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Agro-morphological response of cocoa tree (*Theobroma cacao L*) hybrid families to water deficit in Côte d'Ivoire

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Abstract

Drought caused by climate change is triggered by deforestation. It has altered rainfall distribution, humidity, and air temperature. This situation threatens the sustainability of cocoa cultivation in certain regions where rainfall is between 900 and 1,200 mm. A study was conducted in a zone with insufficient rainfall (Toumodi) and a zone with normal rainfall (Divo). The objective of this study was to determine the impact of drought on 25 hybrid families through agro-morphological parameters. The experimental design was a factorial block including region and family as factors. Drought caused an increase in mortality and a reduction in growth and development of the hybrid families, as well as a decline in production in the Toumodi area. Across the two agro-ecological zones, eleven (11) out of the twenty-five (25) hybrid families (F23, F22, F7, F19, F18, F25, F15, F1, F16, F24, and F13) exhibited the best agro-morphological performance. Moreover, in the drought-affected area of Toumodi, five (05) other hybrid families (F4, F12, F14, F10, and F21) showed superior performance for the evaluated parameters. These hybrid families are potentially resistant to water deficit associated with drought.

Keywords: Evaluation; Cocoa Tree; Agro-Morphological Parameters; Climate Change

1. Introduction

The cocoa tree (*Theobroma cacao* L.) is a perennial plant belonging to the family Malvaceae. It is cultivated for its beans, which are the raw material for chocolate production [10]. West Africa accounts for approximately 74% of the global cocoa production, estimated at about 4.5 million tons of marketable cocoa [14]. Côte d'Ivoire is the world's leading cocoa producer, with an annual output estimated at 1.8 million tons of marketable cocoa [14]. This production contributes 15% to the national GDP and represents about 40% of export revenues [14].

Despite these impressive performances, Ivorian cocoa production is currently facing several constraints, including: the aging of orchards [3; 18] the low level of use of improved plant material [18;27], high pest pressure [16; 17; 19; 21] drought. Over the past few decades, cocoa-producing areas in Côte d'Ivoire have been marked by high climate variability [8 ;11 ;15]. This climate variability has led to a drop in rainfall below threshold values (1,200 mm) [8], thereby

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increasing the number of dry months per year (from 3 to 6 months). The water deficit not only affects the survival of cocoa trees, but also their vegetative growth and physiological development [23].

To address this issue, the National Center for Agronomic Research (CNRA) has developed high-yielding cocoa varieties that combine good technological qualities with resistance to pathogens under optimal growing conditions. However, with the advent of climate change, it has become necessary to study the performance of these varieties under water-deficit conditions. In this context, the present study aims to evaluate the impact of drought on the agro-morphological performance of 25 hybrid families of cocoa (*Theobroma cacao* L.) planted in Divo (normal rainfall zone) and Toumodi (low rainfall zone).

2. Material and methods

2.1. Study area

The study was conducted on two experimental plots, one located in Toumodi (a low-rainfall zone at 6°55' N latitude and 5°03' W longitude) and the other in Divo (a normal-rainfall zone at 5°48' N latitude and 5°18' W longitude). Table 1 presents the climatic characteristics (rainfall and temperature) of the two study zones.

Table 1 Rainfull and temperatures in the areas where the study sites are located

	Rainfull (mm)			**Temperature (°C)**		
	Minimum	**Maximum**	**Average**	**Minimum**	**Maximum**	**Average**
Divo	24	249	1469	24,5	27,6	26,2
Toumodi	12	180	1091	25,5	28,4	26,591

2.2. Study area

The plant material consists of twenty-five (25) hybrid families obtained through controlled hybridization (Table 2). Twenty-seven (27) plants were evaluated per hybrid family. A total of 1,450 genotypes spread over two (02) plots in two (02) areas with different rainfall patterns were monitored. These plants were planted for testing in June 2013.

