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Heterosis and Inbreeding Depression Study in Castor (*Ricinus communis* L.) using 21 Generations

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ABSTRACT: Heterosis and inbreeding depression studies in castor were carried out on twelve characters against two crosses (SKI-346 × JI-35 (cross 1) and SKI-346 × SKI-215 (cross 2) using 21 Generations at Main Oilseeds Research Station, JAU, Junagadh, Gujarat. The information on heterosis and inbreeding depression together facilitates the breeder to take a decision on whether to exploit hybrid vigour or perform selection in segregating generations. The heterosis over better parent was found significant in desirable direction for days to flowering of primary raceme, days to maturity of primary raceme, number of nodes up to primary raceme, number of effective branches per plant, 100-seed weight, seed yield per plant and oil content in SKI-346 × JI-35; and plant height up to primary raceme, number of nodes up to primary raceme and seed yield per plant in SKI-346 × SKI-215. Significant and positive inbreeding depression was also observed for days to flowering of primary raceme and for 100-seed weight in cross, SKI-346 × JI-35; for days to maturity of primary raceme, for plant height up to primary raceme and for number of nodes up to primary raceme in cross, SKI-346 × SKI-215; for number of effective branches per plant, for number of capsules on primary raceme, for oil content and for seed yield per plant in crosses, SKI-346 × JI-35 and SKI-346 × SKI-215. More over there was close agreement between observed and expected (1) heterosis over mid and better parent revealed that trigenic parameter model was more fit for most of the characters in both the crosses.

Keywords: Relative heterosis, Heterobeltiosis. Inbreeding depression, Gene effects, 21 Generations, Castor.

INTRODUCTION

The phenomenon of heterosis has proved to be the most important genetic tool in enhancing the yield of cross pollinated species in general and castor in particular. Heterosis breeding is an important crop improvement method adopted in many crops all over the world. which became feasible due to availability of 100% pistillate lines in castor (Gopani *et al.,* 1968). Castor (*Ricinus communis* L., 2n = 2x = 20) is an industrially an important non-edible oilseed crop widely cultivated in the arid and semi-arid regions of the world. Castor is a sexually polymorphic species with different sex forms *viz*., monoecious, pistillate, hermaphrodite and pistillate with interspersed staminate flowers (ISF). The hybrid vigor in castor was commercially exploited in Gujarat by utilizing pistillate line TSP 10 R introduce from USA initially in early 1970's when the first hybrid GCH-3, giving 124 per cent higher yield than the checks, was released at country and state level by Gujarat. Then after many hybrids were developed and released by Gujarat with higher productivity. As a result, quantum jump in the productivity from 300 kg/ha in 1970 to about 1754 kg/ha during 2017-2018 is also realized. The measurement of heterosis over mid parent is of academic importance for studying genetic of heterosis but has limited practical usefulness. Therefore, the heterosis may better be measured in terms of superiority of F_1 over better parent. In the present investigation, heterosis over mid as well as better parents were estimated and compared with expected values calculated on the basis of gene effects (expected values of various generations). The primary goal of plant breeding is to raise seed yield and improve quality of crop plants through gene recombinants exhibiting vigour. Thus, hybrid vigour is a term encompassing phenotypic potential of F_1 hybrids to perform better than their parents. Inbreeding depression, another face of the same phenomenon of heterosis (Kheradnam, *et al.,* 1975) is the percentage decrease in F_2 over F_1. It is termed as inbreeding depression since F_2 shows a reduction in heterosis. The information on heterosis and inbreeding depression together facilitates the breeder to take a decision on whether to exploit hybrid vigour or perform selection in segregating generations.

