ESTIMATION OF GENETIC PARAMETERS FROM SPECIFIC CROSSES OF COCOA
(*Theobroma cacao* L.)

By

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THESIS

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DECLARATION

I hereby declare that this thesis entitled **"Estimation of genetic parameters from specific crosses of cocoa (*Theobroma cacao* L.)"** is a bonafide record of research work done by me during the course of research and that the thesis has not previously formed the basis for the award to me of any degree, diploma, fellowship or other similar title, of any other University or Society.

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CERTIFICATE

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EXTERNAL EXAMINER

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To my beloved ammama

CONTENTS

LIST OF TABLES

LIST OF PLATES

LIST OF ABBREVIATIONS

CYT	-	Comparative yield trial
Fig.	-	Figure
GA	-	Genetic advance
gcv	-	Genotypic coefficient of variation
GG	-	Genetic gain
G I	-	Germplasm I
G II	-	Germplasm II
G VI	-	Germplasm VI
H	-	Hybrid
h^2	-	Heritability (narrow sense)
ha	-	hectare
HB	-	Heterobeltiosis
IBPGR	-	International Bureau of Plant Genetic Resources
M	-	Mannuthy
MAS	-	Months after sowing
pcv	-	Phenotypic coefficient of variation
PT II	-	Progeny trial II
r	-	Correlation coefficient
r_g	-	Genotypic correlation coefficient
r_p	-	Phenotypic correlation coefficient
RH	-	Relative heterosis
S	-	Shade trial
SH	-	Standard heterosis
V_A	-	Additive genetic variance
V_D	-	Variance due to dominance deviation
YAP	-	Years after planting

Introduction

1. INTRODUCTION

Cocoa, *Theobroma cacao* L., a predominantly outbreeding diploid (2n=20) is the only widely cultivated species of the genus *Theobroma* and belongs to the family Sterculiaceae. In ancient times it was considered divine and hence the name *Theobroma* meaning 'food of the gods'. The genus is indigenous to the upper regions of Amazon river basin and the species range from Southern Mexico in the north to Brazil and Bolivia in the south. The crop was introduced to several other countries of Tropical Africa, Asia, Central and South America.

The world area under cocoa is 59,14,000 ha with a production of 27,18,000 tonnes annually (Anonymous, 1999). The crop was introduced to India in 1798, but large scale commercial cultivation was started only during the seventies. The area under cocoa recorded a negative growth in India since the year 1983-'84 (from 22,227 ha to 7800 ha in 1998-'99). The reason for this is mainly attributed to the high fluctuations in price and high cost of production. The current production is 6000 tonnes per year (Anonymous, 1999).

Eventhough much genetic advancement has been achieved in most of the commercial crops in recent times, the bulk of world's cocoa production is still derived from the material not significantly different from its wild progenitor. Genetic studies are limited in cocoa due to the perennial nature of the crop and complicated genetic behaviour due to the existence of self/cross incompatibility. Production increase is highly crucial to prevent foreign exchange drain in future. Hence, there is a pressing need for the supply of genetically superior planting material for the growers.

The history of crop improvement in cocoa can be traced to the first half of the present century. But these efforts often relied solely upon the selection of local clones rather than breeding *per se.* The crop genetics should be highly comprehensive to formulate efficient breeding programmes.

The progress in cocoa breeding, depends very much on the presence of heritable variation for various agronomic traits. Information on genetic variability and inheritance of yield and yield contributing characters are important for the formulation of a viable breeding methodology in cocoa.

Recent studies indicate that hybridization is a useful tool for crop improvement in cocoa if superior and cross compatible trees from genetically distinct population are selected on the basis of better combining ability and used for breeding programmes (Cherian, 1993; Dias and Kageyama, 1997).

In this background, the studies mentioned herein were proposed to estimate the genetic parameters from specific crosses of cocoa in their early years of bearing with the following objectives:

1. Assessing the spectrum of variability through phenotypic and genotypic coefficient of variation.
2. Determining heritability and genetic advance for different characters influencing yield.
3. Assessing the association of yield and yield attributes at genotypic and phenotypic levels.
4. Determining the direct and indirect effects of each component, on yield by path analysis.
5. Evaluating the extent of heterotic expression for yield and yield attributes in the hybrids.
6. Examining correlation between seedling vigour and subsequent performance of hybrids.

Review of Literature

2. REVIEW OF LITERATURE

Plant breeding aims to improve the characteristics of plants so that they become more desirable agronomically and economically. Improvement of the crop forms an integral part of any crop cultivation.

In cocoa, a systematic crop improvement attempt was started with germplasm collection by Pound in 1937. Genetic improvement of cocoa was started with the domestication of Criollo varieties in Central America, and was gradually superseded by Trinitario selections and Forastero trees. In 1940, crossing Forastero lines with different genetic groups resulted in substantial increase in precocity and productivity (Paulin and Eskes, 1995). Similar breeding works were initiated in many places.

In India, crop improvement work on cocoa was started in 1980 at Vittal and 1984 at Vellanikkara which involved initial selection of desirable parents, assessment of their compatibility positions and their utilisation either for production of inbreds or hybrids.

Formulation of breeding programmes is effective only when the genetics of the crop is highly comprehensible. Information on the genetic behaviour of the crop is only limited. The perennial nature of the crop, outcrossing behaviour with high heterozygosity and the self incompatible nature of the clones confer a highly complex genetic mechanism.

The outcome of the various experiments conducted all over the world are reviewed hereunder:

2.1 Genetic variability

For taking up improvement of the crop, assessment of desirable characters is essential. In cocoa, even within varietal groups, a lot of variability exists and it is so high that in any cocoa population arising from seedlings, about 75 per cent of the yield comes from about 25 per cent of the plants. This variability is still larger in a diverse population and it is this variability that is expected to be exploited through breeding.

While taking up any breeding experiment, a deeper look into the genetic makeup and the extent of variability present in the crop is highly essential. The main objective of cocoa breeding is to increase yield which is a highly variable character.

Pound (1932, 1933) in Trinidad and Enriquež and Soria (1966) in Costa Rica reported that yield expressed in dry or wet weight of beans was a highly variable character.

The results of pod value studies in Amazon and Amelonado varieties revealed varietal differences in mean pod weight, wet bean weight and peeled dry bean weight as reported by Jacob and Atanda (1971).

Vello *et al.* (1972) reported low variability of seed size in majority of simple crosses between local cocoa and Upper Amazon clones in Brazil.

Significant difference for pod length and diameter, total fruit weight, number and wet weight of seeds was observed in 48 hybrids representing top cross of six Trinitario and two Criollo clones to six Amazon clones (Soria *et al.*, 1974).

Soria (1975) reported great variation and high heritability for fruit and bean characteristics like length, diameter, total weight of pod and weight of the husk. Weight of seeds in each pod also exhibited significant variation.

Lockwood and Edward (1980) reported significant variability for pod value and seed number per pod in a trial involving progenies from Upper Amazon x Upper Amazon and Upper Amazon x Amelonado crosses.

Mossu *et al.* (1981) studied variability among Amelonado and Amazon clones. They found that, the variation in seed yield was entirely due to the variation in flowering and pollination. The Amazonian clones were more profusely flowering and better pollinated with absence of fruit drop than the Amelonado clones.

Tan (1981) found considerable variation for yield among progenies of Trinitario x Amazon and Trinitario clones. High degree of variability was observed for pod diameter, pod length, husk thickness, number of beans per pod, weight of beans per pod, number of developed beans and weight of beans with pulp in 25 year old trees. Genotypic coefficient of variability was moderately high for weight of beans per pod. Non-additive gene action was indicated for all characters (Kumaran and Prasannakumari, 1982).

Subramonian and Balasimha (1982) reported significant variation among ten hybrids for number of pods, dry bean production, pod weight, dry bean weight, bean number, percentage pulp per bean and total soluble solids (%) in the pulp. The extent of variability was the largest in dry weight of beans followed by pod value.

Castro and Bartley (1985) analysed genetic variability of floral traits in ten year old trees. The greatest variability existed for ligule length among the ten quantitative characters of flowers studied by them. Ooi and Chew (1985) conducted five progeny trials on hybrid cocoa, and found that individual hybrids showed considerable variation in performance between sites.

Pereira *et al.* (1987) evaluated a number of hybrids and identified best crosses (SIC 24 x ICS1; SIC1 9 x ICS1; TSH 565 x SIAL 169; EEG 48 x ICS 8; TSA 656 x ICS 8). Statistical analysis showed significant genotype, year and genotype x year interaction effects for all traits.

Significant variability in bean size in 25 clones belonging to Upper Amazon, Amelonado and Trinitario clones was reported by Cilas *et al.* (1989). The average bean weight per hundred fermented beans ranged from 212.6 g for clone UF 66 F (Trinitario) to 67.5 g for SCA 6 (Upper Amazon). Bean weight decreased in successive harvest and seemed to depend partly on pod filling rate.

Nair *et al.* (1990) evaluated nine accessions of cocoa for yield and related characters. The results showed that number of pods per plant, bean yield, plant height, canopy spread, single bean weight and pod value were highly variable. Napitupulu (1990) evaluated clones from Kew Gardens from 1984 to 1989. The best clones yielded 20-40 per cent more than hybrid seedlings. Iquitos Mixed Calabacillo (IMC) clones gave the highest number of smallest beans. United Fruit

(UF) clones gave a few large beans, while Parinari (Pa) clones gave a moderate number of medium sized beans. Tan (1990) conducted an experiment involving six Trinitario female plants from a cross between Criollo and Forastero with nine Amazonian male parents. The results showed that general combining ability effects were significant for characters like yield, pod production, pod weight, husk content, number of beans per pod, average bean weight and pod value.

Morera *et al.* (1991) conducted studies in the Ecuadorian traditional cocoa cultivar Nacional at Tropical Agricultural Research and Training Centre (CATIE).They reported that the least variable character is seed index in the Nacional 3 group.

According to Barriga *et al.*, (1992) systematic collections of germplasm made in various zones of the Amazon basin since 1965 have revealed large phenotypic variability and wide dispersion of the species. Harris and Napitupulu (1992) conducted studies in eight year old Trinitario clones. They reported that, Trinitario clones exhibited larger bean size as measured by average dry weight of bean (1.08 g to 1.70 g). Napitupulu(1992a) undertook a diallel cross between eight parents of four clonal populations and revealed significant differences in dry bean yield and bean size. Low variability was observed for number of pods per tree.

Cherian *et al.* (1996) analysed the performance of 19 hybrids and the budded progenies of their parents during 1992-93. Variability for the characters observed followed approximately the same trend for both hybrid and parent population. Variability was maximum for yield expression in terms of wet bean weight per tree and number of pods. It was moderate for pod weight, wet bean weight per pod, dry bean weight and ratio of dry bean weight to wet bean weight.

Lerceteau *et al.* (1997) evaluated the extent of genetic variability in cocoa accessions using RAPD and RFLP markers. Continuous RFLP variability was observed within the species which may reflect the hybridisation and introgressions between trees of different origins. The Nacional type was detected to be specific and different from the well known types such as Forastero, Criollo and Trinitario.

Francies (1998) conducted genetic studies in cocoa using clones, biclonal crosses, biclonal pair crosses and inbreds. The results showed a wide spectrum of variability in the populations studied. The highest variability was observed in yield of dry beans per tree and precocity of bearing. The traits like pod width and bean width showed low variability.

2.2 Heritability

It is a measure of genetic relationship between the parent and progeny. In any variability study, the genetic component is highly important since it is being transmitted to the next generation. Heritability is the ratio between genetic variance and total variance, i.e., phenotypic variance.

Glendinning (1963) in Ghana reported that the number and size of beans in cocoa were highly heritable. Heritability for fruit length (55%), fruit diameter (63%) and total weight of fruit (57%) was studied by Soria *et al.* (1974).Their results suggested that these were highly transmissible characters.

Kumaran and Prasannakumari (1982) worked out heritability of characters in ten year old trees. They reported that heritability estimates were high for weight of bean with pulp and cotyledon weight. It was low for number of beans per pod. Non-additive gene action was indicated for all characters.

In a study conducted by Lopez *et al.* (1988) with a 7 x 7 diallel cross, it was found that number of ovules was an inherited trait, controlled by polygenes.

Ramirez and Enriquez (1988) conducted an experiment of 7 x 7 diallel cross involving cultivars and double hybrids of cocoa. The results revealed that the traits like pod length, pod diameter, pod weight, number of beans, wet bean weight, husk weight and pod and bean indices had high heritability. Low heritability was observed for pod husk thickness.

Based on a study using 20 cocoa clones, it was reported that heritability for bean weight in cocoa was very high (Cilas *et al.*, 1989).

Napitupulu (1992a) indicated that there was low heritability for number of pods per tree. Estimated heritability was high for bean size, pod content (bean weight per pod), and dry bean yield, but relatively low for number of pods per tree.

Napitupulu (1992b) reported that significant differences in yield and related characters were highly heritable and selection for improved yield and bean quality was effective in a progeny trial in North Sumatra.

Cherian (1993) reported high heritability for pod length, pod weight, wet bean weight per pod, dry bean weight and number of beans per pod. Heritability was moderate for number of pods, pod width and seed thickness.

Rabonin *et al.* (1993) in a 12 x 12 half diallel cross of cocoa reported high heritability for style length, sepal length, staminode length and length:diameter ratio of ovary and low coefficient of correlation between them.

The relative importance of the non-additive genetic effects over the additive effects for wet bean yield per pod was reported by Dias and Kageyama (1995) in their study of combining ability for yield components in five cocoa cultivars in Southern Brazil.

Francies (1998) reported moderate heritability combined with genetic advance for traits like precocity of bearing and yield (5 years from planting). High heritability values were obtained for pod morphology descriptors - furrow depth, base, apex and ovary width in case of floral traits. Low/moderate heritability were obtained for traits like pod size (length and width), bean size (length, width and thickness) and pericarp thickness.

2.3 Correlation and path analysis studies

Correlation is the degree of quantitative association among different variables or attributes. Correlation analysis is used to find out the degree of relationship and the direction (positive and negative) of relationship between two variables.

A positive correlation between seed size (length, width, thickness and weight) and fruit size was reported by Ruinard (1961).

Glendinning (1963) indicated that the number and size of beans in cocoa has a direct correlation with pod weight.

Glendinning (1966) also reported positive correlation between seed number per fruit and fruit size (length, width and weight) which was later confirmed by Toxopeus and Jacob (1970).

Positive correlation was also reported between mean unpeeled bean weight and mean pod weight in Amazon and Amelonado clones by Jacob *et al.* (1971).

Eskes *et al.* (1977) conducted studies on correlation of some pod and bean values. Correlation between seven pod and bean characters were calculated in five clones. It was found that the number of beans per pod was closely correlated with many fruit characters.

Moses and Enriquez (1981) reported positive correlation between yield and number of pods and yield with trunk diameter at 0.3m above soil.

Kumaran and Prasannakumari (1982) undertook studies on pod and bean characters in Forastero cocoa and reported a positive correlation for wet bean weight and weight of cotyledons with weight of beans. They indicated a strong relationship for (i) pod weight with pod length, pod diameter, and weight of beans (ii) pod diameter and husk thickness (iii) weight of beans with pulp and weight of cotyledons (iv) weight of beans per pod and number of developed beans.

Correlation was absent between seed number per fruit and fruit size as reported by Engels (1983). He reported a negative correlation between seed number and seed size. He also reported a positive relationship between the thickness of the fruit wall and fruit width, seed size and seed weight.

A positive correlation between commercial economic yield and fresh seed weight was reported by Lachenaud (1984).

Based on the observations on 218 trees belonging to three families of hybrids Cilas *et al.* (1985) , found that the number of orthotropic suckers formed was not correlated with pod yield per tree.

Cherian (1993) reported that the number of pods was the major contributing character to yield followed by wet bean weight per pod. Pod weight and seed size showed negative direct effect on yield.

Paulin *et al.* (1993) reported a close association between production and early vigour on their multi location hybrid trial studies involving Amazon and Amelonado clones.

Almeida *et al.* (1994) reported a high genotypic correlation between trunk height and bean dry weight per tree. Path analysis carried out to estimate the direct and indirect effects of traits revealed a negative direct effect of trunk height on yield. Number of healthy fruits per tree and weight of dry bean per fruit showed direct effects of high value on dry bean weight per tree. Based on their results they suggested to consider the number of seeds per fruit and dry bean weight as secondary yield components.

Dias and Kageyama (1997) conducted genetic divergence studies and calculated genetic distances among cacao cultivars through multivariate analysis. They analysed five yield components viz., number of healthy and collected fruits per plant (NHFP and NCFP), wet seed weight per plant and per fruit (WSWP and WSWF) and percentage of diseased fruits per plant (PDFP). The correlation studies suggested a linear relationship between genetic distance of parents to average performance of hybrids for WSWP and WSWF. The heterotic performance for the same components was also correlated with genetic distance of parents.

Francies (1998) conducted genetic studies in cocoa and reported that traits like plant height (2 years after planting), girth (3 years after planting), pod weight, pod length, pod width, bean size (length, thickness), dry weight per bean and pericarp thickness exhibited significant association with yield. Pod weight exhibited prominent positive correlation with girth (3 years after planting), pod length, pod width, wet bean weight per pod, number of beans per pod and bean size (length, width), dry weight per bean and pericarp thickness. Bean size was correlated positively with number of beans per pod. Absence of correlation was reported between precocity of bearing and yield potential in cocoa at genotypic level.

