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Phenotypic Variability of *Coptodon walteri* Populations in the Cavally River (West, Côte d'Ivoire), a Tool for the Conservation of an Endemic Species

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Abstract

To acquire basic biological data on endemic species living in threatened hydrosystems, the morphological characteristics of the species Coptodon walteri from the Cavally River were evaluated in this study. Specimens of C. walteri were sampled at four stations (Niampleu, Bakatouo, Daapleu, and Floleu) located along the Cavally River from July 2023 to February 2024. A total of one hundred and twenty (120) specimens were sampled, with 30 individuals per station. The analysis using geometric morphometrics focused on sixteen (16) variables measured on each individual using landmarks (a system of reference points), via the software TpsDig and TpsUtil. The sixteen (16) measured parameters were subjected to four statistical analysis: one-way ANOVA, Principal Component Analysis (PCA), Ascending Hierarchical Clustering (AHC), and Discriminant Function Analysis (DFA). The one-way ANOVA test revealed 13 discriminating variables out of the 16 measured. The Principal Component Analysis, Ascending Hierarchical Clustering, and Discriminant Function Analysis structured the Coptodon walteri populations into two distinct groups. The first group consists of specimens from Niampleu, Bakatouo, and Floleu. The second contains only the individuals collected at Daapleu. The Discriminant Function Analysis revealed six variables that best discriminate the Coptodon walteri individuals: dorsal fin base length (LD), caudal peduncle depth (HPC), pelvic fin length (LPe), dorso-anal length (LDA), pre-dorsal fin length (LPrD), and pre-anal fin length (LPrA). This study concluded that there

are two sub-groups within the *Coptodon walteri* specimens, which is likely attributable to the characteristics of the specimens' living environment. The preservation of this species appears feasible in light of its phenotypic variability.

Keywords

Phenotypic Variability, *Coptodon walteri*, Endemic Species, Cavally River, Ivory Coast

1. Introduction

In Ivory Coast, industrial mining and illegal gold panning are causing environmental damage in several regions, particularly in the watershed of the Cavally River, in the locality of Ity (Gbamélé et al., 2020; Kouamé et al., 2018). To carry out their operations, miners adopt both physical and chemical methods in the targeted localities. To this end, they use motorized machinery and chemical substances such as mercury, cadmium, and arsenic for mineral extraction (Gbamélé et al., 2020). The permanent presence of residues from these chemicals negatively impacts the population and the ichthyological diversity of the Cavally River (Doffou, 2020). Furthermore, this ecosystem is home to endemic fish species, among which is *Coptodon walteri* (Doffou, 2020).

Faced with these growing threats, the development of a targeted conservation strategy is essential. According to Fortuna et al. (2024), effective conservation of fish species requires a deep understanding of population dynamics and their mechanisms of local adaptation. Indeed, selective environmental pressures can favor the persistence of certain phenotypes over others (Boag & Grant, 1981). Fish exhibit marked phenotypic plasticity in response to variations in abiotic parameters or pollution (Barrios Rodriguez, 2017). Morphometric studies, such as those (Amidou et al., 2023), have revealed significant differences between tilapia populations in the Sanaga and Niger basins, highlighting morphological adaptations influenced by local environmental conditions. Similarly Barrios Rodriguez (2017) observed that fish living in hypoxic zones developed an increased number of gill rakers. This morphological diversity, shaped by genetic and epigenetic factors, constitutes a major lever for resilience in the face of environmental changes (Amidou et al., 2023; Jacques, 2023).

Thus, Jacquemin & Pyron (2016) recommend integrating the study of habitat-induced phenotypic variation into conservation programs for fish species. The present study, initiated in this context, aims to provide elements for understanding local morphological adaptations in relation to anthropogenic pressures, in order to contribute to the establishment of relevant conservation strategies for this threatened species. More specifically, the objective is to characterize the phenotypic traits of *Coptodon walteri* populations in different habitat types within the Cavally River.

2. Material and Methods

2.1. Study Area Presentation

The study was conducted in the Zouan-Hounien department, located in the far west of Côte d'Ivoire, within the Tonkpi region. The sampling area lies between the geographical coordinates 8˚04' and 8˚08' West longitude and 6˚48' and 6˚54' North latitude. It is situated within the watershed of the Cavally River, one of the main transnational rivers in the region, which stretches approximately 700 km and covers an area of 28,800 km² (Doffou et al., 2024; Kouame-Yoboue et al., 2025).

