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Heterosis of Agronomic Characters in Jatropha (*Jatropha curcas* L.)

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ABSTRACT

An approach to increase the productivity of jatropha (*Jatropha curcas* L.) is to exploit hybrid vigor of the F_1 progeny for possible production of hybrid varieties. In the current study, three toxic accessions (high phorbol ester) from each of Myanmar and Thailand were crossed with non-toxic accession (low phorbol ester) from Mexico. Six F_1 progenies and their parents were determined for the degree of heterosis at Kasetsart University, Thailand. Individual plants from each progeny were observed on major agronomic characters at various growth stages. Heterosis of individual characters in each cross were calculated and tested for significance by a t-test. Four crosses showed significant heterosis in yield per plant. Crosses showing heterosis in yield also showed heterosis in characters related to seedlings, mature fruits, plant growth, and fruit and seed size. Superiority over mid-parent for yield per plant ranged from 32.50% to 262.92%, and over better parent ranged from 11.74% to 195.93%. Across all characters, crosses showing the highest heterosis over mid- parent and better parent were Myanmar 2 × Mexico and Myanmar 3 × Mexico.

Keywords: *Jatropha curcas* L.*,* heterosis, hybrid vigor, jatropha

INTRODUCTION

Jatropha curcas (L.) (jatropha or physic nut) is a potential biofuel crop in tropical and subtropical regions. Among the oil-bearing tree species, jatropha is desirable due to its drought hardiness, rapid growth, easy propagation, high oil content, short duration, wide adaptation, and productivity on waste or degraded soils, as well as having advantages with regard to its environmental and socioeconomic impacts (Heller, 1996; Gubitz *et al*., 1999; Openshaw, 2000; Sujatha *et al*., 2008; Divakara *et al*., 2010). Despite the potential of jatropha, the crop productivity is far too low to be commercialized due mainly to the fact that the plant is still wild. There is limited information available on the genetics and agronomy of jatropha, including a lack of benchmark descriptors and information on genetic variability, effects of environment and genotype × environment interaction (Jongschaap *et al*., 2007). Jatropha has been recently domesticated, and agriculturists see an immediate need to breed for superior genotypes. The objectives should aim at higher seed yield and oil content, earlier maturity, reduced plant height, resistance to pests and diseases, drought tolerance, higher ratio of female to male flowers and improved fuel properties (Sujatha, 2006). Genetic improvement of jatropha can be practiced through many options

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like traditional breeding, heterosis breeding, mutation breeding, interspecific hybridization and genetic transformation (Divakara *et al.*, 2010).

The exploitation of heterosis is a common objective in plant breeding. Heterosis in trees is evident in citrus and oil palm. Commercial exploitation of heterosis has been one of the driving forces behind the rapid and extensive development of the seed industry. Heterosis breeding has allowed yield breakthroughs in several crops, including cross-pollinating, often cross-pollinating and self-pollinating species (Soehendi and Srinives, 2005). Application of heterosis breeding can boost the jatropha yield. To date, there has been no literature reported on jatropha improvement through heterosis (Divakara *et al.,* 2010).

There are a number of traits which could be targeted for the development of high yielding varieties in jatropha including seed yield, high oil content and low phorbol ester (PE) content. Since PE is the only toxic substance in jatropha seed that is not detoxified by heat, most scientists consider high PE varieties as toxic compared to the non-toxic (low PE) varieties. Jatropha is monoecious, with a male to female flower ratio of around 29:1. Increasing the ratio of female flowers may lead to an increase in seed yield. Rao *et al.* (2008) highlighted a correlation between the male to female flower ratio and yield and noted that this trait is highly heritable. Increasing the number of branches in jatropha may lead to an increase in the amount of inflorescence and ultimately the number of seeds per plant. Other target traits for jatropha improvement include synchronous flowering to facilitate mechanical and hand harvestings, large fruit and seed, and reducing the testa thickness to facilitate oil extraction (King *et al.*, 2009).