2.4 Heterosis

Of the several methods to increase genetic variability, hybridisation is very important. Heterotic expression of the progenies is of concern in any hybridisation programme. In cocoa, the progeny produced through seeds can be loosely called hybrids (Hunter, 1990). Actual hybridisation programme was initiated in Trinidad by means of hand pollination when Pound (1932) successfully crossbred different clones. Following this, several works were initiated in other places.

Posnette (1943) revealed the occurrence of heterosis in outcross of Upper Amazon parents and was later confirmed by Montserrin *et al.* (1957). This discovery of strong inter-population heterosis serves as the basis for all present day breeding programmes.

Atanda *et al.* (1972) reported heterosis for pod production exhibited by three Nigerian x Trinidad double cross viz., NT 11 x NT 10, NT 709 x NT 11 and NT 70 x NT 709. The high yielding single hybrid trees NT 70 and NT 709 combined well with each other.

Results of crosses made between local and introduced clones indicate that hybrids were the earliest and highest yielding with lowest average weight and highest per cent of shell. The largest seeds with lowest per cent shell were found in hybrids between local and Trinitario clones (Vello *et al.*, 1972).

Soria *et al.* (1974) reported that the high relative variance, in the progeny of top cross of six Trinitario and two Criollo clones to six Amazon clones, was a result of large heterotic differences, caused by crossing parents of different genetic origin. Studies involving crosses between ICS 1 and six Criollo clones and between ICS 1 and Porcelana clones, revealed a high per cent of hybrid vigour (5.2% and 4.4% respectively).

Cocoa hybrids produced 30-40 per cent more than Amelonado seedling (Kee and Bal,1976). These hybrids yielded 3.6-3.9 tonnes of dry cocoa ha^{-1} $year^{-1}$ at about 11-12 years of planting. Lockwood (1976) compared three selfed local Trinitarios with one outcrossed and three sibbed Upper Amazon progenies and 13 hybrids between Amelonado and local Trinitario. The results indicated that Amazon hybrids and the outcrossed progenies were vigorous, precocious and maintained a higher yield for about 20 years. Mature trees exhibited high variability and showed no relationship between continuous growth and yield.

Hybrids were found to establish earlier and bear early in a series of progeny trials involving Amelonado, Upper Amazon x Amelonado hybrids and local Trinitario x Amelonado hybrids (Lockwood, 1977). According to him, the yield estimates for hybrids were 25-50 per cent higher.

Mejia and Rondon (1981) reported that hybrids with Scavina genes (SCA 6 x ICS 39, SCA 6 x IMC 67) were low in yield in a study with six cocoa hybrids in Colombia.

Heterosis was found to be absent for number of seeds, fruits, total seed weight per fruit and production efficiency among the eight fruit traits studied by Engels (1985).

Earliness in hybrids was reported in a study by Morera and Mora (1991). Significant heterosis for yield and vegetative growth was reported by Yew *et al.* (1991) in Scavina (SCA) hybrids.

Napitupulu *et al.* (1992) in their experiments with Upper Amazon hybrids reported that F_2 hybrids from recurrent selection of F_1 hybrids were high yielding with improved bean yield.

Cherian (1993) compared 19 cocoa hybrids with budded progenies of their parents and reported that hybrids were more uniform and better yielding than the parents. Heterosis was noticed in certain combinations.

Low mean potential yields in certain cocoa hybrids though higher than the local control was reported by Lachenaud (1994).

Dias and Kageyama (1997) studied multivariate genetic divergence and hybrid performance of cacao. They could establish a relationship between genetic divergence and combining ability effects the most divergent cultivar exhibited a high general combining ability generating the best performing hybrids.

Francies (1998) conducted genetic experiments in cocoa using clones, hybrids and inbreds. It was reported that the number of hybrids exhibiting relative heterosis in desirable direction ranged from one (pod width, bean length and thickness) to 17 (number of beans/pod). Results indicated that the chances for occurrence of a high frequency of heterotic crosses and high values of heterosis are more, when the parental divergence is moderate.

2.5 Early vigour and yield

Hybrid production in cocoa, among the compatible parents, though laborious, has been successful. A single hybrid pod can give rise to around 40 hybrid seedlings. Screening and evaluation of these seedlings in the field is not practically feasible due to space and financial constraints. This necessitates the development of a selection criteria based on early growth parameters in the nursery, which bears positive correlation with final yield.

In other perennial crops like coconut (Liyanage, 1967; Sathyabalan and Mathew, 1983)and arecanut (Bavappa and Ramachander, 1967) selection criteria have been developed, and successfully being utilised for breeding programmes for the evaluation of seedlings in the nursery.

In cocoa the relationship between vegetative characters and yield was noted by Glendinning (1966). He reported that the yield in cocoa was positively correlated with the rate of growth before bearing up to five years. After bearing, vegetative growth slowed down and there was a high correlation between the reduction in growth rate and total yield. A high yielding variety will be thus the one making vigorous early growth, which is later reduced relatively.

A highly significant correlation between growth (juvenile phase) and yield has been reported by Ngatchou and Lotode (1971).

Enriquez (1981) reported that the vigour of seedlings is correlated with final yield and that it can be used as a criterion in the initial screening of hybrids.

Monte *et al.* (1985) used dry weight, rate of water uptake, relative growth rate and leaf area index of seedlings of four cultivars to relate with yield. Seedling characters were measured at 105 days after sowing and then at fortnightly intervals. The only two characters which were found to be related to yield were total dry weight and leaf area.

Cilas *et al.* (1989) conducted studies on growth and collar diameter in an almost complete 8 x 8 diallel of cocoa seedlings involving three Upper Amazon, two Trinitario and three Amelonado clones. The results indicated Upper Amelonado clones had significant positive GCA for growth of collar diameter between 7 and 14 month after planting.

Paulin *et al.* (1993) conducted five multilocational hybrid trials of cocoa involving approximately sixty crosses between 16 Upper Amazon clones and four locally selected Amelonado clones in Cote d'Ivoire. The cumulative production results for the first five years showed that under favourable conditions, a close relationship between production and early vigour was apparent.

Francies (1998) in her studies on several cocoa populations reported the absence of significant association between yield and growth in the juvenile phase during early years of bearing.

Verghese (1998) conducted studies on the influence of seedling height and girth on yield. The results pointed out that the influence was more pronounced in the case of seedlings one year after sowing than with those of 4, 5 and 6 months after sowing. The vegetative vigour measured by the height and diameter of trunk was found to be better correlated with precocity.

Materials & Methods

3. MATERIALS AND METHODS

The study was carried out in an ongoing experiment of Cadbury-KAU Co-operative Cocoa Research Project (CCRP), College of Horticulture, Kerala Agricultural University, Vellanikkara. The experimental population is designated as Progeny Trial-II (PT-II), which consists of 25 F_1 hybrids from ten superior parents. The study was taken up during the period from May, 1998 to April, 1999.

Materials

3.1 Experimental details of Progeny Trial-II

Extensive search for parents with general combining ability at CCRP, from 1984 to 1992, resulted in the identification of ten superior combiners. These were crossed in all possible combinations during 1992-'93, to assess the specific combining ability. However, out of the 45 possible cross combinations expected only 25 could be obtained due to the cross-incompatible nature of some of the selected parents. The hybrid seedlings were raised and HD^2 values were recorded. The best plants from each cross combination were planted during June, 1994 in RBD with three replications, maintaining six plants per plot. An open pollinated bulk progeny was also planted along with the hybrids for comparison. (Table 1)

The parents used in the study include several clones from the Germplasm (G) maintained in the CCRP farm (G I-5.9 an Amazon Scavina entry, G II-19.5 a local selection, G VI-24, G VI-51, G VI-59, G VI-60, G VI-64 which are vegetatively propagated progenies of NC-40, IMC 67, ICS 6, Na 33 and accession C3 respectively, shade trial population S-28.3) and local population maintained at Mannuthy (M-9.16 and M-13.12). The hybrids were produced under the Stage II breeding programme of CCRP.

Table 1. Pedigree of progeny trial II (PT-II)

Sl.No.	Hybrid designation	Parentage	
1	H_1	M - 9.16	x G I - 5.9
2	H_2	M - 9.16	x G II - 19.5
3	H_3	M - 9.16	x G VI - 51
4	H_4	M - 13.12	x G I - 5.9
5	H_5	M - 13.12	x G VI - 24
6	H_6	M - 13.12	x G VI - 51
7	H_7	M - 13.12	x G VI - 60
8	H_8	G I - 5.9	x G II - 19.5
9	H_9	G I - 5.9	x G VI - 24
10	H_{10}	G I - 5.9	x G VI - 51
11	H_{11}	G I - 5.9	x G VI - 59
12	H_{12}	G I - 5.9	x G VI - 60
13	H_{13}	G I - 5.9	x G VI - 64
14	H_{14}	G II - 19.5	x G VI - 64
15	H_{15}	G II - 19.5	x G VI - 60
16	H_{16}	G II - 19.5	x G VI - 64
17	H_{17}	G II - 19.5	x S - 28.3
18	H_{18}	G VI - 24	x G VI - 51
19	H_{19}	G VI - 24	x G VI - 59
20	H_{20}	G VI - 24	x G VI - 60
21	H_{21}	G VI - 24	x S - 28.3
22	H_{22}	G VI - 51	x S - 28.3
23	H_{23}	G VI - 59	x G VI - 64
24	H_{24}	G VI - 59	x S - 28.3
25	H_{25}	G VI - 60	x G VI - 64
26	Bulk		

The parents are being maintained in the CCRP farm, as comparative yield trial I and II (CYT I with 26 treatments and CYT II with 45 treatments) which is the replicated clonal trial of the 30 cocoa genotypes from the clonal base population.

Methods

The observations on vegetative and yield characters recorded and available in the CCRP farm from June, 1994 to April, 1998 were gathered. Observations on vegetative, floral and pod traits, yield and yield attributes of 468 trees were recorded from May, 1998 to April, 1999.

Pods from bearing cocoa trees were harvested at an interval of 15-20 days throughout the year and observations on pod yield were recorded. Damaged pods (due to pest and disease attack) were also considered to compute potential plant yield. For all other pod and bean characters only the undamaged fully ripe pods were considered.

Harvested pods from each tree were labelled separately and observations (pod weight, pod length and pod width) were recorded. The wet beans along with the mucilagenous coat, were extracted from each pod and weighed. The number of beans per pod were counted and pericarp thickness was measured using vernier callipers, both at the ridges and furrows on the pod surface. A sample of twenty beans were taken at random from all the pods of a given tree from a single harvest and the mucilagenous coat of the beans was peeled off. Observations like length, width and thickness of five randomly selected beans were recorded. A sample of twenty peeled beans was then oven-dried at 70°C for a period of 7-10 days and dry weight was recorded.

3.2 *Biometric characters studied*

The following biometric observations were recorded in the population.

3.2.1 Growth observations

1. Plant height (cm)

The height of tree trunk was measured from the ground level to the tip of the main chupon.

2. Girth (cm)

The girth of the tree trunk was recorded 15 cm above ground level.

3.2.2 Floral traits

During the period of study, ten fully expanded flowers with pearl coloured thecae (Plate 1.) were collected randomly from each tree on the day of anthesis and evaluated for the following traits according to IBPGR descriptor (IBPGR, 1981) and expressed in millimetre.

1. Pedicel length
2. Flower diameter
3. Sepal length
4. Sepal width
5. Petal length
6. Petal width
7. Ligule width
8. Staminode length
9. Ovary length
10. Ovary width
11. Style length

3.2.3 Pod characters

1. Number of pods

The total number of mature pods including damaged pods (due to insect and disease attack) harvested from each tree was recorded throughout the year.

2. Pod length (cm)

The distance from the base of the pod to its apex was measured and the average pod length for individual trees was computed.

3. Pod width (cm)

The width of each pod harvested was measured and average for individual trees computed.

4. Pod weight (g)

The weight of each pod was recorded per tree and average computed.

5. Pericarp thickness (mm)

The average thickness of pericarp was calculated from the mean pod husk thickness at the ridges and furrows using vernier callipers.

3.2.4 Bean characters

1. Number of beans per pod

The number of beans per pod was recorded on individual tree basis at each harvest and the average value was computed.

2. Wet bean weight per pod (g)

Pods were broken open and wet beans collected. Weight of beans for each pod was taken using a common balance and the average weight of wet beans was calculated.

3. Bean length (mm)

The average length of a bean for each tree was calculated from the measure of five randomly selected fresh peeled beans at each harvest using vernier callipers.

4. Bean width (mm)

The average width of a bean for each tree was computed as above.

5. Bean thickness (mm)

The average thickness of beans for each tree was computed as above.

6. Dry weight per bean (g)

The dry weight of a single bean was computed as an average value of twenty oven dried beans, taken at each harvest at random.

3.2.5 Yield (kg)

Yield was estimated in terms of total wet bean weight produced and was calculated by the formula,

Yield = Total number of pods x Mean wet bean weight per pod

3.2.6 *Qualitative traits*

1. Flowering intensity

The intensity of flowering in each tree was recorded during the peak flowering season in the month of January-February and expressed as :

0 = sparse flowering and 1 = profuse flowering

2. Flush colour

The colour of the newly emerging flushes was recorded based on anthocyanin intensity and expressed as:

Plate 1. A cushion with fresh flowers on the day of anthesis.

Plate 2. A tree with immature pods having intense anthocyanin pigmentation

Plate 3. Pod anthocyanin intensity grades

0 - absent; 3 - slight; 5 - intermediate; 7 - intense

0 = absent, 3 = slight, 5 = intermediate and 7 = intense.

3. Sepal colour

The colour of the sepal was recorded for fully expanded fresh flowers on the day of anthesis and was expressed as :

0 = cream and 1 = greenish cream

4. Fruit colour before ripening

The colour of the fruit before ripening was graded visually based on anthocyanin intensity and expressed as:

0 = absent and 1 = present

Plate 2., shows a tree with immature pods having intense anthocyanin pigmentation.

5. Fruit colour at ripening

Mature cocoa fruit colour was visually graded based on intensity of anthocyanin pigment as (Plate 3):

0 = absent, 3 = slight, 5 = intermediate and 7 = intense

6. Fruit surface rugosity

The fruit surface was visually observed and graded for the presence of protruberances and expressed as (Plate 4):

0 = absent (smooth), 3 = slight, 5 = intermediate, and 7 = intense

7. Fruit apex form

The form of beak in the apical part of the fruit was expressed as (Plate 5):

1 = attenuate, 2 = acute, 3 = obtuse, 4 = rounded, 5 = mammelate and 6 = indented

Plate 4. Fruit surface texture grades

0 - absent (smooth); 3 - slight; 5 - intermediate; 7 - intense

Plate 5. Fruit apex form grades

1 - attenuate; 2 - acute; 3 - obtuse; 4 - rounded; 5 - mammelate; 6 - indented

Plate 6. Fruit base form grades

0 - absent; 1 - slight; 2 - intermediate; 3 - strong; 4 - wide

8. Fruit base form

The nature of shoulder constriction in the basal part of the fruit was coded as (Plate 6):

0 = absent, 1 = slight, 2 = intermediate, 3 = strong and 4 = wide

9. Bean colour

The colour of the beans was graded visually and recorded as:

1 = white, 2 = grey, 3 = slight purple, 4 = intermediate purple, 5 = dark purple and 6 = mottled

3.3 Statistical analysis

The mean values computed for each character for individual trees were taken for analysis. The data were processed to assess genetic variability, heritability, genotypic and phenotypic correlation coefficients, heterosis and path coefficients.

3.3.1 Analysis of variance

The analysis of variance was worked out as done for randomised block design experiments for the different vegetative, pod and yield characters.

Coefficient of variation (CV) in the population with respect to each character was estimated using the formula,

$$CV = \frac{\text{Standard Deviation}}{\text{Mean}} \times 100$$

Statistical model adopted for the analysis was,

$$Y_{ijk} = \mu + S_i + d_{ij} + e_{ijk}$$

where, Y_{ijk} = performance of the k^{th} progeny of the cross between i^{th} female to j^{th} male

μ = effect common to all individuals

S_i = effect due to i^{th} female with $E(S_i) = 0$, $V(S_i) = \sigma f^2$

d_{ij} = effect due to j^{th} male crossed to i^{th} female, with $E(d_{ij})= 0$, $V(d_{ij})= \sigma m^2$

e_{ijk}= random effect attached to k^{th} progenies of the cross between j^{th} males and i^{th} female parents with $E(e_{ijk})= 0$, $V(e_{ijk})= \sigma w^2$

i = 1, 2, 3, ... s

j = 1, 2, 3, ... d

k = 1, 2, 3, ... nij

Anova was worked out and variance split as given below:

Source of variation	df	MSS	E
Between female parents	s-1	MS_f	$\sigma w^2 + k\sigma m^2 + dk\sigma f^2$
Between male parents within female parents	s(d-1)	MS_m	$\sigma w^2 + k\sigma m^2$
Between progeny within male parents	sd(k-1)	MS_w	σw^2

where, s = number of females; d = number of males per female

k = number of progenies

3.3.2 Estimation of genetic parameters

Genetic parameters like additive genetic variance, variance due to dominance deviation and coefficient of heritability were estimated by full sib analysis.

