International Journal of Plant Breeding ©2011 Global Science Books

Heterosis for Seed Yield and its Components in Jatropha (*Jatropha curcas* L.)

A. K. M. Aminul Islam[1*] • Nurina Anuar[1] • Zahira Yaakob[1] • Mohamad Osman[2]

[1] Department of Chemical and Process Engineering, Universiti Kebangsaan Malaysia (UKM), Bangi, 43600, Malaysia
[2] Kulliyyah of Science, International Islamic University Malaysia (IIUM), Kuantan 25200, Malaysia

Corresponding author: ***aminuljkkp@yahoo.com**

ABSTRACT

Heterosis was determined in a population obtained from a 6 × 6 half diallel cross of jatropha genotypes for seed yield per plant and its components traits at the experimental station of Universiti Kebangsaan Malaysia during February 2010 to April, 2011. Results showed that variations for days to flowering, days to fruit maturity, number of primary branches per plant, seed yield per plant and its component characters was significant. Both positive and negative heterosis was found for seed yield per plant. High mid-parent heterosis (254.13%) and better parent heterosis (202.36%) were found for seed yield per plant in the cross $P_2 \times P_5$ and $P_1 \times P_3$, respectively. Small heterosis over mid-parent was also found for days to flowering and days to fruit maturity. The parents P_1, P_2, P_3 and P_5 were found to be superior for seed yield and its components when used in crosses. Considering earliness and seed yield per plant the hybrid combinations $P_1 \times P_2$, $P_1 \times P_3$, $P_2 \times P_5$ and $P_4 \times P_6$ were promising. These combinations could be selected for the development of hybrid varieties in *Jatropha curcas*.

Keywords: Physic nut, biodiesel, breeding, heterosis, seed yield

INTRODUCTION

Jatropha (*Jatropha curcas* L.) is a member of the family Euphorbiaceae. It is a diploid species with chromosome number 2n= 22 (Dahmer *et al*. 2009; Sasikala and Paramathma 2010). Jatropha is an oil-bearing tree has attracted the attention of several workers for the use of its seed oil as a commercially viable alternative source of fuel (Mandpe *et al*. 2005; Shanker and Dhyani 2006; Achten *et al*. 2009; Gunaseelan 2009). However, the productivity of existing *J. curcas* is comparatively low and not of much economic benefit to farmers. The wide gap in potential and actual yield is due to the use of locally available 'wild' material. Superior quality planting material having high oil content and yield are being identified for further multiplication and production of quality planting material from the existing germplasm (Islam *et al*. 2009; Islam *et al*. 2011). The development of high-yielding varieties through plant breeding has significantly increased agricultural productivity, especially in the late half of the 20th century (Evenson and Gollin 2003). *J. curcas* is monoecious and highly cross-pollinated in nature, and has a male: female flower ratio of around 29: 1. Such a pollination mechanism can be exploited for the production of hybrid variety.

Heterosis has been recognized as a phenomenon for almost a century (Shull 1908). Heterosis defined as the increased vigour, size, fruitiness, speed of development, resistance to disease and pests, or to climatic vigour (Shull 1952). Hartl and Clark (2007) defined it as a phenomenon that enhanced hybrid performance. However, there are two predominant theories of heterosis called dominance and over-dominance hypothesis (Crow 1952). Heterosis results from combined action and interaction of allelic and non-allelic factors and is usually closely and positively correlated with heterozygosity (Burton 1968). Heterosis can be expressed as mid-parent, better-parent and standard heterosis. The exploitation of heterosis is a common objective in plant breeding (Mayo 1987). Heterosis has extensively been explored and utilized for boosting various quality traits in corn, brassica and other crops (Duvick 2001; Hassan *et al.* 2006). According to Pal and Sikka (1956), heterosis is a quick, cheap and easy method for increasing crop production. Duvick (1999) reported that field crops such as maize (*Zea mays* L.) sorghum (*Sorghum bicolor* (L.) Moench) and sunflower (*Helianthus annus* L.) are produced as hyb-rids in the industrialized world. Hybrid rice (*Oryza sativa* L.) is grown extensively in China, India, Vietnam, Thailand and other parts of the world.