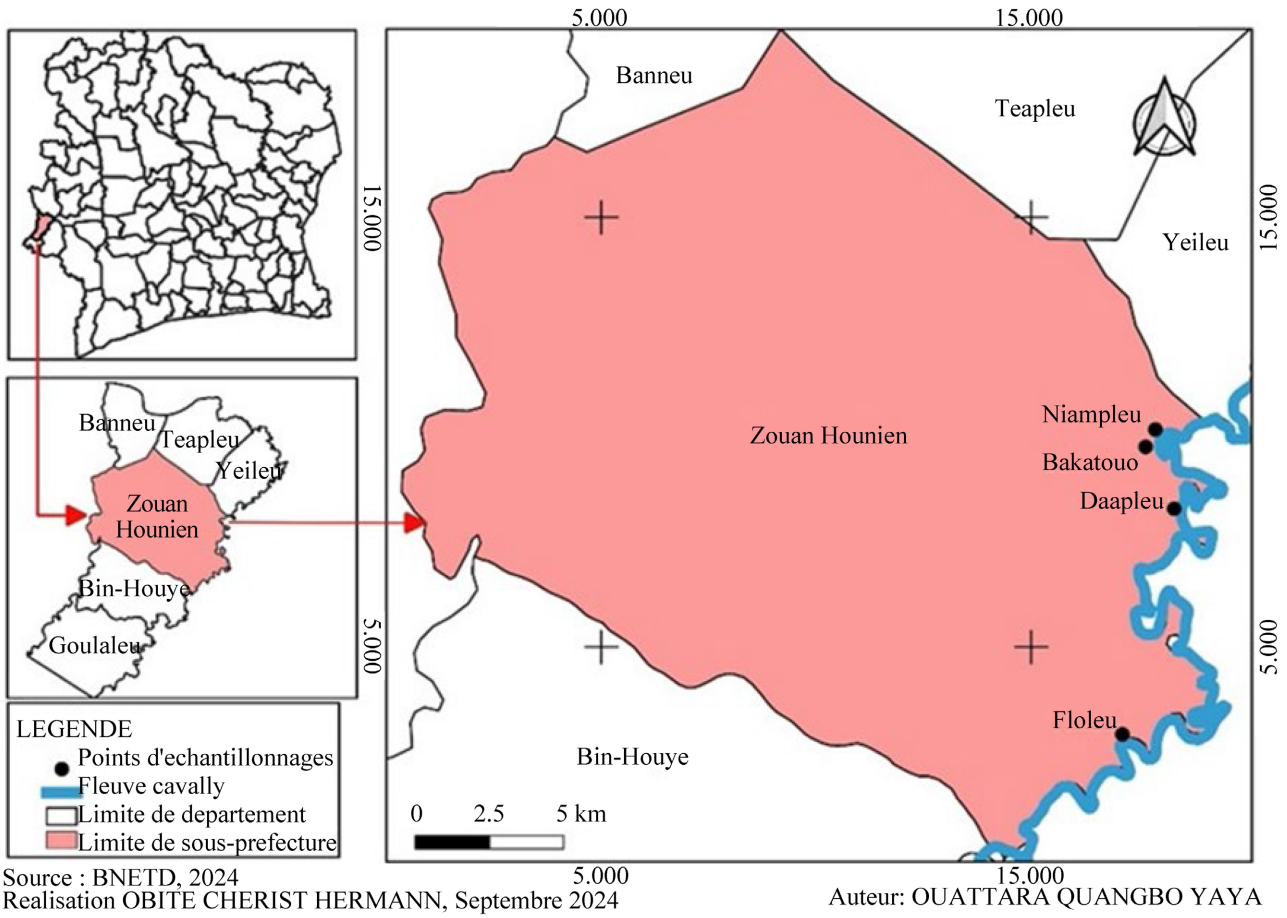

Figure 1. Map of sampling station locations (Niampleu, Bakatouo, Daapleu and Floleu).

Table 1. Geographic coordinates of the sampling stations.

	Stations			
Geographic Co-ordinates	Niampleu	Bakatouo	Daapleu	Floleu
Latitude	6.9500564	6.8643956	6.8716761	6.8030085
Longitude	−8.1022862	−8.1152537	−8.1169601	−8.1165356

For this study, four sampling stations (Niampleu, Bakatouo, Daapleu, and Floleu) were selected. Figure 1 shows the location of the different sampling stations along the Cavally River, and Table 1 indicates the geographical coordinates of each sampled station.

2.2. Choice of Sampling Sites

The sampling stations were selected along a longitudinal gradient of the Cavally River and based on contrasting levels of anthropogenic disturbance, particularly related to gold mining activities.

The first station, Niampleu, located upstream of the gold mining areas, was designated as a reference site due to the absence of nearby mining activities. It represents a relatively pristine habitat, providing a baseline for the river's ecological characteristics.

The second and third stations, located at Bakatouo and Daapleu respectively, are situated immediately downstream of the industrial Ity mine. These sites are heavily influenced by mining effluents and illegal artisanal mining activities. The Daapleu station is notably impacted by direct alluvial mining within the main river channel using dredges, leading to significant habitat modification, primarily through the resuspension of bottom sediments.

Finally, the fourth station, Floleu, located further downstream, is subject to particularly intense anthropogenic pressure. It is characterized by gold mining both within the river channel and on its banks, exacerbating processes of erosion, siltation, and physicochemical contamination of the environment.

