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Studies on Manifestation of Hybrid Vigour in F_1 and Three-Way Crosses of Multivoltine × Bivoltine Silkworm, *Bombyx mori* L.

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An experiment was initiated to evaluate hybrid vigour in twelve F_1 hybrids and seven three-way crosses of multivoltine × bivoltine silkworm between newly evolved multivoltine breed BL67 with productive bivoltine CSR breeds and hybrids. Analysis of variances computed for different characters among F_1 hybrids and three-way crosses showed highly significant differences among them indicating presence of both additive and non-additive gene actions for the expression of these characters. Among twelve F_1 hybrids, two F_1 hybrids *viz.*, BL67 × CSR_4 and BL67 × CSR_5 have expressed significant heterosis for nine characters and two hybrids *viz.*, BL67 × NB_4D_2 and PM × NB_4D_2 for eight characters whereas out of nine three-way crosses, three hybrids *viz.*, BL67 × (CSR_3 × CSR_6), BL67 × (CSR_{16} × CSR_{17}) and BL67 × (CSR_{18} × CSR_{19}) expressed significant heterosis for eight characters. In the present study, it is observed that the cocoons of two hybrids *viz.*, BL67 × CSR_4 and BL67 × CSR_{19} were found to be uniform as these hybrids showed lowest CV% (5.35 and 5.38) among twelve F_1 hybrids and seven three-way crosses between multivoltine × bivoltine hybrids. Four F_1 hybrids *viz.*, BL67 × CSR_4, BL67 × CSR_5, BL67 × NB_4D_2 and PM × NB_4D_2 and three three-way crosses *viz.*, BL67 × (CSR_3 × CSR_6), BL67 × (CSR_{16} × CSR_{17}) and BL67 × (CSR_{18} × CSR_{19}) showed superiority in expressing hybrid vigour and are considered as best heterotic hybrids for commercial exploitation.

Key words: Bivoltine, *Bombyx mori* L., Hybrid vigour, Multivoltine

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Introduction

India is primarily considered as the producer of multivoltine silk, as more than 90% silk produced is from Multivoltine × Multivoltine and Multivoltine × Bivoltine hybrids popularly known as 'sanna mishra' and 'cross breed' respectively. The silk produced from these hybrids are poor in quality and quantity (Datta, 1984). In India, utilization of hybrid vigour came rather late during 1920s, but this could not be compared to the rapid progress achieved in sericulturally advanced countries like Japan. Pure Mysore × C. Nichi was the first hybrid exploited commercially in Karnataka, prior to that only pure breeds of multivoltine silkworm races *viz.*, Pure Mysore, Nistari, Sarupat, Moria were reared on commercial scale in South, East and North Eastern states of India. The exploitation of hybrids in West Bengal and Jammu and Kashmir came much later during 1956 and 1959 respectively (Thangavelu, 1997). During 1960s, cross breeding of multivoltine, Pure Mysore with exotic bivoltine silkworm races like J112, C108, J124 and NN6D were initiated. These hybrids were found to be superior to the pure breeds but expected goals in increasing the productivity could not be fully realized. During late 1960s and early 1970s, systematic breeding programmes at RSRS, Kalimpong and CSRTI, Mysore, resulted in the evolution of new bivoltine breeds *viz.*, KA, NB_4D_2, NB_7 and NB_{18}. These breeds are being used as male parent for the preparation of F_1 hybrids with the indigenous Pure Mysore race in South India and Nistari in Eastern India. The utilization of these multi × bi hybrid combinations has brought quantum jump in cocoon productivity.

Since then, the traditional multi × multi combination, PM × C. Nichi in Karnataka has been replaced by more than 70% by new multi × bi hybrid combinations. During past two decades, number of multi × bi and multi × multi hybrids *viz.* MY1 × NB_4D_2, P2D1 × NB_4D_2, RD1 × NB_4D_2, G × N, MBDIV × MBDV, MH1 × NB_4D_2, MU and MG series were developed by CSRTI, Mysore, CSRTI, Berhampore, KSSRDI, Bangalore, Department of Sericulture, University of Mysore. These hybrids were tested with the farmers in large scale but could not get popularity because of occurrence of diapause eggs, erratic emergence of moths throughout the day (Datta, 1984; Kalpana and Sreerama Reddy, 1998; Raghavendra Rao *et al.,* 2001, 2002).

Several attempts have been made to replace the traditional cross breeds with productive multi × bi hybrids (Pershad *et al.,* 1986; Datta and Pershad, 1988; Singh and Subba Rao, 1994; Das *et al.,* 1997 and Raghavendra Rao *et al.,* 2002). Extensive studies have been carried out on the manifestation of hybrid vigor in silkworms (Singh and Hirobe, 1964; Petkov and Yolov, 1979; Nagaraju *et al.,* 1989; Subba Rao and Sahai, 1989; Ravindra Singh *et al.,* 1990, 1992, 1994, 1998; Singh and Subba Rao, 1996; Nagaraju *et al.,* 1996; Datta *et al.,* 2001, Raghavendra Rao *et al.,* 2001). However, very little information is available regarding the magnitude of hybrid vigor in F_1 hybrids between newly evolved multivoltine breed BL67 and productive bivoltine CSR breeds.