1. Additive genetic variance

Additive genetic variance is calculated by the formula,

$V_A = 4\,\sigma f^2$

2. Variance due to dominance deviation

The variance due to dominance deviation is calculated using the formula,

$V_D = 4\,\sigma m^2 - V_A$

3. Genotypic variance

The variance due to genotypes $\sigma g^2 = V_A + V_D$

4. Phenotypic variance

The variance due to phenotype,

$\sigma p^2 = \sigma f^2 + \sigma m^2 + \sigma w^2$

5. Heritability

Coefficient of heritability is calculated by the formula,

$$h^2 = \frac{V_A}{\sigma f^2 + \sigma m^2 + \sigma w^2}$$

6. Phenotypic and Genotypic coefficients of Variation (pcv and gcv)

These were computed using the formula suggested by Burton (1952).

$$PCV = [\sigma_p / \text{Grand mean}] \times 100$$

$$GCV = [\sigma_g / \text{Grand mean}] \times 100$$

7. Genetic advance

Genetic advance (GA) was estimated using the formula,

$GA = K \times \sigma_p \times h^2$

where, K = 2.06, selection intensity at 5 per cent

8. Genetic Gain

$$\text{Genetic gain (GG)} = \frac{GA}{\text{Grand mean}} \times 100$$

The genetic gain was classified according to Johnson *et al.*(1955)

1 - 10 per cent	- low
11 - 20 per cent	- moderate
21 per cent and above	- high

3.3.3 Correlation study

Genotypic and phenotypic correlation coefficients among various traits studied were computed and tested for their significance.

3.3.4 Path coefficient analysis

Path analysis was adopted to partition the genotypic correlation coefficients into direct and indirect effects.

3.3.5 Estimation of heterosis

Relative heterosis(RH):

Deviation of hybrid from mid-parental value (per cent).

$$RH = \frac{\bar{F}_1 - MP}{MP} \times 100$$

where, $\bar{F}_1$ = Mean value of hybrid

MP = Mean of two parents involved in a cross combination

Heterobeltiosis (HB):

Deviation of hybrid from better parent(per cent)

$$HB = \frac{\bar{F}_1 - BP}{BP} \times 100$$

where, BP = Better Parent

Standard Heterosis (SH):

Deviation of hybrids from check variety (per cent)

$$SH = \frac{\bar{F}_1 - CV}{CV} \times 100$$

where, CV = Check variety

4. RESULTS

Data on various vegetative, pod and bean traits recorded for the 25 hybrids (4YAP), were subjected to statistical analysis. The results are presented below.

Analysis of variance

The data when subjected to analysis of variance revealed significant difference for all the characters except pod weight and plant height (2YAP). Characters like yield, number of pods per tree, height and girth were transformed (square root transformation) to bring down the high coefficient of variation and further analysis was done using transformed data (Table 2).

4.1 Variability

The mean values for the various traits for each particular cross combination are presented in Table 3. The range, mean, pcv and gcv for various characters are given in Table 4. The data showed a wide range of variation among the hybrids. All the 15 traits recorded higher estimates of pcv than gcv.

1. Yield

The coefficient of variation recorded was very high (75.42%) and hence transformed data (square root) were used for analysis. The yield per tree ranged from 700.1 g (H_{22}) to 3665.8 g (H_{16}) with a mean of 2173.8 g. Yield showed a wide spectrum of variability with pcv and gcv estimates 41.55 and 17.86 respectively.

2. Pod length

The data indicated that length of pods ranged from 12.8 cm (H_{21}) to 16.0 cm (H_3) with a mean value of 14.29 cm. The pcv was 14.85 and gcv was 9.79.

Table 2. Analysis of variance for growth, yield and yield attributes

Source	df	Mean sum of squares														
		Yield (g)	Pod length (cm)	Pod width (cm)	Pod weight (g)	Wet bean weight/ pod (g)	Number of beans/ pod	Dry weight/ bean (g)	Bean length (mm)	Bean width (mm)	Bean thickness (mm)	Pericarp thickness (mm)	Number of pods/ tree	HD² (6 MAS)	Height (2YAP) (cm)	Girth (2YAP) (cm)
Between female parents	7	1114.79**	11.41**	1.14*	12734.70	1298.16**	147.27**	0.21**	15.25**	8.76**	2.74**	6.62*	11.38**	23059430.00**	9.27	0.54*
Between male parents within female parents	17	505.02*	10.21**	1.13**	10253.18	1026.99**	38.38	0.15**	17.11**	4.68**	3.11**	3.67	7.05**	19209280.00**	13.89	0.29
Between progeny within male parents	361	267.54	2.54	0.54	6294.44	404.58	30.03	0.04	3.25	1.18	0.85	2.83	2.39	1317056.00	8.44	0.22
cv		37.52	11.16	10.16	23.99	21.23	15.13	19.83	8.9	9.17	12.40	16.36	34.74	33.36	25.96	13.18

*P = 0.05, **P = 0.01

Table 3. Performance of the various cocoa hybrids

	Yield (g)	Pod length (cm)	Pod width (cm)	Pod weight (g)	Wet bean weight/ pod (g)	Number of beans/ pod	Dry weight/ bean (g)	Bean length (mm)	Bean width (mm)	Bean thickness (mm)	Pericarp thickness (mm)	Number of pods/ tree	HD^2	Height (cm)	Girth (cm)
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
H_1	1929.7	14.5	7.1	324.3	83.5	36.4	0.8	19.3	11.2	7.4	10.3	21.7	3750.4	138.1	11.8
H_2	2326.9	14.6	7.5	353.9	94.2	35.6	1.1	20.9	11.9	7.7	10.4	23.4	4466.7	150.3	13.3
H_3	2326.1	16.0	7.4	366.3	103.4	37.9	1.0	21.1	12.5	7.5	11.1	21.2	3741.1	108.0	12.8
H_4	2365.8	13.7	7.4	327.1	81.7	35.2	0.9	19.0	11.6	7.3	9.9	28.8	2485.8	131.2	12.2
H_5	2700.9	12.9	7.2	295.6	78.3	35.9	0.8	18.2	11.1	6.8	10.4	32.9	5176.4	142.0	12.8
H_6	2165.0	15.2	7.4	359.2	101.1	33.5	1.1	21.2	12.5	7.8	10.7	19.4	2285.7	124.8	11.9
H_7	1363.3	15.2	7.8	371.0	91.3	33.6	1.0	20.7	12.2	7.6	11.3	13.0	2036.5	120.7	11.6
H_8	2410.9	13.6	7.6	341.0	97.3	36.8	0.9	19.4	11.4	7.1	9.9	24.9	5250.7	144.1	13.6
H_9	2363.2	12.9	7.2	288.1	86.8	34.9	0.8	18.9	11.0	7.1	9.9	27.9	5140.2	134.5	13.5
H_{10}	2661.3	14.5	7.4	330.7	107.7	35.3	1.0	21.0	12.2	8.0	9.3	23.9	3289.8	128.9	13.6
H_{11}	2183.5	14.0	7.5	321.4	97.5	35.7	0.9	21.6	11.8	7.4	9.9	21.7	4487.5	123.7	13.5
H_{12}	2385.6	14.5	6.8	296.5	86.3	32.3	0.9	20.2	10.6	7.2	9.4	28.1	4143.9	116.1	12.2
H_{13}	2168.0	13.3	6.8	291.4	83.1	37.2	0.8	18.2	10.5	6.8	10.1	26.0	4545.4	100.5	13.9
H_{14}	2031.7	13.7	7.0	303.1	88.4	38.7	0.9	19.5	11.4	6.9	10.2	22.0	2179.6	135.7	12.5

Contd.

Table 3. Continued

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
H_{15}	2916.5	14.7	7.1	335.7	99.5	39.1	1.0	21.0	12.1	7.6	10.1	28.6	2465.3	136.2	13.2
H_{16}	3665.8	14.8	7.6	376.2	97.5	35.7	1.1	21.1	12.3	8.0	11.5	37.5	1956.1	122.5	12.1
H_{17}	1484.2	13.7	6.9	303.3	94.6	36.8	1.0	21.0	12.2	7.6	9.9	15.4	5428.2	131.8	12.9
H_{18}	1849.3	14.4	7.3	337.8	101.2	38.1	1.0	20.2	11.9	7.2	10.3	17.2	3987.8	125.4	12.8
H_{19}	2309.6	14.1	6.8	307.6	98.3	39.5	1.0	20.3	11.8	7.0	9.5	22.9	2326.8	127.9	12.7
H_{20}	1823.3	14.9	7.2	325.3	93.9	36.2	1.0	19.8	12.2	7.6	10.1	18.9	1892.9	117.6	13.6
H_{21}	2684.5	12.8	7.0	317.6	92.3	37.2	1.0	19.5	11.8	7.4	10.6	28.9	3039.9	146.0	12.6
H_{22}	700.1	14.1	6.9	319.7	93.0	30.1	1.1	20.7	12.1	8.3	10.4	8.2	2978.7	131.4	11.0
H_{23}	2455.2	15.0	7.3	355.2	111.1	39.6	1.0	21.7	12.4	7.4	10.5	22.8	2726.9	116.5	13.4
H_{24}	1734.9	15.1	7.4	370.5	104.7	35.8	1.2	21.6	13.1	8.4	10.5	15.5	3413.7	120.9	11.9
H_{25}	1339.8	15.2	7.4	347.4	101.6	38.7	0.9	20.5	11.9	7.2	11.1	13.3	2803.3	92.1	12.7

Table 4. Range, mean, phenotypic and genotypic coefficients of variation

Characters	Range		Mean	Coefficient of variation	
	Minimum	Maximum		Phenotypic (pcv)	Genotypic (gcv)
Yield (g)	700.1	3665.8	2173.80 (43.6)	41.55	17.86
Pod length (cm)	12.8	16.0	14.29	14.85	9.79
Pod width (cm)	6.8	7.8	7.24	11.49	5.36
Pod weight (g)	288.1	376.2	330.64	25.85	9.61
Wet bean weight/pod (g)	78.3	111.1	94.73	25.06	13.31
No. of beans/pod	30.1	39.6	36.23	15.65	4.03
Dry weight/bean (g)	0.8	1.2	0.97	26.20	17.13
Bean length (mm)	18.2	21.7	20.26	12.86	9.28
Bean width (mm)	10.5	13.1	11.83	12.18	8.01
Bean thickness (mm)	6.8	8.4	7.45	16.06	10.20
Pericarp thickness (mm)	9.3	11.5	10.29	16.97	4.50
No. of pods/tree	8.2	37.5	22.56 (4.45)	42.51	24.54
HD^2(6 MAS)	1892.9	5428.2	3439.97	70.53	62.14
Height (2YAP-cm)	92.1	150.3	126.68 (11.19)	28.02	10.59
Girth (2YAP-cm)	11.0	13.9	12.72 (3.56)	13.68	3.97

The figures in parenthesis denote transformed values

3. Pod width

The mean value for this trait was 7.24 cm. The range was from 6.8 cm (H_{12}, H_{13} and H_{19}) to 7.8 cm (H_7). The variability estimates were 11.49 (pcv) and 5.36 (gcv).

4. Pod weight

The analysis of variance revealed that there was no significant difference among the hybrids for pod weight. The weight of pods ranged from 288.1 g (H_9) to 376.2 g (H_{16}) and the mean value was 330.64 g. The pcv and gcv were 25.85 and 9.61 respectively. Plate 7 shows the variability in size, shape and colour of pods.

5. Wet bean weight per pod

The values ranged from 78.3 g (H_5) to 111.1 g (H_{23}) with a mean of 94.73 g. The trait recorded a pcv of 25.06 and gcv of 13.31.

6. Number of beans per pod

This trait exhibited a range of 30.1 to 39.6 with a mean value of 36.23. H_{22} recorded the lowest number of beans and H_{23}, the highest number of beans. The pcv and gcv were relatively low (15.65 and 4.03).

7. Dry weight per bean

There was significant difference among the hybrids for this character. The dry weight per bean ranged from 0.8 g to 1.2 g with a mean value of 0.97 g. The hybrids H_1, H_5, H_9 and H_{13} registered the lowest value and H_{24} produced beans with the highest dry weight. The pcv and gcv estimates were 26.20 and 17.13 respectively.

Plate 7. Pod shape and size variability

Plate 8. Bean shape and size variability

Plate 9. Comparison between hybrids having large and small sized beans

8. Bean length

Bean length exhibited moderate variation with values ranging from 18.2 mm (H_5 and H_{13}) to 21.7 mm (H_{23}). The mean was 20.26 mm. The pcv (12.86) and gcv (9.28) were comparatively low.

9. Bean width

A range of 10.5 mm to 13.1 mm was observed (H_{13} and H_{24}). A mean of 11.83 mm was recorded. The pcv was 12.18 and a lower gcv of 8.01 was observed.

10. Bean thickness

H_5 and H_{13} recorded the lowest thickness of beans (6.8 mm) and H_{24}, the highest value (8.4 mm). The mean was 7.45 mm. The pcv was 16.06 and gcv 10.20. Plate 8 shows the variability in size, shape and colour of beans. Plate 9 shows a comparison between hybrids having large and small sized beans.

11. Pericarp thickness

The values observed ranged from 9.3 mm (H_{10}) to 11.5 mm (H_{16}) with a mean of 10.29 mm. The estimate of pcv was 16.97 and the gcv recorded a lower estimate of 4.50.

12. Number of pods per tree

The coefficient of variation for this trait recorded was 67.89 per cent and hence square root transformation was done to bring down the coefficient of variation to 34.74 per cent and the transformed data was used for further analysis. The values ranged from 8.2 to 37.5 and the mean value recorded was 22.56. H_{22} recorded the lowest number of pods per tree and H_{16} had the highest number. The pcv and gcv estimates were 42.51 and 24.54 respectively.

13. HD^2 (6MAS)

The range of values observed for HD^2 was very high (1892.9 for H_{20} to 5428.2 for H_{17}). Among the different traits highest pcv (70.53) and gcv (62.14) was recorded for HD^2 (6MAP).

14. Height (2YAP)

The coefficient of variation was found to be very high (153.82%) and hence the data were transformed (square root) for further analysis. The values ranged from 92.1 cm (H_{25}) to 150.3 cm (H_2) with a mean of 126.68 cm. The pcv for height was 28.02 and gcv was 10.59.

15. Girth (2YAP)

A high coefficient of variation (45.46%) was registered and hence transformed data were used for further analysis. A range of 11.0 cm (H_{22}) to 13.9 cm (H_{13}) was recorded with a mean of 12.72 cm. Pcv was higher (13.68) when compared to gcv (3.97).

4.2 Heritability

The values for additive genetic variance, variance due to dominance deviation, heritability (narrow sense), genetic advance and genetic gain are presented in Table 5.

Additive genetic variance (V_A) was found to vary between -0.38 (height) to 412452.8 (HD^2). High V_A was recorded for traits like pod weight (232.63), yield (53.92) and wet bean weight per pod (26.25). The variance due to dominance deviation (V_D) ranged from -7.35 (number of beans per pod) to 4156607.20 (HD^2). High V_D values were noted for pod weight (778.30) and wet bean weight per pod (132.69).

Table 5. Additive genetic variance, variance due to dominance deviation, heritability, genetic advance and genetic gain

Characters	Additive genetic variance (V_A)	Variance due to dominance deviation (V_D)	Heritability (h^2) (%)	Genetic advance (GA)	Genetic gain (GG)
Yield (g)	53.92	6.72	18.21	6.79	15.57
Pod length (cm)	0.14	1.82	4.50	0.20	1.38
Pod width (cm)	0.01	0.15	0.62	0.01	0.15
Pod weight (g)	232.63	778.30	3.52	6.20	1.88
Wet bean weight/ pod (g)	26.25	132.69	5.82	2.85	3.00
No. of beans/pod	9.48	-7.35	28.79	3.36	9.28
Dry weight/bean (g)	0.01	0.02	12.36	0.07	6.67
Bean length (mm)	-0.10	3.64	-2.44	-0.13	-0.65
Bean width (mm)	0.37	0.53	24.73	0.73	6.21
Bean thickness (mm)	-0.02	0.60	-2.26	-0.06	-0.75
Pericarp thickness (mm)	0.26	-0.05	8.78	0.32	1.43
No. of pods/tree	0.40	0.80	14.22	0.55	12.36
HD^2 (6 MAS)	412452.80	4156607.20	16.10	804.46	23.39
Height (2YAP-cm)	-0.38	1.77	-4.32	-0.28	-2.50
Girth (2YAP-cm)	0.03	-0.01	10.53	0.11	2.96

Heritability (narrow sense %) for the various traits was found in the range of -4.32 (height) to 28.79 (number of beans per pod). Bean width (24.73), yield (18.21), HD^2 (16.10), number of pods per tree (14.22) and dry bean weight (12.36) recorded comparatively high heritability estimates. The heritability was found to be negative for traits like bean thickness (-2.26), bean length (-2.44) and height (-4.32) due to very low additive genetic variance.

The range observed for genetic advance was between 0.28 (height) to 804.46 (HD^2).

Of all the traits only HD^2 registered a high genetic gain of 23.39. Yield recorded a moderate genetic gain of 15.57 followed by number of pods per tree (12.36).

All the other traits recorded low genetic gain. Genetic gain was found to be negative for characters like bean length (-0.65), bean thickness (-0.75) and height (-2.50).