Heterosis in tree growth is evident in many hybrids and perhaps the best illustrated in studies of *Eucalyptus* and *Populus* (the genus of poplars and aspens). Hybrid vigour and inheritance of economic traits have also been reported in plants from the Euphorbiaceae (Easwari Amma *et al*. 1995; Easwari and Sheela 1998; Unnikrishnan *et al*. 2001; Joshi *et al*. 2002; Peréz *et al*. 2005; Sridhar *et al*. 2009). *J. curcas* as a facultative cross-pollinated crop that shows heterosis. Based on the earlier experience from other cross-fertilized crops, it appears that the application of heterosis breeding in *Jatropha* could justify hybrid variety production. Hybrid cultivars could be bred to use the heterosis effect. Literature on jatropha improvement through heterosis is scarce (Divakara *et al.* 2010). Inter-specific hybrids utilizing *J. curcas* as the female parent and *J. integerrima* as the male parent indicated that the F_1 hybrids had a wide range of variation for vegetative, flowering and fruiting characters (Paramathma *et al.* 2006). Seed and oil yield can be genetically enhanced through development of hybrid varieties. Therefore, the present study was under taken to know heterotic effects of different hybrid combinations for seed yield per plant and its component characters.

MATERIALS AND METHODS

Six parents (P_1, P_2, P_3, P_4, P_5 and P_6) were mated in a half diallel fashion during August to December 2010 to produce hybrid seeds of different combinations. The seeds of six parents and their 15

Received: 19 May, 2011. Accepted: 7 August, 2011.

Original Research Paper

Table 1 Analysis of variance for yield and yield related characters in jatropha.

Sources of variation	df	DFBA	DFMF	DFFF	DFFS	DFFM	PHFF	NPBP
Replication	2	3.05ns	21.39*	4.83ns	13.00**	0.76ns	13.92ns	0.02ns
Genotypes	20	463.00**	499.75**	506.88**	508.89**	618.31**	279.42**	3.33**
P	5	124.76**	313.20**	323.02**	340.89**	414.32**	461.07**	3.52**
F_1	14	589.88**	589.88**	589.88**	589.88**	735.14**	234.04**	2.90**
P *v* F_1	1	378.01**	170.76**	264.23**	214.96**	2.67**	6.50**	8.45**
Error	40	2.48	2.89	2.64	2.45	7.68	17.80	0.77
Sources of variation	**df**	**NIPP**	**NFPI**	**NFPP**	**NSPF**	**NSPP**	**HSW**	**SYPP**
Replication	2	5.53**	3.87**	443.63**	0.01ns	2772.51**	0.91ns	1264.30**
Genotypes	20	22.31**	16.42**	5604.78**	0.25**	48008.31**	152.03**	22067.67**
P	5	10.59**	5.39**	848.99**	0.20ns	7879.67**	94.09**	3201.01**
F_1	14	26.84**	19.76**	7065.17**	0.28**	60082.50**	166.17**	27611.25**
P *v* F_1	1	17.50**	24.80**	8938.30**	0.14**	118976.00**	679.09**	38790.73**
Error	40	1.33	1.30	157.42	0.05	1200.86	1.03	468.69

* & **, significance at 0.05 and 0.01 level, ns= non significant

DFBA= days to first flower bud appearance, DFMF= days to first male flowering, DFFF= days to first female flowering, DFFM= days to first fruit maturity, PHFF= plant height at first flowering, NPBFF= number of primary branches per plant at first flowering, NIPP= number of inflorescence per plant, NFPI= number of fruits per inflorescence, NFPP= number of fruits per plant, NSPF= number of seeds per fruit, NSPP= number of seeds per plant, HSW= Hundred seed weight (g), SYPP (g)= seed yield per plant (g)

Table 2 Mid parent heterosis for growth characters in 6 × 6 diallel population of jatropha.

Hybrids	FFBA	FMF	FFF	FFS	FFM	PHFF	NPBP
$P_1 \times P_2$	-6.32**	-5.48**	-5.07**	-4.91**	-6.56**	4.07ns	8.33ns
$P_1 \times P_3$	-7.59**	-7.71**	-6.71**	-6.39**	-10.92**	3.49ns	6.25ns
$P_1 \times P_4$	-0.27ns	2.25**	2.84**	2.75**	0.27ns	9.16*	7.69ns
$P_1 \times P_5$	-4.33**	-3.10**	-2.47**	-2.84**	-3.07**	-5.53*	-26.67**
$P_1 \times P_6$	-6.51**	-6.85**	-6.43**	-6.33**	-6.96**	7.89**	-24.14**
$P_2 \times P_3$	18.02**	12.67**	13.34**	12.82**	-1.69**	-5.80*	-50.00**
$P_2 \times P_4$	16.17**	14.59**	14.88**	14.16**	6.77**	-2.21ns	-22.22ns
$P_2 \times P_5$	-1.50*	-2.79**	-2.32**	-2.87**	-2.05**	2.74ns	-9.09ns
$P_2 \times P_6$	-2.93**	-5.68**	-5.40**	-5.53**	-2.77**	-2.82ns	-23.81ns
$P_3 \times P_4$	18.83**	15.54**	16.51**	15.85**	9.56**	3.19ns	-23.08*
$P_3 \times P_5$	11.34**	7.36**	8.33**	7.49**	2.62**	-5.16*	-40.00**
$P_3 \times P_6$	0.01ns	-4.24**	-3.46**	-3.56**	-2.19**	-5.26*	-17.24*
$P_4 \times P_5$	10.91**	10.48**	11.08**	9.98**	6.78**	-2.30ns	-41.67**
$P_4 \times P_6$	-2.69**	-3.65**	-3.16**	-3.38**	-6.47**	-1.05ns	4.35ns
$P_5 \times P_6$	19.55**	14.63**	14.90**	13.63**	12.82**	11.35**	-33.33**