2.3. Fish Sampling

Fish sampling was conducted monthly over a two-year period, from July 2023 to February 2024, to encompass the regional hydrological seasons (rainy season and dry season). A total of twelve sampling campaigns were carried out across the four selected stations in the Cavally River basin. A total of 120 individuals of *Coptodon walteri* were collected during these campaigns, representing 30 specimens per site. Fish capture relied on a combined approach of experimental fishing and local artisanal fishing. Experimental fishing was performed using nylon gill nets with various mesh sizes (20 to 40 mm). The nets were deployed in the evening between 5:00 PM and 6:00 PM and retrieved the following morning between 7:00 AM and 8:00 AM (Ayegba et al., 2024; Sánchez-González & Casals, 2022). This method maximized the diversity of sizes captured and limited temporal capture biases. When experimental catches were insufficient to reach the target quota, supplementary *C. walteri* specimens were obtained from local artisanal fishers. These specimens were acquired immediately after their capture to ensure optimal freshness for subsequent morphometric analyses. All collected fish were individually preserved in coolers containing dry ice or ice packs, which were placed inside prior to the commencement of field operations. The samples were transported to the laboratory of the Jean Lorougnon Guédé University (UJLoG) within a maxi-

mum of 24 hours after capture, in accordance with standard protocols for experimental ichthyology.

2.4. Measurement of *Coptodon walteri* Specimens

The morphometric analysis was performed on 120 individuals of *Coptodon walteri*. Upon arrival at the laboratory, the specimens were washed with distilled water, dried with absorbent paper, and individually photographed using a high-resolution digital camera (Canon EOS 4000D, 18 megapixels) mounted on a fixed stand at a standardized distance. For each individual, 16 homologous landmarks were digitized on the image using tpsDig2 software (Porto et al., 2021), following established anatomical references in fish geometric morphometrics (Diamond et al., 2022). These landmarks quantified the following morphological traits: total length (TL), standard length (SL), body depth (BD), head length (HL), snout length (SNL), eye diameter (ED), pre-pectoral length (PPeL), pre-pelvic length (PPvL), dorsal fin base length (DFBL), anal fin base length (AFBL), pre-dorsal fin length (PDFL), pectoral fin length (PeFL), pelvic fin length (PvFL), caudal peduncle depth (CPD), pre-anal length (PAL), and dorso-anal length (DAL) (**Figure 2**). The extracted Cartesian (x, y) coordinates were subjected to a Generalized Procrustes Analysis (GPA) to remove effects of translation, rotation, and scale, preserving only relative shape information (Bookstein et al., 1991). Residual shape variables derived at this stage were used as the basis for both descriptive and multivariate statistical analyses.

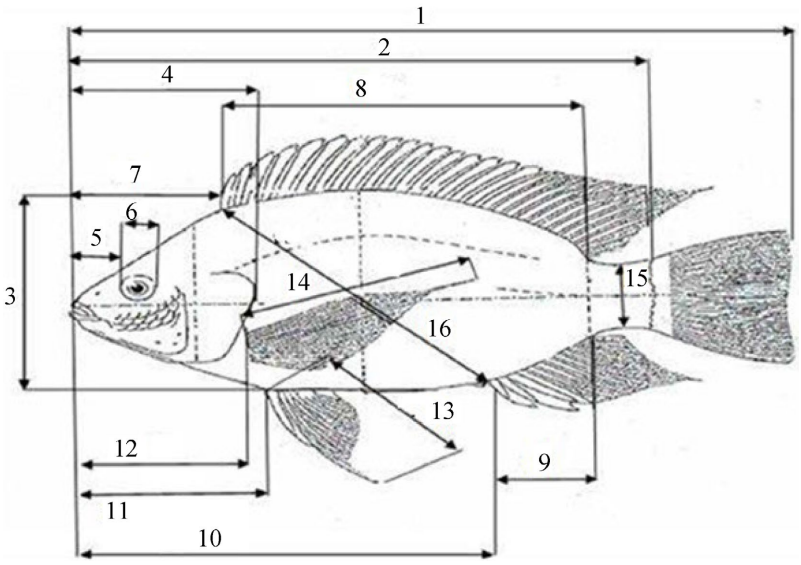

Figure 2. Measurements taken on each specimen (the numbers on the figure represent the corresponding phenotypic traits): 1. **TL :** Total Length; 2. **SL:** Standard Length; 3. **BD:** Body Depth; 4. **HL:** Head Length; 5. **SNL:** Snout Length; 6. **ED:** Eye Diameter; 7. **PDFL:** Pre-dorsal Fin Length; 8. **DFBL:** Dorsal Fin Base Length; 9. **AFBL:** Anal Fin Base Length; 10. **PAL:** Pre-anal Length; 11. **PPvL:** Pre-pelvic Fin Length; 12. **PPeL:** Pre-pectoral Fin Length; 13. **PvFL:** Pelvic Fin Length; 14. **PeFL:** Pectoral Fin Length; 15. **CPD:** Caudal Peduncle Depth; 16. **DAL:** Dorso-anal Length.