4.3 Correlation studies

Correlation coefficients between the characters under study were computed and tested for significance. The genotypic and phenotypic correlation coefficients are presented in Tables 6 and 7 respectively.

Yield was found to be significantly and positively correlated with number of pods per tree both genotypically (r_g = 0.962) and phenotypically (r_p = 0.930). Significant positive genotypic correlation for yield was also found for height (r_g = 0.577) and girth (r_g = 0.646). Significant positive phenotypic correlation with yield was observed for several traits like pod length (r_p = 0.154), pod width (r_p = 0.320), pod weight (r_p = 0.305), wet bean weight per pod (r_p = 0.353), number of beans per pod (r_p = 0.163), dry weight per bean (r_p = 0.183), bean length (r_p = 0.203), bean width (r_p = 0.157), bean thickness (r_p = 0.134) and pericarp thickness (r_p = 0.149).

Table 6. Genotypic correlation coefficients among yield and its components

Characters	Yield (g)	Pod length (cm)	Pod width (cm)	Pod weight (g)	Wet bean weight/ pod (g)	Number of beans/ pod	Dry weight/ bean (g)	Bean length (mm)	Bean width (mm)	Bean thickness (mm)	Pericarp thickness (mm)	Number of pods/ tree	HD^2	Height (cm)	Girth (cm)
Yield (g)	1.000	-0.410	-0.013	-0.342	-0.301	0.419	-0.258	-0.307	-0.400	-0.429	-0.397	0.962^{**}	-0.036	0.577^{**}	0.646^{**}
Pod length (cm)		1.000	0.437	0.999^{**}	0.655^{**}	-0.035	0.577^{**}	0.847^{**}	0.789^{**}	0.569^{**}	0.631	-0.587^{**}	-0.537^{**}	-0.669	-0.289
Pod width (cm)			1.000	0.909^{**}	0.153	-0.205	0.262	0.361	0.556^{**}	0.289	0.614^{*}	-0.131	-0.148	0.058	-0.038
Pod weight (g)				1.000	0.581^{*}	-0.002	0.942^{**}	0.911^{**}	1.123^{**}	0.744^{**}	0.765	-0.534^{*}	-0.659^{**}	-0.430	-0.612
Wet bean wt./pod (g)					1.000	0.294	0.788^{**}	0.964^{**}	0.869^{**}	0.607^{**}	0.053	-0.562^{**}	-0.347	0.033^{**}	0.544^{**}
No. of beans/pod						1.000	-0.035	-0.009	0.105	-0.529^{*}	0.237	0.267	-0.131	-0.426	0.535
Dry wt./ bean (g)							1.000	0.873^{**}	0.975^{**}	0.852^{**}	0.608^{**}	-0.472^{*}	-0.473^{**}	0.073	-0.335
Bean length (mm)								1.000	0.820^{**}	0.800^{**}	0.354	-0.545^{**}	-0.330	-0.118	-0.073
Bean width (mm)									1.000	0.852^{**}	0.795^{**}	-0.602^{**}	-0.544	-0.119	-0.443
Bean thickness (mm)										1.000	0.263	-0.544^{*}	-0.378	0.343^{**}	-0.203
Pericarp thickness (mm)											1.000	-0.420	-0.559^{*}	-1.316	-1.358
No. of pods/ tree												1.000	0.133	0.484	0.450
HD^2(6MAS)													1.000	0.234	0.435
Height (2YAP-cm)														1.000	0.028
Girth (cm) (2YAP-cm)															1.000

Table 7. Phenotypic correlation coefficients among yield and its components

Characters	Yield (g)	Pod length (cm)	Pod width (cm)	Pod weight (g)	Wet bean weight/ pod (g)	Number of beans/ pod	Dry weight/ bean (g)	Bean length (mm)	Bean width (mm)	Bean thickness (mm)	Pericarp thickness (mm)	Number of pods/ tree	HD^2	Height (cm)	Girth (cm)
Yield (g)	1.000	0.154**	0.320**	0.305**	0.353**	0.163**	0.183**	0.203**	0.157**	0.134**	0.149*	0.930**	0.054	0.089	0.101
Pod length (cm)		1.000	0.470**	0.610**	0.500**	0.120**	0.385**	0.319**	0.232**	0.391**	0.312	0.014	-0.159**	-0.026	-0.034
Pod width (cm)			1.000	0.649**	0.491**	0.023	0.327**	0.299**	0.261**	0.341**	0.398**	0.194**	-0.010	0.072	0.096
Pod weight (g)				1.000	0.641**	0.034	0.424**	0.398**	0.377**	0.455**	0.624**	0.134**	-0.096	0.022	0.046
Wet bean wt./pod (g)					1.000	0.315**	0.512**	0.553**	0.496**	0.419**	0.227**	0.067	-0.058	0.022	0.068
No. of beans/pod						1.000	-0.001	0.021	0.027	-0.203**	-0.123*	0.065	-0.027	-0.002	0.009
Dry wt./ bean (g)							1.000	0.642**	0.608**	0.521**	0.172**	0.025	-0.089	0.047	0.023
Bean length (mm)								1.000	0.698**	0.498**	0.138**	0.017**	-0.046	0.031	0.071
Bean width (mm)									1.000	0.567**	0.131*	-0.020	-0.146	0.005	0.010
Bean thickness (mm)										1.000	0.154**	-0.005	-0.107	0.252**	0.178**
Pericarp thickness (mm)											1.000	0.111	-0.084	-0.033	-0.024
No. of pods/ tree												1.000	0.080	-0.038	0.030
HD^2 (6MAS)													1.000	-0.062	-0.043
Height (2YAP-cm)														1.000	0.744**
Girth (cm) (2YAP-cm)															1.000

Significant positive correlation for pod length was seen both at the genotypic and phenotypic levels with pod weight (r_g = 0.999; r_p = 0.610), wet bean weight per pod (r_g = 0.655; r_p = 0.500), dry weight per bean (r_g = 0.577; r_p = 0.385), bean length (r_g = 0.847; r_p = 0.319), bean width (r_g = 0.789; r_p = 0.232) and bean thickness (r_g = 0.569; r_p = 0.391). Significant negative correlations with HD^2 was observed at both the levels (r_g = -0.537; r_p = -0.159). Number of pods per tree was also negatively correlated with pod length (r_g = -0.587). Significant positive correlation at phenotypic level was also seen with pod width (r_p = 0.470) and number of beans per pod (r_p = 0.120).

Both at genotypic and phenotypic levels, significant positive association was observed for pod width with pod weight (r_g = 0.909; r_p = 0.649), bean width (r_g = 0.556; r_p = 0.261) and pericarp thickness (r_g = 0.614; r_p = 0.398). Significant positive correlation were also observed for wet bean weight per pod (r_p = 0.491), dry weight per bean (r_p = 0.327), bean length (r_p = 0.299), bean thickness (r_p = 0.341) and number of pods per tree (r_p = 0.194).

Pod weight was found to be significantly and positively correlated with wet bean weight per pod (r_g = 0.581; r_p = 0.641), dry weight per bean (r_g = 0.942; r_p = 0.424), bean length (r_g = 0.911; r_p = 0.398), bean width (r_g = 1.123; r_p = 0.377) and bean thickness (r_g = 0.744; r_p = 0.455) both genotypically and phenotypically. Significant negative correlation at genotypic level was observed for number of pods per tree (r_g = -0.534 and HD^2 (r_g = -0.659). Positive correlation with significance at phenotypic level was also observed for pericarp thickness (r_p = 0.624) and number of pods per tree (r_p = 0.134).

Wet bean weight per pod was observed to be positively and significantly associated both genotypically and phenotypically with dry weight per bean (r_g = 0.788; r_p = 0.512), bean length (r_g = 0.964; r_p = 0.553), bean width (r_g = 0.869; r_p = 0.496) and bean thickness (r_g = 0.607; r_p = 0.419). Significant positive correlation was also found with height (r_g = 0.033) and girth (r_g = 0.544) and significant negative correlation with number of pods per tree (r_g = -0.562) at genotypic level.

Phenotypically significant positive correlation was also observed for number of beans per pod (r_p = 0.315) and pericarp thickness (r_p = 0.227).

Significant negative correlation for number of beans per pod was observed for bean thickness at both (genotypic r_g = -0.529 and phenotypic r_p = -0.203) levels. Significant negative correlation was also observed with pericarp thickness (r_p = -0.123) phenotypically.

Dry weight per bean was found to be significantly and positively correlated at both levels with bean length (r_g = 0.873; r_p = 0.642), bean width (r_g = 0.975; r_p = 0.608), bean thickness (r_g = 0.852; r_p = 0.521) and pericarp thickness (r_g = 0.608; r_p = 0.172). Also significant negative correlation at genotypic level was observed for number of pods per tree (r_g = -0.472) and HD^2 (r_g = -0.473).

Bean length exhibited significant positive correlation with bean width (r_g = 0.820; r_p = 0.698) and bean thickness (r_g = 0.800; r_p = 0.498) both genotypically and phenotypically. Significant negative genotypic correlation was observed for number of pods per tree (r_g = -0.545). Significant positive phenotypic association was also observed with pericarp thickness (r_p = 0.138) and number of pods per tree (r_p = 0.017).

Significant positive correlation at genotypic and phenotypic level was observed for bean width with bean thickness (r_g = 0.852; r_p = 0.567) and pericarp thickness (r_g = 0.795; r_p = 0.131). Also significant negative genotypic correlation was observed with number of pods per tree (r_g = -0.602).

Bean thickness was significantly and positively correlated with height at both genotypic (r_g = 0.343) and phenotypic (r_p = 0.252) levels. Significant negative genotypic correlation was observed with number of pods per tree (r_g = -0.544). Significant positive phenotypic correlation was also seen with pericarp thickness (r_p = 0.154) and girth (r_p = 0.178).

Pericarp thickness was found to be negatively correlated with HD^2 at genotypic level (r_g = -0.559). There was no significant correlation for number of pods per tree with HD^2, height and girth at both levels.

Absence of significant correlation was also noticed for HD^2 with height and girth at both genotypic and phenotypic levels. Height was found to have a significant positive association with girth phenotypically ($r_p = 0.744$).

The correlation coefficients wherever greater than unity, were not considered, as it occurred due to inadequacy of the model.

4.4 Path analysis

The genotypic correlation between growth, yield and yield components were partitioned into direct and indirect effects and presented in Table 8.

Direct effect

The highest direct effect on yield was shown by number of pods per tree (0.908) followed by wet bean weight per pod (0.270). Positive direct effects were observed for bean width (0.053), number of beans per pod (0.014), pod weight (0.013), girth (0.013), pod length (0.011) and bean length (0.003). Traits like dry weight per bean, pod width, plant height (2YAP), HD^2 (6MAS), bean thickness and pericarp thickness exhibited negative direct effects, the value being -0.008, -0.010, -0.010, -0.013, -0.014 and -0.028 respectively.

Indirect effect

1. Pod length

Positive indirect effect of this trait on yield was maximum via wet bean weight per pod (0.135) and negative effect was the highest via pericarp thickness (-0.009) followed by pod width (-0.005) and bean thickness (-0.005).

Table 8. Direct and indirect effects of the different yield components on yield

Characters	Pod length (cm)	Pod width (cm)	Pod weight (g)	Wet bean weight/ pod (g)	Number of beans/ pod	Dry weight/ bean (g)	Bean length (mm)	Bean width (mm)	Bean thickness (mm)	Pericarp thickness (mm)	Number of pods/ tree	HD² (6MAS)	Height (2YAP) (cm)	Girth (2YAP) (cm)
Pod length (cm)	**0.011**	-0.005	0.008	0.135	0.002	-0.003	0.001	0.012	-0.005	-0.009	0.006	0.002	0.001	-0.001
Pod width (cm)	0.005	**-0.010**	0.009	0.134	0.000	-0.003	0.001	0.014	-0.005	-0.011	0.152	0.000	-0.001	0.002
Pod weight (g)	0.007	-0.006	**0.013**	0.174	0.000	-0.003	0.001	0.020	-0.006	-0.018	0.114	0.001	-0.001	0.001
Wet bean wt./pod(g)	0.006	-0.005	0.009	**0.270**	0.004	-0.004	0.002	0.026	-0.006	-0.007	0.063	0.001	0.000	0.001
No. of beans/pod	0.001	0.000	0.001	0.084	**0.014**	0.000	0.000	0.001	0.003	0.004	0.033	0.000	0.000	0.000
Dry wt./bean (g)	0.004	-0.003	0.006	0.138	0.000	**-0.008**	0.002	0.032	-0.007	-0.005	0.027	0.001	-0.001	0.000
Bean length (mm)	0.004	-0.003	0.005	0.149	0.000	-0.005	**0.003**	0.037	-0.007	-0.004	0.018	0.001	0.000	0.001
Bean width (mm)	0.003	-0.003	0.005	0.134	0.000	-0.005	0.002	**0.053**	-0.008	-0.004	0.013	0.002	0.000	0.000
Bean thickness (mm)	0.005	-0.004	0.006	0.116	-0.003	-0.004	0.002	0.031	**-0.014**	-0.005	0.036	0.001	-0.001	0.000
Pericarp thickness (mm)	0.004	-0.004	0.008	0.062	-0.002	-0.001	0.001	0.007	-0.002	**-0.028**	0.083	0.001	-0.001	0.001
No. of pods/tree	0.000	-0.002	0.002	0.019	0.001	0.000	0.000	0.000	-0.001	-0.003	**0.908**	-0.001	-0.001	0.001
HD² (6MAS)	-0.002	0.000	-0.001	-0.015	0.000	0.001	0.000	-0.007	0.001	0.003	0.063	**-0.013**	-0.001	0.003
Height (2YAP-cm)	-0.001	-0.001	0.001	0.002	0.000	-0.001	0.000	0.000	-0.001	-0.002	0.121	-0.001	**-0.010**	0.002
Girth (cm) (2YAP-cm)	-0.001	-0.001	0.001	0.021	0.000	0.000	0.000	0.001	0.000	-0.002	0.091	-0.003	-0.002	**0.013**

Residual effect: 0.056

The diagonal values printed in bold indicate direct effects

2. Pod width

The influence of pod width on yield was maximum through number of pods per tree (0.152) and negative indirect effect was the highest through pericarp thickness (-0.011).

3. Pod weight

Maximum indirect effect of pod weight was exhibited through wet bean weight per pod (0.174) followed by number of pods per tree (0.114). Pericarp thickness (-0.018) had a high negative influence on pod weight affecting yield.

4. Wet bean weight per pod

This trait showed a high direct effect on yield and its indirect effect was the highest via number of pods per tree (0.063) followed by bean width (0.026). Maximum negative effect was through pericarp thickness (-0.007).

5. Number of beans per pod

This character exhibited a positive direct effect on yield. Positive indirect effect was maximum via wet bean weight per pod (0.084).

6. Dry weight per bean

The highest indirect effect on yield was seen through wet bean weight (0.138) and the highest negative indirect effect was via bean thickness (-0.007).

7. Bean length

Positive indirect effect of this trait was the highest on yield via wet bean weight (0.149) followed by bean width (0.037).

8. Bean width

Bean width exhibited maximum positive indirect effect on yield through wet bean weight per pod (0.134) and the highest negative effect through bean thickness (-0.008).

9. Bean thickness

Positive indirect effect was the highest via wet bean weight per pod (0.116) and negative effect was the highest through pericarp thickness (-0.005).

10. Pericarp thickness

The influence of this character on yield was the highest via number of pods per tree (0.083). Negative indirect effect was the highest through pod width (-0.004).

11. Number of pods per tree

The effect of this trait on yield was maximum through wet bean weight per pod (0.019) and negative effect was the highest through pericarp thickness (-0.003).

12. HD^2

HD^2 value of seedlings was found to influence yield indirectly through number of pods per tree (0.063) which was the highest positive value. Negative indirect effect was the highest via wet bean weight per pod (-0.015).

13. Height

The influence on yield was the highest via number of pods per tree (0.121) and through pericarp thickness (-0.002) the highest negative indirect effect was observed.

14. Girth

Positive indirect influence on yield for girth was found to be the highest via number of pods per tree (0.091) and negative indirect effect was the highest through HD^2 (-0.003).

4.5 Heterosis

Relative heterosis (RH), heterobeltiosis (HB) and standard heterosis (SH) values were computed for the 25 hybrids with respect to pod and bean traits (Tables 9, 10 and 11).

1. Yield

Magnitude of relative heterosis varied between -38.06 (H_{22}) to 271.18 (H_{16}). Significant heterosis (RH) estimates were recorded for all the hybrids except H_{17} and positive values were obtained for all the hybrids except H_{22}.

Heterobeltiosis estimates indicated a variation from -54.08 (H_{22}) to 210.00 (H_{16}). Significant positive estimates were recorded for all the hybrids except H_{17} and H_{22}. The variation in values for standard heterosis was from -52.57 (H_{22}) to 149.94 (H_{16}). Significant heterosis (SH) for yield was recorded for all the crosses except H_7 and H_{17}. Except H_7, H_{22} and H_{25} all other hybrids recorded positive heterosis estimates.