Currently, most areas in the world planted with jatropha are growing toxic varieties, except in some parts of Mexico where non-toxic varieties are being grown (Becker and Makkar, 1997). The meal produced from high PE varieties obtained after oil extraction cannot be used as a source of animal feed because it can induce tumors and cancer. Since varieties of jatropha lacking in PE already exist, it is possible in the future that this trait will be introduced into other elite varieties to increase the uses of and add value to jatropha seed. The non-toxic Mexican accessions are genetically divergent from the toxic accessions (Basha and Sujatha, 2007; Tanya *et al.*, 2010) and their F_1 progeny should display a certain degree of heterosis. Crossing studies followed by phorbol ester quantification revealed that outcrossing with toxic varieties did not affect the phorbol ester content of seeds borne on the non-toxic variety (Sujatha *et al.*, 2005).

The objective of the current study was to determine the heterotic response of major agronomic characters in jatropha. The results can be used in guidelines for plant breeders to commercially produce F_1 hybrids for establishing jatropha plantations.

MATERIALS AND METHODS

Six toxic parental accessions were used as female parents—three from Myanmar (M1, M2 and M3) and three from Thailand (T1, T2 and T3). Each was hand-pollinated by a non-toxic accession from Mexico (Me) that was used as the male parent. The study was conducted on the Kasetsart University, Kamphaeng Saen campus, Nakhon Pathom, Thailand. There were 12 healthy plants grown from each parent, but only one plant was used in making crosses. The F_1 seeds and seeds from the seven parental plants were sown in 22.5 × 12.5 cm plastic bags filled with 2 kg of soil at one seed per bag and watered daily. The germination rate was determined during preparation of seedlings using Equation 1:

$$\text{Germination (\%)} = (\text{number of germinated seeds/total planted seeds}) \times 100 \quad (1)$$

Individual seedlings were observed to

record the days to germination, plant height (cm) and stem diameter (cm). A completely randomized design with an unequal number of plants per entry was used. Once the seedlings were aged 2 mth (about 25 cm tall) with about 6–8 leaves per plant, the F_1 plants were randomly transplanted together with their parents in the same experimental field. The number of plants observed in each cross combination varied from 19 to 30 plants. The spacing was 2m between rows and 2m between plants. The soil in the field was described as a silty-clay type with pH 7.09 and organic matter content of 1.83%. The P_2O_5 and K_2O contents were 79.4 and 166.5 ppm, respectively. No fertilizer was added to the soil considering that jatropha is a wild plant without any genetic improvement for response to fertilizer. Irrigation was applied as needed to supplement natural rainfall. All plants were individually observed to record days to inflorescence initiation, days to 75% flowering per inflorescence, days to the first fruit initiation, days to the first fruit turns yellow and days to maturity of the first inflorescence. At harvesting time (at about age 10 mth), each plant was measured for canopy height (cm) from the ground at the stem base to the top apex, number of primary branches, stem base diameter (cm) using a digital vernier caliper, canopy diameter (cm), leaf length (cm), leaf width (cm), petiole length (cm), peduncle length (cm), seed yield per plant (g), number of fruits per plant, number of seeds per plant, 100 seed weight (g), fruit length (cm), fruit width (cm), seed length (cm), seed width (cm) and seed thickness (cm). The number of sampled plants for each parameter measured is shown in Table 1. The harvesting period spanned about three months which was representative of the normal harvesting period of jatropha in Thailand and Myanmar.

The values of mid-parent heterosis (H) and better-parent heterosis (heterobeltiosis, Hb) were calculated according to Equations 2 and 3, respectively:

$$\%H = (F_1 - MP) \times 100/MP \quad (2)$$

$$\%Hb = (F_1 - BP) \times 100/BP \quad (3)$$

where: MP (mid-parent value) = $(P_1 + P_2)/2$; P_1 and P_2 are the mean values of parent 1 and 2, respectively; F_1 is the mean value of hybrid progeny; BP is the mean value of the better parent (showing the more desirable value of that trait) in a cross.

The data from different characters were analyzed and statistically tested following Soehendi and Srinives (2005), where the significance of H and Hb in each character were determined by t-tests using Equations 4 and 5, respectively:

$$t\text{-test for } H = (F_1 - MP)/S_H \quad (4)$$

$$t\text{-test for } Hb = (F_1 - BP)/S_{Hb} \quad (5)$$

where: S_H and S_{Hb} are the standard error of estimates of H and Hb, respectively.

Pearson's simple correlation coefficients between H and Hb of various traits were calculated but only the high and meaningful ones were further examined.