MATERIALS AND METHODS

The twenty-one generations *viz*., P_1, P_2, F_1, F_2, F_3, B_1, B_2, B_{11}, B_{12}, B_{21}, B_{22}, B_{1S}, B_{2S}, $B_1 \times F_1$, $B_2 \times F_1$, $F_2 \times P_1$, F_2 x P_2, $F_2 \times F_1$, B_1 bip, B_2 bip and F_2 bip of each of the two crosses *i.e.*, SKI-346 × JI-35 (cross 1) and SKI-

346 × SKI-215 (cross 2) were sown in the field on 6th October, 2020 at Main Oilseeds Research Station, Junagadh Agricultural University, Junagadh, Gujarat (INDIA). The final evaluation of experiment was laid out in Compact Family Block Design with three replications. Each replication was divided into two compact blocks each consists of single cross and blocks were consisted of twenty-one plots comprised of twenty-one generations of each cross. The plots of various generations contained different number of rows *i.e.*, parents and F_1 in single row; B_1 and B_2 in two rows and F_2, F_3, B_{11}, B_{12}, B_{21}, B_{22}, B_{1S}, B_{2S} $B_1 \times F_1$, $B_2 \times F_1$, $F_2 \times P_1$, $F_2 \times P_2$, $F_2 \times F_1$, B_1 bip, B_2 bip and F_2 bip in four rows. Each row was of 6 m in length and in each plot, plant at 120 cm from row to row and at 60 cm from plant to plant. Crop protection strategies and measures were used to defend crops against weeds, pests, viruses, plant diseases, and other harmful factors and raise good crop of castor.

Estimation of heterosis and inbreeding depression

1. Observed heterosis and inbreeding depression. The heterotic effects in term of superiority of F_1 over better parent (heterobeltiosis) as per Fonseca and Patterson, (1968) and over mid parent value (relative heterosis) as per Briggle, (1963) was worked out as,

$$\text{Heterobeltiosis} = \overline{F_1} - \overline{BP}$$

$$\text{Relative heterosis} = \overline{F_1} - \overline{MP}$$

The inbreeding depression from F_1 and F_2 was calculated as,

$$\text{Inbreeding depression} = \overline{F_1} - \overline{F_2}$$

Where, $\overline{F_1}$ = Mean of the F_1 hybrid,

$\overline{BP}$ = Mean of the better parent,

$\overline{MP}$ = Mid parental value *i.e.*, $(P_1 + P_2)/2$,

$\overline{F_2}$ = Mean of the F_2 population.

The standard errors for heterosis and inbreeding depression were calculated as,

S. E. for heterobeltiosis = $\sqrt{V_{\overline{F1}} + V_{\overline{BP}}}$

S. E. for relative heterosis = $\sqrt{V_{\overline{F1}} + (V_{\overline{P1}} + V_{\overline{P2}})/2}$

S. E. for inbreeding depression = $\sqrt{V_{\overline{F1}} + V_{\overline{F2}}}$

The test of significance of heterotic effects and inbreeding depression was done by usual t-test.

2. Expected heterosis and inbreeding depression

The specifications of heterosis under different situations are given as under (Based on formulae given by Mather and Jinks, 1982).

(a) The expected heterosis and inbreeding depression for different characters, where simple additive-dominance model was adequate, were calculated as,

(1) Heterosis over better parent

(i) $F_1 - P_1$ = [h] - [d];

(ii) $F_1 - P_2$ = [h] - [-d]

(2) Heterosis over mid parent = [h]

(3) Inbreeding depression = [h]/2

(b) For the characters where the digenic interaction model was found adequate, the expected heterosis and inbreeding depression were determined using the parameters of best fitting model. For example, the expectation of heterosis and inbreeding depression measured on a six parameters scale had the following form,

(1) Heterosis over better parent

(i) $F_1 - P_1$ = ([h] + [1]) - ([d] + [i])

(ii) $F_1 - P_2$ = ([h] + [1]) - (-[d] + [i])

(2) Heterosis over mid parent = ([h] + [1]) - [i]

(3) Inbreeding depression = (1/2) [h] + (3/4) [l]

(c) For the characters where the trigenic interaction model was found adequate, the expected heterosis and inbreeding depression were calculated as under:

