	68.63	3.80
P-9-5 × P-7-2	81.33	2.66	23.08	8.20	1.70	75.73	3.80
P-9-5 × P-7-9	82.67	2.46	23.08	9.07	2.03	86.03	3.43
P-9-5 × P-9-12	88.00	2.83	25.00	8.47	1.80	80.70	2.43
P-9-12	92.00	3.21	28.08	4.27	0.60	41.10	2.70
P-9-12 × PS3	76.00	1.95	20.33	5.63	0.97	50.80	3.70
P-9-12 × PN	89.33	3.28	29.00	7.77	1.30	59.23	4.07
P-9-12 × P-7-2	76.00	2.17	21.33	7.93	1.33	72.50	2.77
P-9-12 × P-7-9	81.33	2.42	22.42	7.40	1.83	56.50	3.50
P-9-12 × P-9-5	92.00	3.65	30.33	8.50	1.70	75.77	2.67
PS3	65.33	1.80	17.67	6.03	1.37	51.77	3.47
PS3 × PN	65.33	1.73	18.67	6.63	1.47	64.63	3.70
PS3 × P-7-2	60.00	1.45	15.42	10.77	3.13	89.67	3.60
PS3 × P-7-9	81.33	2.25	21.00	10.93	3.17	93.10	4.07
PS3 × P-9-5	56.00	1.40	14.17	9.33	2.30	84.77	2.53
PS3 × P-9-12	58.67	1.62	15.50	9.67	2.50	87.87	3.17
C.D.	6.52	0.27	1.76	1.00	0.50	9.58	0.50
SE (m)	2.31	0.10	0.62	0.36	0.18	3.39	0.18
SE (d)	3.27	0.14	0.88	0.50	0.25	4.80	0.25
C.V.	5.13	6.84	4.84	7.97	19.63	8.15	9.38

length (0.60 cm) were recorded in PN × PS 3 and P-7-9, respectively. The hybrids, P-7-2, P-9-12 × PN and PS3 × P-7-9 proved equally good to have higher seedling dry weight (4.07 g in each) than others. The genotype P-9-12 had better seed dimension, moisture, germination percentage, SGI and MGT but still shoot length, root length,fresh weight and dry weight of the seedling were lower. The reason behind this could be the deterioration of the seedlings due to the higher time of residence in the same substrate without any nutrient application after germination.

In this study, crossing of 6 inbreds gave rise to 36 heterotic combinations, which showed heterosis for different seed and seedling traits (Table 3-5). Majority of hybrid combinations, tended to show the negative mid-parent (MPH) and better-parent heterosis (BPH) for physical traits of seed like seed length, diameter and seed weight (Table 3). In case of seed length (mm), PN × P-7-2, PN × P-9-5, P-7-9 × PN, P-9-5 × P-7-2, P-9-12 × PN, P-9-12 × P-7-2, and PS3 × P-7-2 were the only hybrids to show positive better parent heterosis. However, for seed diameter (mm),

Table 3. Mid and better parent heterosis for seed and seedling traits in papaya.

