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Spatiotemporal impact on yield stability of intercropped cocoa (*Thoebroma cocoa* L.) in cyclone prone Indian East Coastal terrains

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Abstract

Cocoa (*Thoebroma cocoa* L) is cross pollinated, perennial and promising inter crop in coconut garden six types *viz.*,VTLCH1-4, VTLCC1 and VTLC- 1 was received from Regional Station working under ICAR-CPCRI, Vittal and planted at Coconut Research Station, Veppankulam in 2008. Single row system of cocoa was inter-cropped in coconut variety ECT. Thirteen critical biometric and yield related parameters were recorded. As per the AICRP trial for bio metric parameters the data for the year 2022- 23 was analysed and descriptive statistics was discussed. The yield of past four years *i.e* yield after GAJA cyclone was taken into consideration to analyse the stability of cocoa varieties and to identify superior types suitable for the East coast Tall. Among the various types, the genotypes Tc2 (VTLCH 1), highest mean yield (1.58 kg tree $^{-1}$ year $^{-1}$), compared to the lowest in Tc6 (0.96 kg tree $^{-1}$ year $^{-1}$). Descriptive statistics indicated moderate variability (CV = 17.72%) for yield. Stability analysis using parametric models showed that Tc2 possessed a regression coefficient less than unity ($\beta_i = 0.55$), low deviation from regression ($S^2_{di} = 0.80$), and low coefficient of variation (2.03%), indicating high adaptability under stress conditions. Variance-based parameters further supported its stability, with low $\theta_{(i)}$ (19.78), W_i^2 (24.66), and σ^2_i (2.81), coupled with high $\theta_{(i)}$ (30.32), reflecting minimal genotype × environment interaction. Non-parametric stability measures (S and NP indices) and Kang's rank-sum method also ranked Tc2 as the most stable genotype. Positive correlations between yield and traits such as canopy spread, trunk girth, and pod characteristics emphasized their role in stress recovery and productivity. Overall, Tc2 demonstrated superior yield stability and resilience, making it a suitable genotype for cultivation in cyclone-prone coastal ecosystems and a valuable candidate for climate-resilient breeding programs.

Keywords: Cocoa, intercrop, genotypes, descriptive statistics, correlation, stability

Introduction

Cocoa (*Thoebroma cocoa* L.) is cross pollinated perennial crop with cauliflorous bearing habit. The word cocoa was derived from the Spanish word 'cacao' and belong to the family Malvaceae. Thiobromine, the prime product of cocoa which is of much industrial value product (Martínez *et al.*, 2015). Being a non-native crop toIndia, it's mostly grown in the humid tropics. The major area was concentrated in southern India *viz.*,Tamil Nadu, Kerala, Andhra Pradesh and Karnataka in an area of 1.03lakh hectare, annual production of 27,702 MT. India's chocolate and confectionery industries require 50,000 MT of dry beans annually. Since the existing domestic production of cocoa beans was insufficient to fulfil the domestic demand, the country was importing worth Rs. 2021 crores (Kireeti *et al.,* 2026). The cocoa industry serves as a primary engine of financial stability, playing a vital role in the agricultural GDP of producing countries.

Cocoa as intercrop in coconut gardens and other plantation cropswas a successful cropping

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model (De Almeida and Valle 2007, Oyekale *et al.*, 2009, Teixeira *et al.*, 2015 and Schroth *et al.*, 2016). In Tamil Nadu and Andhra Pradesh, it is one of the successful crops in multitier cropping system adapted in India. The crop prefers humid tropical climate of 1500 and 2000 mm annual rainfall and dry season less than three months and D/N temperatures 30°C / 18^0C (Wood and Lass 1985). Cocoa cultivation is generally not recommended in cyclone-prone areas due to the crop's sensitivity to environmental stress and can cause significant damage to crops, leading to losses in yield and quality.

Utilization of the genetic diversity within the plant species made it feasible to select high yielding cultivars (Arzani, 2008) to counteract the climate vulnerability on crop production.Thus, stability can be characterized by the consistency of agricultural outputs, primarily yield, across long time periods or across different spatial locations (Urruty *et al.*, 2016). In recent years, increased climate unpredictability also linked to a lower stability of crop yields, thus analyses of yield stability received more attention from farmer's perspective (Tigchelaar *et al.*, 2018).Hence, the stability analysis across environments (various years) may pave way for selection of superior genotypes.