Cocoon shape is important from the standpoint of silk production, breed evolution and evaluation of commercial hybrids (Nakada, 1994). In Japan, several workers have reported variation of cocoon shape in parental strains of silkworm and their hybrids (Hirabayashi, 1982; Gamo *et al.,* 1985; Nakada, 1998). Recently, Ravindra Singh *et al.* (1998, 2001a,b) studied cocoon shape variation in different crosses of silkworm. The present study has been undertaken to know the magnitude of hybrid vigor expressed in F1 hybrids of new productive multivoltine breed, BL67 with authorized productive bivoltine CSR breeds and hybrids and to identify the best heterotic crosses, further to know the variability in cocoon shape in multivoltine × bivoltine hybrids for commercial exploitation.

Materials and Methods

The present study was carried out in Silkworm Breeding Laboratory, multivoltine unit at CSRTI, Mysore. Two multivoltine breeds *viz.,* BL67 and Pure Mysore and eleven bivoltine breeds *viz.,* NB_4D_2, CSR_2, CSR_3, CSR_4, CSR_5, CSR_6, CSR_{12}, CSR_{16}, CSR_{17}, CSR_{18}, CSR_{19} and seven bivoltine hybrids *viz.,* $CSR_2 \times CSR_4$, $CSR_2 \times CSR_5$, $CSR_3 \times CSR_6$, $CSR_{12} \times CSR_6$, $CSR_{16} \times CSR_{17}$, $CSR_{18} \times CSR_{19}$ and KA × NB_4D_2 were used in the present study. Characteristics of the parental pure breeds and bivoltine hybrids are given

Table 1. Characteristics of multivoltine and bivoltine breeds utilized in the study

Sl. no.	Breeds	Origin	Larval pattern	Cocoon characters
Multivoltine breeds				
1.	BL67	Evolved at CSRTI, Mysore, India	Plain, bluish white	Light greenish yellow, oval with medium to coarse grains
2.	Pure Mysore	Karnataka, India	Plain, bluish white	Light greenish yellow, spindle shape with flossy cocoons.
Bivoltine breeds				
1	NB_4D_2	Evolved at CSRTI, Mysore, India	Plain bluish white	Dumbbell cocoons, white with medium to coarse grains
2.	CSR_2	- do -	Plain bluish white	Oval with round ends, white with fine to medium grains
3.	CSR_3	- do -	Sex-limited, male plain, female marked, bluish white	Oval with fine to medium grains
4.	CSR_4	- do -	Plain, bluish white	White dumbbell, fine to medium grains
5.	CSR_5	- do -	Plain, creamish white	Dumbbell, creamish white with medium to coarse grains
6.	CSR_6	- do -	Marked, bluish white	Dumbbell, white with fine to medium grains
7.	CSR_{12}	- do -	Sex-limited, male plain and female marked, bluish white	Oval, white with fine to medium grains
8.	CSR_{16}	- do -	Marked, bluish white	Dumbbell, white with fine to medium grains
9.	CSR_{17}	- do -	Plain, bluish white	Oval, white with fine to medium grains
10.	CSR_{18}	- do -	Sex-limited, male plain and female marked, dull white	Oval, creamish white cocoons with coarse grains
11.	CSR_{19}	- do -	Sex-limited, male plain and female marked, dull white	Dumbbell, creamish white cocoons with coarse grains

Table 2. Characteristics of bivoltine hybrids utilized as male parent in the study

Sl. no.	Hybrid	Origin	Larval pattern	Cocoon characters
1	$CSR_2 \times CSR_4$	Evolved at CSRTI, Mysore, India	Plain, bluish white	White, hybrid shape with fine to medium grains
2	$CSR_2 \times CSR_5$	- do -	Plain, bluish white	Creamish white hybrid shape with fine to medium grains.
3	$CSR_3 \times CSR_6$	- do -	Marked	White, hybrid shape with fine to medium grains
4	$CSR_{12} \times CSR_6$	- do -	Marked	White, hybrid shape with fine to medium grains
5	$CSR_{16} \times CSR_{17}$	- do -	Marked	White, hybrid shape with fine to medium grains
6	$CSR_{18} \times CSR_{19}$	- do -	Sex-limited, male plain and female marked, dull white	Creamish white hybrid shape with fine to medium grains.
7	$KA \times NB_4D_2$	- do -	Plain, bluish white	White hybrid shape with medium to coarse grains.

in Table 1 and 2. Crosses were made by utilizing BL67 as female parent and eleven bivoltine breeds and seven hybrids as male parent, thus producing 18 multivoltine × bivoltine hybrids. Pure Mysore female crossed with NB_4D_2 was maintained as control. All nineteen hybrid combinations along with parents were reared simultaneously in completely randomized design (CRD), following standard rearing technique (Krishnaswami, 1978). Three replications were reared in each hybrid/parent and 300 larvae were retained after third moult. Data were recorded for fecundity, total larval span, 5th instar larval span, pupation rate, cocoon yield/10,000 larvae by weight, cocoon weight, shell weight and shell ratio. Sixty green cocoons from each replication of each hybrid was sent to the Reeling and Fibre Technology division of CSRTI, Mysore to study the reeling and silk technological characteristics. The characters such as, filament length, denier, reelability %, raw silk %, renditta and neatness were recorded.