(1) Heterosis over better parent

(i) $F_1 - P_1$ = ([h] + [l] + [z]) - ([d] + [i] + [w])

(ii) $F_1 - P_2$ = ([h] + [l] + [z]) - ([-d] + [i] - [w])

(2) Heterosis over mid parent = ([h] + [l] + [z]) - [i]

(3) Inbreeding depression= (1/2) [h] + (3/4) [l]+(7/8) [z]

(d) Linkage has no effect on the means of non-segregating generations (P_1, P_2, and F_1), regardless of the presence or absence of epistasis, and thus has no effect on the specification of heterosis. However, it has the potential to cause bias in estimates of the [h], [I] and [l] components, as well as the [w] and [z] components, and to misrepresent the relative importance of these components in the manifestation of heterosis. As a result, the interpretation of the cause of heterosis changes.

Where, (d) = Additive gene effect, (h) = Dominance gene effect, (i) = Additive × additive gene effect, (j) = Additive × dominance gene effect, (l) = Dominance × dominance gene effect, (w) = Additive × additive × additive gene effect, (x) = Additive × additive × dominance gene effect, (y) = Additive × dominance × dominance gene effect and (z) = Dominance × dominance × dominance gene effect.

RESULTS AND DISCUSSION

A review of the results in Table 1 revealed that the extent of heterosis between midparent and better parents was not pronounced for the various characters recorded in two crosses. The low scoring parent was chosen as the better parent for characteristics such as days to flowering of primary raceme, days to maturity of primary raceme, plant height up to primary raceme, and number of nodes up to primary raceme.

A. Days to flowering of primary raceme

For the purpose of estimation of heterosis over better parent, the parent having less number of days to flowering was considered as better parent. Out of two crosses, both crosses showed significant and negative heterosis over mid parent namely, SKI-346 × JI-35 and SKI-346 × SKI-215 and observed significant and negative in only one cross (SKI-346 × JI-35). The observed and expected (1) values of heterosis over mid and better parents were comparatively close in cross 1 indicating adequacy of the trigenic interaction model, while in cross 2 observed value of better parent heterosis was more closer with expected (2) value revealing fitting of linked digenic interaction model. The inbreeding depression was found significant and positive in cross SKI-346 × JI-35. A close agreement between observed and expected (1) value of inbreeding depression was noticed in cross 2 showing fitting of trigenic interaction model, while in cross 1 expected (2) values of linked digenic interaction model were closer with observed values of inbreeding depression. The results confirmed the results of those reported by Joshi *et al.*, (2002); Lavanya and Chandramohan (2003); Delvadiya *et al.*, (2018) for this trait. The significant and positive inbreeding depression was reported by Pathak *et al.*, (1988); Mori, (2019) for days to flowering of primary raceme.

Table 1: Estimates of observed and expected heterosis and inbreeding depression for twelve characters in two crosses of castor.