During study period tropical cyclone during 2018 *viz.*, GAJA cyclone in Tamil Nadu devastated the farming communityin the state especially the East Coast terrains.Crop diversification has been acknowledged as a successful technique for addressing goals related to production risk management, poverty alleviation, food and nutrition security (Reddy and Prabakhar, 2022).Coconut being the primary crop of the study area, cocoa was planted as intercrop in the existing orchards to identify the potential genotypes in spatiotemporal environments.

2. Materials and Methods

During 2008, ICAR-AICRP on Palms operating at Central Plantation Crops Research Institute (CPCRI), Kasaragod, Kerala State introduced six genotypes to evaluate the performance of cocoa in the cyclone prone areas of East Coastal regions of Peninsular India *viz.,* Veppankulam of Tamil Nadu. Single row planting system was followed in cocoa and it was intercropped in coconut garden (Fig. 1). Six cocoa genotypes, namely VTLCC–1 (Tc1), VTLCH–1 (Tc2), VTLCH–2 (Tc3), VTLCH–3 (Tc4), VTLCH–4 (Tc5), and VTLC–1 (Tc6), sourced from ICAR–CPCRI Regional Station, Vittal, Karnataka, India, were used in the study.

Table 1. The details of the experimental block.

S. No.	Coconut Research Station, Veppankulam	Details
1	Latitude	10.29° N
2	Longitude	79.23° E
3	Elevation (MSL)	41
4	Highest Day temp (^{0}C)	35
5	Lowest Night temp (^{0}C)	21
6	Mean Rainfall (mm)	1157
7	Soil type	Sandy loam
8	Soil N status	Medium
9	Soil P status	Medium
10	Soil K status	Low
11	Coconut spacing	25 x 25 ft
12	Coconut variety	ECT
13	Cocoa spacing	3 m
14	Cocoa planting system	Single row
15	Age of coconut	>15 years
16	Year of planting cocoa	2008
17	Yield stabilization in cocoa	2012
18	Cyclone incidence	2012, 2016, 2018

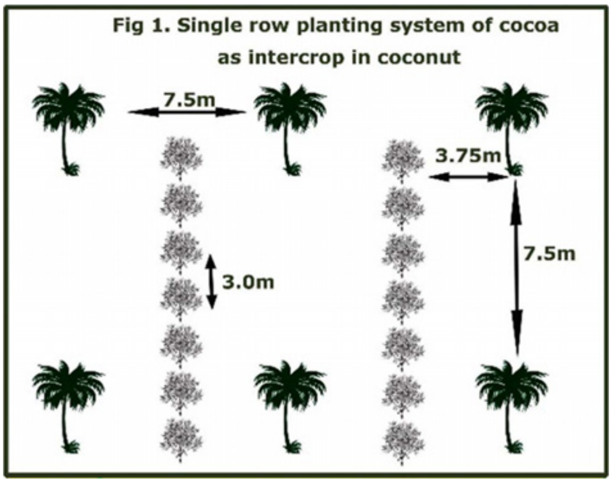

Fig. 1. Planting layout of cocoa genotypes in a coconut-based cropping system

The experiment block had 15 years old coconut palms var. East Coast Tall with planting density of 175 palms per hectare. Cocoa was planted at 3.75m away from coconut trunk and 3m in between two cocoa plants *i.e.* 444 cocoa plants per ha. Six genotypes *viz.*, VTLCC1, VTLCH1, VTLCH2, VTLCH3, VTLCH4 and VTLC1 were planted during 2008 in four replications.