Genotype	Seed length (mm)		Seed diameter (mm)		100-seed weight (g)		Seed moisture (%)		Germination (%)	
	MPH	BPH	MPH	BPH	MPH	BPH	MPH	BPH	MPH	BPH
PN × PS3	9.40	-4.77	-0.75	-14.41	3.41	-14.02	4.16	-9.86	-17.41	-25.13
PN × P-7-2	13.28	2.28	2.39	-8.80	11.10	3.84	13.58	7.26	-3.07	-8.01
PN × P-7-9	-3.58	-7.19	-11.98	-15.85	-12.89	-14.48	-17.22	-19.76	-5.66	-7.79
PN × P-9-5	14.33	8.49	1.00	-3.10	-0.57	-5.77	7.85	5.56	-4.55	-8.71
PN × P-9-12	-14.04	-20.09	-19.99	-21.35	-24.46	-33.43	-27.04	-29.77	0.07	-4.10
P-7-2 × PS3	-27.14	-29.94	-30.06	-32.66	-28.24	-36.45	-12.41	-20.21	-22.39	-32.03
P-7-2 × PN	7.12	-3.22	5.25	-6.23	-6.21	-12.33	6.38	0.45	-5.29	-9.96
P-7-2 × P-7-9	-7.07	-18.89	-10.04	-20.89	-20.54	-24.34	4.15	1.36	-14.07	-18.95
P-7-2 × P-9-5	5.44	-9.07	8.07	-0.07	-28.71	-36.75	7.31	-0.72	-6.39	-8.51
P-7-2 × P-9-12	-19.57	-31.90	-23.96	-31.58	-51.05	-59.42	-28.47	-34.84	-5.03	-7.07
P-7-9 × PS3	-18.56	-31.39	-39.00	-48.19	-18.93	-31.67	-3.41	-14.08	-15.32	-21.62
P-7-9 × PN	5.04	1.11	-0.54	-4.98	-19.94	-21.34	-15.26	-17.85	5.89	3.41
P-7-9 × P-7-2	6.90	-6.63	-9.45	-20.48	-22.17	-25.64	-13.83	-16.15	-9.31	-14.47
P-7-9 × P-9-5	-7.38	-9.86	-9.48	-14.43	10.75	5.33	10.63	5.04	-0.70	-7.13
P-7-9 × P-9-12	-4.02	-7.48	-8.60	-10.97	-17.03	-28.18	-9.61	-15.52	5.43	-1.26
P-9-5 × PS3	-3.79	-20.00	-23.08	-31.22	14.01	-9.16	6.27	-9.75	-10.00	-21.77
P-9-5 × PN	-4.50	-9.31	-18.03	-21.36	-2.02	-7.12	-6.31	-8.28	-4.55	-8.71
P-9-5 × P-7-2	19.81	3.36	10.38	2.14	24.40	10.30	18.46	9.58	-9.29	-11.35
P-9-5 × P-7-9	1.02	-1.68	-6.76	-11.78	12.17	4.38	3.28	-1.96	-2.11	-8.51
P-9-5 × P-9-12	-9.18	-11.10	-15.05	-17.48	-16.93	-23.22	-11.20	-12.68	-1.39	-4.17
P-9-12 × PS3	-26.91	-40.26	-33.39	-42.04	-38.79	-53.77	-11.97	-26.27	-5.01	-17.41
P-9-12 × PN	17.46	9.22	-1.56	-3.36	8.28	-4.85	4.18	0.28	3.03	-1.32
P-9-12 × P-7-2	21.58	3.01	0.10	-9.92	20.70	0.00	10.90	1.03	-13.81	-15.66
P-9-12 × P-7-9	-9.98	-13.19	-16.03	-18.26	-12.07	-23.62	-7.83	-13.89	-2.33	-8.64
P-9-12 × P-9-5	-10.31	-12.19	-6.82	-9.55	-0.51	-8.17	3.86	2.13	0.06	-2.72
PS3 × PN	0.33	-12.67	8.88	-6.16	0.97	-16.38	-0.11	-13.52	-6.84	-15.66
PS3 × P-7-2	17.77	13.08	27.42	22.52	11.32	-1.27	15.08	4.83	-22.57	-32.17
PS3 × P-7-9	-2.94	-18.15	6.55	-9.48	8.54	-8.49	21.97	8.52	9.91	2.09
PS3 × P-9-5	-11.16	-26.14	-2.02	-12.41	-28.20	-42.51	-29.58	-40.21	-26.59	-36.09
PS3 × P-9-12	-9.13	-25.67	1.66	-11.58	-22.37	-41.89	-20.16	-33.10	-24.79	-34.63

Table 4. Mid parent heterosis and better parent heterosis for seed and seedling traits in papaya.