2.5. Statistical Analysis of Morphometric Data

To examine the morphological variations among *Coptodon walteri* populations from the four stations of the Cavally River, the collected morphometric data were subjected to a series of statistical analyses. Initially, the coefficient of variation (CV) was calculated for each variable within each station to assess the heterogeneity of each population, interpreted according to Rakotomalala (2012): CV < 15%: The population is homogeneous, 15% < CV < 30%: Values are relatively dispersed, indicating significant variation within the population, CV > 30%: The variation is very high. Subsequently, a one-way analysis of variance (ANOVA) was performed on the data matrix to identify the significant variables for distinguishing the populations. Post-hoc tests (Tukey HSD) were used to determine which specific stations were responsible for the observed differences. A Principal Component Analysis (PCA) was then applied to the data matrix of significant variables to identify the main axes of morphological variation that separate the different groups, as well as the variables that characterize them. Following this, a Discriminant Function Analysis (DFA), using Wilks' lambda test, was performed on the significant variables to highlight the most relevant variables for the optimal discrimination of the different populations. Finally, an Ascending Hierarchical Clustering (AHC) was implemented to establish the similarities between the groups. All statistical analyses were performed using R software version 4.3.0 (R Core Team, 2023).

2.6. Intra-Population Variability of Phenotypic Traits

Table 2. Descriptive statistics of morphometric variables for *Coptodon walteri* across the four sampling stations: maximum, minimum, and Coefficient of Variation (CV).

Variables	Niampleu		Bakatouo		Daapleu		Floleu	
	Max ± Min	CV (%)	Max ± Min	CV (%)	Max ± Min	CV (%)	Max ± Min	CV (%)
SNL	19.49 ± 11.48	11.12	19.44 ± 12.82	7.9	19.58 ± 12.60	10.59	17.73 ± 13.14	7.57
HL	52.63 ± 32.61	9.57	47.86 ± 39.01	5.6	45.46 ± 33.36	7.67	50.19 ± 34.67	8.56
TL	127.75 ± 110.82	2.63	131.03 ± 93.43	5.11	130.49 ± 121.06	1.67	130.32 ± 93.58	5.52
PPvL	42.91 ± 29.08	9.62	77.68 ± 30.80	21.11	40.67 ± 28.70	8.84	77.75 ± 27.68	22.86
PPeL	33.90 ± 21.26	10.86	71.98 ± 27.80	23.42	31.22 ± 22.40	9.1	62.95 ± 21.18	27.29
ED	9.74 ± 3.07	26.74	10.39 ± 4.14	21.05	9.73 ± 3.90	18.33	7.44 ± 3.60	20.54
DFBL	60.56 ± 45.93	7.01	62.13 ± 51.60	4.72	69.50 ± 51.21	5.67	65.54 ± 52.53	5.51
CPD	18.84 ± 11.55	12.92	26.48 ± 10.73	18.72	18.69 ± 12.67	8.81	22.83 ± 12.50	12.04
AFBL	19.39 ± 8.78	14.72	19.28 ± 4.27	18.43	20.85 ± 13.18	12.05	19.17 ± 5.37	17.97
PvFL	39.98 ± 19.53	13.6	43.23 ± 27.24	11.28	37.76 ± 23.76	13.63	44.17 ± 26.71	13.73
PeFL	46.83 ± 28.67	9.6	46.51 ± 34.16	8.78	47.00 ± 30.11	10.09	48.35 ± 27.10	12.57

Continued

DAL	66.03 ± 38.63	12.57	64.73 ± 35.60	16.07	69.31 ± 54.87	5.16	67.67 ± 23.02	16.71
BD	60.17 ± 32.22	14.43	58.80 ± 35.10	17.3	52.52 ± 38.91	6.57	64.72 ± 37.87	15.85
PDFL	24.84 ± 14.75	11.17	22.96 ± 17.25	6.96	51.16 ± 29.22	14.38	55.31 ± 15.64	34.56
PAL	87.24 ± 71.17	5.52	90.78 ± 72.01	4.3	227.56 ± 164	8.03	89.57 ± 72.83	4.66

Max: Maximum; **Min:** Minimum; **CV:** Coefficient of Variation; **%:** Percentage; **TL:** Total Length; **BD:** Body Depth; **HL:** Head Length; **SNL:** Snout Length; **ED:** Eye Diameter; **PDFL:** Pre-dorsal Fin Length; **DFBL:** Dorsal Fin Base Length; **AFBL:** Anal Fin Base Length; **PAL:** Pre-anal Length; **PPvL:** Pre-pelvic Fin Length; **PPeL:** Pre-pectoral Fin Length; **PvFL:** Pelvic Fin Length; **PeFL:** Pectoral Fin Length; **CPD:** Caudal Peduncle Depth; **DAL:** Dorso-anal Length.

The analysis of the coefficient of variation (CV) for the morphological variables shows values ranging from 1.67% to 34.56% (Table 2). The analysis revealed low intra-population morphological variability, with a coefficient of variation (CV) of less than 15% for the majority of the measured traits. However, specific morphometric variables exhibited more pronounced heterogeneity within each station. For instance, at Niampleu (26.74% for ED) and Daapleu (18.33% for ED), the eye diameter (ED) showed moderate variability. At Bakatouo, seven variables displayed intermediate variability (between 15% and 30%), including pre-pelvic fin length (21.11% for PPvL), pre-pectoral fin length (23.42% for PPeL), dorso-anal length (16.07% for DAL), body depth (17.30% for BD), caudal peduncle depth (18.72% for CPD), anal fin base length (18.43% for AFBL), and eye diameter (21.05% for ED). Finally, at Floleu, seven variables similar to those at Bakatouo showed comparable variability, and the pre-anal length (PAL) was distinguished by a very high variability with a CV of 34.56%.