Table 2 Hybrid families resulting from crosses between parents

Manual hybridization			**Hybrid family codes**
Females		**Males**	
UPA402	X	UF676	F1
UPA409	X	IFC1	F2
UPA608	X	IFC412	F3
UPA413	X	IFC1	F4
UPA603	X	UF667	F5
UPA409	X	POR	F6
T85/799	X	IFC15	F7
SCA6	X	ICS1	F8
PA150	X	IFC5	F9
T79/501	X	IFC5	F10
IFC720	X	ICS46	F11
IMC67	X	IFC1	F12

MOQ413	X	SCA6	F13
POR	X	T60/887	F14
PA150	X	POR	F15
IFC303	X	IFC1	F16
SCA6	X	LAF1	F17
IFC29	X	IFC303	F18
T60/887	X	IMC67	F19
PA150	X	T60/887	F20
P7	X	GU175A	F21
P7	X	GU284 A	F22
IFC303	X	GU175A	F23
IFC303	X	GU284 A	F24
P7	X	IMC67	F25

3. Methodology

3.1. Experimental

The experimentation consisted of a Fisher block for each zone. Treatments were applied to the twenty-five (25) hybrid families, with three (03) replications of nine (09) trees each, totaling twenty-seven (27) trees per hybrid family in the Divo zone, and three (03) replications of seven (07) trees, totaling twenty-one (21) trees per hybrid family in the Toumodi zone. The standard planting density of 1,333 trees per hectare (3 m between rows and 2.5 m between trees) was maintained. Considering both zones and hybrid families together, the study was conducted as a two-factor trial (zone*family). In total, 4,092 trees (genotypes) were evaluated.

3.2. Evaluated Parameters

Two types of parameters were evaluated: (1) the mortality rate and (2) growth and development parameters.

3.3. Mortality Rate

The mortality rate was assessed nine (09) years after field planting. It was expressed as a percentage and calculated as the ratio of the number of dead trees to the total number of trees planted.

3.4. Growth and Development Parameters

These included the collar diameter at 30 cm above the ground, tree cross-sectional area, and leaf dimensions. The collar diameter was measured at 30 cm above the ground using a caliper. The tree circumference was measured at 1.5 m above the ground, and the cross-sectional area was calculated using the following formula:

$$(\boldsymbol{cm^2}) = \frac{(\boldsymbol{Cir})\mathbf{2}}{\mathbf{4\pi}}$$

Leaf dimensions (length and width) were measured using a graduated ruler on three (03) leaves per tree, and the individual leaf area was calculated following the formula of [26]:

$$\boldsymbol{S}\ (\boldsymbol{cm^2}) = \frac{\boldsymbol{\pi}\ \mathbf{ab}}{\mathbf{4}}$$

Where a=A/2 and b=B/2; A= leaf length, B = leaf width. The total leaf zone was calculated by summing the individual leaf zone

3.5. Statistical data analysis

To identify the sources of variation within hybrid families and between zones, one-way (ANOVA) and two-way (MANOVA) analyses of variance were performed. The Newman-Keuls test at a significance level of α = 5% was used to determine the existence of homogeneous groups among hybrid families and between zones. For each analyzed variable, this test allowed comparison of the mean values of hybrid families within each zone. Subsequently, principal component analysis (PCA) was conducted based on the mean values obtained from the variance analysis, aiming to establish correlations between parameters and the principal axes. Finally, hierarchical cluster analysis (HCA) was performed to structure homogeneous groups around discriminant variables. All analyses were conducted using SAS 9.4 (SAS Institute, 2018), XLSTAT version 2014, and R version 4.1.2.

4. Results

4.1. Effects of zones on cocoa tree mortality, growth and development

The zones exhibited significant differences for all evaluated parameters across all hybrid families. The zone * family interactions were significant for the mortality rate (p = 0.0014), collar diameter at 30 cm above the ground (p = 0.0241), cross-sectional area at 1.5 m above the ground (p = 0.0017), and total leaf area (p = 0.01876) (Table 3). The mortality rate of cocoa trees, nine (09) years after field planting, varied highly significantly according to the agroclimatic zones. It averaged 6.15% in the Divo zone, which recorded the lowest mean among all 25 families, compared to 42.29% in the Toumodi zone, which exhibited the highest rate. The largest collar diameters at 30 cm above the ground were obtained in the Divo zone (13.81 cm), whereas the smallest diameters were recorded in the Toumodi zone (12.49 cm). Regarding tree height, the Divo zone showed the highest average value (5.60 m), while the Toumodi zone had the lowest (4.14 m). For cross-sectional area, Divo presented the largest mean (109.96 cm^2), and Toumodi the smallest (87.55 cm^2). For total leaf area, the Divo zone exhibited the highest values with a mean of 201.57 cm^2, whereas the Toumodi zone showed the lowest values (198.38 cm^2).