RESULTS

For all the characters observed in this study, the standard errors associated with the parental means were higher than those with the F_1 means. The parents were more diverse than the F_1 progeny, because the seeds of the parents were derived from open crossing while the F_1 seeds were from single pair crossing.

Heterosis of characters at seedling stage

Emergence is an important indicator of seed and seedling vigor. Early germination is desirable and negative heterosis (earlier) for days to germination is useful. Table 1 shows there were different days to germination among the entries (parents and hybrids). There was no clear trend (positive or negative) regarding heterosis over mid-parent (H) and heterosis over the better parent (heterobeltiosis, Hb). Similarly, means for plant height and stem base diameter of 2-month-old

Table 1 Mean agronomic characters at seedling and fruit maturing stages of six F_1 jatropha hybrids and their parents.

Accession / Cross	No. of plants observed	Days to germination	Plant height at transplanting (cm)	Stem base diameter at transplanting (mm)	Days to inflorescence initiation	Days to 75% flowering per inflorescence	Days to first fruit initiation	Days to the first fruit turns yellow	Days to maturity of the first inflorescence
Myanmar 1 (M1)	3	4.22	17.87	12.28	159	181	183	212	217
Myanmar 2 (M2)	3	3.71	16.82	12.07	162	185	189	219	225
Myanmar 3 (M3)	4	6.71	16.85	10.88	136	158	162	191	197
Thailand 1 (T1)	3	7.17	18.82	10.36	140	162	167	193	198
Thailand 2 (T2)	5	5.83	17.42	10.30	149	173	179	208	213
Thailand 3 (T3)	3	7.33	19.88	11.41	147	171	174	203	208
Mexico (Me)	24	5.08	26.21	11.96	141	170	175	206	212
M1 × Me	22	4.17	24.09	11.55	141	163	168	200	205
M2 × Me	21	4.23	24.70	12.50	136	160	164	195	199
M3 × Me	10	4.67	22.58	13.07	130	152	156	187	190
T1 × Me	14	6.59	22.53	11.10	140	164	167	197	201
T2 × Me	13	6.18	22.59	11.14	146	172	176	207	211
T3 × Me	15	5.53	25.12	11.63	139	165	169	199	205
F-test		**	**	**	**	**	**	**	**
LSD (0.05)		2.14	2.16	0.96	13	14	14	15	16

** = Significantly different at $P \leq 0.01$

seedlings, just before transplanting indicated that F_1 hybrids had either higher or lower values than their parents with no conclusive trend.

Heterosis of characters at fruit maturing stage

Characters observed at fruit maturity of six F_1 hybrids and their parents are shown in Table 1. All five characters were highly correlated and thus the hybrid vigor in maturity is considered in detail here. Myanmar 2, a high PE parent had the longest fruit maturity date (225 d) among parents. The F_1 hybrids were all earlier than their parents, that is, with negative heterosis, giving maturity ranging from 190 to 205 d. However, only M2 × Me showed a significant value for H and negative Hb was significant in four crosses.

Heterosis of characters at harvesting time

The means of characters at harvesting time and their respective H and Hb are presented in Tables 2 and 3. Among the eight traits observed at harvesting, most tended to express positive heterosis (that is, the F_1 progeny had greater values than those of the parents) except for the number of primary branches in the cross T3 × Me. F_1 of M2 × Me that showed impressive H and Hb in several traits, especially canopy height, canopy diameter and stem based diameter. The cross M3 ¥ Me showed positive heterosis in leaf size, with significant H and Hb values between 16.39% and 21.19% (Table 3).

The high PE parents had a shorter peduncle than the Mexican accession. Among the F_1 progeny, M1 × Me had the longest peduncle (11.0 cm), as shown in Table 2. Three out of six crosses showed significance in H and only one cross in Hb. Table 3 shows that the hybrid M1 × Me had the highest value for both H (30.84%) and Hb (12.03%).

Heterosis of fruit and seed characters

The hybrid jatropha showed impressive heterosis in fruit and seed characters (Tables 4 and 5). Although most heterosis was detected over mid-parent, significant Hb was also found in the seed size (100-seed weight) of all crosses, except M1 × Me. Significant values of H in all six crosses varied from 15.87% to 33.20%, while significant

Table 2 Mean agronomic characters at harvesting of six F_1 jatropha hybrids and their parents.

