Character Association, Components of Bean Yield and Compositional Description of Some Early-bearing Cacao (*Theobroma cacao* L.) Hybrids in Nigeria.

Abstract

Cacao (*Theobroma cacao* L.) is one of the most important commodity crops of export in the world, and is crucial to the economies of West African countries including Cote d'Ivoire, Ghana and Nigeria. The tree produces the cocoa beans, the main ingredient used to manufacture chocolate and other confectionery products. The adoption of improved hybrids with good bean yield and nutritional quality in Nigeria is low. Beans from nine new early-bearing cacao hybrids were evaluated to determine their yield and nutritional status. Analysis of variance revealed very highly significant ($p<0.05$) variation among the genotypes for all their descriptive traits as measured, confirming that the hybrids were different from one another. Simple character correlation coefficients between pairs of traits describing their yield, as indicated by pod index, showed significant relationships among the traits. Dry bean weight, number of beans per fruit, number of bean rows, Beans weight after fermentation, weight of one bean and the time to fruit harvest contributed significantly to pod index. These entire variables simultaneously accounted for 97.87% of variation in pod index values.The mean performance of the hybrids showed that they significantly possessed important components of nutrition in varied proportions. The study concluded that the traits under study are important components of yield in cacao, and are desirable for further investigation in future breeding programmes aimed at improving yield in the cacao crop.

Key words: Cocoa beans yield, Pod index, Stepwise regression, Proximate composition, Phyto-chemical properties

Introduction

Cocoa (*Theobroma cacao* L.) is a perennial tropical crop of immense economic importance, serving as the primary source of raw material for the global chocolate industry valued at over $130 billion annually (Kongor *et al.*, 2024; Patel *et al.*, 2023), underscoring its indespesibility as the basic ingredient used to produce chocolate, cocoa butter and other confectionery and cosmetic products. The dried and processed beans serve as a major source of income for millions of small holder farmers in some tropical countries. (Mustiga *et al*., 2018). West Africa, particularly Côte d'Ivoire and Ghana, accounts for approximately 70% of global cocoa production, with Nigeria contributing significantly to regional output (Oluyole *et al.*, 2022). This proportion is produced by small hundreds of holder farmers whose yield has remained low. Two main sub-species of cacao identified are: *T. cacao* subsp. *cacao* Cuat., representing the Criollo population (domesticated by the Amerindians in Central America) and *T. cacao* subsp. *Sphaerocarpum* Cuat., which represents the Forastero population, including the ‘Amelonado’ and ‘Calabacillo’ types (Cuatrecasas, 1964). The Trinitario is a hybrid between Forastero and Criollo, originating from Trinidad. The F_3 Amazon (Mixed Amazon), which descended from the introductions of the Upper Amazon Forastero materials (Pound, 1943) is the most commonly grown in Nigeria. The bean yield in this variety is low. Since cacao populations naturally interbreed among cultivars, wild populations and its relatives, a significant variability exists in taxonomic and agronomic characteristics among the various populations of cacao (Leon, 1984).

Cocoa production currently faces unprecedented challenges including ageing trees, climate variability, pest and disease pressure, and declining productivity, which collectively threaten supply stability and smallholder livelihoods (Läderach *et al.*, 2023; Tetteh *et al.*, 2024).The adoption of improved hybrids with good bean quality potentials (bean yield and nutrition) in Nigeria remains very low, as Eskes (2000) reported that farmers have continued to use their own trees on-farm as sources of materials for new plantings and rehabilitation of old plantations. The genetic base of cacao material on-farm in Nigeria is thus perceived to be narrow (Aikpokpodion, 2012). With the predominant continuous use of the same population of cacao existing in farmer plots for new planting, the on-farm genetic diversity of cacao in Nigeria remains low (Zhang and Motilar, 2016) thereby requiring improved breeding strategies to provide farmers with enhanced genetic diversity. Therefore, new hybrids are needed to enhance on-farm diversity of cacao and the adoption of improved genetic materials.

Information on genetic variability and yield components of cacao hybrids, including early-bearing varieties and their applications to yield strategies become very needful in this regard (Asare and Afoakwah, 2023)

Yield of the cocoa bean is predominantly influenced by time, variety and age of plant (Goenaga *et al*.; 2015, Mustiga *et al*., 2018). Bean yield in cacao is also negatively influenced by climatic changes and increase in the use of land for food crops. Cacao cultivation has increased globally in recent years. However, in West Africa, cacao production faces major challenges which include the unavailability of certified planting materials that can assure farmers of sustained productivity and profitability (Mustiga *et al*., 2018). It is very crucial that new outstanding varieties be bred so as to scale up bean yield per production area. This is true as Mustiga *et al*. (2018) also observed that "cacao yields can be increased significantly using improved genetic materials and better agronomic practices. Breeding therefore requires a deeper understanding of the genetics controlling yield." Cacao production should be geared towards increasing yields by ensuring more efficient partitioning of dry beans relative to vegetative growth.