Heterosis/ Inbreeding depression	Observed/ Expected Values	Days to flowering of primary raceme	Days to maturity of primary raceme	Plant height up to primary raceme	Number of node up to primary raceme	Total length of primary raceme	Effective length of primary raceme	Number of effective branches per plant	Number of capsules on primary raceme	Shelling out turn	100-seed weight	Seed yield per plant	Oil content
SKI-346 × JI-35 (cross 1)													
Mid parent	Observed	-1.80* ±0.74	-6.77** ±0.95	2.97** ±1.00	-1.27** ±0.26	-0.87 ±1.11	-1.33 ±1.14	1.30** ±0.24	10.40** ±2.42	2.19** ±0.50	2.75** ±0.26	56.75** ±2.85	0.38** ±0.10
	Expected (1)	-1.86	-7.01	3.00	-1.21	-0.52	-0.73	1.23	8.25	2.10	2.80	56.63	0.37
	Expected (2)	-0.99	-5.58	2.10	-1.10	-1.92	-2.13	0.31	0.13	0.98	1.62	50.69	0.42
Better parent	Observed	-1.93* ±0.77	-7.67** ±1.00	0.47 ±1.32	-1.60** ±0.29	-7.40** ±1.37	-7.53** ±1.35	0.73* ±0.30	-8.47** ±2.86	-0.02 ±0.67	0.87* ±0.33	52.16** ±3.06	0.27* ±0.12
	Expected (1)	-2.24	-7.40	0.80	-1.54	-6.97	-6.73	0.73	-8.89	0.01	0.90	52.00	0.28
	Expected (2)	-1.30	-5.67	-0.24	-1.50	-6.45	-6.32	-0.34	-12.89	-1.91	0.13	46.44	0.35
Inbreeding depression	Observed	1.68* ±0.76	-7.15** ±1.13	-6.07** ±1.16	-1.57** ±0.30	-7.23** ±1.69	-7.42** ±1.65	0.97** ±0.31	31.50** ±2.68	-0.61 ±0.52	0.77* ±0.37	29.06** ±7.94	0.24* ±0.11
	Expected (1)	1.47	-2.73	-3.43	-0.89	-6.22	-5.85	1.27	27.96	-1.18	-0.18	39.16	0.61
	Expected (2)	1.86	-5.88	-5.15	-1.24	-5.62	-5.70	0.45	24.08	-1.09	0.40	35.35	0.38
SKI-346 × SKI-215 (cross 2)													
Mid parent	Observed	-2.30** ±0.72	-0.30 ±1.20	3.97** ±1.21	-0.73* ±0.29	-4.53** ±1.18	-6.03** ±1.28	1.23** ±0.24	3.97* ±1.86	-1.70* ±0.65	-1.79** ±0.35	52.58** ±3.65	-0.16 ±0.14
	Expected (1)	-2.56	-0.53	4.14	-0.62	-4.60	-6.11	1.17	1.47	-0.65	-1.72	52.74	-0.10
	Expected (2)	-1.21	-0.77	1.64	-0.38	-2.32	-3.35	0.54	1.43	-1.85	-1.82	48.21	-0.26
Better parent	Observed	2.80** ±0.78	-1.87 ±1.37	-6.07** ±1.53	-2.93** ±0.40	-6.53** ±1.37	-8.13** ±1.43	-0.33 ±0.27	-16.67** ±2.02	-6.43** ±0.66	-6.24** ±0.42	16.31** ±4.05	-0.59** ±0.13
	Expected (1)	-3.09	-1.88	-5.63	-2.71	-6.49	-8.10	-0.44	-18.62	-5.36	-5.87	16.37	-0.56
	Expected (2)	-1.97	-1.75	-6.44	-1.82	-4.06	-5.26	-0.92	-15.62	-6.87	-5.61	11.99	-0.61
Inbreeding depression	Observed	0.70 ±0.78	5.33** ±1.28	3.28* ±1.49	0.67* ±-0.32	-1.43 ±1.67	-3.62* ±1.71	1.75** ±0.36	24.88** ±2.33	-0.03 ±0.84	-1.11** ±0.38	32.94** ±8.51	0.54** ±0.14
	Expected (1)	0.30	4.89	2.49	0.10	-3.27	-4.60	2.32	19.79	-2.98	-0.36	46.35	0.18
	Expected (2)	1.12	4.85	3.48	0.88	-1.58	-3.13	1.40	19.94	-2.50	-1.38	28.03	0.44

Expected (1)-Trigenic interaction model; Expected (2)-Linked digenic interaction model