* & **, significance at 0.05 and 0.01 level, ns= non significant

FFBA= first flower bud appearance (days), FMF= first male flowering (days), FFF= first female flowering (days), FFS= first fruit setting (days), FFM= first fruit maturity (days), PHFF= plant height at first flowering (cm), NPBP= number of primary branches per plant

F_1's were planted in poly bag (18 × 10 × 7cm) containing a mixture of soil and compost (made from kitchen waste) in the ratio of 1: 1. Seeds were sown directly to a depth of 3 cm (Henning 2000) in the polybags and watered to saturation three times a week. Seedlings (35-days-old) were transplanted in the field in a randomized complete block design (RCBD) with three replications. Transplantation was done in the field with a spacing of 2m × 2m so as to accommodate about 2500 plants per ha. The plants were grown under rainfed condition at the experimental station of Universiti Kebangsaan Malaysia, Kuala Pilah, Nigeri Sembilan during February 2010 to April, 2011. Healthy seedlings (35-days-old) were planted in pits at required depth in 30 cm × 30 cm pits dug in the field at a spacing of 2 m × 2 m and filled with a mixture of soil, Farm Yard Manure (2-3 kg) and fertilizers (20 g urea, 120 g single super phosphate and 16 g muriate of potash) (Punia 2007). All the necessary cultural practices were followed for raising a good stand of jatropha (Paramathma *et al.* 2004; Jongschaap *et al.* 2007; Kumar and Sharma 2008). Observations on thirty randomly selected plants (10 from each replication) in each population were recorded on 14 quantitative traits viz., days to days to first flower bud appearance (DFBA), days to first male flowering (DFMF), days to first female flowering (DFFF), days to first fruit maturity (DFFM), plant height at first flowering (PHFF), number of primary branches per plant at first flowering (NPBFF), number of inflorescences per plant (NIPP), number of fruits per inflorescence (NFPI), number of fruits per plant (NFPP), number of seeds per fruit (NSPF), number of seeds per plant (NSPP), hundred seed weight in gram (HSW), seed yield per plant in gram (SYPP). The percentage heterosis over the mid-parent (MP%) and better parent or heterobeltiosis (BP%) was calculated using the formulae [(value of F_1 - mean of parents)/(mean of parents) × 100] and [(value of F_1 - value of better parent)/(value of better parent) × 100], respectively (Shull 1952; Fonseca and Patterson 1968; Liang *et al.* 1971). The test of significance of heterosis values were tested by using a t-test at p<0.001 using Microsoft Office Excel 2007 (Wynne *et al.* 1970; Panse and Sukhatme 1978).

RESULTS AND DISCUSSION

Results showed that variations for days to flowering, days to fruit maturity, number of primary branches per plant, seed yield per plant and its component characters were significant (**Table 1**). Heterosis was estimated as percent increase or decrease of F_1 values over mid parent (average performance of two parents involved in the cross) and batter parent (parent with higher performance involved in the cross) are presented in **Tables 2** to **5**. Several crosses were found promising with highly significant and positive heterosis for different characters studied. The magnitude of heterosis over mid parent and better parent varied from cross to cross for seed yield and its components. The range of heterosis, number of significant heterotic crosses and the best heterotic crosses for all the characters are presented in **Table 6**.

Days to flowering and fruit maturity

Early flowering and maturity is useful in most of the plant species also in *Jatropha*; therefore, negative heterosis is desirable for these traits. The crosses exhibiting heterosis in negative direction for the traits like days to flowering and fruit maturity are of immense value for the identification of early hybrids in *Jatropha*. The data presented in **Table 1** for days to first flower bud appearance showed that out of 15

Table 3 Mid parent heterosis for seed yield and yield components in 6 × 6 diallel population of jatropha.