Table 3 Comparison of study zones based on mortality rate and growth and development parameters of cocoa trees

		Growth and development parameters		
Zones	**Mortality Rate (%)**	**Collar diameter at 30 cm Above Ground (cm)**	**Cross-Sectional Area at 1.5 m Above Ground (cm^2)**	**Total Leaf Area (cm^2)**
Divo	6.15± 0.00^b	13.81±2,71^a	109.96±52.68^a	201.57±67.72^a
Toumodi	42.29±0.03^a	12.49±3.58^b	87.55±51.90^b	198.38±73.41^b
Mean	24.22	13.37	102.58	200.52
CV (%)	15.45	21.92	49.68	26.7
P-value < 0.05	<.0001	<.0001	<.0001	<.0001
Zone*family	0.014	0.0241	0.0017	0.01876

In each column, means followed by the same letter are not significantly different at the 5% significance level

4.2. Influence of Zones on the Growth and Development Parameters of Cocoa Trees

Since the zone*family interaction was significant for all evaluated parameters, the ranking of families was performed separately by zone (Table 4). The mortality rate showed uniformity in the Divo zone and significant differences among hybrid families in the Toumodi zone. The highest mortality rate was observed in family F6 (81%) in the Toumodi zone, while the lowest rates were recorded in families F21 and F24 (16.71%). Collar diameter at 30 cm above the ground showed significant differences among hybrid families in the Divo zone and uniformity in the Toumodi zone. The largest diameter was recorded in family F10 (15.76 cm) in Divo, whereas the smallest diameters were observed in families F7 (13.53 cm) and F17 (13.33 cm) in Divo. Cross-sectional area exhibited significant differences among hybrid families across all zones. The largest cross-sectional areas were recorded in family F21 (157 cm^2) in Divo and F14 (128.57 cm^2) in Toumodi, while the smallest areas were observed in families F23 (80.69 cm^2) in Divo and F3 (55.81 cm^2) in Toumodi. Total leaf area also showed significant differences among hybrid families in all zones. The largest leaf areas were obtained by family F13 (245.4 cm^2) in Divo and families F1 (218.47 cm^2) and F22 (215.02 cm^2) in Toumodi. Conversely, the smallest total leaf areas were observed in families F3 (155.39 cm^2) and F8 (154.95 cm^2) in Divo, and F2 (134.35 cm^2) in Toumodi.

Table 4 Comparison of hybrid families based on mortality rate, growth, and development parameters across different zones