Genotype	First count germination (%)		Second count germination (%)		Third count germination (%)		Speed of germination index		Mean germination time (days)	
	MPH	BPH	MPH	BPH	MPH	BPH	MPH	BPH	MPH	BPH
PN × PS3	-83.07	-87.78	-43.21	-49.79	-17.83	-26.80	-43.92	-53.71	-28.05	-37.01
PN × P-7-2	-48.33	-57.50	-10.37	-20.39	-2.29	-7.25	-20.70	-29.77	-7.97	-14.51
PN × P-7-9	-60.74	-66.03	-5.13	-9.55	-6.59	-9.46	-21.17	-24.05	-9.21	-10.77
PN × P-9-5	-35.24	-38.73	-1.23	-6.98	-3.84	-7.32	-12.02	-13.78	-4.95	-8.47
PN × P-9-12	-58.69	-61.27	-17.69	-31.27	-1.48	-5.55	-22.96	-28.10	-9.57	-16.59
P-7-2 × PS3	-66.16	-79.17	-53.90	-63.40	-26.12	-36.46	-48.00	-61.03	-36.69	-48.10
P-7-2 × PN	0.90	-15.83	-19.26	-28.24	-6.80	-11.35	-8.62	-18.98	-9.94	-16.29
P-7-2 × P-7-9	-25.40	-45.00	-25.05	-30.20	-15.00	-20.54	-22.24	-33.38	-18.88	-25.79
P-7-2 × P-9-5	-22.01	-38.33	2.22	-3.66	-10.10	-10.04	-10.02	-19.00	-7.48	-10.89
P-7-2 × P-9-12	9.52	-12.50	7.74	11.41	-5.03	-7.07	3.91	-1.19	-0.15	-1.43
P-7-9 × PS3	-80.95	-85.00	-40.94	-50.17	-16.57	-23.13	-39.88	-48.60	-26.29	-34.37
P-7-9 × PN	15.93	0.00	35.35	29.35	6.67	3.41	19.39	14.86	15.39	13.36
P-7-9 × P-7-2	-32.06	-50.00	3.59	-3.66	-11.79	-17.50	-12.80	-25.26	-8.61	-16.38
P-7-9 × P-9-5	3.03	-6.67	29.50	25.08	-3.84	-10.10	10.41	4.57	6.29	0.84
P-7-9 × P-9-12	40.76	30.56	21.21	5.55	6.28	-1.26	20.08	8.36	12.63	2.36
P-9-5 × PS3	-65.48	-75.56	-27.69	-39.52	-9.24	-21.97	-29.20	-42.40	-16.86	-29.69
P-9-5 × PN	-10.12	-13.97	8.64	2.38	-5.36	-8.84	-2.33	-4.28	-1.90	-5.53
P-9-5 × P-7-2	-25.90	-41.67	-15.27	-20.39	-9.94	-11.36	-17.21	-25.61	-12.69	-15.96
P-9-5 × P-7-9	-23.91	-31.11	-5.66	-8.89	-2.29	-8.71	-9.05	-13.96	-4.36	-9.34
P-9-5 × P-9-12	-0.17	-6.67	-13.91	-24.29	-3.48	-5.43	-6.68	-11.64	-6.55	-10.75
P-9-12 × PS3	-53.70	-66.67	-20.89	-40.33	-3.38	-17.41	-21.80	-38.98	-11.04	-27.57
P-9-12 × PN	-23.93	-27.62	41.09	17.67	1.52	-2.84	9.64	2.06	12.24	3.34
P-9-12 × P-7-2	-67.86	-75.00	-26.17	-31.36	-16.64	-18.43	-36.13	-39.51	-23.13	-24.06
P-9-12 × P-7-9	-14.09	-19.44	-25.25	-35.06	-4.65	-11.48	-15.88	-24.07	-11.91	-20.01
P-9-12 × P-9-5	21.55	13.33	38.24	21.46	0.87	-1.14	20.38	14.27	13.44	8.40
PS3 × PN	-92.59	-95.24	13.44	0.21	-12.42	-21.95	-24.14	-37.40	-9.44	-20.68
PS3 × P-7-2	-77.27	-85.83	-41.07	-53.07	-22.79	-33.56	-45.96	-59.39	-31.62	-43.89
PS3 × P-7-9	31.75	3.33	-21.01	-32.93	12.97	3.60	3.59	-11.36	3.75	-7.73
PS3 × P-9-5	-47.62	-62.22	-47.16	-55.71	-28.00	-38.01	-39.68	-50.76	-34.21	-44.25
PS3 × P-9-12	-27.78	-47.22	-46.38	-59.57	-25.25	-36.15	-34.72	-49.03	-32.04	-44.69

