

Relationship between Physicochemical Parameters and Copepod Community Structure in the Tinguilinta River Estuary (Boké, Guinea)

Mamadou Diouldé Sow*, Mamadou Bhoi Balde, Sory Diakite, Mawiatou Sow, Lamine Konate

Marine and Coastal Research Center of Guinea (CEREMAC-G), Conakry, Guinea

Email: *mamadoudiould66@gmail.com, mbbalde1963@gmail.com, falensorel@gmail.com, sowfonfoya@gmail.com, laminekonate1986@gmail.com

How to cite this paper: Sow, M.D., Balde, M.B., Diakite, S., Sow, M. and Konate, L. (2025) Relationship between Physicochemical Parameters and Copepod Community Structure in the Tinguilinta River Estuary (Boké, Guinea). *Journal of Environmental Protection*, 16, 899-915.

<https://doi.org/10.4236/jep.2025.169048>

Received: August 16, 2025

Accepted: September 23, 2025

Published: September 26, 2025

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Abstract

This study investigates the spatio-temporal distribution of copepods (zooplankton) in the Tinguilinta River estuary, in relation to water physicochemical parameters, during the dry and rainy seasons across fifteen sampling stations. Field sampling was conducted for both physicochemical and biological analyses. The physical and chemical properties of the water were measured in the laboratory. Copepods were collected using a plankton net with a mesh size of 55 μm . Thirty copepod species were identified under the microscope, belonging to four orders and sixteen families, with a marked predominance of Calanoids (77.34%). Overall, the lowest taxonomic richness and abundance were recorded at station S7 during the dry season, while the highest values occurred at station S1 during the rainy season. Species diversity assessed using the Shannon-Weaver index (H'), remained relatively consistent among stations, with lower values observed at S12 (1.97) and S14 (2.00), and higher values at S1 (2.97), S2 (2.93), and S4 (2.92). The evenness index (E') ranged between 0.81 and 0.97, indicating a more balanced distribution of species at station S15. Principal component analysis (PCA) proved effective in discriminating physicochemical variables and highlighting ecological gradients. The analysis distinguished three groups of stations, differentiated by their respective states of imbalance. Redundancy analysis (RDA) further revealed that dissolved oxygen, salinity, conductivity, temperature, and pH are the main drivers influencing taxonomic diversity and abundance. Overall, this study demonstrates the influence of environmental variables on copepod community distribution across the fifteen estuarine stations and supports the use of copepods as potential bioindicators of pollution.

Keywords

Physicochemical Parameters, Copepods, Shannon Index, Equitability Index, Principal Component Analysis, Redundancy Analysis

1. Introduction

Among mesozooplankton, copepods represent the dominant taxonomic group and are considered the most abundant multicellular organisms on Earth; they are frequently compared to terrestrial insects in terms of ecological importance [1]. Their ecological significance in aquatic ecosystems derives from both their exceptional species richness—approximately 11,500 species have been described [2]—and their high abundance. In marine and coastal environments, copepods account for 60% - 80% of total mesozooplankton abundance and up to 90% of its biomass [3]. This dominance confers upon them a pivotal role in trophic networks, mediating the transfer of energy from primary producers to higher trophic levels.

Due to their species diversity, nutritional value, and abundance, copepods constitute a key food resource for a wide range of marine organisms, including chaetognaths, crustaceans, cephalopods, and numerous economically important fish species [4].

As they are highly sensitive to environmental variability, copepods—like zooplankton as a whole—are recognized as effective biological indicators. Their species composition provides valuable information not only on the origin and characteristics of water masses (coastal, oceanic, temperate, or tropical), but also on environmental and climatic fluctuations that may affect biodiversity [3].

In tropical estuarine ecosystems, such as those of Guinea, these characteristics acquire particular importance. The composition and distribution of copepods in these systems are strongly influenced by physicochemical parameters (e.g., temperature, salinity, pH, dissolved oxygen), which vary with the dynamics of freshwater and marine inputs. Consequently, zooplankton—especially copepods—serve as excellent indicators of the origin and properties of estuarine water masses.

The Tinguilinta estuary, also referred to as the Rio Nunez, located in the Boké region of Guinea, represents a particularly relevant case study. Extending over 160 km with a watershed of 4,858 km² [5], the estuary is characterized by extensive mangrove ecosystems and complex physicochemical gradients. It provides essential ecological, economic, and social services, supporting activities such as fisheries, rice cultivation, oyster farming, aquaculture, tourism, and mining.