2. Pod length

The range of relative heterosis was from -14.58 (H_{15}) to 19.65 (H_4). Except H_8, H_{14} and H_{21} all the hybrids registered significant heterosis estimates. Negative heterosis values were recorded for H_2, H_3, H_8, H_9, H_{12}, H_{15}, H_{17}, H_{18}, H_{20}, H_{22} and H_{25}.

Variation in Heterobeltiosis was from -23.68 (H_{12}) to 16.10 (H_4). Except H_4, H_5, H_9 and H_{13} all hybrids recorded significant negative heterosis.

Table 9. Relative heterosis (%) for pod and bean traits

	Yield (g)	Pod length (cm)	Pod width (cm)	Pod weight (g)	Wet bean weight/pod (g)	No. of beans/pod	Dry weight/ bean (g)	Bean length (mm)	Bean width (mm)	Bean thickness (mm)	Pericarp thickness (mm)	Number of pods/tree
1	2	3	4	5	6	7	8	9	10	11	12	13
H_1	30.85**	9.85**	10.08**	40.45**	36.10**	17.61**	25.00**	11.24**	20.43**	-2.63**	18.39**	-10.62**
H_2	70.68**	-4.88**	5.63**	2.96*	3.12**	20.68**	10.00**	3.21**	7.21**	-1.28*	-4.59**	27.52**
H_3	104.02**	-1.84**	3.50**	5.74**	6.27**	28.26**	-13.04**	-7.46**	-1.19*	-10.71**	6.22**	29.82**
H_4	112.28**	19.65**	10.45**	51.96**	28.46**	-4.60**	104.55**	20.63**	27.47**	35.19**	21.47**	65.80**
H_5	208.17**	8.86**	3.60**	26.59**	8.37**	-10.36**	53.85**	8.98**	4.23**	17.24**	22.35**	167.05**
H_6	177.64**	4.46**	0.00	8.60**	1.56	-5.63**	15.79**	0.00	0.40	1.30*	8.08**	105.94**
H_7	70.18**	-1.29*	3.31**	10.38**	-2.14	-4.27**	5.26**	0.24	-0.21*	5.56**	11.33**	31.98**
H_8	86.32**	-0.38	7.80**	17.87**	1.20	-2.26*	21.62**	12.79**	23.91**	14.52**	19.28**	62.75**
H_9	102.43**	12.17**	8.27**	47.93**	15.97**	-17.40**	77.78**	23.93**	22.91**	44.90**	53.49**	72.44**
H_{10}	148.54**	2.11**	4.23**	13.25**	5.43**	-6.37**	12.36**	6.33**	13.49**	17.65**	18.47**	79.97**
H_{11}	121.26**	4.86**	12.78**	35.65**	36.08**	20.20**	-4.26**	8.82**	6.79**	-4.52**	42.45**	51.75**
H_{12}	118.45**	-3.65**	-6.21**	-0.28	-10.01**	-13.41**	1.12	5.21	-0.47	14.29**	16.05**	104.81**
H_{13}	97.26**	11.76**	3.03**	21.26**	4.73**	-8.15**	48.15**	3.71**	12.90**	29.52**	12.85**	74.50**
H_{14}	92.41**	0.37	-4.11**	-1.44	-15.69**	5.15**	9.76**	7.14**	6.05**	4.55**	17.92**	114.63**
H_{15}	197.42**	-14.58**	-10.13**	-18.15**	-20.97**	9.07**	-20.00**	-4.98**	-2.81**	-5.00**	29.65**	177.67**
H_{16}	271.18**	5.34**	4.83**	6.54**	-10.84**	-8.58**	22.22**	3.18**	10.81**	15.11**	3.14**	318.06**
H_{17}	9.65	-5.19**	-6.12**	-27.13**	-32.48**	-10.02**	-9.09**	-8.10**	0.00	-7.88**	-9.17**	59.75**

Contd.

Table 9. Continued

1	2	3	4	5	6	7	8	9	10	11	12	13
H_{18}	122.08**	-1.36*	-0.68	8.88**	-8.66**	-6.73**	3.09*	-2.42**	-3.25**	0.00	25.61**	108.99**
H_{19}	208.44**	2.54**	-1.45*	20.53**	22.42**	20.24**	-1.96	-2.40**	-6.35**	-14.63**	30.14**	147.57**
H_{20}	113.49**	-3.56**	-4.00**	3.07*	-10.19**	-10.51**	3.09*	-1.74**	0.00	13.43**	19.53**	117.99**
H_{21}	118.79**	0.79	0.72	-2.31	-22.27**	-18.24**	21.95**	-6.69**	-1.26**	6.47**	17.13**	174.71**
H_{22}	-38.06**	-8.44**	-6.76**	-23.68**	-36.32**	-26.50**	-12.00**	-18.50**	-12.00**	-6.21**	-0.48	7.61**
H_{23}	260.80**	6.01**	6.57**	18.10**	31.02**	27.33**	-9.09**	-6.06**	-4.25**	-12.94**	7.14**	186.07**
H_{24}	65.79**	3.78**	6.47**	1.83**	-9.39**	8.65**	-7.69**	-15.29**	-6.76**	-14.29**	9.95**	79.40**
H_{25}	70.52**	-4.10**	-0.67	-3.81**	-6.83**	0.00	-14.29**	-8.69**	-5.18**	2.13**	1.37**	79.97**

*P = 0.05, **P = 0.01

Table 10. Heterobeltiosis (%) for pod and bean traits

Genotypes	Yield (g)	Pod length (cm)	Pod width (cm)	Pod weight (g)	Wet bean weight/pod (g)	No. of beans/pod	Dry weight/ bean (g)	Bean length (mm)	Bean width (mm)	Bean thickness (mm)	Pericarp thickness (mm)	Number of pods/tree
1	2	3	4	5	6	7	8	9	10	11	12	13
H_1	24.96**	-5.23**	9.23**	13.67**	26.13**	-6.91**	-11.11**	-5.39**	0.00	-3.90**	-8.85**	-20.60**
H_2	50.69**	-5.19**	-2.60**	-11.99*	-25.36**	-1.66**	0.00	2.45**	6.25**	-2.53**	-7.96**	-14.38**
H_3	50.63**	-7.51**	-5.13**	-10.11**	-25.13**	4.40**	-28.57**	-16.27**	-11.35**	-17.58**	-1.77*	-22.43**
H_4	68.33**	16.10**	5.71**	28.78**	23.41**	-9.97**	80.00**	10.47**	10.47**	15.87**	-2.94**	35.66**
H_5	190.62**	8.40**	2.86**	16.38**	-6.23**	-20.93**	50.94**	5.81**	2.78**	7.94**	1.96*	143.70**
H_6	162.90**	-12.14**	-5.13**	-11.85**	-26.79**	-7.71**	-21.43**	-15.87**	-11.35**	-14.28**	4.90**	43.70**
H_7	65.55**	-20.00**	-3.70**	-11.29**	-27.31**	-5.35**	-28.57**	-14.11**	-12.23**	-6.17**	10.78**	-3.70**
H_8	71.54**	-11.69**	-1.30*	-15.20**	-22.90**	-5.88**	-18.18**	-3.48**	3.63**	-10.12**	-5.71**	17.29**
H_9	68.15**	8.40**	4.35**	13.43**	3.95**	-23.14**	50.94**	16.67**	4.76**	33.96**	45.59**	31.42**
H_{10}	89.36**	-16.18**	-5.13**	18.85**	-22.01**	-9.72**	-28.57**	-16.67**	-13.46**	-12.08**	-3.13**	12.57**
H_{11}	55.36**	-10.26**	8.70**	8.07**	26.46**	-8.70**	-40.00**	-14.96**	-19.73**	-32.73**	26.92**	2.21**
H_{12}	69.74**	-23.68**	-16.05**	-29.10**	-31.29**	-17.39**	-35.71**	-16.18**	-23.74**	-11.11**	20.51**	32.36**
H_{13}	54.26**	4.72**	0.00	-4.18**	-10.16**	-11.22**	14.29**	-2.88**	-6.25**	13.33**	-14.41**	22.46**
H_{14}	71.82**	-11.04**	-9.09**	-24.62**	-29.95**	-14.76**	-18.18**	-2.99**	8.57**	-12.66**	-2.86**	97.66**
H_{15}	146.64**	-22.63**	-12.35**	-19.73**	-21.16**	8.01**	-28.57**	-12.86**	-12.95**	-6.17**	-3.81**	205.23**
H_{16}	210.00**	-4.55**	-7.79*	-6.44**	-22.74**	-14.80**	0.00	14.42**	9.82**	1.27*	-2.54**	300.21**
H_{17}	-2.65	-11.04**	-10.39**	-29.51**	-38.57**	-19.30**	-9.09**	-17.97**	-0.09**	-11.63**	-12.39**	55.56**

Contd.

Table 10. Continued

1	2	3	4	5	6	7	8	9	10	11	12	13
H_{18}	98.99**	-16.76*	-6.41**	-17.10**	-26.72**	-16.08**	-28.57**	-19.84**	-15.60**	-20.88	7.29**	54.54**
H_{19}	148.52**	-9.62**	-1.45*	3.43*	17.72**	-13.00**	-33.33**	-20.08**	-19.72**	-36.36**	21.79**	105.75**
H_{20}	96.19**	-21.58**	-11.11**	-22.21**	-25.24**	-20.26**	-28.57**	-17.84**	-12.23**	-6.17**	0.00	69.81**
H_{21}	76.08**	-5.19**	0.00	-26.19**	-40.06**	-18.42**	-9.09**	-23.83**	-11.94**	-13.95**	-6.19**	159.66**
H_{22}	-54.08**	-18.50**	-11.54**	-25.70**	-39.61**	-33.99**	-2.14**	-19.14**	-14.18**	-8.79**	-7.96	-17.17**
H_{23}	209.45**	-3.85**	5.80**	16.80**	20.11**	-5.49**	-33.33**	-14.57**	-15.64**	-32.73**	-11.02**	166.04**
H_{24}	13.79*	-3.21**	5.71**	-13.90**	-32.01**	-21.49**	-21.49**	-15.63**	19.09**	-25.66**	6.06**	56.57**
H_{25}	69.01**	-20.00**	-8.64**	-16.93**	-19.11**	-7.64**	-35.71**	-14.94**	-19.39**	-11.11**	-5.93**	55.19**

*P = 0.05, **P = 0.01

Table 11. Standard heterosis (%) for pod and bean traits

Genotypes	Yield (g)	Pod length (cm)	Pod width (cm)	Pod weight (g)	Wet bean weight/pod (g)	No. of beans/pod	Dry weight/ bean (g)	Bean length (mm)	Bean width (mm)	Bean thickness (mm)	Pericarp thickness (mm)	Number of pods/tree
1	2	3	4	5	6	7	8	9	10	11	12	13
H_1	31.57**	0.00	-8.97**	-6.35**	-12.57**	-1.36**	-20.00**	-3.98**	-4.27**	-2.63**	0.98	41.83**
H_2	58.65**	0.69	-3.85**	2.19	-1.36	-3.52**	10.00**	3.98**	1.71**	1.32	1.96*	52.94**
H_3	58.59**	10.34**	-5.13**	5.78**	8.27**	2.7**	0.00	4.98**	6.84**	-1.32*	8.82**	38.56**
H_4	61.30**	-5.52**	-5.13**	-5.54**	-14.45**	-4.61**	-10.00**	-5.47**	-0.85	3.95**	-2.94**	88.24**
H_5	84.15**	-11.03**	-7.69**	-14.64**	-18.01**	-2.71**	-20.00**	-9.45**	-5.13**	-10.53**	1.96*	115.03**
H_6	47.61**	4.83**	-5.13**	1.04**	5.86**	-9.21**	10.00**	5.47**	6.84**	2.63**	4.90**	26.79**
H_7	-0.07	4.83**	0.00	7.13**	-4.40**	-8.94**	0.00	-1.99**	4.27**	0.00	10.78**	-15.03**
H_8	64.38**	-6.21**	2.56**	-1.53	1.88	-0.27	-10.00**	-8.45**	-2.56**	-6.58**	-2.94**	62.75**
H_9	61.12**	-11.03**	-7.69**	-16.81**	-9.11**	-5.42**	-20.00**	-5.97**	5.98**	-6.58**	-2.94**	82.35**
H_{10}	81.45**	0.00	-5.13**	-4.50**	12.77**	-4.33**	0.00	4.48**	4.27**	5.26**	-8.82**	56.21**
H_{11}	48.87**	-3.45**	-3.85**	-7.19**	2.09	-3.25**	-10.00**	2.48**	0.85**	-2.63**	-2.94**	41.83**
H_{12}	62.65**	0.00	-12.82**	-14.38**	-9.63**	-12.47**	-10.00**	-4.48**	-9.40**	-5.26**	-7.84**	83.66**
H_{13}	47.81**	-8.28**	-12.82**	-15.85**	-12.98**	0.81	-20.00**	-9.45**	-10.26**	-10.53**	-0.98**	69.93**
H_{14}	38.52**	-5.52**	-10.26**	-12.47**	-7.43**	4.88**	-10.00**	-2.99**	-2.56**	-9.21**	0.00	43.79**
H_{15}	98.85**	1.38*	-8.98**	3.06*	4.19**	5.96**	0.00	4.48**	3.42**	0.00	-0.98	86.93**
H_{16}	149.94**	2.07**	-2.56**	8.63**	2.09	-3.25**	10.00**	4.98**	5.13**	5.26**	12.75**	145.10**
H_{17}	1.19	-5.52**	-11.54**	-12.42**	-0.94	-0.27	0.00	4.48**	4.27**	0.00	-2.94**	0.65**

Contd.

Table 11. Continued

1	2	3	4	5	6	7	8	9	10	11	12	13
H_{18}	26.09**	-0.69	-6.41**	-2.45*	5.97**	3.25**	0.00	0.50	1.71**	-5.26	0.98*	12.42**
H_{19}	57.47**	-2.76**	-12.82**	-11.18**	2.93*	7.05**	0.00	1.00*	0.85	-7.89**	-6.86**	49.67**
H_{20}	24.31**	2.76**	-7.69**	-6.06**	-1.68	-1.90**	0.00	-1.49**	4.27**	1.00**	-0.98	23.53**
H_{21}	83.03**	-11.72**	10.26**	-8.29**	-3.35**	0.81	0.00	-2.99**	0.85	-2.63**	3.92**	88.89**
H_{22}	-52.27**	-2.76**	-11.54**	-7.68**	-2.62*	-18.43**	10.00**	2.99**	3.42**	9.21**	1.96*	-46.40**
H_{23}	67.40**	3.45**	-6.41**	2.57*	16.34**	7.32**	0.00	7.96**	5.98**	-2.63**	2.94**	49.02**
H_{24}	18.29**	4.14**	-5.13**	6.99**	9.63**	-2.98**	20.00**	7.46**	11.97**	10.53**	2.94**	1.31**
H_{25}	-7.39**	4.83**	-5.13**	0.32	6.39**	4.88**	-10.00**	1.99**	1.71**	-5.26**	8.82**	-13.07**

*P = 0.05, **P = 0.01

Magnitude of Standard heterosis ranged from -11.72 (H_{21}) to 10.34 (H_3). All hybrids except H_2 and H_{18} recorded significant estimates. H_4, H_5, H_8, H_9, H_{11}, H_{13}, H_{14}, H_{17}, H_{18}, H_{19}, H_{21} and H_{22} recorded negative values. H_1, H_{10} and H_{12} recorded zero values.

3. Pod width

The range observed for Relative heterosis was from -10.13 (H_{15}) to 12.78 (H_{11}). Hybrids H_{18}, H_{21} and H_{25} did not record significant values. Positive values were obtained for all hybrids except H_{12}, H_{14}, H_{15}, H_{17}, H_{18}, H_{19}, H_{20}, H_{22} and H_{25}. Heterosis was nil for H_6.

The spectrum of Heterobeltiosis varied between -16.05 (H_{12}) to 9.23 (H_1). All the hybrids recorded significant heterosis values. Except H_1, H_4, H_5, H_9, H_{11}, H_{23} and H_{24} all hybrids recorded negative values. H_{13} and H_{21} had nil heterosis.

The range of Standard heterosis observed was from -12.82 (H_{12}, H_{13} and H_{19}) to 2.56 (H_8). All hybrids except H_7 (Nil heterosis) and H_8 (significant positive heterosis) recorded significant negative heterosis values.

4. Pod weight

Magnitude of Relative heterosis varied from -27.13 (H_{17}) to 51.96 (H_4). All hybrids except H_{12}, H_{14} and H_{21} recorded significant values. Negative values were obtained for H_{12}, H_{14}, H_{15}, H_{17}, H_{21}, H_{22} and H_{25}.

Heterobeltiosis ranged between -29.51 (H_{17}) to 28.78 (H_4). All the hybrids recorded significant values. Hybrids H_1, H_4, H_5, H_9, H_{11}, H_{19} and H_{23} registered significant positive heterosis estimates.

The values for Standard heterosis ranged between -16.81 (H_9) to 7.13 (H_7). Except H_2, H_8 and H_{25} all hybrids had significant SH. Hybrids H_2, H_3, H_6, H_7, H_{16}, H_{23}, H_{24} and H_{25} recorded positive SH estimates.

5. Wet bean weight per pod

The variation in Relative heterosis was from -36.32 (H_{22}) to 36.10 (H_1). Except H_6, H_7 and H_8 all hybrids recorded significant heterosis estimates. Hybrids H_7, H_{12}, H_{14}, H_{15}, H_{16}, H_{17}, H_{18}, H_{20}, H_{21}, H_{22}, H_{24} and H_{25} recorded negative values.