	Mortality Rate (%)		**Collar diameter at 30 cm Above Ground (cm)**		**Cross-Sectional Area at 1.5 m Above Ground (cm²)**		**Total Leaf Area (cm²)**	
Famille	**Divo**	**Toumodi**	**Divo**	**Toumodi**	**Divo**	**Toumodi**	**Divo**	**Toumodi**
F1	6.18±0.03^{a}	66.33±0.04^{bdac}	13.52±0.48^{ba}	12.84±2.07^{a}	95.63±10.5^{bc}	62.35±13.2^{bc}	215.74±9.34^{bdac}	218.74±18.3^{a}
F10	5.63±0.02^{a}	28.33±0.14^{egf}	15.67±0.31^{a}	14.56±0.73^{a}	114.88±8.4^{bac}	114.92±13.8^{ba}	187.65±9.4^{fdehcg}	166.39±8.6^{ba}
F11	8.37±0.02^{a}	52.33±0.12^{ebdacf}	14.49±0.61^{ba}	12.63±0.74^{a}	117.53±11^{bac}	106.81±15.1^{ba}	224.22±11.38^{ba}	151.94±16.4^{ba}
F12	10.18±0.07^{a}	34.52±0.15^{edgf}	14.63±0.5^{ba}	11.58±1.25^{a}	124.81±11.08^{bac}	66.62±10.2^{bc}	193.67±8.85^{fbdecg}	173.55±10.7^{ba}
F13	2.89±0.01^{a}	43±0.08^{ebdgcf}	14.21±0.51^{ba}	11.48±0.98^{a}	100.18±10.21^{bc}	80.11±11.2^{bac}	245.4±12.17^{a}	195.98±18.5^{ba}
F14	5.63±0.02^{a}	33.33±0.09^{edgf}	13.12±0.58^{ba}	14.36±0.71^{a}	110.43±11.6^{bc}	128.57±16.8^{a}	182.57±10.08^{fdehg}	176.44±9.6^{ba}
F15	5.63±0.02^{a}	25.19±0.11^{egf}	13.45±0.45^{ba}	11.9±0.87^{a}	129.73±11.34^{bac}	76.11±9.2^{bac}	221.11± 12.22^{bac}	193.75±10.3^{ba}
F16	5.63±0.02^{a}	29.52±0.20^{egf}	13.68±0.47^{ba}	11.86±0.88^{a}	107.83±6.82^{bc}	81.97±13.2^{bac}	217.76±25.62^{bdac}	164.61±8.3^{ba}
F17	6.18±0.03^{a}	71.67±0.14^{bac}	13.33±0.59^{ba}	14.32±1.49^{a}	120.19±10.42^{bac}	84.96±34.1^{bac}	165.24±8.53^{hg}	158.46±13.3^{ba}
F18	8.93±0.03^{a}	28.67±0.08^{egf}	13.26±0.5^{ba}	11.99±1.24^{a}	102.68±11.65^{bc}	74.32±16.8^{bac}	201.7±12.25^{fbdec}	180.48±17.5^{ba}
F19	2.89±0.0^{a}	38.33±0.09^{edgcf}	13.91±0.62^{ba}	12.29±0.98^{a}	104.87±11^{bc}	89.46±17.6^{bac}	202.53±10.15^{fbdec}	204.96±11.4^{ba}
F2	5.63±0.02^{a}	47.67±0.04^{ebdagcf}	12.54±0.38^{b}	11.57±1.05^{a}	94.32±8.88^{bc}	68.39±14.1^{bc}	168.73±11.2^{fhg}	134.35±17.2^{b}
F20	6.18±0.03^{a}	66.67±0.12^{bdac}	13.72±0.68^{ba}	9.36 ±1.39^{a}	112.3±13.84^{bc}	60.73±15.5^{bc}	186.44±11.2^{fdehcg}	186.86±11.1^{ba}
F21	2.89±0.00^{a}	16.71±0.13^{g}	15.17±0.49^{ba}	13.33±0.89^{a}	157.53±11.32^{a}	86.55±9.5^{bac}	207.32±11.68^{bdec}	200.83±12.2^{ba}
F22	2.89±0.00^{a}	25.19±0.11^{egf}	13.44±0.59^{ba}	12.73±1.05^{a}	125.14±13.46^{bac}	85.76±10.2^{bac}	203.36±14.48^{fbdec}	215.02±9.5^{a}
F23	6.18±0.03^{a}	20.19±0.11^{gf}	12.43±0.37^{b}	13.71±0.78^{a}	80.69±7.36^{c}	113.96±14.3^{ba}	214.17±7.72^{bdac}	199.97±9.1^{ba}
F24	9.3±0.06^{a}	16.71±0.13^{g}	12.93±0.5^{ba}	13.14±0.72^{a}	100.36±9.92^{bc}	99.31±10.4^{ba}	216.05±12.36^{bdac}	186.9±9.2^{ba}
F25	2.89±0.00^{a}	20.52±0.08^{gf}	14.03±0.54^{ba}	13.14±1.05^{a}	110.82±7.74^{bc}	108.31±15.3^{ba}	219.07±13.13^{bac}	166± 8.4^{ba}
F3	2.89±0.00^{a}	76±0.05^{ba}	13.33±0.36^{ba}	9.92±1.76^{a}	100.29±8.75^{bc}	55.81±17.1^{c}	155.39±9.09^{h}	166.91±20.4^{ba}
F4	2.89±0.00^{a}	24.86±0.16^{egf}	13.99±0.45^{ba}	11.93±0.51^{a}	106.12±7.83^{bc}	78.6±8.2^{bac}	174.59±9.49^{fehg}	188.14±9.6^{ba}
F5	6.18±0.03^{a}	52.33±0.12^{ebdacf}	13.69±0.67^{ba}	10.69±0.95^{a}	101.94±10.55^{bc}	63.84±13.1^{bc}	193.81±9.06^{fbdecg}	177.51±7.9^{ba}