Accession / Cross	Canopy height (cm)	Canopy diameter (cm)	Stem base diameter (cm)	No. primary branches	Leaf length (cm)	Leaf width (cm)	Petiole length (cm)	Peduncle length (cm)
Myanmar 1 (M1)	133	114	6.7	6.0	12.1	13.6	15.4	7.0
Myanmar 2 (M2)	89	99	5.8	4.0	10.7	12.6	11.8	6.2
Myanmar 3 (M3)	118	119	5.4	5.8	10.7	12.0	13.2	5.5
Thailand 1 (T1)	125	92	5.5	4.7	11.0	11.8	11.6	6.1
Thailand 2 (T2)	126	100	5.6	5.2	10.7	12.1	10.1	8.2
Thailand 3 (T3)	117	91	4.9	3.3	10.0	11.8	9.5	6.0
Mexico (Me)	138	92	5.1	4.6	11.4	12.7	7.7	9.7
M1 × Me	152	131	6.1	5.9	12.5	14.2	11.8	11.0
M2 × Me	162	146	6.6	4.7	11.9	14.0	10.8	10.2
M3 × Me	139	129	5.6	6.4	12.4	14.4	11.2	8.3
T1 × Me	145	131	6.1	4.1	12.0	13.6	10.0	10.2
T2 × Me	141	124	5.9	4.2	11.3	12.9	9.3	9.2
T3 × Me	121	96	5.1	2.9	10.9	12.6	9.7	8.4
F-test	**	**	**	**	**	**	**	**
LSD (0.05)	25	32	1.1	2.2	1.6	2.0	2.1	1.6

** = Significant by different at $P \leq 0.01$

Table 3 Heterosis (%H) over mid-parent and heterobeltiosis (%Hb) over the better parent for plant growth characters at harvesting stage of six F_1 jatropha hybrids.

Cross	Canopy height (cm)		Canopy diameter (cm)		Stem base diameter (cm)		No. primary branches		Leaf length (cm)		Leaf width (cm)		Petiole length (cm)		Peduncle length (cm)	
	%H	%Hb	%H	%Hb	%H	%Hb	%H	%Hb	%H	%Hb	%H	%Hb	%H	%Hb	%H	%Hb
M1 × Me	8.70	3.99	35.42 *	14.86	6.70	-7.85	15.86	-1.52	3.12	2.56	6.28 *	4.47	-2.13	-23.31**	30.84 **	12.03*
M2 × Me	43.70*	18.35**	47.68**	47.18**	20.23**	15.20**	38.66	17.8	11.48 *	11.48	14.33 *	10.86	13.17	-8.74	26.91 **	3.27
M3 × Me	13.64	9.70	30.89*	8.84	7.58	3.88	16.36	11.30	17.04**	16.39 **	21.19 **	20.00 **	10.30	-15.55*	13.40	-8.81
T1 × Me	8.17	1.12	38.12**	33.58*	17.11 *	11.27	-15.76	-18.57	5.91	3.53	8.19	1.68	4.20	-13.75	26.26 **	1.06
T2 × Me	5.34	-0.60	24.86*	24.23*	8.63	4.25	-21.63	-23.08	1.12	-2.96	2.99	-0.96	3.65	-7.30	3.33	-4.38
T3 × Me	-3.20	-9.25	2.27	-0.61	3.01	1.94	-32.55*	-44.52**	1.70	-4.61	1.09	-3.59	13.50	2.10	9.22	-10.59

* = Significant at $P \leq 0.05$; ** = Significant at $P \leq 0.01$

Hb values were between 15.34% and 28.53%. Heterosis in the 100-seed weight in all crosses came from the combined contribution of all three seed traits, that is, seed length, seed width and seed thickness.

Table 4 showed that T1 had the longest seed (1.85 cm) among the parents; its hybrid with Me also shared this highest value (1.85 cm). Five crosses had significant H values varying from 2.92% to 6.26%, while only T2 × Me had a significant Hb value (2.41%) (Table 5). High PE parents from Myanmar and Thailand produced wider seeds than the low PE Mexican accession. All F_1 progeny had wider seeds than the low PE parent, but there was no difference from the high PE ones. Five out of six crosses showed significant H values ranging from 3.18% to 6.26%. All hybrids had thicker seeds than their parents; the parent seeds had an average thickness of 0.85 to 0.88 cm, whereas for their crosses it was 0.88 to 0.92 cm. Five out of six crosses displayed significant H values for seed thickness ranging from 3.42% to 5.24%. Significant Hb values were detected in three crosses, varying from 2.68% to 4.57%.