Hybrids	**NIPP**	**NFPI**	**NFPP**	**NSPF**	**NSPP**	**HSW**	**SYPP**
$P_1 \times P_2$	105.94**	31.03**	167.67**	4.05ns	179.06**	1.29ns	181.26**
$P_1 \times P_3$	71.43**	48.15**	161.83**	1.86ns	165.89**	15.99**	208.77**
$P_1 \times P_4$	2.44ns	23.64**	28.19*	8.22ns	36.37**	22.81**	61.55**
$P_1 \times P_5$	0.00ns	16.00*	11.49ns	15.70**	22.78ns	-4.39**	16.55ns
$P_1 \times P_6$	18.92*	25.00**	46.70**	-3.34ns	40.91**	7.65**	49.07**
$P_2 \times P_3$	2.33ns	4.00ns	13.45ns	1.57ns	15.58ns	16.39**	35.40*
$P_2 \times P_4$	20.00*	13.73*	39.52**	5.92ns	51.15**	-6.19**	41.34*
$P_2 \times P_5$	135.71**	47.83**	253.55**	12.32*	289.05**	-9.38**	254.13**
$P_2 \times P_6$	22.58*	0.00ns	21.97ns	-19.07**	-0.99ns	-10.74**	-11.88ns
$P_3 \times P_4$	-48.00**	-14.89*	-56.59**	6.97ns	-54.43**	-7.79**	-58.79**
$P_3 \times P_5$	-39.53**	-19.05*	-55.70**	-2.27ns	-58.85**	-1.64ns	-58.45**
$P_3 \times P_6$	0.00ns	50.00**	53.89**	11.52*	70.37**	6.67**	79.21**
$P_4 \times P_5$	-25.71*	-6.98ns	-30.47*	-3.07ns	-32.03ns	25.66**	-11.18ns
$P_4 \times P_6$	68.42**	38.78**	136.25**	25.61**	200.04**	8.81**	225.47**
$P_5 \times P_6$	-9.68ns	-22.73**	-33.62*	-14.67**	-44.39ns	19.01**	-32.74ns

* & **, significance at 0.05 and 0.01 level, ns= non significant

NIPP= number of inflorescence per plant, NFPI= number of fruits per inflorescence, NFPP= number of fruits per plant, NSPF= number of seeds per fruit, NSPP= number of seeds per plant, HSW= hundred seed weight (g), SYPP= seed yield per plant (g)

Table 4 Better parent heterosis for growth characters in 6 × 6 diallel population of jatropha.

Hybrids	**FFBA**	**FMF**	**FFF**	**FFS**	**FFM**	**PHFF**	**NPBP**
$P_1 \times P_2$	-1.63*	1.25ns	1.73*	1.91**	0.00ns	-4.23ns	-18.75*
$P_1 \times P_3$	-5.96**	-2.75**	-2.22**	-1.91**	-4.25**	1.30ns	6.25ns
$P_1 \times P_4$	0.00ns	2.25**	2.97**	2.87**	1.11ns	-2.93ns	-12.50ns
$P_1 \times P_5$	-1.08ns	1.75*	2.22**	2.39**	2.22*	-8.28**	-31.25**
$P_1 \times P_6$	-0.81ns	2.00*	2.47**	2.63**	-1.11ns	-4.23ns	-31.25**
$P_2 \times P_3$	26.02**	14.45**	15.77**	15.28**	-1.30ns	-11.56**	-62.50**
$P_2 \times P_4$	22.35**	22.75**	23.27**	22.20**	13.27**	-5.81*	-30.00ns
$P_2 \times P_5$	0.00ns	-0.91ns	-0.23ns	-1.30*	-0.67ns	-7.98**	-28.57**
$P_2 \times P_6$	-1.97**	-3.72**	-3.46**	-3.56**	-2.13*	-6.59*	-38.46**
$P_3 \times P_4$	21.26**	21.75**	22.28**	21.24**	16.73**	-6.46*	-37.50**
$P_3 \times P_5$	13.09**	7.73**	8.33**	8.08**	4.50**	-9.82**	-43.75**
$P_3 \times P_6$	4.19**	-0.68ns	0.68ns	0.66ns	-1.15ns	-14.29**	-25.00*
$P_4 \times P_5$	14.99**	16.00**	16.58**	15.75**	11.64**	-15.34**	-50.00**
$P_4 \times P_6$	3.55**	5.50**	6.19**	5.73**	-1.45ns	-1.26ns	-7.69ns
$P_5 \times P_6$	22.90**	19.32**	19.82**	17.93**	13.67**	-3.68ns	-35.71**