Cyclonic effect was observed during 2018 (Veppankulam) as expected in this study objective. Around 25% of the cocoa plants were damaged due to fall of nearby coconut palms and the palms fell at random (represents whole farm including experimental area). Damaged, uprooted, or severely lodged cocoa plants were excluded from further observations.After excluding damaged plants, a uniform sampling strategy was adopted by selecting five healthy cocoa plants per treatment within each replication, resulting in a final effective sample size of 5 plants except in R_4 T_5 and R_3 T_2 in these treatments only four plants were remained, we have adopted missing plot technique to estimate the missing observations and maintained the balance of the experimental design. These selected plants were maintained consistently for all post-cyclone observations and analysis. The following biometric parameters viz., Plant height (m), Trunk girth (cm), Jorquet height (m), Canopy spread (EW& NS) (m), Total canopy area (m^2), Single fruit weight (g), number of pods per tree, single bean weight (g), dry bean parameters and yield (kg) were documented following the standard procedures prescribed (Kireeti *et al.*, 2026), and analyzed data using randomized block design for ANOVA after cyclone effect in GraphPad Prism ver. 8. All statistical tests were evaluated at a significance level of $p \leq 0.05$.Dry bean characters viz., length, breadth, thickness of single bean and dry bean yield was recorded from harvested cocoa pods and were stored in the shade. Pulped cocoa seeds were fermented for 6-7 days in wooden barrels after the pulp and seedswere removed from the pod. Under the sun, cocoa beans were naturally dried at 30^0C for 7-8 days after fermentation,to attain well dried beans (Phuoc, 2009).

In the present study stability parameters were utilized to identify the genotypes with consistent performance after cyclonic effect by evaluating genotype × environment (GE) interactions using complementary statistical approaches. The parametric and non-parametric models were employed to overcome the limitations associated with individual models for stability analysis of cocoa dry beans yield per plant. Parametric measures such as variance components (Plaisted and Peterson1959), Wricke's ecovalence (1962), and Shukla's stability variance by Shukla (1972) quantify the contribution of genotypes to GE interaction, while regression-based approach (Eberhart and Russell (1966)) assess genotype responsiveness and predictability across environments. However, as these methods rely on assumptions of normality and linearity, non-parametric statistics (Nassar and Huhn's (1987), Huhn's (1990), Thennarasu's (1995)) were additionally included to provide a distribution-free assessment of stability based on genotype rankings. Furthermore, Kang's rank-sum method by Kang's (1988) was used as an integrative selection criterion combining both yield performance and stability.The inclusion of multiple indices ensured a robust and unbiased identification of stable genotypes, as different statistics capture distinct aspects of stability. Yield was considered the primary trait due to its direct economic importance in cocoa. All analyses were performed using STABILITYSOFT online free software based on Java Script and R, which enabled standardized computation of diverse stability parameters, ensuring accuracy and reproducibility

The analysis incorporated several stability measures to identify superior varieties across diverse environments are as detailed below

- Variance-Based Metrics: This included the mean variance component (θ_i) and GE variance component ($\theta_{(i)}$), as proposed by Plaisted and Peterson, alongside Wricke'secovalence stability index ($W_i^{\,2}$).
- RegressionAnalyses: Stability was further assessed using Shukla's stability variance ($\sigma_{i\,2}$), the environmental coefficient of variance (CV_i) and the regression models of Finlay and Wilkinson (bi) and Eberhart and Russell (S^2_{di})
- Non-Parametric Techniques: To ensure a robust selection, the study applied Nassar and Huhn's statistics ($S^{(1)}$, $S^{(2)}$)Huhn's formulas ($S^{(3)}$ and $S^{(6)}$), and Thennarasu's non-parametric indices ($NP^{\,i\text{-}iv}$).

3. Results and Discussion

3.1. Vegetative parameters

The vegetative parameters *viz.*, height of the plant, girth of the trunk, Jorquetting height, canopy as whole and in both directions (Table 2) were measured during 2023. The data of all the six genotypes were subjected descriptive analysis. The plant height varied from 2.7m to 3.05m with range of 0.35m. The coefficient of variation observed was 7.32%. The plant girth ranged between 32.23 cm and 40.67 cm with an average of 37.03 cm. Since cocoa fruits bear on the stem, the girth of the stem is one of the important parameters. Higher girth was observed in Tc5 (40.67 cm) and lower in Tc6 (32.23 cm). The coefficient of variation was 11.40%. Among the genotypes, maximum height of thejorquet was observed in Tc3 (1.76 m) and minimum in Tc1 (1.34 m). The average height of jorquet observed was 1.53 m with coefficient of variation was 9.65 %.Earlier reports (Thondaiman *et al.*, 2013 & Sumitha *et al.*, 2018) suggest that the variation in the height and girth of the cocoa plant may be due to the effect of available soil moisture, genetic factors and prevailing environmental conditions during the production phase of the plant, height of jorquetting by genotypes varied based on the genetic factors, training and pruning methods adopted. Some of the findings confirm that plant growth depends on cell expansion and enlargement, which was probably a plant's most sensitive physiological aspect governed by genotype potential and GxE interaction Ofori *et al.,* 2015 and Avendano *et al.,* 2025.