In plant breeding programs, Understanding the genetic relationship among traits is important, enabling the breeder to know how the selection for a character may possibly induce simultaneous changes in other characters (Santos *et al*., 2018). Relationships between and among plant characters can be explained by the influence of a single gene on multiple phenotypic traits (pleiotropic effects). This holds true, as genes closely linked within the same chromosome are important in character expression, especially in populations derived from wide crosses. It is possible to obtain gains for one trait that has a significant genetic relationship with another trait by indirect selection. The findings of Parveen *et al*. (2022) suggests that there are cases in which the indirect selection based on the correlated response may produce much more than direct selection for a desired trait. The effects of hybidisation could have a significant implications on biochemical compositionof cacao, especially the fat content, flavonoids and other key compounds (Udoh and Osunsami, 2023; Williams and Zhang, 2021).

Bauman and Dufour (2022), reported the significant effects of hybridisation and climate on early bearing and productivity in cacao, while Akeredolu and Olayemi (2022) outlined the important impact of hybridisation, particularly early bearing varieties on the sustainability of cocoa farming and its economic potentials in regions like West Africa. Adoption of early-bearing cacao hybrids, therefore, has significant implications on the economy of the smallholder farming systems (Perez and Smith, 2023). Therefore, indirect selection can be done by selecting a trait of high heritability strongly related to a desired trait. The foregoing is very crucial in the selection of cacao genotypes for dry bean yield.

Selection of cacao genotypes for dry bean yield should be done among candidate trees that exhibit significantly low values of pod index, since low values of pod index (implying fewer numbers of pods needed to obtain 1.0kg of dry cocoa beans) are desired so as to minimise the cost of production. Pod index in cacao is obtained by calculating the number of healthy pods required to produce 1 kg of healthy dry bean per genotype. It is therefore a suitable trait that depicts dry bean yield in cacao (Adenuga *et al*., 2018).

Further improvement attempts were made on cacao genotypes in Nigeria, as a follow-up to the achievement of the Cocoa Research institute of Nigeria (CRIN) in the release of the new cacao hybrids in 2011. These hybrids that are now under cultivation by farmers were involved in some further hybridisation procedures that led to the production of 15 F_1 offspring. These new offspring were established at two cacao agro-ecologies, and nine of this new F_1 generation were found to have fruited early in the Owena (Ondo State) sub-station of the institute, with first fruit harvest occurring from 104-124 weeks of field establishment. The beans from the 9 new early-bearing hybrids were therefore subjected to analysis in the current study. The objectives of this study were: (1) to determine the relationship between dry bean yield (as observed in pod index) and the yield-related characters of the hybrids under study, (2) identify the components that contribute to dry bean yield among the hybrids and (3) assess the nutritional and sensory quality of beans from the cacao hybrids under study as revealed by their proximate and phyto-chemical composition.

Materials and Methods

Fifteen (15) newly-produced cacao hybrids were established at two different cacao agro-ecologies: Ibadan (7^0 13'N, 3^0 51'E), a derived savannah agro-ecology and Owena (7^0 11'N, 5^0 1'E) a humid rain forest agro-ecology, Nigeria. Sixty (60) individual seedlings were established per genotype as ten (10) seedlings per plot in three (3) replications in a Randomized Complete Block Design (RCBD) in each of the two locations.