However, this ecosystem is subject to intense anthropogenic pressures. The proximity of the cities of Boké and Kamsar, combined with inadequate wastewater treatment infrastructure, exposes the estuary to domestic and industrial pollutants, particularly during the rainy season. Additional stressors include wood harvesting, charcoal production, salt extraction, and, most critically, intensified mining activities since the 2010s. The expansion of Kamsar Port resulted in the loss of

approximately 700,000 m² of mangroves, although reforestation efforts with *Rhizophora* sp. and *Avicennia* sp. were undertaken between 1993 and 1998 to mitigate these impacts [6]. In 2011, an accidental hydrocarbon spill from Kamsar Port extended across the Rio Nunez estuary, affecting adjacent shorelines and fisheries [7]. Collectively, these activities have disrupted the ecological balance of the estuary.

Although several studies have investigated general pollution and mangrove deforestation in the region, the impacts of these disturbances on aquatic biological communities, particularly copepods, remain poorly documented.

The present study seeks to examine how physicochemical parameters influence qualitative and quantitative variations in copepod communities within the Tinguilinta estuary of Boké, Guinea. By elucidating the relationships between water quality and copepod community structure, this work aims to advance scientific understanding of estuarine ecosystem functioning and to provide insights for improved management strategies.

2. Study Area Description

The Tinguilinta River basin covers an area of approximately 4858 km² and extends over a length of 160 km. It traverses the Boké region before discharging into the Atlantic Ocean through the Rio Nunez estuary at Kamsar [5]. The river originates to the west of Bambaya, along the former caravan route linking the Rio Nunez to the Fouta Djallon, at an elevation of about 350 m (10°05'3"N; 13°47'W) [8]. The present study focuses on the upper portion of the Tinguilinta basin, near the port of Dapilon (10°49'55.31"N; 14°30'48.50"W), and extends downstream to its mouth at Kamsar in the lower basin (10°34'35.24"N; 14°41'24.18"W) (Figure 1).

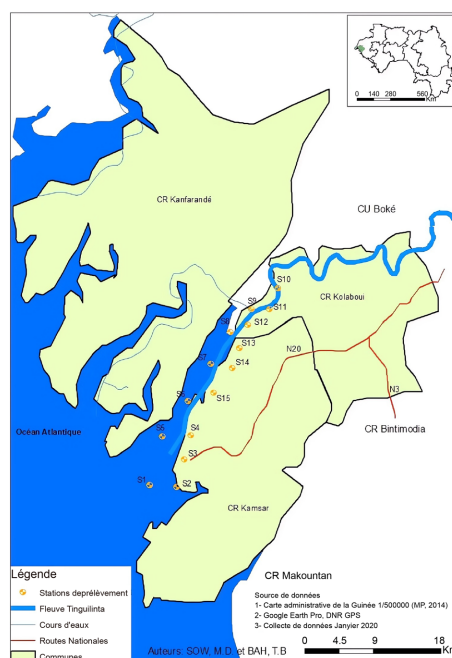


Figure 1. Map of the Tinguilinta Estuary (source: Geomatics Laboratory, CERE-UGANC, 2024).

The climate of the study area is classified as Sudano-Guinean, characterized by the alternation of a dry season and a rainy season. The mean annual temperature in Boké is 27.5°C, with an average annual precipitation of 2513 mm [9]. Located about 35 km southwest of the prefecture of Boké, the rural commune of development (CRD) of Kamsar experiences a subtropical climate, which is moderated by maritime influences [10]. Temperatures typically range between 20 and 35°C, with rainfall concentrated in the wet season (June–October) and markedly reduced during the dry season (November–May). The dominant winds include the monsoon, sea breeze, and the Harmattan, which occurs moderately between January and March [10]. The total annual precipitation reaches 2562.2 mm.

According to [11], the main economic activities in the region include agriculture, livestock farming, fishing, forestry, salt production, handicrafts, and trade. These activities engage nearly 80% of the local population. However, despite their prevalence, they remain insufficient to fully meet the population's needs in terms of food security, healthcare, education, and other essential services.

3. Materials and Methods

3.1. Methodology

3.1.1. Period and frequency of data collection

The data collection extended over a period of three consecutive years (from January 2020 to October 2022). Sampling was carried out four times per year, corresponding to one campaign per quarter, for a total of twelve sampling campaigns. This approach made it possible to take into account the two main climatic regimes present in the study area:

- **Low rainfall period:** from November to May.
- **High rainfall period:** from June to October, characterized by heavy precipitation, particularly during July and August (exceeding 4,000 mm/year in the coastal zone due to the influence of the monsoon).