B. Days to maturity of primary raceme

Heterobeltiosis calculated by taking early maturing parent as better parent. The heterosis over mid parent was found to be significant and negative in only cross, SKI-346 × JI-35. Heterosis over better parent was significant and negative in cross (SKI-346 × JI-35). Closer agreement between observed and expected (1) heterosis over mid and better parents were observed in all the both crosses indicating fitting of trigenic interaction model. The inbreeding depression fluctuated from -7.15 % (SKI-346 × JI-35) to 5.33 % (SKI-346 × SKI-215) and was significant and negative in SKI-346 × JI-35. The observed inbreeding depression was quite close to expected (2) values in cross 1 showing fitting of linked digenic interaction model, while in cross 2 expected (1) values of trigenic interaction model was closer with observed values of inbreeding depression. Similar findings for days to maturity of primary raceme have also been reported by Joshi *et al.,* (2002); Lavanya and Chandramohan (2003); Delvadiya *et al.,* (2018). The significant and positive inbreeding depression was reported by Singh *et al.,* (2013) for days to maturity of primary raceme, which supports the results obtained in the present study.

C. Plant height up to primary raceme (cm)

A short statured parent was considered as better parent for this trait. Significant and negative heterobeltiosis was observed in cross (SKI-346 × SKI-215). The observed and expected (1) values of heterosis over mid and better parents were comparatively close in cross 1 indicating adequacy of the trigenic interaction model fitted, while in cross 2, expected values of linked digenic interaction model was close with observed values for better parent heterosis. The inbreeding depression significant and positive inbreeding depression in only one cross *i.e.* SKI-346 × SKI-215 and was found significant and negative in cross namely SKI-346 × JI-35. The observed and expected (2) values of inbreeding depression were comparatively close in all the both crosses suggesting adequacy of the linked digenic interaction model. Significant estimates of heterosis for plant height up to primary raceme have been also reported by Patel *et al*., (2013); Punewar *et al.,* (2017); Movaliya, (2020). The significant and positive inbreeding depression was reported by Singh *et al.,* (2013); Mori, (2019); Movaliya (2020) for plant height up to primary raceme.

D. Number of nodes up to primary raceme

The parent having less number of nodes up to primary raceme was taken as a better parent. The estimates of significant and negative relative heterosis and heterobeltiosis was recorded in both crosses *viz.,* SKI-346 × JI-35 and SKI-346 × SKI-215. The observed and expected (1) values of heterosis over mid and better parents were comparatively close in both the crosses indicating adequacy of the trigenic interaction model fitted. The estimates of inbreeding depression was significant and positive in cross, SKI-346 × SKI-215. The observed inbreeding depression was quite close to expected (2) values in cross 1 and 2 revealing fitting of linked digenic interaction model. Positive estimation of heterosis for this trait was also reported by Thakkar *et al.,* (2005); Punewar *et al.,* (2017); Aher *et al.,* (2020). The significant and positive inbreeding depression was reported by Singh *et al.,* (2013); Mori, (2019); Movaliya, (2020) for number of nodes up to primary raceme.

E. Total length of primary raceme (cm)

Any cross combination dose not exhibited significant and positive values of relative heterosis and heterobeltiosis as well as positive inbreeding depression. The observed and expected (1) values of heterosis over mid and better parents were comparatively close in both the crosses indicating adequacy of the trigenic interaction model fitted. The observed inbreeding depression was quite close to expected (1) values in cross 1 showing fitting of trigenic interaction model, while in cross 2 observed values of inbreeding depression were more closer with expected (2) values revealing fitting of linked digenic interaction model. High magnitude of desirable heterosis for this trait was also reported by Punewar *et al.,* (2017); Delvadiya *et al.,* (2018); Mori, (2019); Movaliya, (2020); Aher *et al.,* (2020). The significant and positive inbreeding depression was reported by Singh *et al.* (2013); Barad *et al.,* (2019), Mori, (2019); Movaliya, (2020) for total length of primary raceme.