Table 2. Vegetative parameters of various cocoa clones

Cocoa clones/ Hybrids	Plant height(m)	Girth(cm)	Height at 1st branching(m)	Canopy spread		Canopy Area (m^2)
				E-W(m)	N-S(m)	
Tc1	2.70	36.28	1.30	1.64	2.18	5.08
Tc2	2.92	40.57	1.61	2.73	2.59	7.80
Tc3	2.95	37.06	1.76	2.42	2.83	7.30
Tc4	3.05	35.21	1.58	2.10	2.53	6.80
Tc5	2.97	40.67	1.50	2.08	2.48	6.66
Tc6	2.94	32.23	1.43	2.00	2.21	6.08
S Em ±	0.15	1.16	0.18	0.24	0.19	0.39
CD at 5%	0.42	3.44	0.48	0.74	0.57	1.17
CV (%)	7.32	11.40	9.65	5.78	10.09	6.94

EW- East West direction; NS- North South direction

The larger canopy *i.e.* in EW (2.73 m) & NS (2.59 m) was recorded in Tc2 genotype and also the total canopy area *i.e.*7.80sq.m. Smaller canopy 5.08 sq.m. was observed in Tc1 (EW) (1.64 m) and Tc6 (NS) (2.18 m). The mean of total canopy area was 6.62sq.m with co-efficient of variation was 6.94% for this trait. The observed variation in canopy area among cocoa genotypes can be attributed primarily to genotypic difference governed by plant architecture, including branching pattern, leaf size, and vegetative vigor and also GxE interaction (Kireeti *et al.,* 2026). The larger canopy observed in genotypes Tc 2 and 3 following Gaja cyclonic effect in 2018, was typically resulted in defoliation and structural injury, however, genotypes with superior regenerative capacity were able to rapidly restore leaf area through enhanced shoot proliferation and biomass accumulation which indicates their inherent ability to withstand mechanical damage and regenerate vegetative structures efficiently. This recovery is likely associated with better physiological resilience, including efficient assimilate utilization and stronger root support (Lahive *et al.,* 2019). Therefore, increased canopy area in these genotypes reflects not only genetic potential but also their ability to recover from adverse environmental stress, contributing to greater stability and sustained productivity Ofori *et al.,* 2015 and Avendano *et al.,* 2025.

3.2. Economic traits of cocoa

The economic parameters *viz.,* weight of the pod, number of pods per tree, weight of single dry bean and dry bean parameters (Table 3) were measured for 4 years *viz.,* 2019-20 to 2022-23. The pod weight varied from 282.60g in Tc6 to 376.00g in Tc2. This trait exhibited an average weight of 316.5 g at this center with standard deviation of 31.42. The coefficient of variation observed was 9.93% which indicate the precision of the experimentas reported in earlier studies (Vithya *et al.,* 2018 &Phukon *et al.,* 2021).

Table 3. Performance of cocoa genotypes for economic traits

Descriptive statistics	Fruit Weight (g)	No. of pods per tree	Single bean weight (g)	Dry bean			Yield (kg tree^{-1})
				Length (cm)	Breadth (cm)	Thickness (cm)	
No. of Genotypes	6	6	6	6	6	6	6
Minimum	282.60 (Tc6)	20.04 (Tc6)	0.99 (Tc4&6)	2.39 (Tc6)	1.32 (Tc5)	0.89 (Tc3&5)	0.96(Tc6)
Maximum	376.00 (Tc2)	28.09 (Tc2)	1.14(Tc2)	2.85(Tc2)	1.46 (Tc2)	0.95(Tc4)	1.58(Tc2)
Range	93.45	8.05	0.15	0.46	0.14	0.06	0.618
Mean	316.9	23.34	1.04	2.54	1.39	0.94	1.19
SD	31.46	2.82	0.06	0.17	0.05	0.02	0.21
SEM	12.84	1.15	0.02	0.07	0.02	0.01	0.12
CV (%)	9.93	12.09	5.60	6.71	3.50	2.75	17.72