F6	16.26±0.08[a]	81±0.05[a]	14.6±0.58[ba]	12.9±1.55[a]	98.6±9.7[bc]	86.27±17.2[bac]	187.98±12.9[fbdehcg]	159.85±14.3[ba]
F7	2.89±0.00[a]	29.86±0.15[egf]	13.53±0.51[ba]	12.13±0.77[a]	86.21±8.05[bc]	83.63±13.1[bac]	198.23±13.3[fbdecg]	165.84±12.2[ba]
F8	2.89±0.00[a]	57±0.14[ebdac]	14.13±0.59[ba]	12.38±0.79[a]	138.39±11.3[ba]	88.15±20.3[bac]	154.95±8.1[h]	162.59±12.2[ba]
F9	15.71±0.06[a]	71.33±0.08[bac]	14.54±0.71[ba]	11.66±1.16[a]	103.95±9.21[bc]	68.17±16.2[bc]	218.34±12.7[bdac]	182.15±13.1[ba]
Mean	6.15	42.29	13.8	12.48	109.96	87.55	201.566	181.18
CV (%)	9.96	48.96	19.27	28.349	46.427	31.15	29.557	24.24
P<0.05	0.4214	0.0007	0.0029	0.1865	<.0001	0.037	<.0001	0.0003

In each column, means followed by the same letter are not significantly different at the 5% significance level

4.3. Structuring of Hybrid Families Based on Mortality and Growth and Development Parameters

In the Divo zone, the two principal axes from the principal component analysis (PCA) of hybrid families explained 72.17% of the observed variability. Axis 1 accounted for 42.53% of the total variability and was primarily defined by mortality rate and collar diameter at 30 cm above the ground, with squared cosines ranging from 0.485 to 0.723. Axis 2 explained 29.29% of the variability and was mainly associated with total leaf area (squared cosine = 0.654) (Figure 1A). Hierarchical cluster analysis (HCA) (Figure 1B) identified three groups of cocoa trees based on growth and development parameters. The first group, comprising families F2, F14, F20, F17, F4, F3, and F8, was characterized by low values for total leaf area, mortality rate, and collar diameter. The second group included families F23, F22, F7, F19, F5, F18, F25, F15, F1, F16, F24, and F13 and exhibited high total leaf area, low mortality rates, and intermediate collar diameter. The third group, consisting of families F11, F21, F12, F9, and F6, showed high values for total leaf area, collar diameter, and mortality rate.

In the Toumodi zone, PCA explained 81.13% of the observed variability. Axis 1 accounted for 48.58% and was defined by total leaf area and collar diameter at 30 cm above the ground (squared cosines = 0.586 and 0.578, respectively). Axis 2 explained 32.55% of the variability and was primarily associated with mortality rate (squared cosine = 0.512) (Figure 2). HCA in Toumodi also revealed three groups. The first group, composed of families F3, F20, F5, and F9, was characterized by high mortality rates and low total leaf area and collar diameter. The second group, including families F8, F11, F17, F2, and F6, displayed high collar diameter and moderate total leaf area but moderate mortality rates. The third group, consisting of families F1, F13, F19, F15, F4, F18, F12, F16, F7, F25, F14, F10, F22, F24, F21, and F23, was characterized by high total leaf area and collar diameter and low mortality rates.