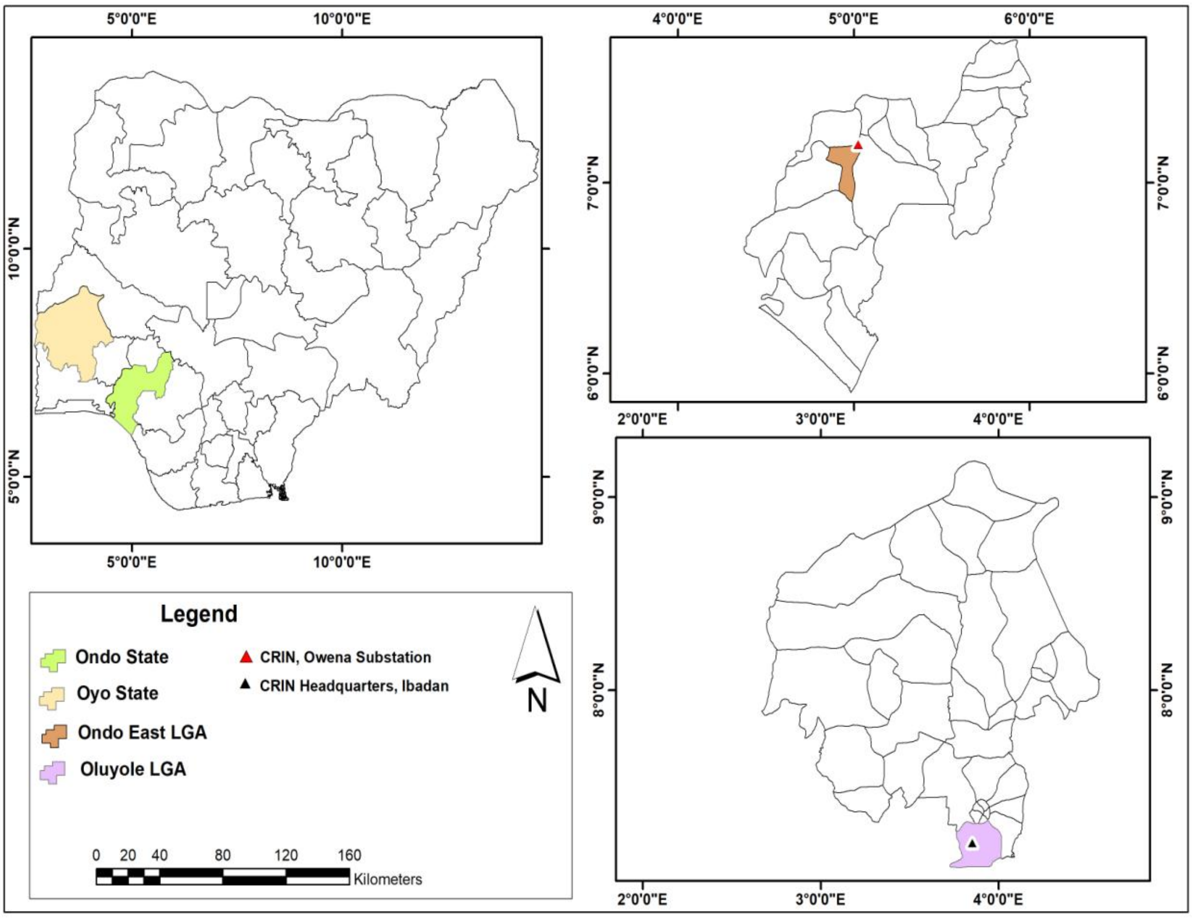

Figure 1: Map showing the two locations used in the study.

Nine of these hybrids were found to have started fruiting early, with first-fruit harvest ranging between 104-124 weeks of field establishment. Therefore these nine precocious cacao hybrids were subjected to the current study. The list of the nine hybrids and their pedigree is shown in Table 1. The spacing used was 2.5 x 2.5m. The plant population used for this study was 270 (9 Hybrids x 10 stands x 3 replications). Data were collected from five randomly sampled individual stands per hybrid per replicate.

Quantitative data were collected from five uniformly matured and ripe cocoa pods, which were harvested per hybrids in each replication, giving a total of fifteen pods (fruits) per hybrid. The fruits (pods) were weighed and their dimensions (length and width) measured before they were broken. The fruits were carefully broken to extract the beans. The pod thickness was measured. The number of beans was recorded per row and per pod. The beans were weighed before and after fermentation, and the weight recorded per fruit, and per individual bean as the average of ten beans weighed per fruit. Fermentation was done by heaping the extracted beans per genotype separately in the fermentation trays initially covered with banana leaves. The heaped beans were again covered with banana leaves and fermented for 6 days, with consecutive openings and turning after every 48 hours. The fermented beans were sun-dried and further weighed and their dimensions measured. Pod index in (P.I.) this study was calculated (with adoption from Mustiga *et al*., 2018) as:

$$\mathbf{P.I.} = \frac{\text{NP x 1000}}{\text{FBW x 0.4}}$$

Where NP = Total number of pods; FBW = Total weight of fresh beans; 0.4 = the conversion factor of FBW to dry bean weight (Somarriba and Beer, 2011)

Statistical Analysis System software, SAS-V9.2 (SAS Institute Inc., 2007) was used to calculate correlation coefficients (Steel and Torrie, 1987), and also to estimate the stepwise regression coefficients (Draper and Smith, 1981), to determine the appropriate variables responsible for most variation in bean yield among the hybrids. In statistics, stepwise regression includes models in which the choice of predictive variables is carried out by an automatic procedure (SAS Institute, 1989). Therefore, in this study, stepwise regression procedure was used to determine the variables which accounted for the majority of pod index values (which reflect dry bean yield in cacao). At each step, one variable was added to the equation. The variable added was the one that included the greatest reduction in the error sum of square. It was also the variable that had the highest partial correlation with the dependent variable for fixed values of those variables already added. It was also the variable with the next highest F-value.