The magnitude of variation in Heterobeltiosis ranged from -40.06 (H_{21}) to 26.46 (H_{11}). All the hybrids exhibited significant heterosis estimates. Hybrids H_1, H_4, H_9, H_{11}, H_{19} and H_{23} recorded significant positive heterosis.

The observed variation for Standard heterosis was from -18.01 (H_5) to 16.34 (H_{23}). Except H_2, H_8, H_{11}, H_{16}, H_{17} and H_{20} all other hybrids recorded significant heterosis (SH). Negative heterosis estimates were obtained for H_1, H_2, H_4, H_5, H_7, H_9, H_{12}, H_{13}, H_{14}, H_{17}, H_{20}, H_{21} and H_{22}.

6. Number of beans per pod

Relative heterosis values ranged from -26.5 (H_{22}) to 28.26 (H_3). All hybrids recorded significant RH values. For H_{25} RH was nil. Except H_1, H_2, H_3, H_{11}, H_{14}, H_{15}, H_{19}, H_{23} and H_{24} all hybrids recorded negative values.

Heterobeltiosis varied between -33.99 (H_{22}) to 8.01 (H_{15}). All the hybrids recorded significant negative values other than H_3 and H_{15} which recorded significant positive values.

Magnitude of Standard heterosis varied between -18.43 (H_{22}) to 7.32 (H_{23}). Significant values were obtained for all the hybrids except H_1, H_8, H_{13}, H_{17} and H_{21}. Hybrids H_3, H_{13}, H_{14}, H_{15}, H_{18}, H_{19}, H_{21}, H_{23} and H_{25} recorded positive heterosis estimates.

7. Dry weight per bean

The spectrum of relative heterosis varied between -20.00 (H_{15}) to 104.55 (H_4). All hybrids except H_3, H_{11}, H_{15}, H_{17}, H_{19}, H_{22}, H_{23}, H_{24} and H_{25} recorded positive values. Except H_{12} and H_{19} significant values were recorded for all hybrids.

Heterobeltiosis ranged from -40.00 (H_{11}) to 80.00 (H_4). All the hybrids recorded significant values for HB. H_4, H_5, H_9 and H_{13} recorded positive HB values. The values for heterobeltiosis was nil for H_2 and H_{16}.

Standard heterosis ranged from -20.00 (H_1, H_5, H_9 and H_{13}) to 20.00 (H_{24}). Significant values for heterosis were obtained for all the hybrids. Heterosis was absent for hybrids H_3, H_7, H_{10}, H_{15}, H_{17}, H_{18}, H_{19}, H_{20}, H_{21} and H_{23}. Positive values were recorded for H_2, H_6, H_{16}, H_{22} and H_{24}.

8. Bean length

The values for Relative heterosis varied between -18.5 (H_{22}) to 23.93 (H_9). Except H_7 and H_{12} significant values were obtained for all the hybrids. H_1, H_2, H_4, H_5, H_7, H_8, H_9, H_{10}, H_{11}, H_{12}, H_{13}, H_{14} and H_{16} recorded positive RH estimates. H_6 recorded nil heterosis.

Magnitude of Heterobeltiosis ranged from -23.83 (H_{21}) to 16.67 (H_9). All the hybrids recorded significant heterosis estimates. Except H_2, H_4, H_5, H_9 and H_{16} all hybrids recorded negative values.

Standard heterosis was observed to range from -9.45 (H_5 and H_{13}) to 7.96 (H_{23}). All values except H_{12} and H_{18} were found to be significant. Negative values were recorded for H_1, H_4, H_5, H_7, H_8, H_9, H_{12}, H_{13}, H_{14}, H_{20} and H_{21}.

9. Bean width

The relative heterosis for this trait varied from -12.00 (H_{22}) to 27.47 (H_4). Significant values were recorded for all the treatments except H_6 and H_{12}. H_3, H_7, H_{12}, H_{15}, H_{18}, H_{19}, H_{21}, H_{22}, H_{23}, H_{24} and H_{25} recorded negative heterosis. H_{17} and H_{20} recorded nil heterosis.

The limits for Heterobeltiosis were -23.74 (H_{12}) to 19.09 (H_{24}). Heterosis was significant for all hybrids. There was no heterosis for H_1. Positive values for heterosis were obtained for H_2, H_4, H_5, H_8, H_9, H_{14}, H_{16} and H_{24}.

The range for Standard heterosis was found to be -10.26 (H_{13}) to 11.97 (H_{24}). Significant heterotic expression were noticed in all hybrids except H_4, H_{19} and H_{21}. Negative heterosis was observed in H_1, H_4, H_5, H_8, H_{12}, H_{13} and H_{14}.

10. Bean thickness

The range observed for this trait was -14.63 (H_{19}) to 44.9 (H_9) for Relative heterosis. Significant heterosis was observed in all the hybrids. Heterosis was absent in H_{18}. Heterotic vigour was observed to be negative for H_1, H_2, H_3, H_{11}, H_{15}, H_{17}, H_{19}, H_{22}, H_{23} and H_{24}.

The values for Heterobeltiosis was found to be in between -36.36 (H_{19}) and 33.96 (H_9). Significant heterotic performance was observed for all the hybrids and H_4, H_5, H_9, H_{13} and H_{16} recorded positive values.

The spectrum of variability in Standard heterosis was from -10.53 (H_5 and H_{13}) to 10.53 (H_{24}). Except H_2 significant heterosis was observed in all the hybrids. Heterosis was absent in H_7, H_{15}, H_{17} and H_{20}. Positive Standard heterosis was recorded for H_2, H_4, H_6, H_{10}, H_{16}, H_{22} and H_{24}.

11. Pericarp thickness

The magnitude of heterosis (Relative heterosis) varied between -9.17 (H_{17}) and 53.49 (H_9). Except H_{22} significant heterosis values were recorded for all hybrids. H_2, H_{17} and H_{22} recorded negative heterosis.

The limits for Heterobeltiosis were -14.41 (H_{13}) and 45.59 (H_9). Significance in heterotic performance was observed for all hybrids. In H_{20} heterosis was not observed and in H_5, H_6, H_7, H_9, H_{11}, H_{12}, H_{18}, H_{19} and H_{24} positive heterosis was seen.

The range observed for Standard heterosis were between -8.82 (H_{10}) and 12.75 (H_{16}). Except H_1, H_{15} and H_{20} significant SH values were obtained for all the hybrids. There was no heterosis in H_{14} and H_4, H_8, H_9, H_{10}, H_{11}, H_{12}, H_{13}, H_{15}, H_{17}, H_{19} and H_{20} recorded negative values for standard heterosis.

12. Number of pods per tree

Magnitude of Relative heterosis was found to vary between -10.62 (H_1) and 318.06 (H_{16}). All the treatments showed significant heterotic performance. Except H_1 all the hybrids showed positive and relatively high heterosis.

The values for Heterobeltiosis ranged from -22.43 (H_3) and 300.21 (H_{16}). Significance in heterotic performance was observed for all the hybrids. Negative heterosis was recorded for H_1, H_2, H_3, H_7 and H_{22}.

The values for Standard heterosis varied between -46.40 (H_{22}) and 145.10 (H_{16}). All the hybrids recorded significant heterotic performance. Negative heterosis was observed in H_7, H_{22} and H_{25}.

4.6 Floral and qualitative traits

The floral characters of the 25 hybrids and the range and mean for each character are presented in Table 12 and 13.

The diameter of the flowers varied between 1.18 cm (H_{18}) and 1.44 cm (H_9) and had a mean of 1.36 cm. Length of the pedicel had a mean of 1.81 cm and ranged from 1.50 cm (H_7) to 1.90 (H_{11}).

The minimum value for sepal length and width were 0.55 cm (H_{18}) and 0.17 cm (H_{13}) respectively, and the maximum value for sepal length and width were 0.78 cm (H_4 and H_{13}) and 0.24 cm (H_8). These traits had a mean of 0.73 cm (sepal length) and 0.23 cm (sepal width).

H_2 and H_9 had the maximum petal length (0.51 cm) whereas H_{18} had the minimum value (0.41 cm). The mean value for this trait was found to be 0.49 cm. Flowers with very low petal width were found in H_{12} and H_{22} (0.18 cm) whereas H_8 and H_{11} had flowers with maximum petal width (0.22 cm). The mean was 0.21 cm.

The spectrum of variability observed for ligule width varied between 0.17 cm (H_{22}) and 0.23 cm (H_{13}) with a mean of 0.21 cm. Staminode length was

Table 12. Catalogue of floral traits in cocoa hybrids

	Flower diameter (cm)	Pedicel length (cm)	Sepal length (cm)	Sepal width (cm)	Petal length (cm)	Petal width (cm)	Ligule width (cm)	Staminode length (cm)	Ovary length (cm)	Ovary width (cm)	Style length (cm)
1	2	3	4	5	6	7	8	9	10	11	12
H_1	1.32	1.69	0.71	0.22	0.43	0.21	0.19	**0.42**	0.13	0.10	0.20
H_2	1.33	1.83	0.73	0.22	**0.51**	0.21	0.22	0.49	0.16	0.10	**0.27**
H_3	1.34	1.69	0.75	**0.17**	0.49	0.19	0.18	0.52	0.15	0.10	0.20
H_4	1.40	1.66	**0.78**	0.21	0.45	0.20	0.20	0.51	**0.11**	0.10	0.21
H_5	1.27	1.55	0.60	0.20	0.45	0.19	0.18	**0.42**	0.12	0.10	0.22
H_6	1.38	1.88	0.63	0.20	0.48	0.19	0.19	0.47	0.13	**0.09**	0.20
H_7	1.30	**1.50**	0.72	0.21	0.46	0.21	0.21	0.52	0.15	0.10	0.21
H_8	1.30	1.70	0.69	**0.24**	0.44	**0.22**	0.21	0.51	0.15	0.10	0.23
H_9	**1.44**	1.81	0.77	0.22	**0.51**	0.21	0.21	0.51	0.14	**0.12**	0.25
H_{10}	1.42	1.78	0.77	0.22	0.49	0.21	0.19	**0.53**	0.15	0.10	0.26
H_{11}	1.40	**1.90**	0.69	0.22	0.49	**0.22**	0.22	0.49	0.15	0.10	0.23
H_{12}	1.28	1.70	0.66	0.20	0.44	**0.18**	0.18	0.52	0.13	0.10	**0.18**
H_{13}	1.34	1.79	**0.78**	0.22	0.46	0.21	**0.23**	**0.53**	0.13	0.10	0.23
H_{14}	1.29	1.87	0.73	0.23	0.44	0.21	0.22	0.48	**0.17**	0.11	0.23
H_{15}	1.26	1.52	0.71	0.20	0.42	0.20	0.19	0.47	0.16	0.11	0.21

Contd.

Table 12. Continued

1	2	3	4	5	6	7	8	9	10	11	12
H_{16}	1.29	1.89	0.66	0.22	0.44	0.20	0.20	0.47	0.19	0.11	0.26
H_{17}	1.22	1.78	0.67	0.20	0.45	0.19	0.19	0.48	0.15	0.10	0.25
H_{18}	**1.18**	1.65	**0.55**	0.21	**0.41**	0.20	0.19	0.48	0.13	0.10	0.20
H_{19}	1.33	1.71	0.65	0.20	0.42	0.19	0.19	0.51	0.16	0.10	0.20
H_{20}	1.37	1.82	0.73	0.23	0.44	0.20	0.22	0.45	0.12	0.10	0.24
H_{21}	1.31	1.70	0.73	0.21	0.44	0.21	0.21	0.46	0.13	0.10	**0.18**
H_{22}	1.37	1.70	0.70	0.20	0.43	**0.18**	**0.17**	0.51	0.12	0.10	0.22
H_{23}	1.32	1.77	0.64	0.19	0.48	0.19	0.21	0.49	0.13	0.10	0.23
H_{24}	1.23	1.84	0.69	0.20	0.45	0.19	0.18	0.49	0.15	0.10	0.25
H_{25}	1.26	1.78	0.69	0.22	0.46	0.20	0.20	0.51	0.15	0.11	0.22
Bulk	1.23	1.81	0.72	0.23	0.49	0.21	0.22	0.47	0.15	0.11	0.22

Table 13. Range and mean values of the different floral traits

Characters	Range (cm)	Mean (cm)
Flower diameter	1.18 - 1.44	1.36
Pedicel length	1.50 - 1.90	1.81
Sepal length	0.55 - 0.78	0.73
Sepal width	0.17 - 0.24	0.23
Petal length	0.41 - 0.51	0.49
Petal width	0.18 - 0.22	0.21
Ligule width	0.17 - 0.23	0.21
Staminode length	0.42 - 0.53	0.51
Ovary length	0.11 - 0.17	0.15
Ovary width	0.09 - 0.12	0.10
Style length	0.18 - 0.27	0.23

found to be maximum for H_{10} and H_{13} (0.53 cm) and minimum for H_1 and H_5 (0.42 cm). The mean value for this trait was found to be 0.51 cm.

The magnitude of variability for ovary length and width was very low. The length of ovary had a mean of 0.15 cm and it ranged from 0.11 cm (H_4) to 0.17 cm (H_{14}). Ovary width varied between 0.09 cm (H_6) and 0.12 cm (H_9) with a mean of (0.10 cm). H_{12} and H_{21} had the minimum style length (0.18 cm) and H_2 had the maximum value for style length (0.27 cm). The mean value was 0.23 cm.

A catalogue of pod morphology descriptors, colour of flush, sepal and beans was compiled.

Flush colour was recorded based on anthocyanin intensity and it ranged from green to intense red in the various hybrids. Sepal colour was found to range from cream to greenish cream. The colour of pods before ripening were generally green except for H_2 and H_{16} which had pigmented pods and at ripening the colour ranged from green to yellow. The apex end of the pods varied between acute and rounded. The various hybrids exhibited variation in pods for base form from no shoulder to intermediate shoulder. The surface of the pods were graded visually for the presence of protuberances and the pods were found to range from slight to intermediate rugosity.

The colour of beans were recorded after peeling the mucilagenous coat. It was found to range between slight purple to dark purple in the various hybrids.

Table 14. Catalogue of qualitative traits in cocoa hybrids

Hybrids	Flush colour	Sepal colour	Pod colour before ripening	Pod colour at ripening	Apex form	Pod base form	Pod surface rugosity	Bean colour
H_1	3	1	0	3	3	2	3	4
H_2	5	0	1	3	3	1	3	4
H_3	7	1	0	3	2	2	3	3
H_4	7	0	0	3	3	1	3	4
H_5	3	0	0	3	4	0	3	4
H_5	0	1	0	3	3	1	5	4
H_6	3	0	0	3	2	2	3	3
H_7	3	0	0	5	3	1	3	4
H_8	3	0	0	3	4	1	3	4
H_9	5	0	0	3	2	1	5	4
H_{10}	5	1	0	3	3	1	3	4
H_{11}	5	0	0	3	2	2	3	3
H_{12}	7	0	0	3	3	1	3	3
H_{13}	3	0	0	3	3	0	5	4
H_{14}	3	0	0	3	2	2	3	3
H_{15}	5	1	1	5	3	2	3	3
H_{16}	3	0	0	3	3	1	3	3
H_{17}	3	0	0	3	3	1	5	5
H_{18}	0	0	0	3	3	1	5	3
H_{19}	3	0	0	3	3	2	5	4
H_{20}	0	1	0	3	3	0	3	4
H_{21}	0	0	0	3	2	2	5	4
H_{22}	0	1	0	0	3	2	3	4
H_{23}	3	1	0	0	2	2	5	3
H_{24}	0	1	0	3	3	2	5	4
Bulk	7	1	0	3	2	1	5	4

5. DISCUSSION

In any breeding programme, information on the genetic mechanism of the crop is very crucial. Cocoa is a crop with a highly complicated genetic background with its self/cross incompatibility and high degree of heterozygosity. Moreover, in such perennial crops, formulation of effective breeding programmes is highly time consuming due to the long juvenile phase. Evaluation, if made possible during the early years of the crop, may be of immense use for further selection and other breeding works. In this background, the present investigations were carried out to assess the genetic parameters in specific crosses of cocoa during the early years of bearing.

5.1 Variability

Considerable knowledge on the genetic variability present in the crop is important for formulating effective crop improvement programmes. The results of the present study showed significant difference for most of the traits studied like yield, pod length, pod width, wet bean weight per pod, number of beans per pod, dry weight per bean, bean length, bean width, bean thickness, pericarp thickness, number of pods per tree and girth. The estimates of pcv were higher than gcv for all the traits studied revealing the higher influence of environment in trait expression. Similar observations have been made by Kaushik *et al.* (1996).

High gcv and pcv were observed for yield. Pound(1932), Enriquez and Soria (1966), Tan (1981), Cherian *et al.*(1996) and Francies (1998) have reported considerable variability for yield in the hybrids studied by them.

Pod length and pod width showed relatively moderate variability among the hybrids as revealed by their gcv and pcv. Variability for these traits have also been reported earlier by Soria *et al.* (1974) and Kumaran and Prasannakumari (1982). Significant variability for pod weight was reported by Soria (1975) and Cherian *et al.* (1996). The results of the present study confirmed the reports by the above authors. Influence of environment on the expression of pod weight, was revealed by its higher pcv.