The number of pods per tree ranged between 20.04 (Tc6) and 28.09 (Tc2) with an average of 23.34. The coefficient of variation was 12.09%, with standard deviation of 2.82 within the experiment.There was considerable variability among the genotypes for single dry bean weight *i.e*. it weighed from 0.99g (Tc4&6) to 1.14g (Tc2). The standard error of mean was 0.02 and the coefficient of variation was 5.60 which might be indication of accurate representation of the population mean. The length and breadth of dry bean was higher in TC2 (2.85cm and 1.46cm respectively) and lower bean length in Tc6 (2.39cm) and lower bean breadth in Tc5(1.32cm). Tc4 recorded higher thickness of the bean (0.95cm) and observed lower in Tc3 and Tc5(0.89cm). The coefficient of variation was below 6% for all the physical parameters of the dried bean. The higher bean weight in Tc2 can be attributed to an optimal balance between source and sink dynamics in the cocoa plants. Despite reduced plant height (Tc4), the plants maintained a relatively larger canopy area, which enhances light interception and overall photosynthetic capacity. This indicates that sufficient assimilates were produced due to the expanded canopy, while the shorter plant stature limited excessive vegetative growth, thereby reducing competition for assimilates. As a result, a greater proportion of carbohydrates could be efficiently translocated and partitioned toward the developing beans, leading to increased bean weight. Thus, the combination of high canopy area and reduced plant height supports the conclusion of improved assimilate utilization and effective source–sink relationship favoured reproductive yield. The results are in confirmation with Arunkumar *et al*., 2019, Sumitha *et al.,* 2018.

As farmer point of view, the yield of cocoa beans is of prime importance. The yield observed from 2019-20 to 2022-23after the cyclone analysed and presented in Table 4. Among the genotypes under study, Tc2 recorded higher yield as compared to its counter parts. In Tc2, the average higher yield was 1.58 tree$_{-1}$ year$_{-1}$ and lower yield was recorded in Tc6 (0.96kg /tree/ year). The coefficient of variation of the bean yield was 17.72% which illustrates the extent of variability present in the genotypes mean yield, consonant with the previous findings (Minimol *et al.,* 2016). This also confirms that some of inherent characters for the stress recovery might have played a key role in yield of Tc2 compared to other cocoa clones under evaluation. Furthermore, reproductive resilience, reflected in traits like number of fruits per tree and fruit weight, indicates the plant's capacity to reinitiate flowering and fruit set after stress. These characters can therefore be considered important selection criteria for developing cyclone-resilient cocoa genotypes. The highest yield in Tc2might be due to higher dry bean traits and a greater number of pods per plant and inherent genotype character to efficiently utilize the environment factors viz., sun light, humidity, rain fall, resources like water and nutrients and efficient resource allocation during recovery from Gaja cyclone effect. Similar results like relationship between yield, vigour and yield efficiency was reported by Efron *et al.,* 2005 and Apshara 2017.

3.3. Correlation

After analyzing the individual traits, the data was setup to understand the relationship of the traits *i.e.inter* and *intra* correlations in cocoa. The data was analysed using Pearson Correlation matrix and presented in Fig 2. For better understanding, the *inter* and *intra* correlation matrix observed from Fig.2 was subjected to ranking based on number of positive and negative correlations (Table 4). It was observed that, Ist ranking for inter and intra positive correlation was observed in the traits *viz.,* Canopy (N-S) and Total canopyand bean breadth. The observed correlations among traits were strongly supported by their morphological data, due to their role in increasing leaf area and photosynthetic efficiency, which enhanced assimilate production and ultimately yield in Tc2 1.58 kg/plant. In contrast, jorquetting height showed predominantly negative correlations, which can be attributed to its effect on reducing the effective canopy and fruit-bearing area. Bean thickness also showed inconsistent associations, suggesting possible trade-offs in growth. However, the jorquetting height and bean thickness were the critical characters towards yield which ranked III to IV.