* & **, significance at 0.05 and 0.01 level, ns= non significant

FFBA= first flower bud appearance (days), FMF= first male flowering (days), FFF= first female flowering (days), FFS= first fruit setting (days), FFM= first fruit maturity (days), PHFF= plant height at first flowering (cm), NPBP= number of primary branches per plant

Table 5 Better parent heterosis for seed yield and yield components in 6 × 6 diallel population of jatropha.

Hybrids	**NIPP**	**NFPI**	**NFPP**	**NSPF**	**NSPP**	**HSW**	**SYPP**
$P_1 \times P_2$	75.05**	22.58**	112.98**	1.80ns	125.47**	0.51ns	125.88**
$P_1 \times P_3$	44.83**	29.03**	155.25**	0.49ns	156.40**	9.74**	202.36**
$P_1 \times P_4$	0.00ns	9.68ns	15.87ns	-5.02ns	9.73ns	7.69**	17.88ns
$P_1 \times P_5$	-15.00ns	-6.45ns	-20.67ns	4.02ns	-18.11ns	-5.13**	-22.61*
$P_1 \times P_6$	10.00ns	12.90*	23.08*	-5.52ns	15.76ns	1.03ns	16.61ns
$P_2 \times P_3$	-24.14**	-3.70ns	-11.42ns	0.72ns	-9.15ns	10.94**	10.52ns
$P_2 \times P_4$	0.00ns	7.41ns	-7.31ns	-8.76ns	50.34**	-17.19**	24.22ns
$P_2 \times P_5$	135.71**	25.93**	122.02**	-0.96ns	201.76**	-9.38**	172.94**
$P_2 \times P_6$	11.76ns	-3.70ns	30.89ns	-22.57**	-3.08ns	-15.63**	-14.90ns
$P_3 \times P_4$	-55.17**	-16.67*	-40.43*	-7.20ns	-64.32**	-14.94**	-69.52**
$P_3 \times P_5$	-55.17**	-26.09**	-68.95**	-13.19*	-73.04**	-6.25**	-72.11**
$P_3 \times P_6$	-20.69**	44.06**	26.48*	7.57ns	34.55**	7.60**	42.38**
$P_4 \times P_5$	-38.10**	-16.67*	-47.02**	-5.66ns	-47.39*	10.94**	-23.87ns
$P_4 \times P_6$	52.38**	36.05**	117.26**	12.48*	193.27**	1.17ns	195.14**
$P_5 \times P_6$	-17.65ns	-31.97**	-46.10**	-21.68**	-57.40**	12.50**	-46.39*

* & **, significance at 0.05 and 0.01 level, ns= non significant

NIPP= number of inflorescence per plant, NFPI= number of fruits per inflorescence, NFPP= number of fruits per plant, NSPF= number of seeds per fruit, NSPP= number of seeds per plant, HSW= hundred seed weight (g), SYPP= seed yield per plant (g)

crosses, seven crosses exhibited significant negative heterosis over mid-parent with a range of -2.69 to -7.59% (**Table 2**). The maximum significant negative value (-7.59%) was recorded for cross $P_1 \times P_3$. Data for better parent heterosis showed significant negative heterosis in three crosses. The negative values ranged from -1.63 to -5.96% with maximum being shown by crosses $P_1 \times P_3$ (**Table 2**). For days to first male and female flowering, eight crosses out of 15 showed significant negative mid-parent heterosis and among these crosses, four crosses ($P_1 \times P_3$, $P_1 \times P_6$, $P_2 \times P_6$ and $P_1 \times P_2$) showed most desirable significant negative values in rank order (**Table 6**). Regarding best parent heterosis, it could be seen from **Table 2** that out of 15 crosses, significant negative effects were exhibited by two crosses ($P_2 \times P_6$ and $P_1 \times P_3$). Heterotic data presented in **Table 1** showed that out of 15 crosses, nine crosses showed significant negative heterosis over mid parent and the data for these crosses ranged from -1.69 to -10.92% (**Table 2**). Significant negative heterosis over better parent was demonstrated by two crosses where effects ranged from -2.13 to -4.25% (**Table 4**) with the maximum negative value being observed for cross $P_1 \times P_3$ (**Table 4**). Heterosis for earliness over standard varieties has been reported by Patil *et al.* (1998).