The gcv and pcv for wet bean weight per pod and number of beans per pod revealed the magnitude of variability among the different hybrids. For both the traits, influence of environment was found to be high. Variability for wet bean weight per pod was reported by Soria *et al.* (1974), Kumaran and Prasannakumari (1982) and Cherian *et al.* (1996). Lockwood and Edward (1980) and Subramonian and Balasimha (1982) reported significant variability for bean number per pod.

All the hybrids, in general recorded high dry bean weight with values above 0.8g, which indicates their superiority. Dry weight per bean showed comparatively higher variability as revealed by their high gcv and pcv. Subramonian and Balasimha (1982) also reported similar results.

For traits like bean length and bean width the gcv and pcv were closer indicating the lower environmental influence on the expression of these traits.

Significant variability was observed for bean thickness and the pcv was moderate. The influence of environment was very high on pericarp thickness as revealed by the distance between the gcv and pcv. High degree of variability for husk thickness has also been reported by Kumaran and Prasannakumari (1982).

The different hybrids exhibited high variability with respect to number of pods per tree. Cherian *et al.*(1996) also reported maximum variability for this trait in the hybrids studied by them.The high influence of environment was evident from the high pcv.

Very high gcv and pcv were obtained for HD^2 (6MAS). The influence of environment was found to be very low on the expression of this trait as the gcv and pcv were closer.

Relatively moderate variability was observed for height (2YAP) whereas, for girth (2YAP) very low gcv and pcv were recorded. The collar girth was more influenced by the environment than plant height. Francies (1998) reported low gcv and pcv for this traits.

5.2 Heritability

The heritability of a metric character expresses, the proportion of the total variance that is attributable to the average effects of genes, and this is what determines the degree of resemblance between relatives. The results of the present investigation indicated a low heritability and genetic gain for almost all the traits. This shows the preponderance of non-additive gene action and high influence of environment.

Yield recorded a low heritability coupled with moderate genetic gain. Soria *et al.* (1974) reported a low heritability for yield and Francies (1998) reported a moderate heritability for yield. However, in contrast to the results of the present study, Soria (1975), Palaniappan and Shamsuddin (1989) and Napitupulu (1992b) indicated high heritability estimates for yield. This may be due to the fact that the hybrids used in the study were in their early years of bearing.

Pod size (length, width and weight) registered low heritability coupled with low genetic gain. Francies (1998) also recorded a low heritability along with low genetic gain for pod size. Cherian (1993) observed a very high heritability for pod size (length and weight) in his studies with nine year old hybrids.

The results of the study showed the relative importance of the non-additive genetic effects over the additive genetic effects for wet bean weight per pod. This trait recorded lower values for heritability and genetic gain. This is in agreement with the findings reported by Dias and Kageyama (1995). However, Cherian (1993) reported a high heritability for weight of beans with pulp in older hybrids.

Number of beans per pod exhibited relatively moderate heritability. Among the different traits studied, the highest heritability was recorded by this trait. Report by Kumaran and Prasannakumari (1982) also indicated the predominance of non-additive gene action for this trait. However, Ramirez and Enriquez (1988) observed a high heritability estimate for bean number per pod.

Cherian (1993) observed a very high heritability for dry bean weight. In contrast to his findings, the hybrids in the present study registered a low heritability and genetic gain. This may be due to the fact that the hybrids included in the study did not attain steady bearing.

Bean length and thickness recorded negative estimates for heritability. Bean width registered a comparatively moderate heritability coupled with low genetic gain indicative of non-additive gene action. Hence selection for these traits will not be rewarding. Reports by Glendinning (1963), Napitupulu (1992a) and Francies (1998) indicated that bean size in cocoa is a highly heritable trait.

Ramirez and Enriquez (1988), Cherian (1993) and Francies (1998) reported low heritability for pod husk thickness and the results of the present investigations were in agreement with the above reports with a low heritability and low genetic gain.

Number of pods per tree had a low heritability coupled with a moderate genetic gain. The effect of additive and non-additive genes were comparatively closer. Hence the trait may give moderate response to selection. Low heritability for pod number has been reported by Napitupulu (1992a).

Height (2YAP) recorded a negative estimate and girth (2YAP) a low value for heritability. The genetic gain was also low. This is contradictory to the report by Francies (1998). She observed a moderate heritability estimate for plant height and girth.

In general, the low heritability and genetic gain for all the traits indicated the major role played by the non-additive genes and influence of environment. Hence, at this early bearing stage, there is less scope for selection as most of the traits are accounted for by non-additive effects.

5.3 Correlation studies

Yield is a complex character contributed by many mutually related components. Hence information on the magnitude of relationship of individual yield components to the final yield and interrelationship among themselves would help the breeder for identification of characters which could influence the economic traits.

Significant positive correlation was observed between yield and number of pods per tree both at the genotypic and phenotypic levels. Higher value of genotypic correlation coefficient indicates a strong association between these traits at the genotypic level. The results are in agreement with the reports by Moses and Enriquez (1981) and Cherian (1993). Yield was also found to be significantly correlated with height and girth of the tree (2 YAP). Similar results have been reported by Soria (1975) and Francies (1998).

In cocoa, selection of seedlings is being made usually, based on HD^2 values. But the present study revealed that there is no significant association between seedling vigour as recorded by HD^2 (6 MAS) and yield, which was contradictory to the observations made by Enriquez (1981) and Paulin *et al.* (1993). They reported the existence of a close association between seeding vigour and yield. However, the results of the study is in agreement with the observations by Francies (1998) who reported the absence of correlation between yield and growth in the juvenile phase. The reason for lack of positive correlation in the present study and that by Francies (1998) between yield and early vigour of seedlings might be attributed to the fact that yield has been observed only during the initial years of bearing. Therefore, observations have to be continued, and confirmatory results could be obtained only after stable bearing is attained.

There was significant association between pod length and pod weight. This confirms the report by Kumaran and Prasannakumari (1982). Pod length was also significantly correlated with wet weight of beans and seed size. The effect of environment on these traits was low, as indicated by the higher genotypic correlation coefficient. The negative correlation between pod length and number of pods suggested that more the number of pods per tree, lesser will be the length of pods produced. Seedling vigour was also found to have an inverse relationship with pod length.

The genotypic coefficients were found to be higher than phenotypic coefficients for pod width and traits like pod weight, bean width and pericarp thickness indicating a strong association between these traits at the genotypic level.

Pod weight exhibited a close association with wet and dry weight of beans, seed size and pericarp thickness. Glendinning (1963) reported the existence of a significant correlation between pod weight and seed size. A negative correlation was observed for pod weight with pod number per tree and HD^2 (6 MAS). This implies that as the pod number increases the pod size reduces.

Strong association at the genotypic level was observed between wet weight of beans and dry bean weight. Similar results have been reported by Francies (1998). Wet bean weight was also correlated with bean size, height and girth (2 YAP). It was also noted that as the wet bean weight increased, the number of beans per pod and pericarp thickness also increased. The high phenotypic correlation coefficients suggest the role of environment in influencing these traits.

An inverse relationship between wet weight of beans and pod number per tree was observed. This indicates that as the pod production increases, wet bean weight per pod reduces. This may be due to the diversion of nutrients towards the production of more number of pods of small sized beans.

The relationship between bean number and bean thickness was negative. Engels (1983) also observed simillar results.

The high genotypic correlation coefficients observed for dry bean weight with bean size and husk thickness indicate the strong interrelationship between these traits at the genotypic level.

Length, width and thickness of beans (bean size) were strongly associated among themselves at the genotypic level with little influence of environment. Contradictory to the report by Francies (1998), bean size exhibited a negative correlation with pod number.

Husk thickness and seedling vigour (HD^2 at 6 MAS) were found to have an inverse relationship. Height and girth of the tree were phenotypically associated in a way, that an increase in height may favour an increase in girth.

It can be inferred that number of pods per tree is a major contributing character to yield, which has a strong positive genotypic correlation. In general, the genotypic correlation coefficients were higher than phenotypic correlation coefficients indicating the smaller influence of environment on the association between the different traits.

5.4 Path analysis

Path coefficient analysis reveals the direct and indirect association of different traits with yield. It is used to predict the effect of selection based on an independent character with reference to its dependent character.

The genotypic correlation coefficients were partitioned into direct and indirect effects on yield. It was observed that pod number per tree had the highest positive direct effect on yield. Cherian (1993) has observed similar results various cocoa hybrids studied by him. This suggests the usefulness of this trait as an index of selection for high yielding cocoa genotypes.

Wet bean weight was the trait with the next highest direct effect on yield and hence the next yield contributing trait. Cherian (1993) also observed that wet weight of beans was the second best character contributing to yield next to pod number. Bean width, bean number, pod length, pod weight and girth of the tree also exhibited positive direct effect on yield. This reveals a true association of these traits with yield and hence direct selection for these characters will bring about desirable yield improvement. The effect of bean length was negligible. Traits like dry weight of beans, pod width, height HD^2 (2 YAP), bean thickness and pericarp thickness exhibited negative direct effects on yield.

Pod length had a positive direct effect on yield though negatively correlated with yield. This was made possible through the high indirect effect of wet bean weight per pod.

The negative direct effect of pod width on yield and the negative correlation reflects the negative association of this trait with yield. Similar results have been reported by Francies (1998).

The high direct effect of pod weight on yield was made possible through the indirect effects of wet bean weight per pod and number of pods per tree. But negative correlation was observed due to the modifying indirect effects of pericarp thickness. Wet bean weight had a positive direct effect on yield and selection can be made via. number of pods per tree.

Number of beans per pod exhibited positive direct effects though the correlation was found to be negative, which was made possible through the high indirect effect of wet bean weight per pod and number of pods per tree.

Dry weight of beans had a negative direct effect on yield and selection can be made through wet bean weight and pod number per tree. This was contradictory to the observation by Cherian (1993) who reported a positive direct effect for bean dry weight.

The effect of bean length on yield was observed to be negligible and hence need not be considered. Bean width contributed positively to yield and hence selection for this trait can be done via wet weight of beans and number of pods per tree.

Bean thickness and husk thickness were found to have negative direct effects on yield and was also negatively correlated with yield. As for all the above traits, selection can be done via wet bean weight and number of pods per tree since these traits had a high positive indirect effect.

Number of pods per tree had the maximum direct effect on yield which revealed the use of this trait in selection for superior types.

A negative direct effect was observed for HD^2 on yield. The correlation with yield was also negative. Almeida *et al.* (1994) reported a negative direct effect of height on yield as it was observed in the present study. Girth of the tree had a positive direct effect contributed by wet weight of beans and pod number.

Hence, in general, selection for yield considering pod number per tree may be rewarding since it indirectly influences all other traits.

5.5 Heterosis

Hybridisation is important as it contributes to genetic variability in crops. Reports on heterosis in cocoa was made early in 1943 by Posnette and later confirmed by Montserrin *et al.* (1957).

Among the 25 cross combinations, the number of hybrids which expressed significant positive relative heterosis estimates varied from 11 to 18. For number of pods per tree, yield and pericarp thickness heterotic vigour was observed in 24, 23 and 22 hybrids respectively. Yew *et al.* (1991) and Cherian (1993) have reported significant heterosis estimates for yield. In the present study H_{16} exhibited the highest heterotic estimate for yield. In contrast to the observations by Francies (1998), the results of the present study showed high heterosis estimates for pericarp thickness. Engels (1985) reported the absence of heterotic expression for number of beans per pod. However in the present investigations significant heterosis was found in nine hybrids with respect to number of beans per pod.

The number of hybrids which showed significant positive values for heterobeltiosis was found in the range of four to nine. However for yield and number of pods per tree hybrids that expressed heterosis equalled 23 and 20 respectively.

The standard heterosis estimates in the hybrids for various traits ranged from one to twelve. For yield and number of pods per tree heterotic expression was observed in 21 hybrids whereas for bean width heterotic vigour was found in 15 hybrids. The results of the present study for standard heterosis was contradictory to the report by Francies (1998). She reported the absence of significant positive standard heterosis for bean width, in a population of half-sibs.

The data indicated that H_{23} (G VI-59 x G VI-64) was the best cross combination. This exhibited very high heterotic performance for yield, number of pods per tree and wet bean weight per pod. This implies that the specific combining ability (sca) of the parents was good due to better complementation of desirable genes. H_{16} (G II-19.5 x G VI-64) and H_5 (M-13.12 x G VI-24) were found to be the next best cross combinations with high heterosis for yield and number of pods per tree. The data suggested that the parents of the hybrids H_{23}, H_{16}, and H_5 could be successfully used for raising biclonal seed gardens.

The performance of H_{22} (G VI-51 x S-28.3) was found to be very poor and it recorded a negative heterosis estimate for all the traits (HB). H_{17} (G II-19.5 x S-28.3) also revealed a similar trend in heterotic expression and recorded a positive estimate only for pod number (HB). This indicates the poor specific combining ability of the crosses G VI-51 x S-28.3 and G II-19.5 x S-28.3 though the general combining ability of the parents was good.

5.6 Floral and qualitative traits

The various floral and qualitative traits were evaluated according to IBPGR descriptor list. Flower diameter, pedicel length and sepal length exhibited a low variability among the various hybrids. For all other traits, the variability was negligible. H_9 was found to have maximum flower diameter, petal length and ovary width. Flush colour ranged from green to intense red. Pod colour before ripening was uniform in all the hybrids except H_2 and H_{16} which had pigmented pod. The apex, base and surface of pods and colour of beans exhibited a wide spectrum of variation in the different hybrids. The hybrids exhibited wide variability for the various qualitative traits due to the high degree of heterozygosity in the segregating population.

Summary

6. SUMMARY

The present study entitled `Estimation of genetic parameters from specific crosses of cocoa (*Theobroma cacao* L.)' was carried out in the Department of Plantation Crops and Spices and CCRP, College of Horticulture, Kerala Agricultural University, Vellanikkara, Thrissur during 1998-99.

The programme envisaged the assessment of performance, variability, heritability, extent of association of several traits with yield including the direct and indirect effects of traits on yield and the extent of heterotic expression in 25 cross combinations of cocoa during their early years of bearing. The design adopted for the experiment was RBD with three replications. The data were subjected to statistical analysis. The salient findings are summarised below:

1. The analysis of variance revealed that the 25 hybrids varied significantly with respect to most of the characters studied viz. yield, pod length, pod width, wet weight of beans, dry weight per bean, number of beans per pod, bean size, pod number, pericarp thickness, seedling vigour and girth of the tree.
2. Maximum yield of 3665.8 g was obtained from H_{16} (G II-19.5 x G VI-64). It also recorded a maximum of 37.5 pods per tree. H_{23} (G VI-59 x G VI-64) recorded the maximum wet bean weight per pod (111.1 g). It also recorded the highest number of beans per pod (39.6). All the hybrids included in the study recorded high dry weight per bean (0.8g and above) which indicated the superiority of hybrids.
3. The estimates of pcv were higher than gcv for all the traits studied indicating the high influence of environment on trait expression. HD^2(6MAS), number of pods per tree, yield, dry weight per bean and wet weight per pod showed higher gcv when compared to other traits.

4. Low heritability and genetic gain was evident for most of the traits. This indicated the preponderance of non-additive gene action and high influence of environment. The highest heritability was recorded by number of beans per pod (28.79 %) followed by bean width (18.21 %). Seedling vigour (HD^2 at 6MAS) recorded a high genetic gain. Moderate genetic gain was registered for yield and number of pods per tree.
5. Yield was positively correlated with number of pods per tree, height (2YAP) and girth (2YAP) genotypically. Significant phenotypic correlation with yield was observed for all the traits except HD^2 (6MAS), height (2YAP) and girth (2YAP).
6. There was no significant association between seedling vigour as recorded by HD^2 (6MAS) and yield (4YAP).
7. The results of path analysis suggested that number of pods per tree had the highest direct effect on yield followed by wet bean weight per pod. The positive correlations of most of the other traits with yield were made possible through the indirect effects of these traits.
8. Traits like yield and number of pods per tree showed high heterotic expression in most of the hybrids. Among the 25 cross combinations H_{23} (G VI-59 x G VI-64) was found to be the superior one with very high heterosis estimates for yield, number of pods per tree and wet weight of beans followed by H_{16} (G II-19.5 x G VI-64) and H_5 (M-13.12 x G VI-24). The parents of these cross combinations had a good specific combining ability. Hence they can be used for raising biclonal seed gardens.

9. Observations on floral traits indicated that only flower diameter, pedicel length and sepal length showed some extent of variability. The other traits did not differ markedly among the hybrids.

10. Flush colour showed wide variation from green to intense red. Except H_2 and H_{16} which had pigmented pods, all the other hybrids had green coloured pods before ripening. Variation was also noticed in pod apex form, base form and surface rugosity and bean colour among the different hybrids.

11. As the study has been conducted on hybrids in their early years of bearing, the results are to be confirmed by repeating the experiment after attainment of steady bearing.