2.7. Inter-Population Variation of Phenotypic Traits

The analysis of variance (ANOVA) revealed a significant difference among the populations from the four stations for all examined variables, except for snout length (SNL), pre-pelvic fin length (PPvL), and pectoral fin length (PeFL) (Table 3). Tukey's multiple comparison test indicates that all *Coptodon walteri* populations exhibit significant differences ($p < 0.001$) from each other regarding pre-pectoral fin length (PPeL) and eye diameter (ED). Furthermore, the variables head length (HL), dorsal fin base length (DFBL), caudal peduncle depth (CPD), anal fin base length (AFBL), dorso-anal length (DAL), body depth (BD), pre-dorsal fin length (PDFL), and pre-anal length (PAL) distinguish the specimens from Daapleu from those of the other stations.

Table 3. Mean of parameters measured on *Coptodon walteri* from the different collection sites.

Variables	Niampleu	Bakatouo	Daapleu	Floleu	ANOVA < 0.05
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	
SNL	15.79 ± 1.76[a]	16.27 ± 1.29[a]	15.93 ± 1.69[a]	15.46 ± 1.17[a]	NS

Continued

HL	44.13 ± 4.22^{a}	42.82 ± 2.4^{ab}	40.72 ± 3.12^{b}	41.97 ± 3.59^{ab}	**
TL	123.04 ± 3.24^{b}	124.19 ± 6.34^{ab}	126 ± 2.1^{a}	123.26 ± 6.8^{ab}	**
PPvL	36.59 ± 3.52^{a}	38.34 ± 8.09^{a}	34.99 ± 3.1^{a}	37.08 ± 8.48^{a}	NS
PPeL	28.96 ± 3.15^{b}	32.85 ± 7.7^{a}	26.62 ± 2.42^{c}	29.61 ± 8.08^{bc}	***
ED	6.96 ± 1.86^{ab}	7.88 ± 1.66^{a}	6.32 ± 1.16^{bc}	5.63 ± 1.16b^{c}	***
DFBL	54.77 ± 3.84^{c}	57.15 ± 2.7^{b}	62.5 ± 3.55^{a}	58.6 ± 3.23^{c}	***
CPD	14.72 ± 1.9^{b}	14.32 ± 2.68^{b}	16.45 ± 1.45^{a}	15.14 ± 1.82^{b}	**
AFBL	16.59 ± 2.44^{ab}	15.72 ± 2.9^{ab}	17.27 ± 2.08^{a}	15.37 ± 2.76^{b}	***
PvFL	33.74 ± 4.59^{ab}	35.92 ± 4.05^{a}	31.19 ± 4.25^{b}	34.71 ± 4.77^{a}	**
PeFL	38.54 ± 3.7^{a}	39.36 ± 3.46^{a}	39.29 ± 3.97^{a}	37.99 ± 4.78^{a}	NS
DAL	56.86 ± 7.15^{b}	54.32 ± 8.73^{b}	64.97 ± 3.35^{a}	57.06 ± 9.54^{b}	***
BD	44.58 ± 6.43^{ab}	44.81 ± 7.75^{b}	47.53 ± 3.12^{a}	46.53 ± 7.38^{ab}	*
PDFL	19.91 ± 2.22^{b}	20.64 ± 1.44^{b}	37.86 ± 5.45^{a}	19.78 ± 6.84^{c}	***
PAL	79 ± 4.36^{b}	79.62 ± 3.42^{b}	190.72 ± 15.31^{a}	80.29 ± 3.74^{b}	***

Mean: Mean; **SD:** Standard Deviation; *($p < 0.05$): Slightly significant difference; **($p < 0.01$): Significant difference; ***($p < 0.001$): Highly significant difference; **NS** ($p > 0.05$): Non-significant difference. Means in the same column followed by at least one common letter are not significantly different (ANOVA and Tukey test).; **TL:** Total Length; **BD:** Body Depth; **HL:** Head Length; **SNL:** Snout Length; **ED:** Eye Diameter; **PDFL:** Pre-dorsal Fin Length; **DFBL:** Dorsal Fin Base Length; **AFBL:** Anal Fin Base Length; **PAL:** Pre-anal Length; **PPvL:** Pre-pelvic Fin Length; **PPeL:** Pre-pectoral Fin Length; **PvFL:** Pelvic Fin Length; **PeFL:** Pectoral Fin Length; **CPD:** Caudal Peduncle Depth; **DAL:** Dorso-anal Length.

2.8. Morphological Differentiation of *Coptodon walteri* Populations

2.8.1. Population Differentiation by Principal Component Analysis (PCA)

Principal component analysis was performed on the data matrix of twelve (12) morphometric variables that showed significant variation across the four populations. Axes with an eigenvalue greater than or equal to 1 were retained. The eigenvalues, percentage of variability, and cumulative percentage of variability for the five retained axes are presented in Table 4. In the ordination analysis, the first two axes, cumulatively accounting for 45.99% of the total variability (30.15% for axis 1 and 15.84% for axis 2, respectively), were considered. The PCA successfully separated the *Coptodon walteri* populations into two groups. Figure 3 shows the projection of the variables and the *C. walteri* individuals. Group 1 (Cluster 1), consisting of individuals from Niampleu, Bakatouo, and Floleu, tended to move from the origin towards the negative coordinates of axes 1 and 2. This population is characterized by a longer head length (HL) and a longer pre-pectoral fin length (PPeL). The second group, associated with the positive coordinates of the primary axis, is characterized by high values for dorsal fin base length (DFBL), dorso-anal length (DAL), pre-dorsal fin length (PDFL), and pre-anal length (PAL). This group corresponds to the population from the Daapleu station.