Heterosis of yield components

The highest seed yield per plant was recorded in the cross M2 × Me (233.9 g), followed by M1 × Me (200.7 g) and M3 × Me (189.8 g) as shown in Table 6. Five out of six crosses gave higher yields than the mid-parent and four crosses gave higher yields than the better parent (Table 7). Values ranged from 85.66% to 262.92% in H and from 105.38% to 195.93% in Hb. The maximum heterosis over mid parent was displayed by M3 × Me followed by M2 × Me and T1 × Me. The heterosis over better parent was also in the same order. Data in Table 7 show that heterosis in seed yield comes from a contribution of all yield components, that is, number of fruits per plant, number of inflorescences per plant and number of seeds per plant. High yield heterosis in some

Table 4 Mean fruit and seed characters of six F_1 jatropha hybrids and their parents.

Accession / Cross	Fruit length (cm)	Fruit width (cm)	Seed length (cm)	Seed width (cm)	Seed thickness (cm)	100 seed weight (g)
Myanmar 1 (M1)	2.93	2.70	1.78	1.16	0.85	64.91
Myanmar 2 (M2)	2.76	2.55	1.69	1.15	0.85	61.39
Myanmar 3 (M3)	2.81	2.62	1.78	1.16	0.88	64.37
Thailand 1 (T1)	2.83	2.63	1.85	1.17	0.88	54.92
Thailand 2 (T2)	2.80	2.63	1.79	1.17	0.87	59.43
Thailand 3 (T3)	2.71	2.62	1.80	1.16	0.87	59.37
Mexico (Me)	2.72	2.40	1.72	1.03	0.86	60.38
M1 × Me	3.10	2.81	1.84	1.12	0.88	73.88
M2 × Me	3.01	2.80	1.83	1.15	0.91	75.22
M3 × Me	2.97	2.74	1.83	1.15	0.90	74.62
T1 × Me	3.00	2.77	1.85	1.16	0.92	75.92
T2 × Me	2.89	2.74	1.83	1.16	0.90	71.37
T3 × Me	2.82	2.63	1.80	1.12	0.89	69.11
F-test	**	**	**	**	**	**
LSD (0.05)	0.18	0.18	0.07	0.04	0.03	5.96

** = Significant at $P \leq 0.01$

crosses in the current experiment may encourage plant breeders to utilize hybrid vigor in jatropha.

Correlation between H and Hb of yield and major agronomic characters

The correlations of mid-parent heterosis between seed yield, yield components and major agronomic characters in the F_1 crosses are given in Table 8. High correlations among heterosis were found between yield per plant and number of fruits per plant, number of inflorescences per plant and number of seeds per plant. H for the number of seeds per plant was correlated with number of fruits per plant and number of inflorescences per plant. The number of inflorescences per plant was correlated with canopy diameter and number of fruits per plant.

Similarly, positive correlations were found between Hb of yield per plant with canopy height, number of fruits per plant, number of inflorescences per plant and number of seeds per plant (Table 8). Hb for the number of seeds per plant was correlated with canopy height, number of fruits per plant and number of inflorescences per plant. Hb for the number of inflorescences per plant was correlated with Hb in canopy height and number of fruits per plant. The number of fruits per plant was correlated with canopy height. Finally, Hb of 100-seed weight was correlated with days to germination.

DISCUSSION

Characters at the seedling stage are important in the establishment of seedlings and the eventual yield produced. Days to germination, plant height and stem base diameter at 2 months old, just before transplanting time, showed H and Hb in some F_1 hybrids. Among the combinations, M3 × Me had the highest H and Hb for these characters. However, seedling stage characters were not significantly correlated with yield per plant.

Table 5 Heterosis (%H) over mid-parent and heterobeltiosis (%Hb) over the better parent for fruit and seed characters of six F_1 jatropha hybrids.