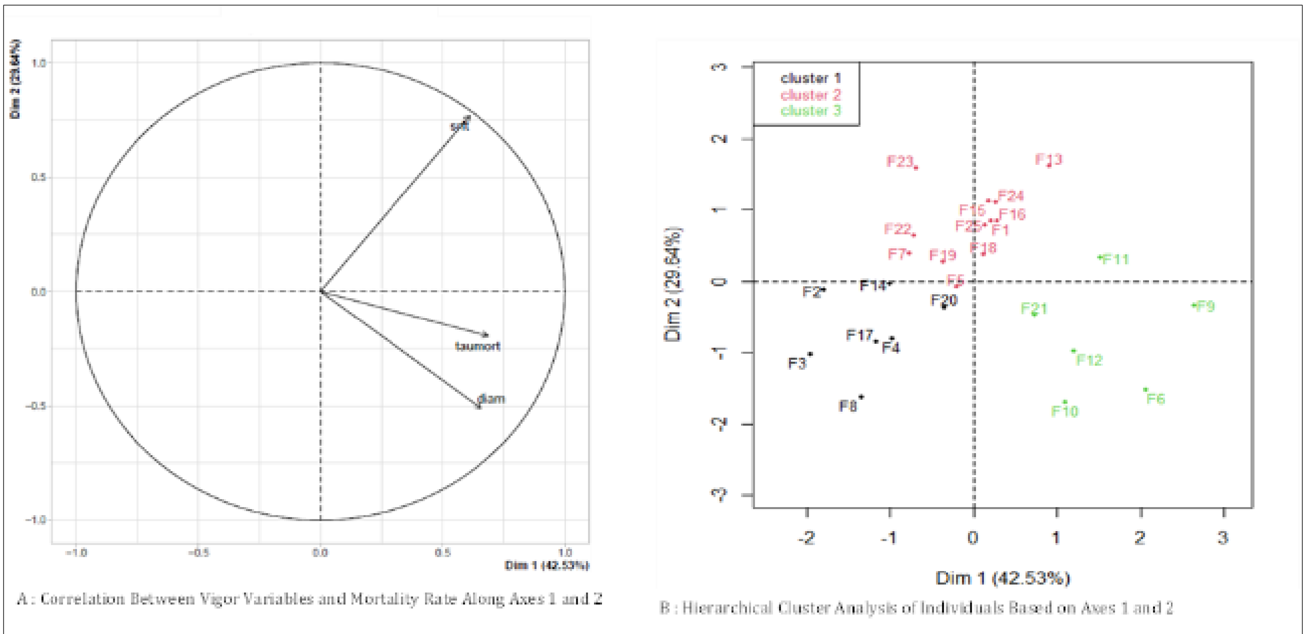
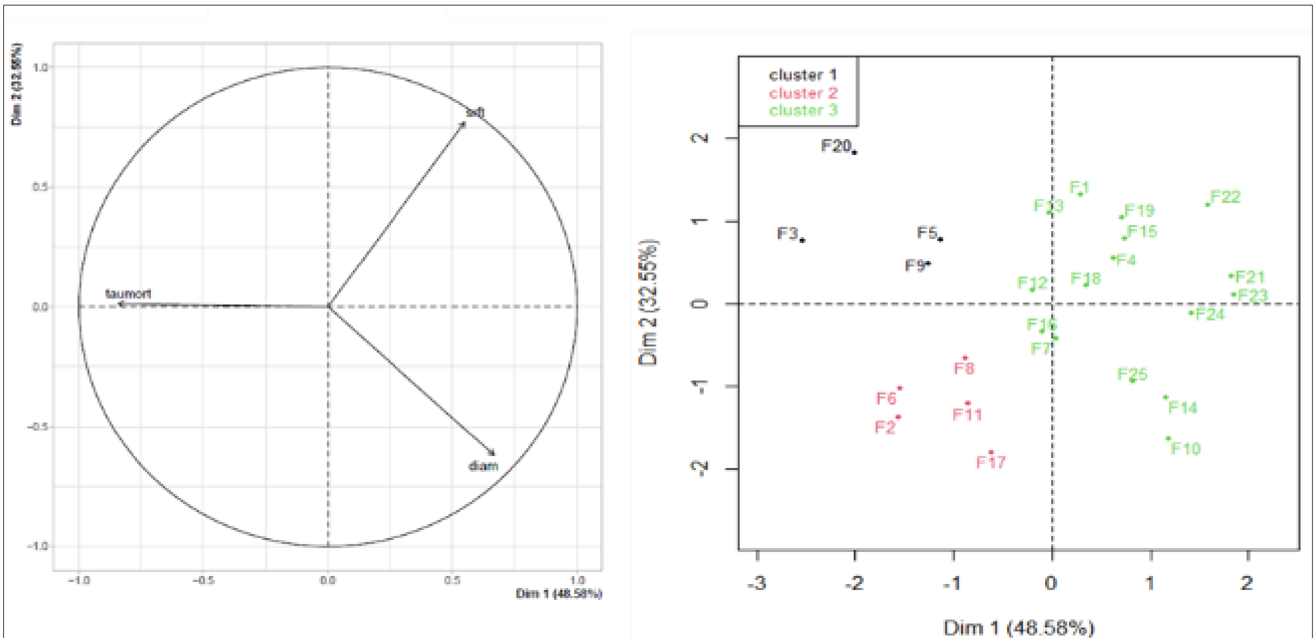


Figure 1 Structuring of Hybrid Families into Homogeneous Groups Based on Vigor Variables and Mortality Rate Evaluated in the Field in the Divo Zone



A : Correlation Between Vigor Variables and Mortality Rate Along Axes 1 and 2

B : Hierarchical Cluster Analysis of Individuals Based on Axes 1 and 2

Figure 2 Structuring of Hybrid Families into Homogeneous Groups Based on Vigor Variables and Mortality Rate Evaluated in the Field in the Toumodi Zone

5. Discussion

The study conducted on twenty-five (25) cocoa hybrid families across two zones with different rainfall regimes demonstrated the depressive effect of drought on growth and development parameters, including trunk diameter, trunk cross-sectional area, and total leaf area. However, the mortality rate increased proportionally with the severity of the drought.