References

REFERENCES

Almeida, C.M.V.C.D., Vencovsky, R., Cruz, C.D. and Bartley, B.G.D. 1994. Path analysis of yield components of cacao hybrids (*Theobroma cacao* L.) *Revista-Brasileira-de-Genetica* **17**(2):181-186

Anonymous. 1999. Cocoa Market Report No. 364, ED and F. Man Cocoa Ltd.,p.12

Atanda, O.A., Murray, D.B., Jones, E., Quesnel, V.C., Chaimers, W.S., Fordham, R. and Iton, E.F. 1972. Heterotic pod production of double over single crosses in *Theobroma cacao* L. *Proc. IV Int. Cacao Res. Conf.* St. Augustine, Trinidad, p.82-89

Barriga, J.P., Machado, P.F.R., Almeida, C.M.V.C.D. and Almeida, C.F.G.D. 1992. *Preservacao, e utilizacao dos recorsos geneticos de cacao na Amazonia Brasileira. Comunicado Tecnico Especial-Comissao Executiva do Plano de Lavoura Cacaveira Copes* **5**:24

Bavappa, K.V.A. and Ramachander, P.R. 1967. Improvement of arecanut palm *Areca catechu* L. *Indian J. Genet.* **27**:93-100

Burton, G.W. 1952. Quantitative inheritance in grasses. *Proc. VI Int. Grassland Cong.* **1**:277-283

Castro, G.C.T.D. and Bartley, B:G.D. 1985. Characteristics of cocoa genetic resources. II. Flowers of Bahia selections of the SIC and SIAL. *Revista-Theobroma* **15**(2):49-55

Cherian, H. 1993. Genetic analysis of yield attributes in cocoa (*Theobroma cacao* L.) M.Sc.(Ag.) thesis, Kerala Agricultural University, Thrissur, p.146

Cherian, H., Vijayakumar, N.K. and Nair, R.V. 1996. Evaluation of variability in crosses and their parent populations of cacao (*Theobroma cacao* L.) *J. Plantn Crops* **24**(1):43-49

Cilas, C., Amefia, Y., Legrand, B. and Pelissou, H. 1985. *Etude de la stabilite' du caracters de productivite' chez le cacaoyer. Cafe', Cacao, The'*. **29** (2):89-94

Cilas, C., Duchemin, C. and Lotode, R. 1989. *L' amelioration genetique de la qualite' du Cacao: e' tude de la granulometric. Cafe', Cacao, The'*. **33**(1):3-8

Dias, L.A.S. and Kageyama, P.Y. 1995. Combining ability for cacao (*Theobroma cacao* L.) yield components under Southern Bahia conditions. *Theoritical Appl. Genet.* **90**(3-4):534-541

Dias, L.A.S. and Kageyama, P.Y. 1997. Multivariate genetic divergence and hybrid performance of cacao (*Theobroma cacao* L.) *Brazilian J. Genet.* **20**(1):63-70

Engels, J.M.M. 1983. A systematic description of cacao clones. III. Relationships between clones, between characteristics and some consequences for the cacao breeding. *Euphytica* **32**:719-733

Engels, J.M.M. 1985. A systematic description of cacao clones. V. Quantitative genetic aspects of several fruit characters. *Cafe', Cacao, The'*. **29**(1):3-10

Enriquez, G.A. 1981. Early selection for vigour of hybrid seedlings. *Proc.* VIII *Int. Cocoa Res. Conf.* p.535-539

Enriquez, C.G.A. and Soria, B.J. 1966. *Estudio de la variabilidad de varias characteristicas de las mazorcas de cacao* (*Theobroma cacao* L.) *Fitotecnia Latinoamericana* **3**(1-2):99-118

Eskes, A.B., Beck, M.A. and Toxopeus, H.1977.Variation and correlations of some pod and bean values in cacao (*Theobroma cacao* L.) with reference to the parental effects on fruit setting and bean number. *Turrialba* **27**(2):193-198

Francies, R.M. 1998. Genetic analysis of certain clones, hybrids and inbreds in cocoa. Ph.D. thesis, Kerala Agricultural University, Thrissur, p.213

Glendinning, D.R. 1963. The inheritance of bean size, pod size and number of beans per pod in cocoa (*Theobroma cacao* L.) with a note on bean shape. *Euphytica* 12(13):311-322

Glendinning, D.R. 1966. The relationship between growth and yield in cacao varieties. *Euphytica* 9(35):1-355

Harris, S.A. and Napitupulu, L.A. 1992. Evaluation of yield and its components of some Trinitario type cocoa clones at Aek Pancur estate. *Buletin Perkebunan* 23(3):155-166

Hunter, J.R. 1990. The status of cacao in the western hemisphere. *Econ. Bot.* 44(4):425-439

IBPGR. 1981. Genetic resources of cocoa. IBPGR working group on Genetic Resources of Cocoa. IBPGR Secretariat, Rome

Jacob, V.J. and Atanda, O.A. 1971. Podvalue studies of Amelonado and Amazon cacao. *Proc. SAN Conf.* March, 1971. Ile-Ife

Jacob, V.J., Atanda, O.A. and Opeke, L.K. 1971. Cacao breeding in Nigeria. *Progress in Tree Crop Research in Nigeria*. Cocoa Research Institute of Nigeria, Ibadan, p.9-21

Johnson, H.W., Robinson, H.F. and Comstock, R.E. 1955. Estimates of genetic and environmental variability in soybean. *Agron. J.* 47:314-318

Kaushik, S.K., Sharma, S.C., Panwar, I.S. and Sharma, G.R. 1996. Effectiveness of sibmating in wheat breeding. *Indian J. Genet.* 56(2):202-206

Kee, L.H. and Bal, D. 1976. Performance of cocoa hybrids in two early progeny trials on BAL estates. *Proc. East Malaysia Planters Association*, Sandakan, Sabah,p.47-57

Kumaran, K. and Prasannakumari, S. 1982. Genetic variability and correlation of some pod and bean characters in cocoa 'Forastero'. *Proc. IV Annual Symp. Plantn Crops* (Placrosym IV) (Ed. Vishveshwara, S.) Mysore, p.183-190

Lachenaud, P. 1984. A method of evaluating fresh seed yield which can be applied to completely randomised trials. *Cafe', Cacao, The'.* **28**(2):83-88

Lachenaud, P. 1994. Description of incomplete pod filling in *Theobroma cacao* L. in the Cote-d' Ivoire. *Cafe', Cacao, The'.* **38**(2):81-89

Lerceteau, E., Robert, T., Petiard, V. and Crouzillat, D. 1997. Evaluation of the extent of genetic variability among *Theobroma cacao* accessions using RAPD and RFLP markers. *Theoretical Appl. Genet.* **95**:1-2, 10-19, 46

Liyanage, D.V. 1967. Identification of genotype of coconut palms suitable for breeding. *Exp. Agric.* **3**:205-210

Lockwood, G. 1976. A comparison of the growth and yield during a 20 year period of Amelonado and Upper Amazon hybrid cocoa in Ghana. *Euphytica* **25**(3):647-658

Lockwood, G. 1977. Reflection on yield from hybrid cocoa varieties in Ghana. *Cocoa Grower's Bull.* **26**:4-10

Lockwood, G. and Edward, D.F. 1980. Determination of pod and bean characters in progeny trials with cocoa. *Trop. Agric.* **57**(4):289-300

Lopez, O., Enriquez, G.A. and Soria, V.J. 1988. *Herencia del numero de ovules por ovario en Theobroma cacao L. Turrialba* **38**(3):163-167

Mejia, P.V.E. and Rondon, C.J.G. 1981. *Estudio comparative de seis hibridos de cacao en la zona de Uraba, Columbia. Proc. VIII Int. Cocoa Res. Conf.* Lagos, Nigeria, p.689-693

Monte, M.J.S., Alvum, P., Machado, R.C.R. and Miller, M.W. 1985. Evaluation of production potential of the cacoa tree based on the analysis of young plant growth. *Proc. IX Int. Cocoa. Res. Conf.*, Layos, Nigeria, p. 131-136

Montserrin, B.G., Verteuil, L.L.D. and Freeman, W.E. 1957. A note on cocoa hybridisation in Trinidad with reference to clonal selection and hybrid seed. *Carribean Comm. Public Exch. Service* No.33

Morera, J. and Mora, A. 1991. Comparison of 56 interclonal crosses of cocoa in Pococi, Costa Rica. *Turrialba* 41(4):578-582

Morera, J., Mora, A. and Paredes, A.C. 1991. Characterization of a population of 'Nacional' cocoa at CATIE, Costa Rica. *Turrialba* 41(4):583-588

Moses, D.D. and Enriquez, G.A. 1981. Calibrating varieties for yield of cocoa, as well as the relationships of several cocoa features with the environment. *Proc. VII Int. Cocoa Res. Conf.* p.51-55

Mossu, G., Paulin, D. and Reffye, P.D. 1981. *Liaisons mathematiques entre les donnees experimentales - Equation du rendement. Cafe', Cacao, The'.* 25(3):155-168

Nair, R.V., Appaiah, G.N. and Nampoothiri, K.U.K. 1990. Variability in some exotic accessions of cocoa in India. *Indian Cocoa, Arecanut, Spices J.* 14(2):49-51

Napitupulu, L.A. 1990. *Panempilan Klon Kakao introduksi (Laporan Kedua)Buletin Perkebunan* 23(1):7-15

Pound, F.J. 1932. The genetic constitution of the cacao crop. *Annu. Rep. Cocoa Res.* Imperial College of Tropical Agriculture, Trinidad, **2**:9-25

Pound, F.J. 1933. Criteria and method of selection in cacao. *Annu. Rep. Cacao Res.* Imperial College of Tropical Agriculture, Trinidad, **2**:27-29

Rabonin, L.M., Paulin, D., Cilas, C. and Eskes, A.B. 1993. Genetic analysis of a few quantitative characters of cocoa (*Theobroma cacao* L.) Their merits for evaluating the diversity of species. *Cafe', Cacao, The'*. **37**(4):273-282

Ramirez, L.G. and Enriquez, G.A. 1988. Some inherited characteristics of the cocoa pod. *Proc. X Int. Cocoa Res. Conf.* Nigeria, p.587-592

Ruinard, Y.1961. Variability of various pod characters as a factor in cacao selection. *Euphytica* **10:**134-146

Sathyabalan, K. and Mathew, J. 1983. Identification of prepotent palms in West Coast Tall coconuts based on the early stages of growth of the progenies in the nursery. *Coconut Research and Development.* (Ed. Nayar, N.M.) Wiley Eastern Ltd., New Delhi, p.15-21

Soria, V.J. 1975. The genetics and breeding of cacao. *Proc. V. Int. Cocoa Res. Conf.* Ibadan, Nigeria, p.18-24

Soria, V.J., Ocampo, F. and Paez, G. 1974. Parental influence of several cacao clones on the yield performance of their progenies. *Turrialba* **24**(1):58-65

Subramonian, N. and Balasimha, D. 1982. Variability in pod and bean characters in some cacao hybrids. *Proc. IV Annu. Symp. Plantn Crops* (Placrosym IV) (Ed. Vishveshwara, S.) Mysore, p.168-174

Napitupulu, L.A. 1992a. Diallel cross analysis in eight parent clones for certain characters of cocoa. *Buletin Perkebunan* **23**(2):63-89

Napitupulu, L.A. 1992b. Performance of some cocoa hybrids and derived selected clones. *Buletin Perkebunan* **23**(1):7-15

Napitupulu, L.A., Keane, P.J. and Putter, C.A.J. 1992. Seletion for high yielding bulk cocoa in North Sumatra, Indonesia. *Cocoa Pest and Disease Management in Southeast Asia and Australia* (Ed. Keane, P.J.) Food and Agricultural Organisation, Rome, Italy, p.145

Ngatchou, N.J. and Lotode, R. 1971. Variability in precocity of the first hybrids obtained in the Cameroon Republic and search for a correlation between girth at a given age and precocity of the hybrids. *Trop. Abstracts* **26**(4):232

Ooi, L.H. and Chew, P.S. 1985. Results of five progeny trials on hybrid cocoa in peninsular Malaysia. *Planter* **61**(707):54-69

Palaniappan, S. and Shamsuddin, S. 1989. An analysis of cocoa (*Theobroma cacao* L.) yield and its components. *Planter* **66**(775):536-544

Paulin, D. and Eskes, A.B. 1995. Cocoa:Breeding strategies. *Plantations, Recherche, Development.* **2**(6):5-18

Paulin, D., Mossu, G., Lachenaud, P. and Cilas, C. 1993. Cocoa breeding in Cote-d' Ivoire. Performance analysis of sixty two hybrids in four localities. *Cafe', Cacao, The'.* **37**(1):3-20

Pereira, M.G., Carletto, G.A., Dias, L.A. and Doss, S. 1987. Evaluation of cocoa hybrids under the conditions of Linhares, Espirito Santo. *Buletin Tecnico, Center de Pesquisas do cacao* **150**:40

Posnette, A.F. 1943. Cocoa selection in the Gold Coast. *Trop. Agric.* **22**:184-187

Pound, F.J. 1932. The genetic constitution of the cacao crop. *Annu. Rep. Cocoa Res.* Imperial College of Tropical Agriculture, Trinidad, **2**:9-25

Pound, F.J. 1933. Criteria and method of selection in cacao. *Annu. Rep. Cacao Res.* Imperial College of Tropical Agriculture, Trinidad, **2**:27-29

Rabonin, L.M., Paulin, D., Cilas, C. and Eskes, A.B. 1993. Genetic analysis of a few quantitative characters of cocoa (*Theobroma cacao* L.) Their merits for evaluating the diversity of species. *Cafe ', Cacao, The '.* **37**(4):273-282

Ramirez, L.G. and Enriquez, G.A. 1988. Some inherited characteristics of the cocoa pod. *Proc. X Int. Cocoa Res. Conf.* Nigeria, p.587-592

Ruinard, Y.1961. Variability of various pod characters as a factor in cacao selection. *Euphytica* **10:**134-146

Sathyabalan, K. and Mathew, J. 1983. Identification of prepotent palms in West Coast Tall coconuts based on the early stages of growth of the progenies in the nursery. *Coconut Research and Development.* (Ed. Nayar, N.M.) Wiley Eastern Ltd., New Delhi, p.15-21

Soria, V.J. 1975. The genetics and breeding of cacao. *Proc. V. Int. Cocoa Res. Conf.* Ibadan, Nigeria, p.18-24

Soria, V.J., Ocampo, F. and Paez, G. 1974. Parental influence of several cacao clones on the yield performance of their progenies. *Turrialba* **24**(1):58-65

Subramonian, N. and Balasimha, D. 1982. Variability in pod and bean characters in some cacao hybrids. *Proc. IV Annu. Symp. Plantn Crops* (Placrosym IV) (Ed. Vishveshwara, S.) Mysore, p.168-174

Tan, G.Y. 1981. Breeding for disease resistance to vascular streak dieback, canker and black pod in hybrid cocoa. *Proc. VIII Int. Cocoa Res. Conf.* Lagos, Nigeria, p.731-734

Tan,G.Y. 1990. Combining ability analysis of yield and its components in cacao. *J. Amer. Soc. hort. Sci.* **115** (3):509-512

Toxopeus, H. and Jacob, V.J.1970. Studies on pod and bean values of *Theobroma cacao* L. in Nigeria II. Number of beans per pod, with special reference to the natural pollination process. *Netherlands J. agric. Sci.* **18:**188-194

Vello, F., Garcia, J.R. and Magalhaes, W.S. 1972. Production and selection of cacao hybrids in Bahia. *Revista-Theobroma* **2**(3):15-35

Verghese, R. 1998. Standardisation of selection criteria for cocoa hybrids. M.Sc.(Ag.) thesis, Kerala Agricultural University, Thrissur, p.110

Yew, C.C., Chee, K.H. and Ling, A.H. 1991. Performance of Scavina hybrids under inland conditions of peninsular Malaysia. *Planter* **67**(785):359-374

ESTIMATION OF GENETIC PARAMETERS FROM SPECIFIC CROSSES OF COCOA (*Theobroma cacao* L.)

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ABSTRACT OF THE THESIS

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ABSTRACT

The research project entitled 'Estimation of genetic parameters from specific crosses of cocoa (*Theobroma cacao* L.)' was carried outnan ongoing experiment of Cadbury-KAU Co-operative Cocoa Research Project (CCRP), College of Horticulture, Kerala Agricultural University, Vellanikkara, Thrissur during 1998-99. The studies were conducted in four year old hybrids. The major objectives were to study the genetic variability, heritability, correlation of different traits with yield, extent of heterotic expression of various traits and to examine the association between seedling vigour and yield. Twenty five cocoa hybrids were maintained in randomised block design with three replications.

The hybrids exhibited significant variability for most of the traits studied. The estimates of pcv were higher than gcv for all the traits studied. The highest heritability was recorded for number of beans per pod and seedling vigour recorded as HD^2 (6 MAS) had a high genetic gain. Yield and number of pods per tree recorded moderate genetic gain.

Yield was found to be significantly and positively correlated with number of pods per tree, height (2 YAP) and girth (2 YAP) of the tree. Absence of significant correlation between yield and seedling vigour was observed. Path analysis revealed the importance of pod number per tree and wet bean weight per pod in determining yield.

Yield and number of pods per tree showed a very high heterotic expression in most of the hybrids. Among the 25 cross combinations H_{23} was identified as the superior cross combination followed by H_{16} and H_5. The parents of

these cross combinations can be used for raising biclonal seed gardens, as they had a good specific combining ability.

The floral traits did not vary markedly in the hybrids. However the qualitative traits exhibited wide variation in the different hybrids.