Cross	Fruit length (cm)		Fruit width (cm)		Seed length (cm)		Seed width (cm)		Seed thickness (cm)		100-seed weight (g)	
	%H	%Hb	%H	%Hb	%H	%Hb	%H	%Hb	%H	%Hb	%H	%Hb
M1 × Me	7.92 **	5.78 **	9.11**	3.83	4.93 **	3.34	2.14	-3.42	2.75	2.02	16.71 **	13.82
M2 × Me	9.50 **	9.05 **	12.08 **	9.87 **	6.26 **	4.24	5.63 **	0.30	5.24 **	4.20 **	23.28 **	22.53 **
M3 × Me	8.57 **	5.72	10.68 **	4.74	5.58 **	2.56	5.23 **	-0.63	3.42 **	2.68 *	18.99 **	15.92 **
T1 × Me	7.67 **	5.84 *	10.86 **	5.31	2.92 *	-0.24	5.00 **	-1.04	5.23 **	4.57 **	33.20 **	28.53 **
T2 × Me	5.43 *	3.37	9.02 **	4.17	5.44 **	2.41**	6.26 **	-0.87	3.91 *	3.02	19.62 **	19.14 **
T3 × Me	4.88 *	4.32	4.79	0.26	3.15	0.31	3.18 *	-3.44 *	3.42 *	1.77	15.87 **	15.34 **

* = Significant at $P \leq 0.05$; ** = Significant at $P \leq 0.01$

Early flowering and maturity in jatropha can lead to higher yield per period of time. Therefore, negative heterosis (that is, shorter maturity in the hybrids) is desirable. All hybrids showed negative H over the mid-parent; however, early flowering and maturity were not correlated with yield per plant in the current study (data not shown). A similar relationship was reported by Rao *et al*. (2008) where the number of days from fruiting to maturity was negatively correlated with seed yield.

When jatropha was younger than one year, canopy height, canopy diameter, stem base diameter and number of primary branches were considered important agronomic characters affecting yield per plant (Koutroubas *et al*., 1999; Sunil *et al*., 2008). According to these criteria, M2 × Me would be considered a high yielding hybrid. Canopy height and diameter were correlated with seed yield in the current study. Similar results were reported by Rao *et al*. (2008) where the plant height was positively correlated with seed yield, while leaf length, leaf width, petiole length and peduncle length were less important characters for high yield.

Rao *et al*. (2008) reported that large jatropha seeds produced larger and more vigorous seedlings with a better chance of survival than those produced from small seeds. Seed length, width and thickness were useful characters for early selection of seed sources (Kaushik *et al*., 2007). Larger fruits and seeds tended to give higher 100-seed weights and yields per plant. M2 × Me showed the highest H and Hb in fruit and seed sizes (Table 5). Seed length, width and thickness showed less variation among the genotypes used in the current study (Table 4). The 100-seed weight was correlated with seed yield and all crosses showed significant H and Hb in 100-seed weight with T1 × Me hybrid producing the highest values (Table 5).

Heterosis in the number of fruits per plant, number of inflorescences per plant and

Table 6 Mean yield component of six F_1 jatropha hybrids and their parents.

Accession / Cross	No. fruits /plant	No. inflorescences /plant	No. seeds /plant	Yield/plant (g)
Myanmar 1 (M1)	54.3	11.7	144.7	91.8
Myanmar 2 (M2)	41.0	6.0	93.7	57.4
Myanmar 3 (M3)	43.8	9.7	105.8	64.1
Thailand 1 (T1)	32.0	2.7	75.7	42.3
Thailand 2 (T2)	32.0	5.5	78.0	45.4
Thailand 3 (T3)	37.7	5.7	91.0	54.8
Mexico (Me)	59.0	7.5	132.5	78.2
M1 × Me	95.8	12.7	266.5	200.7
M2 × Me	127.2	13.7	317.4	233.9
M3 × Me	96.1	12.2	249.6	189.8
T1 × Me	85.0	9.9	231.7	171.5
T2 × Me	63.0	7.1	171.4	120.9
T3 × Me	49.6	3.9	133.3	89.1
F-test	**	**	**	**
LSD (0.05)	52.0	6.1	133.4	95.9

** Significant at P ≤ 0.01

Table 7 Heterosis (%H) over mid-parent and heterobeltiosis (%Hb) over the better parent for yield component characters of six F_1 jatropha hybrids.