The dried beans were transported to the laboratory for subsequent chemical analysis per hybrid. Triplicate samples were analysed in the laboratory per replication per hybrid. The samples were analysed for their pH, Proximate Composition: Crude Protein, Crude Fibre, Crude Fat, Ash, Moisture Content, Carbohydrate and Butter Fat; and Phyto-chemical Properties: Thoebromine, Flavonoid and Caffeine content. The analysis was according to the methods described by AOAC (2005)

The data obtained (sample means for each parameter) were subjected to Analysis of Variance (ANOVA) to estimate the variability among the genotypes while the means were separated using Duncan Multiple Range Test, with the aid of Statistical Analysis System, SAS-V9.2 (SAS Institute Inc., 2007).

Results and Discussion

Simple correlation coefficient among the traits describing yield among the cacao hybrids are shown in Table 2. There was a negative significant ($P<0.05$) correlation between pod index and each of fruit length ($r = -0.376$), number of beans per row ($r = -0.592$), number of beans per fruit ($r = -0.711$), weight of beans per fruit ($r = -0.765$), weight of beans after fermentation ($r = -0.674$), weight of one bean after fermentation ($r = -0.380$), pod value ($r = -0.969$) and weight of one dry bean ($r = -0.534$), while the correlation of pod index with dry bean length was positive ($r = 0.309$). Mustiga *et al*., (2018) reported that mean cocoa bean yield increased considerably over time particularly at tree ages 2 and 3 years and peaked at age 4. Nevertheless, the findings from the current study give a pointer towards the factors that influence bean yield in cacao. The negative significant values of all the traits under study with pod index indicate an inverse relationship between each of the traits and pod index, which is a desirable phenomenon. Usually, high weight of beans per pod may be expressed as a ‘pod index’, (the number of pods required to produce 1kg of dried beans). A low pod index is normally associated with good bean size and weight, and often results in a saving in harvesting costs (Adenuga, 2017). Therefore a plant breeder can incorporate these desirable traits as highlighted in this result in breeding programmes of the cacao crop targeted at improving bean yield.

Results on Table 3 show the relative contribution of each variable to yield as indicated by pod index, and also in predicting pod index.

The best prediction equation is as follows:

$$Y = 60.5856 - 0.5993X_1 - 0.1853X_2 - 1.9426X_3 + 0.0354X_4 - 1.6337X_5 + 0.0692X_6$$

This result revealed that the most contributing variables to pod index in cacao were weight of dry beans, number of beans per fruit, number of rows (bean rows), weight of beans after fermentation, weight of one bean and the time to fruit harvest. These entire variables simultaneously accounted for 97.89% of variation in pod index values. Among these variables, the weight of dry beans was observed as the most important, followed by the number of beans per fruit, number of rows, weight of beans after fermentation, weight of one bean and the time to fruit harvest. The relative contributions to pod index values in cacao were 93.88%, 1.86%, 0.75%, 0.55%, 0.49% and 0.36% for the above mentioned variables respectively.

The direction of the variables in predicting pod index is significant as most of the regression coefficients were of negative values (except for weight of beans after fermentation), denoting inverse relationships between each of these variables and pod index, which is desirable. The positive value of the regression coefficient of the time to fruit harvest is also desirable in this study, denoting a direct relationship of this trait with pod index. The proportion of total variation accounted for by these six variables (97.87%) indicates that other variables not included in the stepwise regression model played insignificant roles in predicting the values of pod index.

The means scores of the variance components for 8 characters explaining the proximate composition (Table 4) and 3 characters explaining the phyto-chemical properties (table 5) of the 9 hybrids the study was based on revealed very highly significant ($P<0.01$) variation among the hybrids for all traits measured. This result indicates that the hybrids under study are different from one another in their composition for all the nutritional traits describing them. A basis is therefore advanced for their inclusion in selection procedures for further improvement of the species.

The separation of the means for the 11 (proximate and phyto-chemical properties) characters discriminating among the 9 hybrids (Table 6) showed that hybrid CRAD 001 had the highest mean (7.02) for pH, while hybrids CRAD 006 and CRAD 007 had the least means (6.80). Hybrid CRAD 004 had the highest mean (15.83) for crude protein while hybrid CRAD 006 also had the least mean. For crude fibre, hybrids CRAD 002 and CRAD 005 had the highest means (5.72 and 5.78), while hybrid CRAD 003 had the least (3.79). Hybrids CRAD 001 and CRAD 004 had the highest means for crude fat (25.62 and 25.71), while hybrid CRAD 006 had the least (22.75). Hybrids CRAD 007 and CRAD 009 had the highest means (3.02 and 3.07) for ash content, while hybrids CRAD 001, CRAD 002, CRAD 005 and CRAD 006 had the least values. Hybrid CRAD 008 had the highest mean for moisture content while CRAD 001 had the least value (9.86). Hybrid CRAD 006 had the highest mean (46.67) for carbohydrate, while CRAD 004 had the least value (39.68).