Heterosis over mid parent value (MPV) and better parent value (BPV) for each character was calculated by the following formulae:

$$\text{Heterosis over MPV} = \frac{\text{F1} - \text{MPV}}{\text{MPV}} \times 100$$

$$\text{Heterosis over BPV} = \frac{\text{F1} - \text{BPV}}{\text{BPV}} \times 100$$

To study the variation in cocoon shape of F1 hybrids and three way crosses, 100 cocoons were randomly picked up and length/width ratios were determined by using the following formula:

$$\text{Length/width ratio} = \frac{\text{Length}}{\text{Width}} \times 100$$

Cocoon length and width were measured by using Vernier Callipers. Cocoon shape variability was determined by using 'uniformity test' on the basis of Standard Deviation (SD) suggested by Mano *et al.*, (1993). The ratio between cocoon length and width was calculated for each cocoon and its SD and coefficient of variation (CV %) were considered for cocoon uniformity. Hybrids showing less SD and CV were considered uniform in cocoon shape. Data recorded for each character was pooled and analysed statistically to know the level of variance using the following formula:

$$Y_{ij} = \mu + r_j + g_j + e_{ij}$$

Where, Y_{ij}=the observations on the 'j' th genetic group of the 'i' th replicate
μ=population mean
r_i=effect of the 'i' th replicate
g_j=effect of the 'j' th replicate
e_{ij}=random component effect

Results

Rearing performance of eleven F_1 hybrids and seven three-way crosses of multivoltine × bivoltine hybrids are presented in Table 3 and 4 respectively. Heterosis calculated for each character in F_1 and three-way crosses over Mid Parent Value (MPV) and Better Parent Value (BPV) are presented in Tables 5, 6 and 7, 8 respectively. Cocoon uniformity evaluated among 19 hybrids is presented in Table 9.

Fecundity

It is clear from the data that great deal of variation exists among F_1 and three- way crosses of multivoltine × bivoltine hybrids. It ranged from 497 {BL67 × ($CSR_{16} \times CSR_{17}$)} to 701 (BL67 × NB_4D_2). Analysis of variance computed for this trait in different hybrids and three-way crosses revealed (Table 3 and 4) significant differences among them. Heterosis percentage estimated for fecundity over MPV and BPV revealed that only one hybrid combination, BL67 × NB_4D_2 (Table 5, 6, 7, 8) expressed significant hybrid vigour.

Table 3. Mean performance of some multivoltine × bivoltine F_1 hybrids of silkworm

Sl. no	Hybrid	Fecundity	Larval span (hrs)	Fifth age larval span(hrs)	Pupation rate	Yield/ 10,000 larvae (kg)	Cocoon weight (g)	Shell weight (cg)	Shell ratio (%)	Filament length (m)	Denier	Renditta	Raw silk%	Reelability (%)	Neatness (p)
1	BL67 × NB_4D_2	701	510	147	91.5	17.08	1.895	39.2	20.6	838	3.17	6.39	15.6	86.8	93.0
2	BL67 × CSR_2	636	480	143	93.7	18.02	1.962	41.3	21.0	877	3.02	6.20	16.1	86.7	93.0
3	BL67 × CSR_3	631	486	144	89.7	17.30	1.977	43.6	22.1	1034	2.84	5.95	15.9	88.6	93.0
4	BL67 × CSR_4	604	486	144	92.3	17.63	1.943	39.2	20.2	876	3.15	6.37	15.8	89.1	93.0
5	BL67 × CSR_5	514	486	144	86.0	15.58	1.854	39.6	21.4	931	2.96	6.07	16.5	87.6	93.0
6	BL67 × CSR_6	560	494	146	88.7	15.98	1.825	38.7	21.2	872	2.94	6.38	15.7	87.6	93.0
7	BL67 × CSR_{12}	504	488	162	90.0	16.87	1.883	42.7	22.7	996	2.95	5.76	17.4	86.8	93.0
8	BL67 × CSR_{16}	592	480	140	88.7	16.185	1.850	38.4	20.8	863	3.09	6.25	15.7	85.3	93.0
9	BL67 × CSR_{17}	603	504	162	89.2	17.55	2.015	43.0	21.3	968	2.99	6.17	16.2	84.3	93.0
10	BL67 × CSR_{18}	571	502	144	94.5	17.63	1.921	41.4	21.6	976	2.82	6.27	16.0	86.8	93.0
11	BL67 × CSR_{19}	528	486	144	95.5	17.57	1.867	38.5	20.6	895	2.97	6.31	15.9	84.6	93.0
12	PM × NB_4D_2 (Control)	534	504	144	90.5	15.23	1.697	32.1	18.9	704	3.00	7.25	13.9	86.0	90.0
CD at 5%		68.0	7.0	2.0	4.74	1.08	0.077	0.20	0.80	57.0	0.20	0.40	0.90	2.18	0.30

Table 4. Mean performance of some three-way crosses of multivoltine × bivoltine hybrids of silkworm

Sl. no	Hybrid	Fecundity	Larval span (hrs)	Fifth age larval span (hrs)	Pupation rate	Yield/ 10,000 larvae (kg)	Cocoon weight (g)	Shell weight (cg)	Shell ratio (%)	Filament length (m)	Denier	Renditta	Raw silk%	Reelability (%)	Neatness (p)
1	BL67 × (CSR_2 × CSR_4)	551	486	144	91.3	16.93	1.919	38.9	20.3	975	2.92	6.06	16.5	83.8	93.0
2	BL67 × (CSR_2 × CSR_5)	541	486	138	87.3	17.03	1.979	41.1	20.8	821	3.25	6.69	15.0	87.6	92.0
3	BL67 × (CSR_3 × CSR_6)	514	480	144	87.0	16.20	1.927	43.8	22.6	923	3.48	5.42	18.5	84.7	93.0
4	BL67 × (CSR_{12} × CSR_6)	523	486	144	87.3	17.50	2.031	42.3	20.8	992	3.06	6.05	16.6	85.2	93.0
5	BL67 × (CSR_{16} × CSR_{17})	497	486	144	89.0	15.88	1.825	38.1	20.9	836	3.30	5.96	16.8	88.3	93.0
6	BL67 × (CSR_{18} × CSR_{19})	558	480	140	96.3	17.20	1.870	37.6	20.1	938	2.84	6.33	15.9	83.0	93.0
7	BL67 × (KA × NB_4D_2)	562	486	144	90.0	15.73	1.793	36.6	20.4	825	3.11	6.28	15.9	85.9	93.0
	CD at 5%	68.0	7.0	2.0	4.74	1.08	0.077	0.20	0.80	57.0	0.20	0.40	0.90	2.18	0.30