Cross	No. fruits/plant		No. inflorescences / plant		No. seeds/plant		Yield/plant (g)	
	%H	%Hb	%H	%Hb	%H	%Hb	%H	%Hb
M1 × Me	55.89	39.68	37.37	8.72	77.86 *	71.94 *	111.75 **	105.38 **
M2 × Me	133.89 **	87.67 *	61.44 *	24.75	162.44 **	114.16 **	222.18 **	166.53 **
M3 × Me	166.02 **	119.66 *	69.56	26.44	185.67 **	136.03 *	262.92 **	195.93 **
T1 × Me	79.89 *	36.00	68.98 *	9.52	116.13 **	67.00	183.25 **	117.52 *
T2 × Me	29.63	-3.37	14.00	1.79	53.02 *	17.39	85.66 **	42.44
T3 × Me	0.71	-19.35	-37.16 **	-41.88	16.53	-3.26	32.50	11.74

* = Significant at $P \leq 0.05$; ** = Significant at $P \leq 0.01$

number of seeds per plant were correlated with yield per plant (Table 8). Similar results were shown in castor bean (Koutroubas *et al*., 1999; Joshi *et al*., 2002) where seed yield depended on the number of racemes per plant, the number of capsules per raceme, number of branches per plant and the thousand-seed weight. Thus these three traits, as well as 100-seed weight, canopy height and canopy diameter contributed to improved seed yield in the hybrid jatropha.

Yield superiority of the F_1 hybrids in jatropha was clearly shown in four out of the six crosses in the current study. Crosses showing heterosis for yield traits also showed hybrid vigor in some of the seedling stage characters, fruit maturity characters, plant growth characters, and fruit and seed size characters. The highest H and Hb values for seed yield in the crosses M3 × Me and M2 × Me were 262.92% and 195.93% compared to 222.18% and 166.53%, respectively. Since the current experiment was conducted over a single one-year period, it has provided some initial information about heterosis at the early stage of jatropha breeding.

Table 8 Correlations between heterosis and between heterobeltiosis (in parentheses) of major agronomic characters from six F_1 jatropha hybrids.

Character	Days to inflorescence initiation	Canopy height (cm)	Canopy diameter (cm)	100 seed weight (g)	Fruits /plant	Inflorescences /plant	Seeds /plant	Yield /plant (g)
Days to germination	0.792	-0.053	0.153	0.532	-0.405	-0.023	-0.324	-0.280
	(0.557)	(-0.218)	(0.569)	(0.823*)	(-0.481)	(-0.144)	(-0.430)	(-0.363)
Days to inflorescence initiation		-0.615	-0.368	0.330	-0.632	-0.335	-0.582	-0.516
		(-0.767)	(-0.274)	(0.269)	(-0.637)	(-0.458)	(-0.653)	(-0.599)
Canopy height (cm)			0.773	0.237	0.687	0.591	0.705	0.661
			(0.663)	(0.206)	(0.859*)	(0.878*)	(0.882*)	(0.871*)
Canopy diameter (cm)				0.532	0.689	0.895*	0.743	0.739
				(0.752)	(0.298)	(0.599)	(0.370)	(0.404)
100 seed weight (g)					0.265	0.595	0.362	0.428
					(0.064)	(0.289)	(0.120)	(0.198)
Fruits/ plant						0.850*	0.994**	0.984**
						(0.845*)	(0.991**)	(0.985**)
Inflorescences/plant							0.893*	0.912**
							(0.881*)	(0.890*)
Seeds /plant								0.996**
								(0.996**)

* = Significant at $P \leq 0.05$; ** = Significant at $P \leq 0.01$; (Degrees of freedom = 4)

CONCLUSION

Commercialization of hybrid cultivars in jatropha can be considered based on the significant heterosis for yield and other major agronomic characters. Although the hybrid vigor in seed yield was high, hybrid seed production in jatropha was still achieved by hand pollination and thus would not be commercially feasible. Genetic/cytoplasmic male sterility should be identified and incorporated into the female parent for commercial hybrid production of jatropha seeds. Although jatropha grown from seeds has many advantages with regard to root systems and planting flexibility over those grown from seedlings, stem cutting propagation or tissue culture of the best F_1 hybrid can be initially employed to produce hybrid plants, while male sterility characters are yet to be found.

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