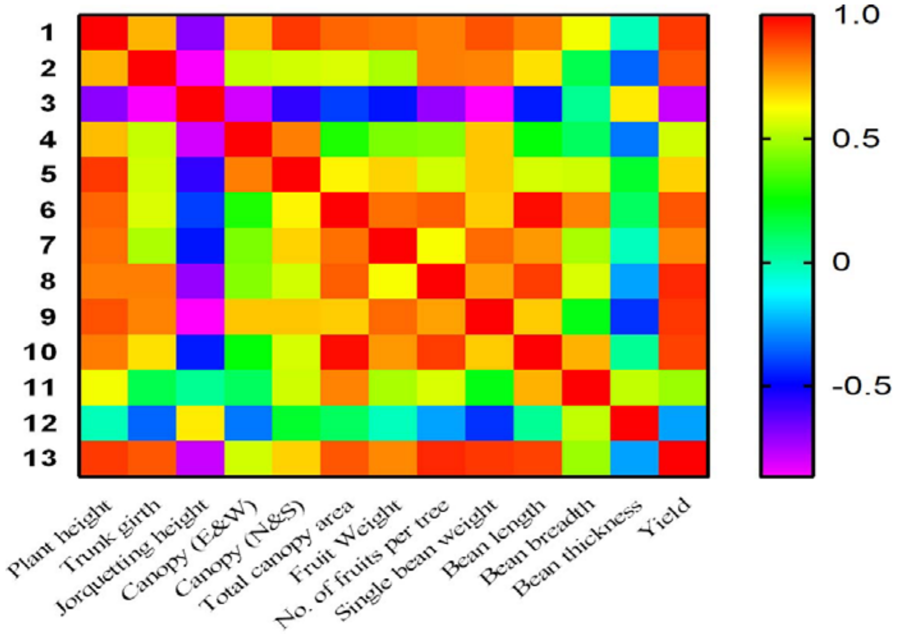

Fig. 2. Heatmap of morphological and yield-related traits in cocoa under cyclone stress conditions

Table 4. Ranking of traits based on inter and intra correlation matrix

S.No.	Characters	Correlation		
		No.of positive traits	No. of negative traits	Ranking
1	Plant height	11	2	II
2	Trunk girth	11	2	II
3	Jorquetting height	2	11	IV
4	Canopy (E-W)	11	2	II
5	Canopy (N-S)	12	1	I
6	Total canopy	12	1	I
7	Fruit weight	11	2	II
8	No of fruits per tree	11	2	II
9	Single bean weight	11	2	II
10	Bean length	11	2	II
11	Bean breadth	12	1	I
12	Bean thickness	5	8	III
13	Yield	11	2	II

It is evident from the correlation matrix that the yield of cocoa was positively correlated to majority of the traits except jorquetting height and bean thickness. Hence optimizing these characters would enhance the economic yield of cocoa in this region. The similar results were reported by (Vithya *et al.*, 2018).

3. 4. Stability index

Crop breeding always envisages yield stability as an important factor to release a variety. Environmental instability remains a significant challenge, largely driven by the ongoing volatility of global weather patterns. The observable characteristics of a plant, or its phenotype, are determined by the interplay between its genetic composition (G) and the external environment (E). Because of the G x E interaction, the performance of specific crop strains often varies significantly when grown across different locations (Schroth *et al.*, 2016).

The genetic makeup and phyto-physical factors that influence the growth and development of cocoa genotypes. Hence, a primary objective in stability modeling is to isolate genotypes that maintain consistent productivity, phenotypic performance regardless of environmental shifts (Fasahat *et al.*, 2015 and Vaezi *et al.*, 2018). Choosing high-performing varieties for specific regional conditions is a fundamental priority for modern agricultural breeding programs (Schwenk and Wagner 2001).

3.4.1. Parametric stability indices

Table 5. Stability parameters of cocoa genotypes for yield under cyclone stress conditions based on Eberhart and Russell model

Genotype	Yield Ranking	Regression coefficient(βi)	Deviation from regression(S^2_{di})	Coefficient of variance(%)
Tc1	2	0.07	1.62	1.28
Tc2	1	0.55	0.80	2.03
Tc3	3	1.20	11.21	6.87
Tc4	5	0.53	0.86	2.87
Tc5	4	2.62	3.50	13.15
Tc6	6	1.03	2.14	5.93