Table 5. Heterosis percentage over Mid Parent Value (MPV) in some multivoltine × bivoltine F_1 hybrids of silkworm

Sl. no.	Hybrid	Fecun-dity	Larval span	Fifth age larval span	Pupation rate	Yield/ 10,000 larvae	Cocoon weight	Shell weight	Shell ratio	Filament length	Denier	Renditta	Raw Silk %	Reelability	Neatness
1	BL67 × NB_4D_2	51.90*	6.92	20.33	-4.22	26.52**	34.64**	44.12**	7.29**	8.48	12.61	-13.06**	7.22**	-0.36	3.91**
2	BL67 × CSR_2	17.34	-0.83**	17.21	4.95	38.58**	35.08**	36.75**	2.44**	6.63	5.41	-10.92**	-0.92	0.49	3.91**
3	BL67 × CSR_3	18.39	0.00	17.07	0.19	33.08**	38.64**	57.97**	8.87**	22.95	2.90	-12.63**	-4.79	4.89**	4.49**
4	BL67 × CSR_4	16.67	-1.82**	9.09	-0.95	35.64**	35.87**	36.35**	1.25**	10.82	8.62	-9.32**	0.64**	4.84**	3.33**
5	BL67 × CSR_5	1.18	-2.21*	9.09	-3.03	19.88**	31.07**	34.47**	4.14**	14.44	1.89	-11.64**	0.61**	4.85**	2.76**
6	BL67 × CSR_6	9.27	0.00	10.61	-2.60	18.40**	32.29**	35.31**	3.16**	5.63	5.57	-8.33**	-3.68	0.67	3.33**
7	BL67 × CSR_{12}	-2.61	3.39	22.73	-1.66	29.75*	34.89**	44.26**	8.10**	11.66	7.86	-15.60**	5.45**	2.11	3.33**
8	BL67 × CSR_{16}	13.41	1.69	6.06	-4.14	19.87**	28.43**	28.64**	1.71**	5.18	13.81	-11.03**	0.00	0.92	3.33**
9	BL67 × CSR_{17}	17.09	6.78	22.73	-2.13	32.29**	41.30**	42.38**	2.16**	18.41	11.36	-11.41**	3.51**	0.20	3.33**
10	BL67 × CSR_{18}	18.46	6.58	9.09	-1.79	28.13**	33.22**	40.82**	7.46**	35.56	5.82	-14.93**	4.23**	0.37	3.33**
11	BL67 × CSR_{19}	10.46	2.53	9.09	-0.21	33.53**	37.23**	37.50**	2.23**	25.09	12.08	-14.90**	6.00**	-2.88	3.33**
12	PM × NB_4D_2 (Control)	10.56	-11.58**	-9.43	-1.00	28.37**	27.64**	38.22**	11.64**	10.64	19.87	-44.40**	11.41**	1.05	5.30**

*, **denotes significant at 5% and 1% respectively.

Table 6. Heterosis percentage over Mid Parent Value (MPV) in some three-way crosses of multivoltine × bivoltine silkworm

Sl. no	Hybrid	Fecun-dity	Larval span	Fifth age larval span	Pupa-tion rate	Yield/ 10,000 larvae	Cocoon weight	Shell weight	Shell ratio	Filam-ent length	Denier	Rend-itta	Raw silk	Reela-bility	Neat-ness
1	BL67 × (CSR_2 × CSR_4)	6.99	-2.41*	6.67	-4.02	7.65**	18.02**	14.08**	-0.73	12.23	0.17	-7.62**	-1.20	-4.44	1.64**
2	BL67 × (CSR_2 × CSR_5)	3.64	-3.61*	2.22	-6.99	12.37**	24.23**	18.96**	-1.42	-11.15	9.80	5.19	-11.24	3.06	0.55**
3	BL67 × (CSR_3 × CSR_6)	1.48	-2.41*	6.67	-7.83	5.69**	20.59**	41.02**	20.38**	-1.91	24.73	-15.44**	10.45*	-0.97	1.64**
4	BL67 × (CSR_{12} × CSR_6)	-0.85	-2.41*	6.67	-8.44	13.27**	27.70**	21.55**	-2.12	8.65	9.29	-5.62**	-0.60	-1.56	1.64**
5	BL67 × (CSR_{16} × CSR_{17})	-0.70	-2.41*	6.67	-4.53	4.53**	13.46**	11.57**	1.21**	-5.48	15.59	-7.02**	1.82**	0.91	1.64**
6	BL67 × (CSR_{18} × CSR_{19})	12.39	-3.61*	3.70	-0.34	1.35**	18.17**	19.55**	2.55**	18.36	6.77	-8.39**	4.95**	-3.45	1.64**
7	BL67 × (KA × NB_4D_2)	4.17	-2.41*	6.67	-5.04	-0.46	10.10**	14.55**	5.43**	2.55	14.76	-14.76	8.16**	-1.31	3.33**

*, **denotes significant at 5% and 1% respectively.