The effect of drought altered the visual appearance of cocoa trees in the Toumodi zone, which experiences low rainfall, compared to those in the Divo zone. Cocoa leaves exhibited folding of the lamina around the central vein. Simultaneously, leaf color changed from deep green to light green, with yellowing patches appearing from the apical tip and spreading inward. This phenomenon marks the onset of water deficit. As the duration of drought increased, necrotic areas spread across the leaf lamina, which appeared less turgid, followed by progressive desiccation of the cocoa plants from the apex toward the roots, ultimately causing tree death. Hybrid families F21, F24, F23, F25, F4, F22, and F15 showed the lowest mortality rates. These findings are consistent with those of [9]and [24], who reported that leaf growth and development are strongly disrupted under limited water conditions. Plants subjected to severe water deficit due to drought generally exhibit accelerated leaf senescence, and excessive water loss can lead to cell death and, consequently, the death of the entire tree [22; 5].

The growth and development parameters (trunk diameter, trunk cross-sectional area, and leaf area) of cocoa genotypes decreased according to the severity of drought in the Toumodi zone. Hybrid families F14, F17, and F24 were less affected in collar diameter growth at 30 cm above the ground compared to their controls in the Divo zone, while families F14, F23, F25, and F24 showed higher trunk cross-sectional area relative to other hybrids in the same zone. This enhanced capacity for diameter and cross-sectional growth may be attributed to the hybrid vigor (heterozygosity) of these families under water stress conditions. These findings are consistent with Boyer [6; 7; 26; 21] , who demonstrated that vegetative growth parameters such as diameter and cross-sectional area can be used to discriminate varieties subjected to drought-induced water stress.

The depressive effect of drought was also observed on total leaf area in the Toumodi zone. However, only hybrid families F22, F1, F19, and F21 produced the largest leaf areas. This high variability among hybrid families for total leaf area confirms the sensitivity of cocoa trees to minor fluctuations in soil moisture. According to [25], one of the first plant responses to water deficit is the reduction of leaf area and the number of functional leaves. Our results also corroborate those of [12; 4; 1; 2; 21], who reported that vegetative development under limited water availability in the field is strongly disrupted, primarily due to a significant decrease in the number of functional leaves and leaf area. This reduction in vegetative growth represents a plant response to dehydration, aimed at conserving water resources and ensuring survival [25; 21]. Leaves of plants subjected to water deficit typically reach smaller final sizes than those of control plants [13], with denser venation and enhanced peripheral protections, including a thicker cuticle and increased leaf pubescence.

6. Conclusion

The objective of this study was to evaluate the agromorphological parameters of 25 cocoa hybrid families (*Theobroma cacao* L.) planted in two zones with different rainfall regimes. The results provided insights into how the cultivation zone can impact the agromorphological performance of these hybrid families. The findings revealed substantial genetic variability for vigor, growth, and development parameters in both the Divo and Toumodi zones. In the Divo zone, families F23, F22, F7, F19, F5, F18, F25, F15, F1, F16, F24, and F13 were characterized by large collar diameters at 30 cm above the ground, large trunk cross-sectional areas, and large total leaf areas. In the Toumodi zone, families F1, F13, F19, F15, F4, F18, F12, F16, F7, F25, F14, F10, F22, F24, F21, and F23 stood out for collar diameter, trunk cross-sectional area, and total leaf area. Across the two agroecological zones, eleven (11) hybrid families (F23, F22, F7, F19, F18, F25, F15, F1, F16, F24, and F13) demonstrated the best overall agromorphological performance among the 25 families. In the drought-prone Toumodi zone, five (5) additional hybrid families (F4, F12, F14, F10, and F21) exhibited superior performance for the evaluated parameters.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declared no conflict of interest

Statement of informed consent

All contributing authors read and approved the final manuscript for publication.

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