As the pH of unfermented cocoa pulp has been reported to range between 3.3-4.0 (Thompson *et al*., 2007; Ardhana and Fleet, 2003; Schwan and Wheals, 2004), mainly due to a high concentration of citric acid, and increase progressively to a range of 4.8-4.9 at the end of fermentation (Ardhana and Fleet, 2003), it is normal to assert that all these hybrids, which exhibited much higher pH after fermentation are non-acidic, and are therefore suitable for consumption by individuals who are averse to acidic food. Afoakwa *et al* (2013) also reported a pH range of 3.98-5.04 for fermented beans obtained from pods initially stored for three days.

All the nine hybrids have reasonable amounts of the components of proximate composition such as crude protein, crude fibre, crude fat, ash, moisture content and carbohydrates. The moisture content, though higher than the amounts in literature (ICCO, 2012; Williams and Zhang 2021), can be significantly reduced by sufficient drying of the beans after fermentation. The crude protein and crude fat contents also were less than those reported (ICCO,2012; Williams and Zhang 2021). A general decrease in crude protein with fermentation of cocoa beans have previously been reported thus making a case that the low crude protein values may be due to the length of fermentation of the beans. Low values of crude fat could have been due to increased storage (Udoh and Osunsami, 2023), and variations in the bean sizes (Wood and Lass, 1985; Dand, 1997). The values of the ash content are consistent with the findings of Udoh and Osunsami (2023) who also reported reductions in ash content due to fermentation. The observed values of crude fibre were higher than the records of ICCO (2012) for all the hybrids, while carbohydrate contents were similar to those reported by Udoh and Osunsami (2023). Hybrids with high crude fibre and carbohydrate could therefore be selected for. For the phyto-chemical properties of these nine cacao hybrids, the butter fat, theobromine and caffeine contents were lower than the values recorded by CRIN (2011) and ICCO (2012), indicating the need for them to be improved upon to obtain better confectionery and cosmetic values. The reduced caffeine values however, are considered an advantage to consumers with allergies to caffeine intake.

Conclusion

The traits discriminating among the cacao hybrids under study are desirable as they are important components of yield in cacao. Significant variation exists among the cacao hybrids under study based of their nutritional and sensory quality as revealed by their proximate and phyto-chemical composition, which discriminated among them.

Recommendation

The hybrids under study are recommended for selection and inclusion in further breeding programmes aimed at improving yield in the cacao crop, with more emphasis on the traits that this study was based on.

References

1. Adenuga, O. O. (2017). Development of hybrid cacao (*Theobroma cacao* L.) varieties for improved precocity, bean yield and quality in Nigeria. PhD Thesis. Federal University of Agriculture, Abeokuta, Nigeria. 150pp.
2. Adenuga, O.O., Adepoju, A.F., Olaniyi, O.O. and Balogun, S.T. (2018). Relationships among bean yield traits in some cacao (*Theobroma cacao* L.) genotypes. *Journal of Agricultural Science and Technology* B 8(2018): 303-310
3. A.O.A.C. (2005). Official methods of analysis 18th edition. Association of Official Analytical Chemists. Washington D.C., USA
4. Afoakwa, E. O., Kongor, J. E., Takrama, J. F. and Budu, A. S. (2013). Changes in acidification, sugars and mineral composition of cocoa pulp during fermentation of pulp pre-conditioned cocoa (*Theobroma cacao*) beans. *International Food Research Journal* 20 (3): 1215-1222
5. Aikpokpodion, P.O. (2012). Defining genetic diversity in the chocolate tree, *Theobroma cacao* L. grown in West and Central Africa. In M.C. alis¸kan (Ed.), *Genetic diversity in plants*, Chap.10. InTech. doi:10.5772/33101
6. Akeredolu, O. A., and Olayemi, S. I. (2022). Sustainability of hybrid cocoa farming in West Africa: Implications for early-bearing varieties and economic gains. *Agriculture,* 12 (2), 321.
7. Ardhana, M. M. and Fleet, G. H. (2003). The microbial ecology of cocoa bean fermentation in Indonesia. *International Journal of Food Mocrobiology* 86: 87-99
8. Asare, R. A., and Afoakwah, R. (2023). Genetic diversity and yield performance of cocoa (Theobroma cacao L.) hybrids: Implications for breeding programs. *Euphytica* 219 (1), 1-15.
9. Baumann, M., and Dufour, A. (2022). Early-bearing cocoa hybrids: The influence of genetics and environmental factors on productivity. *Field Crops Research*, 285, 108-119.
10. CRIN, (2011). New Cocoa Varieties for Nigeria – Attribute and Field Management Requirements. Cocoa Research Institute of Nigeria. 43 pages.

11. Cuatrecasas. J, (1964). Cocoa and its allies: A taxonomic revision of the genus *Theobroma*. *Contributions of the U.S. Natural Herbarium* 35 (6): 379-614.