Total larval span

The mean values computed for this character in nineteen hybrids were found to exhibit variation ranging from 480 hrs (BL67 × CSR_{16}) to 510 hrs (BL67 × NB_4D_2). ANOVA computed for this character revealed highly significant differences in different hybrid combinations (Table 3 and 4). Heterosis calculated for total larval span over MPV expressed significant negative heterosis (which is desirable for this character) in four F_1 hybrids and all three-way crosses whereas over BPV none of the hybrids expressed negative heterosis (Table 5, 6 and 7, 8) respectively.

Fifth age larval span

Great deal of variation was found for fifth age larval span, which ranged from 138 hrs {BL67 × (CSR_2 × CSR_5)} to 162 hrs (BL67 × CSR_{12}). Analysis of variance for this character revealed highly significant variances among the hybrids (Table 3 and 4). Evaluation of heterosis over MPV and BPV for this character (Table 5, 6, 7, 8) revealed that none of the hybrids expressed negative heterosis except in PM × NB_4D_2 where non-significant negative heterosis was recorded.

Pupation rate

Studies on pupation rate among multivoltine × bivoltine hybrids revealed variation which ranged from 86.00 (BL67 × CSR_5) to 96.30 {BL67 × (CSR_{18} × CSR_{19})}. ANOVA computed for this character showed highly significant differences among them (Table 3 and 4). Heterosis percentage calculated for pupation rate over MPV and BPV did not express significant differences in F_1 hybrids and three-way crosses (Table 5, 6, 7, 8).

Yield/10,000 larvae by weight

The mean values computed for this character in multivoltine × bivoltine F_1 hybrids and three-way crosses were found to exhibit variability ranging from 15.23 kg (PM × NB_4D_2) to 18.02 kg (BL67 × CSR_2). Analysis of variance computed for this character showed highly significant variances among different hybrids. Heterosis percentage estimated over MPV expressed highly significant differences in all twelve F_1 hybrids and six three-way crosses except PM × (KA × NB_4D_2) (Table 5 and 6) where as heterosis estimated over BPV showed significant hybrid vigour in all twelve F_1 hybrids while all seven three-way crosses expressed non-significant negative heterosis (Table 7 and 8).

Cocoon weight

Data computed for cocoon weight for nineteen multivoltine × bivoltine F_1 hybrids and three-way crosses exhibited variability ranging from 1.697 g (PM × NB_4D_2) to 2.031 g {BL67 × (CSR_{12} × CSR_6)}. ANOVA computed for cocoon weight revealed highly significant variations among different hybrid combinations. Heterosis calculated over MPV and BPV revealed highly significant differences except four three-way crosses over BPV (Table 5, 6, 7, 8) where negative heterosis was noticed.

Cocoon shell weight

Cocoon shell weight also exhibited variations in different hybrid combinations, which ranged from 32.1 cg (PM × NB_4D_2) to 43.8 cg {BL67 × (CSR_3 × CSR_6)}. Analysis of variance computed for this character exhibited highly significant variations among all hybrids. Heterosis percentage calculated for cocoon shell weight over MPV in F_1 hybrids and three-way crosses expressed highly significant differences (Table 5 and 6), where as heterosis estimated over BPV in all twelve F_1 hybrids expressed highly significant differences while seven three-way crosses exhibited non-significant negative heterosis (Table 7 and 8).

Shell ratio

The mean values computed for this character exhibited variability ranging from 18.9% (PM × NB_4D_2) to 22.6% {BL67 × (CSR_3 × CSR_6)}. ANOVA computed for this character revealed highly significant variances among the hybrid combinations. Percentage of heterosis estimated over MPV revealed highly significant differences in all F_1 hybrid combinations whereas only four three-way crosses *viz.*, BL67 × (CSR_3 × CSR_6), BL67 × (CSR_{16} × CSR_{17}), BL67 × (CSR_{18} × CSR_{19}) and PM × (KA × NB_4D_2) exhibited significant differences (Table 5 and 6). None of the F_1 hybrids and three-way crosses expressed desirable heterosis over BPV (Table 7 and 8).

Filament length

Computation of data on filament length revealed great deal of variation, ranging from 704 m (PM × NB_4D_2) to 1034 m (BL67 × CSR_3) in different hybrids. Analysis of variance estimated showed significant differences among the hybrids (Table 3 and 4). Estimation of heterosis over MPV and BPV revealed non-significant differences both in F_1 hybrids and three-way crosses (Table 5, 6, 7, 8).

Denier

The mean values for this character in different hybrids showed variability which ranged from 2.82 (BL67 × CSR_{18}) to 3.48 {BL67 × (CSR_3 × CSR_6)}. Estimation of ANOVA for this character revealed significant variances among all the hybrids studied (Table 3 and 4). Only one hybrid combination BL67 × (KA × NB_4D_2) expressed significant differences in the expression of heterosis over MPV while none of the hybrids expressed heterosis over BPV in desired direction (Table 5, 6, 7, 8).