In this study, yield was taken as prime factor to identify stable cocoa genotypes. In the present study, the regression coefficient (bi) derived from the average performance of all genotypes in each environment (Eberhart and Russell model, 1966) exhibited Tc1 (0.07), Tc2 (0.55) and Tc4 (0.53) greater resistance to environmental change, thereby demonstrated a robust resistance to climatic fluctuations. The genotypes Tc3 (1.20), Tc5 (2.62) and Tc6 (1.03) indicate higher sensitivity to environmental change and greater specificity of adaptability to high-yielding environments (Table 5)

In addition to slope regression, variance of deviations from the regression has been suggested as one of the most-used parameters for the selection of stable genotypes. Genotypes with lower values are the most desirable and hence the genotypes Tc2 (0.80) and Tc4 (0.86) are more stable compared to its counterparts in different environment.

The coefficient of variation ranged between 1.28 (Tc1) and 13.15 (Tc5). Genotypes with low CV % and yield rank are considered to be the most desirable. In this study, the genotypeTc2 had second lower Coefficient of variation and 1st in yield ranking and hence expressed stability compared to other genotypes. The stability analysis revealed significant variation among cocoa genotypes in their response to cyclone stress conditions. Genotype Tc2 exhibited superior performance with a regression coefficient less than unity (0.55), low deviation from regression (0.80), and low coefficient of variation (2.03), indicating high stability and adaptability under stress. Tc1 also showed high stability with very low variability, though with comparatively lower responsiveness.In contrast, genotypes such as Tc3 and Tc5 exhibited regression coefficients greater than unity along with high deviation and coefficient of variation, indicating sensitivity to environmental fluctuations and poor stability under cyclone stress. These genotypes performed well only under favorable conditions but were unreliable under stress. The results are in confirmation with the finding of Kireeti *et al.*, 2026 for stress or unfavourable conditions.

Table 6. Stability ranking based on genotypic and environmental variance

Genotype	θ_i	$\theta_{(i)}$•	W_i^2	σ^2_i
Tc1	30.12	25.15	93.54	28.64
Tc2	19.78	30.32	24.66	2.81
Tc3	28.45	25.99	82.45	24.48
Tc4	20.18	30.12	27.27	3.79
Tc5	56.85	11.79	271.75	95.47
Tc6	18.34	31.04	15.06	0.79

The variance component was represented as θ_i" (Plaisted and Peterson, 1959).According to this method, the genotypes which show lower value for the è$_i$ are considered more stable. In the present study, the genotype Tc6,Tc2 and Tc4 were found to have lower values compared to other genotypes. It was observed that the genotype Tc5 expressed higher variance (56.85) compared to other genotypes (Table 6).

Based on the GE variance component, the genotype that express higher values for $\theta_{(i)}$ are stable than the other genotypes. In this study, the genotypes Tc6,Tc2 and Tc4 expressed higher values for the variance parameter compared to other genotypes.The concept of ecovalence (Wricke, 1962), (*Wi*) of the i^{th} genotype is its interaction with the environments, squared and summed across environments. It was opined that the genotypes with lower values have less deviation from the mean across environments and considered to be more stable. From Table 5 it was observed that the genotypes Tc6, Tc2 and Tc4 were found to have lower values *i.e*. 15.06, 24.66 and 27.27 respectively.

According to Shukla statistic (σ^2b"), the stability variance of genotype *i* with minimum values are intended to be more stable, the genotypes Tc6, Tc2 and Tc4 (0.79, 2.48 and 3.79 respectively) expressed lower values and can be considered to be stable.

From all the above parameters of Plaisted and Peterson (1959), concept of ecovalence (Wricke, 1962) and Shukla stability variance (σ^2b"), based GE variance, it was observed that genotypes Tc6 and Tc2 exhibited low θ_i (18.34, 19.78), W_i^2 (15.06, 24.66), and σ^2_i" (0.79, 2.81) values along with high è$_{(i)}$ (31.04, 30.32) respectively, indicating minimal interaction and high stability across environments. These genotypes were less influenced by environmental fluctuations and demonstrated consistent yield performance, suggesting strong inherent recovery mechanisms after cyclone stress. In contrast, genotype Tc5 was analysed with maximum θ_i", W_i"², and σ^2_i" values and the lowest θ_i, indicating high instability and poor adaptability. Similar analysis was being adopted by Pinto *et al.*, 2007 to identify the cocoa stability for biotic stress.