12. Dand, R. (1997). The International cocoa Trade. New York USA: John Wiley and Sons, Inc. Pp 102

13. Draper, N. And Smith, H. (1981). Applied regression analysis. 2nd Edition. New York: John Wiley and Sons, Inc.

14. Eskes, A. B. (2000). International cocoa breeding and selection initiatives. *INGENIC Newsletter* 5: 2-3

15. Goenaga, R., Guiltinan, M., Maximova, S., Seguine, E., and Irizarry, H. (2015). "Yield Performance and Bean Quality Traits of Cacao Propagated by Grafting and Somatic Embryo-Derived Cuttings." *Journal of the American Society for Horticultural Science* 50 (3): 358-62

16. ICCO (2012). Physical and chemical information on cocoa beans, butter, mass and powder. International Cocoa Organization, March 2012

17. Kongor, J. E., De Steur, H., Van de Walle, D., Gellynck, X., Afoakwa, E. O., Boeckx, P., Dewettinck, K. (2024). Cocoa research priorities for sustainable production: Perspectives from producer countries. Agroforestry Systems 98, 1567-1585.

18. Läderach, P., Martinez-Valle, A., Schroth, G., Castro, N. (2023). Climate change impacts on cocoa production and adaptation strategies: A global perspective. Agricultural Systems 212, 103741.

19. Leon, J. (1984). The spread of Amazonian crops into Mesoamerica: the botanical evidence. *Pre-Columbian plant migration*. Stone, D. (Ed.) *Peabody Museums Archeology and Ethnology*, Harvard Univ Press, 76. Cambridge, Massachusetts, USA. 165-173

20. Mustiga, G.M., Gezan, S.A., Phillips-Mora, W., Arciniegas-Leal, A., Mata-Quiros, A. And Motamayor, J.C. (2018). Phenotypic description of *Theobroma cacao* L. For yield and vigour traits from 34 hybrid families in Costa Rica based on the genetic basis of the parental population. *Plant Science*, 19. June 2018

21. Oluyole, K. A., Dada, O. A. and Adebiyi, S. (2022). Analysis of technical efficiency of cocoa production in Nigeria: A stochastic frontier approach. Journal of Agriculture and Rural Development in the Tropics and Subtropics 123, 231-239.

22. Parveen, Z., Bock, C. H., & Gifford, J. (2022). Selection for high-yielding cocoa hybrids: New insights into the genetic basis of early-bearing traits. Crop Science, 62 (4), 1980-1995.

23. Patel, S., Singh, A., Singh, H., Kumar, N. (2023). Cocoa: A comprehensive review on origin, nutritional composition, bioactive compounds and health benefits. *Journal of Food Science and Technology 60, 2467-2483.*

24. Perez, M. E., and Smith, J. D. (2023). Economic modeling of cocoa hybrid adoption in smallholder systems: Early bearing varieties as a potential solution for productivity gaps. Agricultural Economics, 54 (3), 451-463

25. Pound, F. J. (1943). Cacao and 'witches' broom disease (*Marasmus prniciosus*). A report on a recent visit to the Amazon territory of Peru. September 1942- February, 1943. Dept of Agric., Trinidad and Tobago, 14p.

26. SAS Institute (2007). The SAS system for Windows. Release 9.2 SAS Inst Inc, Gary, NC, USA

27. SAS Institute Inc. (1989). SAS/STAT User's Guide, Version 6, Fourth Edition, Volume 2**,** Cary, NC: SAS Institute Inc.

28. Santos, E. Ad, Almeida. A.Fd, Branco, M.C. dS, Santos, I.Cd, Ahnert, D., Baligar, V.C and Valle, R.R. (2018). Path analysis of phenotypic traits in young cacao plants under drought conditions. *PloS ONE*. 13(2): e0191847. doi: 10.1371/journal.pone.0191847

29. Schwam, R. F. and Wheals, A. E. (2004). The microbiology of cocoa fermentation and its role in chocolate quality. *Critical Reviews in food Science and Nutrition* 44: 205-221

30. Somarriba, E., and Beer, J. (2011). Productivity of *Theobroma cacao* agroforestry systems with timber or legume service shade trees. Agrofor. Syst. 81, 109–121. doi: 10.1007/s10457-010-9364-1

31. Steel, R.G.D. and Torrie, J.H., (1987). Principles and procedures of statistics. A biometrical approach. 2nd Edition 6th printing. Mc. Graw. Hill Book company. USA: 272-277

32. Tetteh, J. P., Lowor, S. T., Padi, F. K., Opoku, S. Y., Adu-Ampomah, Y. (2024). Cocoa breeding in Ghana: Past, present, and future. Experimental Agriculture 60, e3.