Table 7. Heterosis percentage over Better Parent Value (BPV) in some multivoltine × bivoltine F_1 hybrids of silkworm

Sl. no.	Hybrid	Fecun-dity	Larval span	Fifth age larval span	Pupation rate	Yield/ 10,000 larvae	Cocoon weight	Shell weight	Shell ratio	Fila-ment length	Denier	Renditta	Raw Silk %	Reelabil-ity	Neatness
1	BL67 × NB_4D_2	43.65*	10.39	23.33	-5.76	22.00**	22.65**	24.84**	1.48	-5.42	20.99	-7.12**	1.96**	-4.63	3.33**
2	BL67 × CSR_2	6.71	3.90	19.17	-3.54	38.58**	20.00**	10.43**	-8.30	-11.05	15.27	1.64	-13.90	-4.70	3.33**
3	BL67 × CSR_3	9.17	5.19	20.00	-7.66	33.08**	24.97**	35.40**	-1.78	1.08	8.40	2.59	-18.88	-2.60	4.49**
4	BL67 × CSR_4	10.66	5.19	20.00	-4.92	35.64**	22.20**	13.62**	-7.34	-4.99	20.23	2.25	-10.23	-2.08	2.20**
5	BL67 × CSR_5	-2.65	5.19	20.00	-11.44	19.88**	18.92**	10.31**	-6.96	-3.82	12.98	2.53	-13.16	-3.79	1.09**
6	BL67 × CSR_6	4.28	6.93	21.67	-8.69	14.17**	22.57**	13.16**	-7.83	-12.10	12.21	4.59	-16.49	-3.76	2.20**
7	BL67 × CSR_{12}	-7.86	5.63	35.00	-7.32	29.75**	23.72**	17.96**	-5.02	-11.47	12.60	-1.20**	-9.38	-4.63	2.20**
8	BL67 × CSR_{16}	6.47	3.90	16.67	-8.69	15.59**	14.84**	4.63**	-8.77	-12.12	17.94	0.32	-10.80	-6.29	2.20**
9	BL67 × CSR_{17}	11.25	9.09	35.00	-8.18	29.68**	27.37**	14.97**	-9.75	-0.82	14.12	0.98	-7.43	-7.34	2.20**
10	BL67 × CSR_{18}	19.96	8.66	20.00	-2.69	21.40**	19.02**	15.64**	-2.26	24.97	7.63	-9.39**	-5.33	-4.59	2.20**
11	BL67 × CSR_{19}	8.20	5.19	20.00	-1.66	31.97**	28.67**	16.67**	-7.21	15.93	13.36	-9.99**	-1.85	-7.04	2.20**
12	PM × NB_4D_2 (Control)	0.56	2.44	14.29	-3.72	8.81**	9.84**	9.84**	2.12	-7.06	8.23	5.38	-9.35	-1.16	2.96**

*, **denotes significant at 5% and 1% respectively.

Table 8. Heterosis percentage over Better Parent Value (BPV) in some three-way crosses of multivoltine × bivoltine silkworm

Sl. no.	Hybrid	Fecun-dity	Larval span	Fifth age lar-val span	Pupation rate	Yield/ 10,000 larvae	Cocoon weight	Shell weight	Shell ratio	Filament length	Denier	Renditta	Raw silk %	Reelabil-ity	Neatness
1	BL67 ×CSR_2 × CSR_4)	1.66	5.19	20.00	-5.94	-8.26	-3.18	-13.94	-10.96	-12.16	11.45	14.34	-15.82	-7.90	-1.06
2	BL67 × (CSR_2 × CSR_5)	-2.70	3.90	15.00	-10.07	-1.64	3.29**	-10.85	-13.69	-30.95	24.05	36.53	-25.00	-3.74	-2.13
3	BL67 × (CSR_3 × CSR_6)	-2.10	5.19	20.00	-10.41	-8.25	0.05**	6.15**	6.36**	-24.53	32.82	8.40	-6.09	-6.96	-1.06
4	BL67 × (CSR_{12} × CSR_6)	-7.76	5.19	20.00	-10.06	-2.23	6.28**	-9.23	-14.75	-15.00	16.79	21.00	-15.31	-6.43	-1.06
5	BL67 × (CSR_{16} × CSR_{17})	-3.12	5.19	20.00	-8.35	-8.67	-6.27	-15.89	-9.91	-24.68	25.95	19.20	-12.50	-2.97	-1.06
6	BL67 × (CSR_{18} × CSR_{19})	10.50	3.90	16.67	-0.80	-17.87	-1.32	-5.76	-4.74	1.30	8.40	5.50	-3.64	-8.76	-1.06
7	BL67 × (KA × NB_4D_2)	-4.91	5.19	20.00	-7.32	-15.46	-9.76	-10.51	-0.97	-13.16	18.70	-8.99**	1.92**	-5.65	2.20**

*, **denotes significant at 5% and 1% respectively.

Renditta

Computation of mean values for renditta revealed variation ranging from 5.42 {BL67 × (CSR_3 × CSR_6)} to 7.25 (PM × NB_4D_2). ANOVA estimates for this character expressed significant variances in different hybrids (Table 3 and 4). Calculation of heterosis over MPV revealed highly significant differences in F_1 hybrids where as five three-way crosses *viz.*, BL67 × (CSR_2 × CSR_4), BL67 × (CSR_3 × CSR_6), BL67 × (CSR_{12} × CSR_6), BL67 × (CSR_{16} × CSR_{17}) and BL67 × (CSR_{18} × CSR_{19}) expressed significant differences in the expression of heterosis (Table 5 and 6). Expression of heterosis over BPV was significant only in five hybrid combinations (Table 7 and 8).