Table 4. Eigenvalue, percentage of variability, and cumulative percentage of variability associated with morphometric variables.

	Axis 1	Axis 2	Axis 3	Axis 4	Axis 5
Eigenvalue	3.62	1.9	1.26	1.09	0.98
Percentage of variance	30.15	15.84	10.57	9.11	8.19
Cumulative percentage of variance	30.15	45.99	56.56	65.67	73.87
HL	−0.45	**0.58**	−0.10	0.42	−0.07
TL	0.40	−0.43	−0.02	−0.15	0.37
PPeL	**−0.50**	0.31	0.44	−0.34	0.28
ED	−0.30	0.13	**0.78**	−0.069	0.006
DFBL	**0.78**	−0.08	−0.16	−0.35	0.15
CPD	0.51	**0.64**	0.00	0.22	0.004
AFBL	0.29	0.25	0.10	0.20	**0.75**
PvFL	−0.41	0.25	−0.33	0.11	0.23
DAL	**0.66**	−0.15	0.10	0.57	0.06
BD	0.10	**0.70**	−0.39	−0.45	0.01
PDFL	**0.71**	0.39	0.28	−0.08	−0.25
PAL	**0.89**	0.16	0.17	−0.06	−0.16

TL: Total Length, **BD**: Body Depth, **HL**: Head Length, **ED**: Eye Diameter, **PDFL**: Pre-dorsal Fin Length, **DFBL**: Dorsal Fin Base Length, **AFBL**: Anal Fin Base Length, **PAL**: Pre-dorsal Fin Length, **PPeL**: Pre-pelvic Fin Length, **PvFL:** Pelvic Fin Length, **CPD**: Caudal Peduncle Depth, **DAL**: Dorso-anal Length.

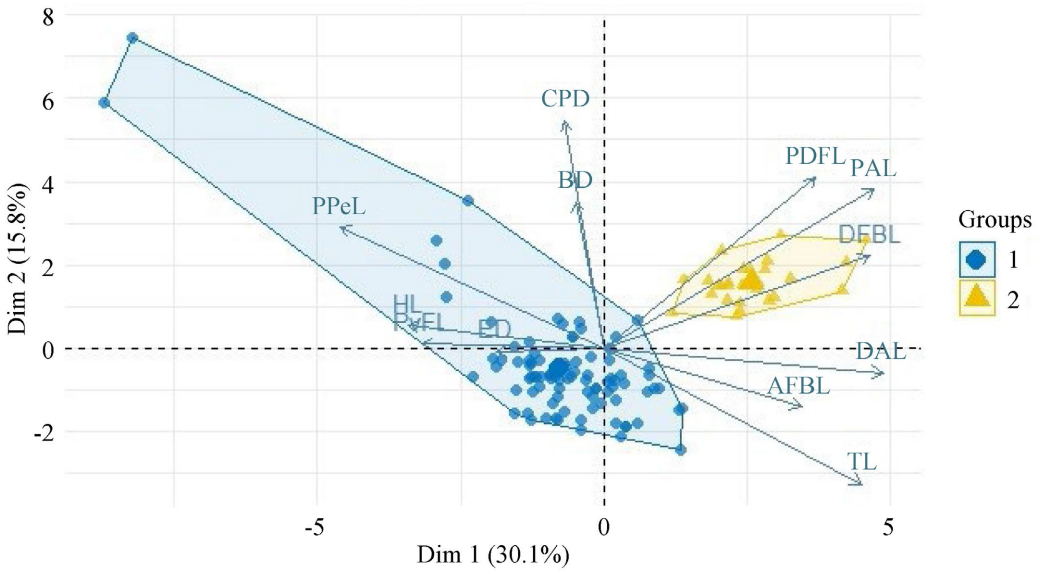

Figure 3. Projection of variables and individuals of *Coptodon walteri* populations by Principal Component Analysis (PCA).

2.8.2. Morphological Similarity between Populations

The Ascending Hierarchical Clustering (AHC) of the *Coptodon walteri* populations produced a dendrogram consisting of two main groups (**Figure 4**). The dis-

tribution of samples within these groups is consistent with the pattern revealed by the Principal Component Analysis (PCA).