33. Thompson, S. S., Miller, K. B. and Lopez, A. S. (2007). Cocoa and Coffee. In:Doyle, M. P., Beuchat, L. R. and Montville, T. J., editors. Food microbiology fundamentals and frontiers. Washington, D.C.: ASM Press, pp. 837-850

34. Udoh, E. T., and Osunsanmi, F. O. (2023). The impact of hybridization on the chemical composition and sensory attributes of cocoa beans. *Food Chemistry*, 415, 135849.

35. Williams, S. J., and Zhang, H. (2021). Cocoa bean compositional analysis: New hybrid varieties and their influence on flavor profiles and antioxidant content. *Journal of Food Science*, 86 (5), 1789-1800.

36. Wood, G. A. and Lass, R. A. 1985. Cacao 4th edition, Longman, U.K. 620pp

37. Zhang, D., Motilar, L. (2016). Origin, dispersal and current global distribution of cacao genetic diversity. In: Bailey, B. A., Meinhardt, L.W., editors, Cacao Diseases: A history of old enemies and new encounters. Switzerland: Springer. 3-31.

Table 1: List of nine cacao Hybrid used in the study

S/N	Genotypes	Pedigree	Weeks to Harvest
1	CRAD 001	($T_{82/27}$ x $T_{12/11}$) x ($T_{65/7}$ x $T_{57/22}$)	122
2	CRAD 002	($T_{82/27}$ x $T_{12/11}$) x ($T_{53/5}$ x $_{N38}$)	117
3	CRAD 003	(P_7 x $T_{60/887}$) x ($T_{65/7}$ x $T_{57/22}$)	124
4	CRAD 004	($T_{86/2}$ x $T_{9/15}$) x ($T_{65/7}$ x $T_{57/22}$)	114
5	CRAD 005	($T_{86/2}$ x $T_{9/15}$) x ($T_{53/5}$ x $_{N38}$)	105
6	CRAD 006	($T_{86/2}$ x $T_{22/28}$) x ($T_{65/7}$ x $T_{22/28}$)	117
7	CRAD 007	($T_{65/7}$ x $T_{9/15}$) x ($T_{65/7}$ x $T_{57/22}$)	104
8	CRAD 008	(P_7 x P_{A150}) x ($T_{101/15}$ x N_{38})	117
9	CRAD 009	(P_7 x P_{A150}) x ($T_{65/7}$ x $T_{57/22}$)	114

Table 2: Correlation coefficients among 16 fruit and bean characters of the nine cacao hybrids used in the study

	Fruit Wgt	Frt Lth	Fruit Wth	P T	Rows	Bns/Row	Bns/Frt	Bns Wgt /Frt	Wgt of 1 Bn	Bns Wgt Ferm	1 Bn Wgt Ferm	Pd Val	1 D B Wgt	D B L	D B W	P. I.
TFH	0.16	0.306*	-0.310*	0.08	0.07	-0.06	-0.04	0.19	0.360*	0.18	0.338*	0.28	0.05	-0.13	0.04	-0.22
Fruit Wgt		0.313*	-0.11	0.29	-0.17	0.09	0.02	0.544**	0.562**	0.621**	0.467**	0.29	0.21	-0.13	-0.384**	-0.24
Frt Lth			0.04	0.467**	-0.335*	0.355*	0.20	0.26	0.23	0.11	0.20	0.427**	0.303*	-0.441**	-0.500**	-0.376*
Fruit Wth				0.04	0.11	0.00	0.05	-0.07	-0.21	-0.06	-0.15	0.08	0.498**	0.15	-0.16	-0.10
P T					-0.26	0.29	0.18	0.316*	0.28	0.20	0.16	0.27	0.314*	-0.03	-0.05	-0.27
Rows						-0.23	0.305*	0.08	-0.351*	0.15	-0.401**	0.09	-0.27	0.17	-0.04	-0.21
Bns/Row							0.797**	0.539**	-0.11	0.410**	0.16	0.571**	0.337*	-0.20	-0.304*	-0.592**
Bns/Frt								0.615**	-0.28	0.483**	-0.06	0.624**	0.20	-0.11	-0.372*	-0.711**
Bns Wgt /Frt									0.462**	0.874**	0.417**	0.737**	0.417**	-0.08	-0.327*	-0.765**
Wgt of 1 Bn										0.440**	0.694**	0.27	0.29	0.01	0.00	-0.21
Bns Wgt Ferm											0.554**	0.698**	0.344*	0.01	-0.24	-0.674**
1 Bn Wgt Ferm												0.501**	0.480**	-0.14	0.07	-0.380*
Pd Val													0.593**	-0.328*	-0.19	-0.969**
1 D B Wgt														-0.01	-0.08	-0.534**
D B L															0.29	0.309*
D B W																0.25