Raw silk

The mean values computed for raw silk % revealed a great deal of variation ranging from 13.9% (PM × NB_4D_2) to 18.5% {BL67 × (CSR_3 × CSR_6)}. Analysis of variance estimated for this character showed highly significant variances among the hybrids (Table 3 and 4). Estimation of heterosis over MPV revealed significant differences in eight F_1 hybrids and four three way crosses, including control PM × NB_4D_2 (Table 5 and 6). Expression of heterosis over BPV in F_1 hybrids was significant in the hybrid *viz.*, BL67 × NB_4D_2, whereas BL67 × (KA × NB_4D_2) expressed significant heterosis in three-way crosses (Table 7 and 8).

Reelability

Computation of data for reelability in F_1 hybrids and three-way crosses showed variability ranging from 83.0 {BL67 × (CSR_{18} × CSR_{19})} to 89.1 (BL67 × CSR_4). ANOVA shows highly significant variances in different hybrids (Table 3 and 4). Expression of heterosis over MPV for this trait showed significant differences in three hybrids *viz.*, BL67 × CSR_3, BL67 × CSR_4 and BL67 × CSR_5, while none of the hybrids expressed desirable magnitude of heterosis over BPV (Table 7 and 8).

Neatness

The mean values calculated for neatness showed variability ranging from 90 to 93 P. Analysis of Variance estimated in different hybrids revealed significant variances among them (Table 3 and 4). Estimation of heterosis over MPV for this trait revealed highly significant differences in all nineteen hybrids, whereas expression of heterosis over BPV was significant in twelve F_1 hybrids and three way cross BL67 × (KA × NB_4D_2) (Table 7 and 8).

Studies on cocoon uniformity

Studies on cocoon uniformity in F_1 hybrids and three way crosses are presented in Table 9. It is observed that cocoon length in different hybrids ranged from 3.46 cm (BL67 × (CSR_{18} × CSR_{19})) to 3.88 cm (PM × NB_4D_2), whereas cocoon width ranged from 1.85 cm (BL67 × CSR_4) to 2.22 cm

Table 9. Cocoon uniformity in F1 and three way crosses of multivoltine × bivoltine silkworm

Sl. no.	Hybrid combination	Cocoon length	Cocoon width	Length/width ratio	Standard deviation	CV%
1	BL67 × NB_4D_2	3.68±0.23	2.11±0.15	174.15	9.92	5.69
2	BL67 × CSR_2	3.47±0.18	2.07±0.12	167.92	12.10	7.21
3	BL67 × CSR_3	3.60±0.17	2.18±0.11	166.67	11.13	6.70
4	BL67 × CSR_4	3.66±0.13	1.85±0.09	198.14	10.60	5.35
5	BL67 × CSR_5	3.60±0.26	1.86±0.09	193.90	15.86	8.18
6	BL67 × CSR_6	3.66±0.16	1.87±0.09	195.85	10.88	5.56
7	BL67 × CSR_{12}	3.58±0.14	2.17±0.10	165.17	9.00	5.45
8	BL67 × CSR_{16}	3.55±0.15	1.85±0.11	192.27	13.05	6.79
9	BL67 × CSR_{17}	3.53±0.16	2.22±0.18	159.81	13.51	8.45
10	BL67 × CSR_{18}	3.47±0.14	2.06±0.12	168.96	10.62	6.28
11	BL67 × CSR_{19}	3.62±0.13	1.92±0.09	189.31	10.19	5.38
12	BL67 × (CSR_2×CSR_4)	3.56±0.14	2.01±0.12	177.30	10.47	5.91
13	BL67 × (CSR_2×CSR_5)	3.54±0.14	2.04±0.15	174.53	13.23	7.58
14	BL67 × (CSR_3×CSR_6)	3.64±0.16	2.04±0.14	178.94	13.16	7.35
15	BL67 × (CSR_{12}×CSR_6)	3.62±0.16	2.07±0.09	175.04	9.75	5.57
16	BL67 × (CSR_{16}×CSR_{17})	3.55±0.15	1.98±.010	179.96	10.77	5.98
17	BL67 × (CSR_{18}×CSR_{19})	3.46±0.14	1.95±0.10	177.69	9.87	5.55
18	BL67 × (KA×NB_4D_2)	3.49±0.17	1.98±0.11	176.73	10.85	6.14
19	PM × NB_4D_2 (Control)	3.88±0.15	2.05±0.11	189.27	10.62	5.61

(BL67 × CSR_{17}). Cocoon length/width ratio showed variation ranging from 159.81 (BL67 × CSR_{17}) to 198.14 (BL67 × CSR_4). Standard deviation computed for different hybrids revealed variation ranging from 9.00 (BL67 × CSR_{12}) to 15.86 (BL67 × CSR_5). Coefficient of Variation among the hybrids showed the variability ranging from 5.38 (BL67 × CSR_{19}) to 8.45 (BL67 × CSR_{17}).

Discussion

The silkworm, in animal kingdom and maize in plant kingdom are the two leading examples where exploitation of hybrid vigour has paid rich dividends in increasing the production. Japan was the first country to exploit hybrid vigour in silkworm. In India, exploitation of hybrid vigour came late sometime during 1920 (Sreerama Reddy and Raju, 1998). However, this did not contribute to the rapid progress in the productivity as both the parents involved were multivoltine breeds with poor quantitative characters. After the introduction of new bivoltine breeds during early seventies and their use as male parents for preparation of multivoltine × bivoltine F_1 hybrids have brought new era to the Indian sericulture industry. Though significant improvement is noticed in silk yield during past three decades, the quality of silk and also yield remains poor. In view of the above, an attempt has been made to know the magnitude of hybrid vigour expressed in F_1 hybrids of new productive multivoltine breed, BL67 with authorized productive bivoltine CSR breeds and hybrids and to identify the best heterotic crosses, further to know the variability in cocoon shape in multivoltine × bivoltine hybrids for commercial exploitation.