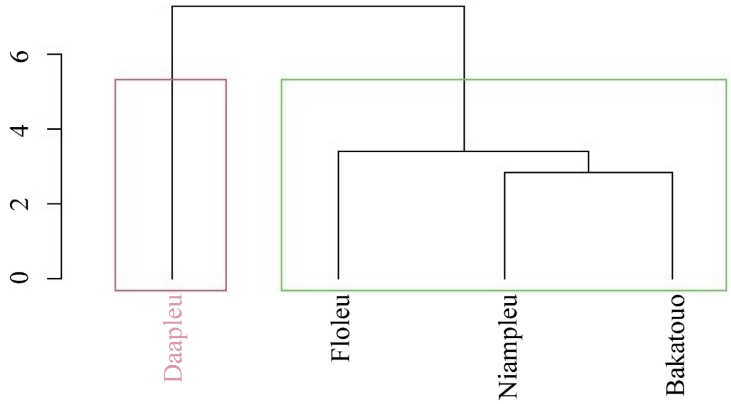

Figure 4. Dendrogram showing the morphological similarities among *Coptodon walteri* populations from four stations on the Cavally River.

2.8.3. Discriminant Function Analysis of Populations

The discriminant analysis, using Wilks' lambda test, revealed that of the 12 descriptors, only eye diameter (ED) and body depth (BD) did not significantly contribute ($p < 0.05$) to discriminating the studied populations (Table 3). Among the 10 significant descriptors, six were particularly effective in separating the examined populations: dorsal fin base length (DFBL), caudal peduncle depth (CPD), pelvic fin length (PvFL), dorso-anal length (DAL), pre-dorsal fin length (PDFL), and pre-anal length (PAL) (Table 5).

Table 5. Discrimination of morphometric variables in *Coptodon walteri* populations by discriminant function analysis.

Variable	Lambda de wilks	*F*	*P*
SNL	0.075	9.53	**0.002**
HL	0.045	5.61	**0.01**
TL	0.072	9.09	**0.003**
PPvL	0.017	2.04	0.156
PPeL	0.320	55.53	**0.000**
ED	0.122	16.41	**0.000**
DFBL	0.051	6.35	**0.01**
CPD	0.110	14.65	**0.000**
AFBL	0.207	30.88	**0.000**
PvFL	0.022	2.69	0.104
PeFL	0.745	343.95	**0.000**
DAL	0.972	4032.73	**0.000**

TL: Total Length; **BD:** Body Depth; **HL:** Head Length; **SNL:** Snout Length; **ED:** Eye Diameter; **PDFL:** Pre-dorsal Fin Length; **DFBL:** Dorsal Fin Base Length; **AFBL:** Anal Fin Base Length; **PAL:** Pre-anal Length; **PPvL:** Pre-pelvic Fin Length; **PPeL:** Pre-pectoral Fin Length; **PvFL:** Pelvic Fin Length; **PeFL:** Pectoral Fin Length; **CPD:** Caudal Peduncle Depth; **DAL:** Dorso-anal Length.

The classification matrix confirmed a 100% correct reclassification of *Coptodon walteri* individuals into their respective populations (Table 6). Out of a total of 120 individuals, 90 specimens constituted Group 1 and 30 individuals formed Group 2. Figure 5 shows the distribution of individuals in the factorial plane defined by the first discriminant function, forming two well-distinguished populations, a result consistent with the pattern observed in the Principal Component Analysis (PCA).

Table 6. Classification matrix of *Coptodon walteri* individuals into their respective groups.

Stations	**Classification Rate %**	Group I	Group II	Total
Group I	100	90	00	90
Group II	100	00	00	30
Total	100	90	30	120

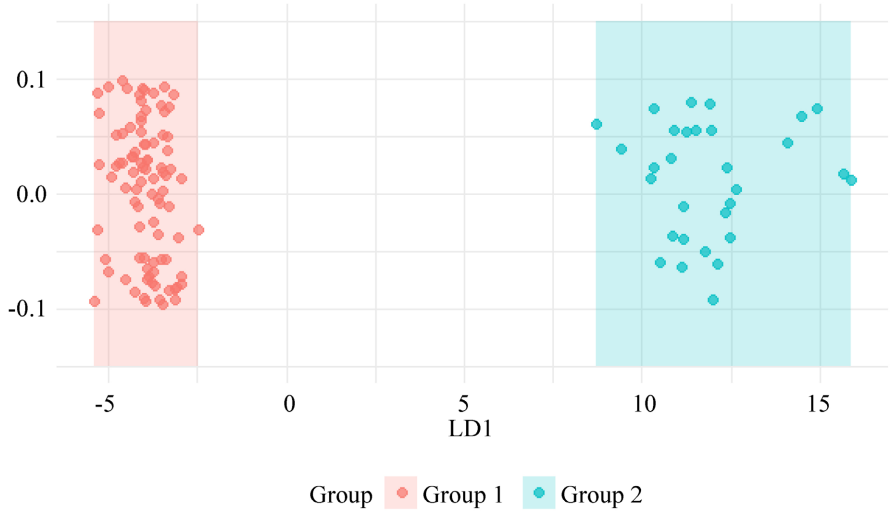

Figure 5. Discrimination of *Coptodon walteri* populations based on individual similarity.

3. Discussion

The analysis of morphological variability in one hundred and twenty specimens of *Coptodon walteri*, collected from four stations along the Cavally River in western Côte d'Ivoire, revealed significant intra- and inter-population differences. The morphological homogeneity observed across several stations, indicated by coefficients of variation (CV) below 15%, suggests these populations inhabit relatively stable environmental conditions (Alambiaga et al., 2021).