only two hybrids (P-9-5 × P-7-2 and PS3 × P-7-2) could show the heterobeltiosis in positive direction. Hybrids, PN × P-7-2, P-7-9 × P-9-5, P-9-5 × P-7-2, and P-9-5 × P-7-9 exhibited positive better parent heterosis for 100-seed weight (g).For the traits like seed length (mm), seed diameter (mm), and 100-seed weight (g), the hybrids exhibiting positive mid parent heterosis were PN × P-7-2, P-9-5 × P-7-2, P-9-12 × P-7-2, PS3 × PN, and PS3 × P-7-2. The similar results were also observed by Wang (17) in the hybrid progenies of maize. Positive mid-parent and better parent heterosis for above mentioned traits is desirable as bigger and heavier seeds of F_1 hybrids have more food reserves and may give rise to more vigorous and healthy seedlings. Positive average heterosis and heterobeltiosis for seed moisture was recorded in hybrids like PN × P-7-2, PN × P-9-5, P-7-2 × PN, P-7-2 × P-7-9, P-7-9 × P-9-5, P-9-5 × P-7-2, P-9-12 × PN, P-9-12 × P-7-2, P-9-12 × P-9-5, PS3 × P-7-2 and PS3 × P-7-9. Enhanced moisture content in F_1 hybrids over the parents is a positive sign for germination of more number of healthy and vigorous

Table 5. Mid-parent heterosis and better parent heterosis for seedling traits in papaya.