NB: * and ** = significance at 0.05 and 0.01 respectively.
TFH = Time to fruit harvest; Fruit Wgt = Fruit weight (g); Frt Lth = Fruit length (mm); Fruit Wth = Fruit width (mm); P.T. = Pod Thickness (mm); Rows = number of beans rows in fruit; Bns/Row = Number of beans per row; Bns/Frt = Number of beans per fruit; Bns Wgt /Frt = Weight of beans per fruit (g); Wgt of 1 Bn = Weight of one bean (g); Bns Wgt Ferm = weight of beans per fruit after fermentation (g); 1 Bn Wgt Ferm = Weight of one bean after fermentation (g); Pd Val = Pod Value (Weight of dry fermented beans per pod, in grammes); 1 D B Wgt = Weight of one dry bean (g); D B L = Dry bean length (mm); D B W = Dry bean width (mm); P.I. = Pod Index

Table 3: Relative contribution of each variable to yield (Pod Index)

Step	Contributing variables	Regression coefficients		F value	Level of significance	Cumulative R^2	Partial R^2 %
		β	Standard Error				
1.	Weight of dry beans (g)	-0.5993	0.0259	659.88	0.0001***	0.9388	93.88
2.	No. of beans/fruit	-0.1853	0.0314	18.33	0.0001***	0.9574	1.86
3.	No. of rows	-1.9426	0.3944	8.70	0.0052**	0.9649	0.75
4.	Weight of beans after fermentation (g)	0.0354	0.0105	8.66	0.0054**	0.9704	0.55
5.	Weight of 1 bean (g)	-1.6337	0.3168	6.23	0.0168*	0.9753	0.49
6.	Time to fruit harvest	0.0692	0.0273	6.42	0.0156*	0.9789	0.36

Intercept = 60.5856; R^2 = 97.89%; *, ** and *** = significance at 0.05, 0.01 and 0.001 respectively.

Table 4: The ANOVA of the proximate composition of beans from the nine cacao hybrids

Source of variation	Df	pH	Crude Protein (%)	Crude Fibre (%)	Crude Fat (%)	Ash (%)	Moisture Content (%)	Carbohydrate (%)	Butter Fat (%)
Block	2	0.0034	0.0015	0.0016	0.0082	0.0017	0.0357	0.0659	0.0145
Hybrid	8	0.0148**	2.3728***	1.1254***	2.3129***	0.0689***	0.2532***	10.4091***	4.2804***
Error	16	0.0034	0.0067	0.0049	0.0040	0.0017	0.0217	0.0302	0.0260

ANOVA= Analysis of variance ; *, **, ***= Significance at P≤ 0.05, 0.01 and 0.001 respectively

Table 5: The ANOVA of the phyto-chemical composition of beans from the nine cacao hybrids

Source of Variation	Df	Theobromine (mg/100g)	Flavonoid (mg/100g)	Caffeine (mg/100g)
Block	2	0.0001	0.0000	0.0000
Hybrid	8	0.0006***	0.0002***	0.01***
Error	16	0.0001	0.0000	0.0000

ANOVA= Analysis of variance ; *, **, ***= Significance at P≤ 0.05, 0.01 and 0.001 respectively

Table 6: Means of the proximate composition and phyto-chemical properties of beans from the nine cacao hybrids

Hybrid	pH	C.P. (%)	C.F. (%)	C. Fat (%)	Ash (%)	M.C. (%)	CH2O (%)	Butter Fat (%)	Theobromin	Flavonoid	Caffeine
CRAD 001	7.020a	13.960e	4.727d	25.620a	2.703c	9.860e	43.130b	42.603f	0.843ab	0.144bc	0.126c
CRAD 002	6.893bc	14.907c	5.717a	24.807d	2.653c	10.463bc	41.450e	43.743c	0.846a	0.143bc	0.123c
CRAD 003	6.833bc	14.750d	3.790f	25.390b	2.846b	10.267cd	42.960b	43.233d	0.843ab	0.153a	0.134b
CRAD 004	6.840bc	15.833a	5.183b	25.710a	2.853b	10.717ab	39.676f	44.467b	0.831ab	0.152a	0.125c
CRAD 005	6.883bc	13.940e	5.783a	24.807d	2.653c	10.467bc	42.417c	42.893e	0.850a	0.144b	0.132b
CRAD 006	6.800c	12.783f	4.590e	22.753f	2.703c	10.493bc	46.676a	40.833f	0.825b	0.132e	0.124c
CRAD 007	6.800c	15.233b	4.563e	24.703d	3.017a	10.433c	42.050d	42.473f	0.825b	0.136de	0.126c
CRAD 008	6.923ab	14.837cd	4.947c	24.537e	2.807b	10.767a	42.107d	43.553c	0.807c	0.139cd	0.131b
CRAD 009	6.833bc	14.907c	4.947c	25.033c	3.067a	10.063de	41.983d	44.876a	0.834ab	0.151a	0.139a

Means with the same letters along the column are not significantly different using DMRT at 0.05 level of probability