The marked differentiation recorded at the Daapleu station appears linked to specific local environmental pressures. Indeed, artisanal gold mining, the dominant activity in the Cavally basin, causes profound physical and chemical disturbances, characterized by increased turbidity, high loads of heavy metals (Hg, Pb, Cd), and substrate modification (Coulıbaly et al., 2021; Santos et al., 2021). These disturbances directly influence fish morphology through mechanisms of adaptive

phenotypic plasticity (Kouame-Yoboue et al., 2025; Nicole et al., 2019; Oladimeji et al., 2020). Thus, the strong representation of dorsal and anal fin lengths in Daapleu individuals could constitute an adaptation to an unstable habitat, requiring better hydrodynamic stability and sustained swimming in turbid environments (França, 2023). Conversely, individuals from the Niampleu and Bakatouo stations retain morphologies associated with larger heads and developed pre-pectoral fins, characteristic of a predation strategy in relatively preserved habitats.

These results corroborate observations (Amidou et al., 2023) on *Oreochromis niloticus* in Cameroon, where variables such as anal fin base length, pre-anal length, head length, eye diameter, and caudal peduncle depth were decisive in population differentiation. Similarly, Issaka (2017) highlighted some of these traits as having high discriminatory power in *O. niloticus* in Benin.

These findings suggest that the morphological variations observed in *C. walteri* could reflect, beyond phenotypic plasticity, a progressive genetic divergence between populations. According Ouédraogo & Amyot (2013), mining and metallic pollution accentuate intra-specific morphological variability, either by exerting selective pressures or by disrupting normal development. Olivier et al. (2018) specify that disturbance during development can lead to the production of divergent phenotypes, with pollutants acting as major disruptors in aquatic environments. Furthermore, fish exposed to high constraints from gold mining frequently exhibit morphological alterations associated with energy deficits and an impoverished diet, due to the scarcity of benthic and planktonic resources (Chukwuka et al., 2019; Kamagaté, 2021). These conditions can lead to increased mortality of the most plastic individuals, decreased reproduction and growth, or, conversely, the selection of more tolerant genotypes capable of developing survival strategies. This situation could explain the growing rarity of *C. walteri* populations observed in the study area.

The multivariate analyses (PCA, AHC, DFA) converge to reveal the structuring of individuals into two distinct morphological groups, confirming population differentiation. These results corroborate the observations of Olopade et al. (2018) on *Coptodon guineensis*, who established a morphological distinction between freshwater and brackish water populations in Nigeria, as well as those of Oladimeji & Olaosebikan (2017), who highlighted similar differentiations between populations of *Tilapia zillii* from different reservoirs.

This morphological disparity seems explainable by a geographical proximity effect. Indeed, the Niampleu, Bakatouo, and Floleu stations form a geographically close cluster, while the Daapleu station is unique due to its isolation, constituting the only geographically distinct group. This differentiation of the Daapleu station is likely driven primarily by direct alluvial mining within the main river channel using dredges, leading to significant aquatic habitat modification.

This phenotypic diversity suggests the existence of underlying genetic variability, which could translate into diverse zootechnical performances and resistance to environmental variations among the different populations.

The identification of these two distinct morphotypes suggests they could represent separate conservation units, possessing critical local adaptations for their survival. Future management should consider specifically protecting the adapted Daapleu population to preserve its unique adaptive potential, while maintaining the integrity of the source populations from the other stations.

Although the morphological analysis revealed certain variations between populations, it has important limitations. The observed differences can result from phenotypic plasticity as much as from true genetic divergence, and morphometric data alone cannot distinguish between them with certainty (Besbes, 2013; Gibert, 2012). Character overlap, variability linked to sex or developmental stage, as well as methodological choices, can also influence the results. These limitations highlight the necessity to complement these studies with molecular analyses to confirm the differentiation between populations, quantify gene flow between them, and elucidate the underlying mechanisms of their divergence

4. Conclusion

The study of morphological variation in *Coptodon walteri* from the Cavally River, under the pressure of artisanal gold mining, revealed significant differentiation among sampling stations. Analysis of variance indicated significant differences ($p < 0.05$) for the majority of variables, with the exception of snout length (SNL), pre-pelvic fin length (PPvL), and pectoral fin length (PeFL). Tukey's test specified that all populations exhibited highly significant differences ($p < 0.001$) for pre-pectoral fin length (PPeL) and eye diameter (ED).

Furthermore, a set of morphological variables head length (HL), dorsal fin base length (DFBL), caudal peduncle depth (CPD), anal fin base length (AFBL), dorso-anal length (DAL), body depth (BD), pre-dorsal fin length (PDFL), and pre-anal length (PAL), specifically distinguished the specimens from Daapleu from the other stations.

These results suggest the existence of two subpopulations, structured based on morphological variations and geographical distances. The observed morphological diversity indicates an adaptive potential favorable for species preservation. For a comprehensive understanding, complementary molecular characterization would nevertheless be necessary to confirm this population structure and accurately assess the adaptation capabilities of *C. walteri* in the face of environmental disturbances.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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