Table 6 Promising hybrid combinations based on mid parent heterosis and better parent heterosis for yield and yield components in jatropha.

Traits	Number of cross with				Cross with	
	Significant heterosis over		Significant favourable heterosis		The highest heterosis in rank order over	
	MP (% range)	BP (% range)	MP	BP	MP	BP
FFBA	13 (-7.59 to 19.55)	11 (-5.96 to 26.02)	7	3	$P_1{\times}P_3$, $P_1{\times}P_6$ $P_1{\times}P_2$, $P_1{\times}P_5$	$P_1{\times}P_3$, $P_2{\times}P_6$, $P_1{\times}P_2$
FMF	15 (-7.71 to 15.54)	12 (-3.72 to 21.75)	8	2	$P_1{\times}P_3$, $P_1{\times}P_6$, $P_2{\times}P_6$, $P_1{\times}P_2$	$P_2{\times}P_6$, $P_1{\times}P_3$
FFF	15 (-6.71 to 16.51)	13 (-3.46 to 23.27)	8	2	$P_1{\times}P_3$, $P_1{\times}P_6$ $P_2{\times}P_6$, $P_1{\times}P_2$	$P_2{\times}P_6$, $P_1{\times}P_3$
FFS	15 (-7.71 to 15.54)	15 (-3.56 to 22.20)	8	3	$P_1{\times}P_3$, $P_2{\times}P_6$ $P_1{\times}P_6$, $P_1{\times}P_2$	$P_2{\times}P_6$, $P_1{\times}P_3$ $P_2{\times}P_5$
FFM	14 (-10.92 to 12.82)	8 (-4.25 to 13.67)	8	2	$P_1{\times}P_3$, $P_1{\times}P_6$ $P_4{\times}P_6$, $P_2{\times}P_2$	$P_2{\times}P_6$, $P_1{\times}P_3$
PHFF	7 (-5.80 to 11.35)	9 (-15.34 to 11.35)	7	9	$P_4{\times}P_5$, $P_3{\times}P_6$ $P_3{\times}P_5$	$P_4{\times}P_5$, $P_3{\times}P_6$ $P_2{\times}P_3$
NPBP	7 (-50.00 to -17.24)	7 (-62.50 to -18.75)	0	0	--	--
NIPP	10 (-48.00 to 135.71)	9 (-55.17 to 135.71)	7	4	$P_2{\times}P_5$, $P_1{\times}P_2$ $P_1{\times}P_3$, $P_4{\times}P_6$	$P_2{\times}P_5$, $P_1{\times}P_2$, $P_4{\times}P_6$, $P_1{\times}P_3$
NFPI	12 (-22.73 to 50.00)	10 (-31.97 to 44.06)	9	6	$P_3{\times}P_6$, $P_1{\times}P_3$, $P_2{\times}P_5$, $P_4{\times}P_6$	$P_3{\times}P_6$, $P_4{\times}P_6$, $P_1{\times}P_3$
NFPP	12 (-6.71 to 16.51)	10 (-69.95 to 155.25)	8	6	$P_2{\times}P_5$, $P_1{\times}P_2$ $P_1{\times}P_3$, $P_4{\times}P_6$	$P_1{\times}P_3$, $P_2{\times}P_5$ $P_4{\times}P_6$, $P_1{\times}P_2$
NSPF	12 (-19.07 to 25.61)	4 (-3.56 to 22.20)	7	1	$P_4{\times}P_6$, $P_1{\times}P_5$ $P_2{\times}P_5$, $P_3{\times}P_6$	$P_4{\times}P_6$
NSPP	10 (-58.85 to 289.05)	10 (-73.04 to 201.76)	7	6	$P_2{\times}P_5$, $P_4{\times}P_6$ $P_1{\times}P_2$, $P_1{\times}P_3$	$P_2{\times}P_5$, $P_4{\times}P_6$ $P_1{\times}P_3$, $P_1{\times}P_2$
HSW	14 (-10.74 to 25.66)	12 (-17.19 to 12.50)	9	6	$P_2{\times}P_5$, $P_1{\times}P_4$ $P_5{\times}P_6$, $P_1{\times}P_3$	$P_5{\times}P_6$, $P_2{\times}P_3$ $P_4{\times}P_5$, $P_1{\times}P_3$
SYPP	11 (-58.79 to 254.13)	9 (-72.11 to 202.36)	9	5	$P_2{\times}P_5$, $P_4{\times}P_6$ $P_1{\times}P_3$, $P_1{\times}P_2$	$P_1{\times}P_3$, $P_4{\times}P_6$ $P_2{\times}P_5$, $P_1{\times}P_2$