F. Effective length of primary raceme (cm)

The heterosis over mid parent was significant and negative in cross 4, while heterosis over better parent was significant and negative in cross 1 and 2. The observed and expected (1) values of heterosis over mid and better parents were comparatively close in all the both crosses indicating adequacy of the trigenic interaction model fitted. The observed values of inbreeding depression was found significant and negative in the cross 1 and 2. A close agreement between observed and expected (1) inbreeding depression was noticed in cross 1 showing fitting of trigenic interaction model, while in cross 2 expected values of linked digenic interaction model were closer with observed value of inbreeding depression. Significant estimates of heterosis for effective length of primary raceme have been also reported by Punewar *et al.,* (2017); Delvadiya *et al.,* (2018); Mori, (2019); Movaliya, (2020); Aher *et al.,* (2020). The significant and positive inbreeding depression was reported by Singh *et al.,* (2013); Barad *et al.,* (2019); Mori, (2019) for effective length of primary raceme.

G. Number of effective branches per plant

For number of effective branches per plant, the estimates of heterosis over mid parent was significant and positive in both the crosses. The estimate of heterosis over better parent was significant and positive in the cross SKI-346 × JI-35. The observed and expected (1) values of heterosis over mid and better parents were comparatively close in all the both crosses indicating adequacy of the trigenic interaction model for this trait. Significant and positive inbreeding depression in both the crosses, The observed inbreeding depression was quite close to expected (1) values in cross 1 showing fitting of trigenic interaction model, while in cross 2 observed values of inbreeding depression were more closer with expected (2) values revealing fitting of linked digenic interaction model. Significant estimates of heterosis for number of effective branches per plant have been also reported by Patel *et al*., (2013); Punewar *et al.,* (2017); Movaliya, (2020). The significant and positive inbreeding depression was reported by Pathak *et al.,* (1988) for number of effective branches per plant, which supports the results obtained in the present study.

H. Number of capsules on primary raceme

The heterotic estimate over mid parent was significant and positive in both the crosses. The observed and expected (1) values of heterosis over mid parents were comparatively close in both the crosses indicating adequacy of the trigenic interaction model fitted. The observed and expected (1) values of heterosis over better parents were comparatively close in cross 1 indicating adequacy of the trigenic interaction model fitted and widely differed in cross 2 with trigenic interaction model. The inbreeding depression was significant and positive in both the crosses. The observed inbreeding depression was quite close to expected (1) values in cross 1 showing fitting of trigenic interaction model, while in cross 2 observed values of inbreeding depression were more closer with expected (2) values revealing fitting of linked digenic interaction model. As observed in present study, several research worker have also reported heterosis in desirable direction for number of capsules on primary raceme by Patted *et al.,* (2016), Punewar *et al*., (2017); Delvadiya *et al.,* (2018). The significant and positive inbreeding depression was reported by Singh *et al.*, (2013); Barad *et al.,* (2019); Movaliya, (2020) for number of capsules on primary raceme.

I. Shelling out turn (%)

Significant and positive mid parent heterosis was found in only cross namely, SKI-346 × JI-35. The observed and expected (1) values of heterosis over mid parents were comparatively close in cross 1 indicating adequacy of the trigenic interaction model fitted and widely differed in cross 2 with trigenic interaction model. The observed heterobeltiosis was quite close to expected (1) values in cross 1 showing fitting of trigenic interaction model, while in cross 2 observed values of heterobeltiosis was more closer with expected (2) values revealing fitting of linked digenic interaction model. Significant inbreeding depression was not observed in any crosses. The observed and expected (2) values of inbreeding depression was comparatively close in all the both cross suggesting adequacy of the linked digenic interaction model. The results confirmed the results of those reported by Delvadiya *et al.*, (2018), Mori, (2019); Movaliya, (2020) for this trait. The significant and positive inbreeding depression was reported by Pathak *et al.,* (1988) for shelling out turn.