3.4.2. Non-parametric stability indices

Table 7. Ranking based on non-parametric models

Genotype	Yield	$S^{(1)}$	$S^{(2)}$	$S^{(3)}$	$S^{(6)}$	Mean	$NP^{(1)}$	$NP^{(2)}$	$NP^{(3)}$	$NP^{(4)}$	Mean	*K*R
Tc1	2	1	1	1	1	1.20	5	2	2	1	2.20	2
Tc2	1	1	1	1	1	1.00	2	1	1	1	1.20	1
Tc3	3	4	4	4	4	3.80	6	4	4	4	4.40	2
Tc4	5	4	4	5	5	4.60	3	5	3	5	4.20	5
Tc5	4	6	6	6	6	5.60	3	2	6	6	4.60	6
Tc6	6	1	1	1	1	2.00	1	6	5	1	2.80	2

The compute four non-parametric statistics (Nassarand Huhn 1987 & Huhn 1990) $S^{(1)}$, $S^{(2)}$, $S^{(3)}$ and $S^{(6)}$, the mean yield data was transformed into ranks for each environment and genotype. The genotypes with ranks similar across environments in each statistic were considered stable. The statistics indicate that the genotype Tc2's value was 1.00 across the statistics and mean of all the statistics and hence stable as compared to other genotype.Thennarasu's non-parametric statistics (Thennarasu, 1995) also utilise four statistic *i.e.*$NP^{(1-4)}$.The higher stability was reflected in the genotype Tc2 where in the statistics mean value across the four statistics was 1.20 and found to be lowest compared to other genotypes. Kangranking (Kang 1988) used both yield and $\acute{o}^2_i$ as selection criteria. This parameter identifies high-yielding and stable genotype. The most desirable genotype was identified with the lowest rank-sum.According to Kang's rank, the genotype Tc2 was observed to be 1st rank and can be considered to be more stable as compared to other genotypes (Table 7).

Based on the convergence of results from multiple stability models clearly demonstrates that Tc2 was identified as the most stable genotype under cyclone stress, securing the highest yield rank (1), low regression coefficient (βi = 0.55), indicating better adaptability to stress conditions. The genotype showed minimal deviation from regression (S^2di = 0.80) and low variability (CV = 2.03%), confirming consistent performance. Further supported with low θ_i" (19.78), W_i^2 (24.66), and (2.81), along with high $\theta_{(i)}$ (30.32), indicating minimal genotype × environment interaction. Non-parametric measures also ranked Tc2 as most stable, with the lowest S mean (1.00), NP mean (1.20), and best Kang's rank (KR = 1).

Overall, Tc2 demonstrated superior inherent stress recovery ability and is highly suitable for cultivation in cyclone-prone regions.

Conclusion

The present investigation clearly demonstrated significant differences among cocoa genotypes in their response to cyclone-induced stress, with stability parameters and correlation analysis providing strong evidence for the role of inherent recovery traits. Among the genotypes evaluated, Tc2 consistently exhibited superior performance, combining high yield ranking with desirable stability parameters, including a regression coefficient less than unity, low deviation from regression, and minimal interaction effects (low θ_i, W_i^2, and σ^2_i). Quantitatively, Tc2 showed reduced variability (low coefficient of variation) and stable yield performance across stress environments, indicating a clear advantage over other genotypes. The strong positive association of yield with morphological traits such as canopy spread, trunk girth, and fruit-related characters further confirms that structural and physiological attributes contribute significantly to stress recovery. These traits enhance photosynthetic efficiency, support better assimilate partitioning, and enable rapid regeneration following cyclone damage. Based on these findings, Tc2 is recommended for cultivation in cyclone-prone regions due to its superior stability, adaptability, and recovery potential. Adoption of such stable genotypes can provide substantial benefits to farmers by ensuring more consistent yields, reducing risk under extreme weather events, and improving overall income stability.

From a breeding perspective, the results highlight the importance of selecting genotypes with low genotype × environment interaction and strong morphological recovery traits as key criteria for developing climate-resilient cocoa varieties. Incorporating these stability parameters into breeding programs will enhance the development of genotypes capable of withstanding increasing climatic uncertainties.Thus, genotype Tc2 will not only improve productivity but also strengthen the sustainability of coconut-cocoa-based farming systems under cyclone prone areas.

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