FFBA= first flower bud appearance (days), FMF= first male flowering (days), FFF= first female flowering (days), FFS= first fruit setting (days), FFM= first fruit maturity (days), PHFF= plant height at first flowering (cm), NPBP= number of primary branches per plant, NIPP= number of inflorescence per plant, NFPI= number of fruits per inflorescence, NFPP= number of fruits per plant, NSPF= number of seeds per fruit, NSPP= number of seeds per plant, HSW= hundred seed weight (g), SYPP= seed yield per plant (g)

Plant height and number of primary branches per plant at first flowering

Among the crosses, mid and better parent heterosis ranged from -5.80% to 11.35% and -15.34% to 11.35%, respectively (**Table 6**). The nature and magnitude of heterosis revealed that among 15 hybrids, seven exhibited significant negative heterosis for plant height at first flowering. Out of 15 hybrids, seven hybrids recorded significant negative heterosis for less plant height over mid parent and three hybrids exhibited significant positive heterosis (**Table 2**). Present observations are in compliance with Prasath and Ponnuswami (2008) while inconsistent with the earlier findings of Patil *et al.* (1998) who reported positive heterosis for plant height. On the other hand, eight hybrids exhibited significant negative heterosis over better parent and only one hybrid exhibited positive non significant better parent heterosis for plant height (**Table 6**). Plants containing more number of primary branches provide opportunity for more yields, so positive heterosis is desirable for number of primary branches. Heterosis estimates over mid-parent (**Table 6**) showed that out of 15 crosses; only three crosses had positive but non-significant effects ranged from 4.35 to 7.69%. For number of branches per plant, none of the hybrids recorded positive and significant mid parent heterosis. Regarding better parent heterosis, it could be seen from **Table 6** that out of 15 crosses, one exhibited non significant positive effects and 11 crosses presented significant negative heterosis (**Table 4**).

Seed yield per plant and its components

Ten hybrids recorded significant mid parent or relative heterosis and better parent heterosis for number of inflorescence per plant. The highest mid parent heterosis in rank order was recorded in hybrids $P_2 \times P_5$, $P_1 \times P_2$, $P_1 \times P_3$ and $P_4 \times P_6$ (**Table 6**). Maximum positive (135.71%) significant relative heterosis and heterobeltiosis for this trait was ex-

Fig. 1 Promising hybrids $P_1 \times P_3$ (**A, B**) and $P_1 \times P_2$ (**C, D**). (**A**) Plants with many inflorescences; (**B**) inflorescences with many fruits; (**C**) plants with several inflorescences; (**D**) inflorescence with several fruits.

hibited by the hybrids $P_2 \times P_5$ (**Tables 3, 5**). Out of 15 hybrids, seven recorded significant positive mid parent heterosis and four recorded better parent heterosis for number of inflorescence per plant. Number of fruits per inflorescence is generally associated with higher productivity. The highest significant positive mid parent heterosis for number of fruits per inflorescence was estimated for the cross $P_3 \times P_6$ (50.00%), $P_1 \times P_3$ (48.15%), $P_2 \times P_5$ (47.83%) and $P_4 \times P_6$ (38.78%) (**Tables 2, 5**). Significant positive better parent heterosis was observed in six crosses and the range of heterosis was 12.90 to 44.06%. The highest significant positive better parent heterosis (44.06%) was exhibited by the cross $P_3 \times P_6$ (**Table 5**). Heterosis over mid parent ranged from -6.71 to 16.51% (**Table 6**) for number of fruits per plant which is also associated with higher productivity. Among 15 hybrids, 12 hybrids showed significant mid parent heterosis for number of fruits per plant. The hybrids with significant better parent heterosis in rank order for number of fruits per plant are $P_1 \times P_3$ (155.25%), $P_2 \times P_5$ (122.02%), $P_4 \times P_6$ (117.26%) and $P_1 \times P_2$ (112.98) (**Fig. 1**). Dwivedi *et al.* (1989) found 220.4% better parent heterosis for fruits per plant in 8 × 8 diallel F_1 cross progenies of peanut. The estimates of heterosis over best parent ranged from -22.94 to 137.61% for fruits per plant (Prasath and Ponnuswami 2008).