J. 100-seed weight (g)

For 100-seed weight, the significant and positive mid parent heterosis was found in cross 1. The observed relative heterosis was quite close to expected (1) values in cross 1 showing fitting of trigenic interaction model, while in cross 2 observed values of relative heterosis was more closer with expected (2) values revealing fitting of linked digenic interaction model. A heterotic estimate for better parent as well as inbreeding depression were found significant and positive in cross namely, SKI-346 × JI-35. The observed and expected (1) values of heterosis over better parents was comparatively close in both crosses indicating adequacy of the trigenic interaction model for 100-seed weight. The observed and expected (2) values of inbreeding depression was comparatively close in all the both crosses suggesting adequacy of the linked digenic interaction model. Similar findings for 100-seed weight have also been reported by Punewar *et al.*, (2017); Mori, (2019); Movaliya, (2020). The significant and positive inbreeding depression was reported by Pathak *et al.,* (1988); Singh *et al.,* (2013); Barad *et al.*, (2019); Mori, (2019); Movaliya, (2020) for 100-seed weight.

K. Seed yield per plant (g)

Maximum estimate for heterosis over mid parent was recorded by cross, SKI-346 × JI-35 (56.75 %) followed by SKI-346 × SKI-215 (52.58 %) and both crosses were significant and positive for this trait. The estimates of heterosis over better parent significant and positive in both the crosses. The observed and expected (1) values of heterosis over mid and better parents were comparatively close in all the both crosses suggesting more probability of adequacy of the trigenic interaction model fitted. The inbreeding depression was positive and significant in both the crosses. The observed inbreeding depression was quite close to expected (2) values in cross 1 and 2 showing fitting of linked digenic interaction model. Significant estimates of heterosis for seed yield per plant by Delvadiya *et al.*, (2018); Patel *et al.,* (2018); Dube *et al.,* (2018); Mori, (2019); Movaliya, (2020); Aher *et al.,* (2020). The significant and positive inbreeding depression was reported by Pathak *et al.,* (1988); Singh *et al.*, (2013); Movaliya, (2020) for seed yield per plant.

L. Oil content (%)

Maximum estimate for heterosis over mid parent was recorded by cross, SKI-346 × JI-35 (0.38 %) followed by SKI-346 × SKI-215 (-0.16 %) and cross 1 were significant and positive for oil content. The observed and expected (1) values of relative heterosis was comparatively close in all the both crosses suggesting more probability of adequacy of the trigenic interaction model fitted. The estimates of heterosis over better parent significant and positive in the cross namely SKI-346 × JI-35. The observed heterobeltiosis was quite close to expected (1) values in cross 1 showing fitting of trigenic interaction model, while in cross 2 observed values of heterobeltiosis was more closer with expected (2) values revealing fitting of linked digenic interaction model. The inbreeding depression was positive and significant in both crosses. The observed and expected (2) values of inbreeding depression was comparatively close in all the both crosses suggesting adequacy of the linked digenic interaction model. Positive estimation of heterosis for this trait was also reported by Lavanya and Chandramohan (2003); Patel *et al.*, (2013); Punewar *et al*., (2017); Mori, (2019); Movaliya, (2020). The significant and positive inbreeding depression was reported by Pathak *et al.*, (1988); Singh *et al.*, (2013); Mori (2019); Movaliya, (2020) for oil content.

Days to flowering, plant height up to primary raceme and number of nodes up to primary raceme are not directly related to seed yield per plant, but they are important in determining the maturity period. Short stature lines with fewer nodes up to the primary raceme typically mature earlier than taller lines with a greater number of nodes. Thus, in terms of developing early maturing and short stature varieties/hybrids, the trend of negative heterosis for plant height up to primary raceme and number of nodes up to primary raceme is the most desirable and essential feature that should be exploited in terms of negative heterosis. In this study, the cross SKI-346 × SKI-215 had significant and negative better parent heterosis for number of nodes up to primary raceme and plant height up to primary raceme, which could be used to develop short stature hybrids.