Genotype	Shoot length (cm)		Root length (cm)		Fresh weight (mg)		Dry weight (mg)	
	MPH	BPH	MPH	BPH	MPH	BPH	MPH	BPH
PN × PS3	-23.64	-30.00	-33.93	-47.82	-21.74	-37.27	-15.91	-21.07
PN × P-7-2	11.82	3.44	20.40	-5.05	-0.17	-6.04	19.07	3.85
PN × P-7-9	1.46	-7.80	-1.88	-27.43	-8.58	-10.94	6.68	-5.10
PN × P-9-5	1.26	0.43	37.64	26.19	-3.62	-14.41	-6.32	-9.01
PN × P-9-12	38.20	31.24	83.90	56.53	17.99	-12.42	2.54	-14.27
P-7-2 × PS3	-24.94	-33.91	-29.08	-31.99	-6.57	-21.11	11.10	20.34
P-7-2 × PN	-27.51	-32.90	25.38	-2.10	-16.70	-21.56	-8.30	-19.90
P-7-2 × P-7-9	4.05	-1.55	-15.98	-30.32	4.20	-4.36	-20.13	-23.10
P-7-2 × P-9-5	5.29	-2.32	10.49	-8.30	8.27	0.11	-25.23	-32.86
P-7-2 × P-9-12	37.93	5.95	70.95	22.40	40.12	9.64	8.32	-1.94
P-7-9 × PS3	-15.27	-29.11	-60.60	-68.13	-28.65	-43.76	-15.99	-10.61
P-7-9 × PN	-8.06	-16.80	-34.14	-52.52	-18.74	-20.93	12.31	0.09
P-7-9 × P-7-2	0.63	-4.67	-12.72	-28.01	0.27	-7.98	4.40	0.41
P-7-9 × P-9-5	8.77	-0.59	12.89	-13.22	10.20	-3.72	-33.88	-39.42
P-7-9 × P-9-12	38.68	2.46	44.36	-7.87	35.20	-0.80	2.93	-7.33
P-9-5 × PS3	-8.34	-16.64	-48.33	-57.94	-6.88	-17.37	3.42	-0.02
P-9-5 × PN	-9.03	-9.76	42.08	30.36	-8.35	-18.38	0.38	-2.53
P-9-5 × P-7-2	6.64	-1.09	31.17	9.01	8.62	0.44	15.34	3.44
P-9-5 × P-7-9	11.22	1.61	23.00	-5.15	12.08	-2.07	1.42	-6.73
P-9-5 × P-9-12	45.57	15.10	108.27	62.50	51.88	23.39	-23.72	-34.36
P-9-12 × PS3	10.41	-5.41	8.48	-19.31	12.09	2.73	21.52	37.29
P-9-12 × PN	34.98	7.34	66.13	38.99	-5.46	-29.69	24.84	3.76
P-9-12 × P-7-2	29.25	-0.77	30.59	-6.84	26.35	-1.33	-0.32	-10.76
P-9-12 × P-7-9	11.74	-17.47	30.53	-16.84	-12.25	-35.77	22.40	10.50
P-9-12 × P-9-5	46.29	15.93	101.50	61.11	43.12	16.27	-15.47	-27.79
PS3 × PN	0.53	-7.92	28.49	0.45	-3.74	-23.10	0.54	-5.59
PS3 × P-7-2	54.18	35.76	140.51	121.42	44.85	22.67	13.27	4.73
PS3 × P-7-9	45.86	22.20	82.17	47.55	33.91	5.95	24.74	16.55
PS3 × P-9-5	39.48	26.70	86.95	52.12	46.17	29.74	-29.55	-32.40
PS3 × P-9-12	87.96	60.85	162.10	92.33	92.63	76.91	3.58	-8.56

seedlings. Manifestation of heterosis at early seed development stage can be used to predict heterosis at later stages.

In case of physiological seed trait (Tables 3-5) the genotypes, PN × P-9-12, P-7-9 × PN, P-7-9 × P-9-12, P-9-12 × PN, P-9-12 × P-9-5 and PS3 × P-7-9 were recorded with positive mid parent heterosis, whereas only two hybrids,(P-7-9 × PN and PS3 × P-7-9) were recorded with positive heterobeltiosis. Proteomic studies conducted in maize hybrid seeds, provided evidence for heterosis during seed germination (Guo *et al.,*2 and Meena *et al.*,8). Positive heterosis for seed germination is desirable in papaya as there are varieties, which are observed with very low seed germination rate.

The hybrids, P-7-2 × PN, P-7-2 × P-9-12, P-7-9 × PN, P-7-9 × P-9-5, P-7-9 × P-9-12, P-9-12 × P-9-5, and PS3 × P-7-9 exhibited the positive average heterosis for the trait FCG. The hybrids recorded with better parent heterosis for FCG were P-7-9 × P-9-12, P-9-12 × P-9-5 and PS3 × P-7-9. For the trait SCG, the hybrids showing positive mid-parent heterosis were P-7-2 × P-9-5, P-7-2 × P-9-12, P-7-9 × PN, P-7-9 × P-7-2, P-7-9 × P-9-5, P-7-9 × P-9-12,