Number of seeds per plant is one of the most important components for seed yield and will be helpful in breaking the yield ceiling. Thus, the hybrids with positive heterosis were desirable for this important trait. For number of seeds per plant, significant mid parent heterosis ranged from -58.85 to 289.05% and better parent heterosis from -73.04 to 201.76% (**Table 6**). Seven crosses showed significant positive mid parent heterosis whereas six hybrids showed better parent heterosis. The hybrids with significant positive mid parent heterosis in rank order for number of seeds per plant are $P_2 \times P_5$ (289.05%), $P_4 \times P_6$ (200.04%), $P_1 \times P_2$ (179.06%) and $P_1 \times P_3$ (165.89) (**Table 3**). The hybrid $P_2 \times P_5$ exhibited the highest percentage of better parent heterosis (201.76%) followed by $P_4 \times P_6$ (193.27%), $P_1 \times P_3$ (156.40%) and $P_1 \times P_2$ (125.47%) (**Table 5**). Heterosis for 100-seed weight ranged from -85.48% to 93.33% (**Table 6**). Only the cross $P_4 \times P_6$ (93.33%) exhibited significant positive heterosis over better parent. On the other hand, two hybrids showed significant positive heterosis over mid parent for this trait.

Out of 15 hybrids tested, only nine hybrids recorded significant and desirable heterosis over both mid parent and better parent (**Table 2**). Significant positive heterosis for seed yield per plant ranged from 35.40 to 254.13% over mid-parent and 42.38 to 202.36% over better parent (**Table 5**). The cross combination $P_2 \times P_5$ depicted the highest values (254.13%) over mid parent followed by the cross $P_4 \times P_6$ (225.47%), $P_1 \times P_3$ (208.77%) and $P_1 \times P_2$ (181.26%). Maximum (202.36%) seed yield per plant over better parent was recorded in $P_1 \times P_3$ (**Table 5**) followed by the cross $P_4 \times P_6$ (195.14%), $P_2 \times P_5$ (172.94%) and $P_1 \times P_2$ (125.88%). Heterosis for seed yield per plant was also reported by Dangaria *et al.* (1987) and Thakker *et al.* (2005). It will be considerable interest to know the cause of heterosis for seed yield per plant. A comparison of heterosis (**Table 6**) for seed yield per plant in most of the heterotic crosses over mid parent and better parent along with heterosis in other related characters indicated that positive and significant heterosis for seed yield per plant was also accompanied by significant and positive heterosis over mid parent and better parent one or more important yield contributing characters viz., number of inflorescence per plant, number of fruits per inflorescence, number of fruits per plant, number of seeds per plant and 100-seed weight (**Table 6**). This emphasized that high degree of heterosis for seed yield per plant might be due to heterosis observed in one or more of the important component traits. High association of heterosis between yield components and seed yield per plant have also been reported earlier by others (Manivel *et al.* 1999; Thakker *et al.* 2005; Patel and Pathak 2006). High heterosis to the extent of 328% for seed yield was reported by Singh *et al.* (1983). Krishnaswamy *et al.* (1985) reported heterosis in seed yield of sesame ranging from 50 to 325% and hetero-beltiosis from 50 to 263%. Delgado (1972) produced several high yielding hybrids yielded the best parents heterosis range from 200-275%. Kotecha and Yermanos (1979) reported heterosis over better parents ranging from 28.0 to 238% for seed yield in 8 × 8 diallel cross of sesame. Duhoon (2004) reported the extent of standard heterosis in sesame from 9.5 to 327% for seed yield. Hybrids showed highly significant increase in yield with a standard heterosis from 67.92 to 369.27% (Joshi 2001).

CONCLUSION

The results from analysis of variance showed jatropha parents posses some extent of diversity in days to flowering, fruit maturity, seed yield per plant and its component traits except number of seeds per fruit. Significant variation also observed among hybrids and parent *vs* hybrids for all the traits. The magnitude of heterosis over mid parent and better parent varied from cross to cross for seed yield and its components. Heterosis results in the phenotypic superiority of a hybrid over its parents with respect to traits such as days to first flower bud appearance, days to first male flowering, days to first female flowering, days to first fruit maturity, number of primary branches per plant at first flowering, number of inflorescence per plant, number of fruits per inflorescence, number of fruits per plant, hundred seed weight and seed yield per plant. The cross combinations $P_1 \times P_2$, $P_1 \times P_3$, $P_2 \times P_5$ and $P_4 \times P_6$ was found promising for earliness and seed yield per plant.

ACKNOWLEDGEMENTS

The research is financed by Universiti Kebangsaan Malaysia, Grant No. UKM-GUP-KRIB-15/2008. The authors would like to thank university authority for financial support.

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