The observed discrepancy between actual and expected related heterosis and heterobeltiosis in the above cases may be due to the involvement of high-level interactions and/or the presence of a linkage. According to Mather and Jinks (1980), if heterosis is measured when the over-control model is sufficient, positive and negative heterosis can only occur if [h] is greater than [d]. Because this [h] must be greater than [d] in some or all of the genes, that is, there must be greater dominion or over dominion in some or all places. Second, there must be a complete or partial disruption of the genes. Unfortunately no level of governance or level of integration can be measured by production methods. The distinction between the two causes of heterosis cannot be made without obtaining second degree statistics *i.e*., variance and covariance.

When heterosis is measured in both a digenic or trigenic interaction model, its definition becomes complex and there are many ways in which heterosis can occur. Nevertheless, it is more likely to arise with a greater magnitude when [h], [l] and [z] have the same sign, that is, interaction is predominantly of a complementary kind as well as the interacting pairs of genes are dispersed so that their contribution to the degree of association is either very small or zero and hence their contribution to [d], [i] and [w] is negligible. In the present study, the presence of duplicate type of epistasis, whenever found in the experiment as a whole, support the magnitude of observed heterosis for most of the traits recorded in both of the crosses. Though linkage does not affect the specification of the parental and F_1 means, it bias the estimates of three of the four components of heterosis *viz*., [h], [i] and [l] for digenic interaction and five of the six components of heterosis *viz*., [h], [i], [l], [w] and [z]. So if linkage is present, it will distort the relative magnitude of these components and affect the interpretation of the causes of heterosis. The observed heterosis was found to have resulted either due to the action of dominance component only or due to the combinations with either trigenic or linked digenic types of epistasis for different characters in two crosses of castor. In most of the cases, the observed heterosis was either due to [h], [l] interaction and [z] interaction or only due to [h] effect or [l] or [z] interactions especially in the case where trigenic model was adequate.

Inbreeding depression is associated with the presence of deleterious and lethal alleles in homozygous genotypes. Many recessive alleles remain hidden under heterozygous conditions in panmictic populations. As homozygosity increases in inbred populations, there is greater probability of manifestation of recessive characteristics, many of which are deleterious, resulting in loss of vigor. Inbreeding depression was found significant but negative for days to maturity of primary raceme, for plant height up to primary raceme, for number of nodes up to primary raceme and total length of primary raceme in cross, SKI-346 × JI-35; for 100-seed weight in cross, SKI-346 × SKI-215; and for effective length of primary raceme in both crosses, SKI-346 × JI-35 and SKI-346 × SKI-215 (Table 1).

It is also noticed that both crosses SKI-346 × JI-35 and SKI-346 × SKI-215 had high and significant relative heterosis and heterobeltiosis for seed yield per plant, the varied degree of heterosis for seed yield and its components in castor has been reported earlier by Punewar *et al.,* (2017); Bindupriya *et al.,* (2018); Delvadiya *et al.,* (2018); Patel *et al.,* (2018); Mori, (2019); Barad *et al.,* (2019); Movaliya, (2020); Aher *et al.,* (2020).

CONCLUSION

From the results and discussion, it can be concluded that both crosses SKI-346 × JI-35 and SKI-346 × SKI-215 had high and significant mid parent and better parent heterosis for seed yield per plant, of which SKI-346 × JI-35 for days to flowering of primary raceme, days to maturity of primary raceme, number of nodes up to primary raceme, number of effective branches per plant, 100-seed weight and oil content; and SKI-346 × SKI-215 plant height up to primary raceme and for number of nodes up to primary raceme as well as moderate inbreeding depression was found in the present study as a whole. Therefore heterosis breeding is fully exploited in castor for genetic improvement in term of seed yield and its components traits. The observed and expected (1) values of heterosis over mid and better parents were comparatively close in both of the crosses for most of the traits suggesting more probability of adequacy of the trigenic interaction model fitted. Biparental mating could be better tools for exploitation of both additive and non-additive gene effects simultaneously for genetic improvement in castor.

Conflict of Interest: None.

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