P-9-5 × PN, P-9-12 × PN, P-9-12 × P-9-5 and PS3 × PN. While, the hybrids, P-7-2 × P-9-12, P-7-9 × PN, P-7-9 × P-9-5, P-7-9 × P-9-12, P-9-5 × PN, P-9-12 × PN, P-9-12 × P-9-5 and PS3 × PN had positive better parent heterosis for SCG. In case of TCG, the genotypes showing average heterosis and better parent heterosis in positive direction were P-7-9 × PN, P-7-9 × P-9-5, P-7-9 × P-9-12, P-9-12 × PN, P-9-12 × P-9-5 and PS3 × P-7-9. The hybrids showing positive mid-parent heterosis for speed of germination index were P-7-2 × P-9-12, P-7-9 × PN, P-7-9 × P-9-5, P-7-9 × P-9-12, P-9-12 × PN, P-9-12 × P-9-5 and PS3 × P-7-9. Hybrids, P-7-9 × PN, P-7-9 × P-9-12, P-9-12 × PN, and P-9-12 × P-9-5 showed positive better-parent heterosis for the same traits.In case of mean germination time (days), the hybrids P-7-9 × P-9-5, P-7-9 × P-9-12, P-9-12 × PN, and P-9-12 × P-9-5, exhibited positive average heterosis and heterobeltiosis. The hybrids recorded with positive mid-parent heterosis for traits like germination percentage, speed of germination index and mean germination time can be selected and taken for further heterosis analysis in the bearing stage. Hoecker *et al*. (3) reported heterosis in maize for initial root development, comprising of traits like root length, root width and number of seminal roots. The increased size of primary roots of hybrids happens mainly due to the elongated cortical cells (Hoecker *et al*., 3). Jin *et al*. (4) conducted heterosis study in hybrid maize plumules and coleoptiles, and concluded that emergence and vigour of the seedling influenced heterosis during maize development. Rockenbach *et al*. (12) suggested the positive heterosis for root length (27% and 8.2% for MPH and BPH, respectively), root dry matter (19.5% and 2.4% for MPH and BPH, respectively) and negative heterosis for root fresh matter (-3.5% and -23.9% for MPH and BPH, respectively) and seedling fresh matter (-9.4% and -22.2% for MPH and BPH, respectively) in maize.

For traits like shoot length (cm) and root length (cm), positive average heterosis was observed in majority of the hybrids, but only a few hybrids like PN × P-9-5, PN × P-9-12, P-7-2 × P-9-12, P-9-5 × P-9-12, P-9-12 × PN, P-9-12 × P-9-5, PS3 × P-7-2, PS3 × P-7-9, PS3 × P-9-5 and PS3 × P-9-12 exhibited better-parent heterosis. In *Arabidopsis*, heterosis studies have been conducted for biomass production in F_1 hybrids and it was found that F_1 hybrids showed heterosis for the traits contributing to the initial seedling biomass (Meyer *et al*. 10). The trait fresh weight (mg) also showed positive mid-parent heterosis in majority of hybrids and positive heterobeltiosis was observed in hybrids like P-7-2 × P-9-5, P-7-2 × P-9-12, P-9-5 × P-7-2, P-9-5 × P-9-12, P-9-12 × PS3, P-9-12 × P-9-5, PS3 × P-7-2, PS3 × P-7-9, PS3 × P-9-5, and PS3 × P-9-12. The hybrids like PN × P-7-2, P-7-2 × PS3, P-7-9 × PN, P-7-9 × P-7-2, P-9-5 × P-7-2, P-9-12 × PS3, P-9-12 × PN, P-9-12 × P-7-9, PS3 × P-7-2 and PS3 × P-7-9 exhibited average heterosis and heterobeltiosis in positive direction for seedling dry weight.

From the study, it can be concluded that, bolder and heavier seeds of good quality when screened in seed lot in papaya transformed into a more vigorous and healthy seedlings. Further, the phenomenon of heterosis could be detected in the seed as well as the seedling stage in papaya. The better performing 11 hybrids were identified and will be further tested for heterosis in the fruit bearing stage.

AUTHORS' CONTRIBUTION

Conceptualization of research (JP); Designing of the experiments (JP, PS); Contribution of experimental materials and Execution of field/lab experiments and data collection (PS, JP); Analysis of data and interpretation (PS, JP); Preparation of the manuscript (P, JP, SKS, AKG, ZK).

DECLARATION

All authors declare that they do not have any conflict of interest.

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