A great deal of variation was observed in the expression of fourteen characters in twelve F_1 hybrids and seven three-way crosses of multi × bi hybrids. Analysis of variance computed for different characters among F_1 hybrids and three-way crosses showed highly significant differences among them indicating presence of both additive and non-additive gene actions for the expression of these characters (Table 3 and 4). Krishnaswami *et al.* (1964) and Sengupta *et al.* (1974) have reported operation of non-additive gene actions for the genetic control of cocoon weight and shell weight. Contrary to the above findings, Bhargava (1995) and Pershad *et al.* (1986) have exported operation of additive gene actions for the expression of cocoon weight and shell ratio.

Generally, heterosis is manifested in F_1 hybrids when two individuals are crossed. The magnitude of heterosis manifested in F_1 could be variable depending upon the genetic back ground and the geographical origin of the individuals crossed. Further, the choice of parents and mating system followed will play an important role in the expression of this phenomenon.

Therefore, the evaluation of heterosis with respect to the phenotypic expression of the economic characters in the crosses made is an important task which enables to understand its manifestation independently for each character and also in conjugation with others. In order to utilize the phenomenon of heterosis in the hybrids for commercial exploitation, the degree of its manifestation was evaluated in twelve F_1 hybrids and seven three-way crosses of multivoltine × bivoltine hybrids.

In the present study, it is observed that none of the F_1 hybrids and three-way crosses expressed significant hybrid vigour for all fourteen characters studied over MPV and BPV. However, two F_1 hybrids *viz.*, BL67 × CSR_4 and BL67 × CSR_5 have expressed significant heterosis for nine characters and two hybrids *viz.*, BL67 × NB_4D_2 and PM × NB_4D_2 for eight characters, whereas in three-way crosses, three hybrids *viz.*, BL67 × (CSR_3 × CSR_6), BL67 × (CSR_{16} × CSR_{17}) and BL67 × (CSR_{18} × CSR_{19}) expressed significant heterosis for eight characters. One F_1 hybrid (BL67 × B_4D_2) and one three-way cross BL67 × (KA × NB_4D_2) expressed significant heterosis for seven and three characters respectively. Expression of heterosis for different characters in different hybrids showed the presence of partial dominance in the expression of these characters. Ravindra Singh *et al.* (2001a) have reported expression of significant hybrid vigour for fecundity, cocoon yield/ 10000 larvae by weight, cocoon weight, cocoon shell weight and shell ratio in different multivoltine × bivoltine hybrids. Tayade (1989) reported high hybrid vigour for cocoon weight, cocoon shell weight and cocoon yield in multivoltine × bivoltine hybrid, Hosa Mysore × NB_4D_2. Expression of very high hybrid vigour for cocoon weight and cocoon shell weight was found in F_1 hybrids between low yielding multivoltine and bivoltine silkworm breeds (Ram Mohana Rao *et al.*, 1998). Recently, Raghavendra Rao *et al.* (2001) have found high degree of heterosis for cocoon yield/10000 larvae by weight, cocoon weight and cocoon shell weight in 135 F_1 hybrids between multivoltine and bivoltine silkworm breeds.

Cocoon uniformity is considered an important parameter from the standpoint to get uniform cocoon filament particularly when cocoon are reeled on automatic or semi-automatic reeling machines. In the present study it is observed that BL67 × CSR_4 and BL67 × CSR_{19} were found to be uniform in cocoon shape as these hybrids showed lowest CV % (5.35 and 5.38) among twelve F_1 hybrids and seven three-way crosses of multivoltine × bivoltine hybrids. Ravindra Singh *et al.* (1998) have observed variations in cocoon shape in different crosses of bivoltine × bivoltine, multivoltine × bivoltine hybrids of silkworm.

Recently, Raghavendra Rao *et al.* (2002) have reported cocoon shape variations in thirty F_1 hybrids of multi × bi hybrids. Present findings are in agreement with the findings of Nakada (1994) and Ravindra Singh *et al.* (2001a, b). Contrary to the above findings, Ram Mohan Rao *et al.* (2002) have reported variations in cocoon shapes in the three-way crosses of multivoltine × bivoltine hybrids of silkworm.

In the present study, it is observed that different hybrids expressed significant hybrid vigour for different characters. Manifestation of high hybrid vigour for some characters in some hybrids may be due to accumulation of certain gene complexes during the course of breeding. Based on the expression of hybrid vigour for different characters, they can be utilized for improvement of specific characters in specific hybridization programmes. Among twelve F_1 hybrids evaluated in the present study, four hybrids *viz*., BL67 × CSR_4, BL67 × CSR_5, BL67 × NB_4D_2 and PM × NB_4D_2 and among seven three- way crosses, three hybrids *viz*., BL67 × (CSR_3 × CSR_6), BL67 × (CSR_{16}×CSR_{17}) and BL67 × (CSR_{18} × CSR_{19}) are adjudicated as best heterotic hybrids and recommended for commercial exploitation.

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