3.1.2. Sampling Protocol and Location of Collection Points

Sampling targeted the main course of the Tinguilinta River, from the offshore marine area near Kamsar to the vicinity of the Dapilon port. Following a reconnaissance phase, fifteen fixed sampling points were georeferenced using a GPS device (Garmin). These stations were selected to reflect the diversity of environments and the gradient of anthropogenic impact (Table 1).

Table 1. Location of sampling stations.

Sector	Stations	Number
Estuary	S1, S2, S3, S4, S5	5
Middle zone	S6, S7, S8, S12, S13, S14, S15	7
Upstream	S9, S10, S11	3
Total	—	15

Each study site was sampled during each expedition, with operations conducted between 08:00 and 16:00.

3.1.3. Tidal Regime and Hydrological Context

The system under study is characterized by a semi-diurnal tidal regime, with two high and two low tides each day, separated by an interval of about six hours. To account for this temporal variability, plankton samples were collected at both high tide and low tide. The flow of the Tinguilinta River, measured at the Tanéné hydrometric station (located approximately 15 km upstream of Boké), averages $250 \text{ m}^3 \cdot \text{s}^{-1}$, with substantial increases during the rainy season that can exceed $500 \text{ m}^3 \cdot \text{s}^{-1}$.

3.1.4. Water Sample Collection

A surface water sample was collected at each site during each mission, regardless of the tidal phase.

- **Volume per sample:** 500 ml.
- **Total per mission:** 15 samples.
- **Total for the entire study (12 missions):** 180 samples.

Temperature ($^{\circ}\text{C}$) and pH were measured in situ using a VWR pHenomenal pH1100 multiparameter probe. The other samples were preserved in polyethylene containers, transported in refrigerated devices, and then analyzed at CERE (Gamal Abdel Nasser University of Conakry). The quantified physicochemical parameters included: Temperature ($^{\circ}\text{C}$), pH, Nitrates (NO_3^-), Nitrites (NO_2^-), Phosphates (PO_4^{3-}), Total Dissolved Solids (TDS), Suspended Particulate Matter (SPM), Turbidity (NTU), Dissolved Oxygen ($\text{mg} \cdot \text{L}^{-1}$), Salinity (g/L), and Conductivity ($\mu\text{S} \cdot \text{cm}^{-1}$).

3.1.5. Plankton (Copepod) Collection

Copepods were collected using a Hensen plankton net (mesh size: $55 \mu\text{m}$; opening diameter: 70 cm) following a stratified procedure (vertical hauls covering 8 - 16 m depth per tow).

At each site:

- Low tide: 3 net hauls.
- High tide: 3 net hauls.
- **Total per site:** 6 net hauls.
- **Total per mission:** $15 \text{ sites} \times 6 = 90$ net hauls.
- **Total for the entire study (12 missions):** 1080 net hauls.

Plankton samples were immediately fixed in a 4% formalin solution. Taxonomic identification was carried out in the laboratory using a stereomicroscope and a compound microscope, based on the taxonomic keys of [12] and [13].

3.2. Data Analysis

Statistical analyses included Principal Component Analysis (PCA) and Redundancy Analysis (RDA). PCA was applied to maximize the graphical representation

of information contained in the dataset and to objectively discriminate between sampling stations or compare them pairwise [14]. The PCA matrix was used to highlight the main environmental factors by cross-referencing physicochemical parameters with copepod assemblages across the 15 stations.

RDA was employed to investigate the relationships between physicochemical variables and variations in the abundance of dominant copepod species.

Biodiversity was assessed using the Shannon-Wiener diversity index, calculated as:

$H' = -\sum_i^s (P_i \times \log_2 P_i)$; where $P_i = N_i / N$; where H' = representing the Shannon-Wiener diversity index; S = the total number of species in the sample; P_i = the relative abundance of species i ; N_i = the number of individuals of species i in the sample; N = the total number of individuals in the sample.

The diversity index H' ranges from 0 to 5. Values below 2 indicate an imbalanced or disturbed environment, whereas values above 2 suggest a relatively stable community structure.

Evenness (or equitability) E was calculated to compare the diversity of two or more communities comprising different numbers of species. It is determined using the following formula:

$$E = H' / \log_2 S$$

where H' represents the Shannon-Wiener diversity index, \log_2 denotes the logarithm to base 2, and S corresponds to the total number of species present.

4. Results and Discussion

4.1. Qualitative Analysis of the Community

A survey conducted across fifteen sampling sites in the Tinguilinta Estuary revealed a total of 30 species of zooplanktonic copepods. The taxonomic composition of this assemblage was dominated by the order *Calanoida* (20 species), followed by *Cyclopoida* (6 species), *Poecilostomatoidea* (3 species), and *Harpacticoida* (1 species). These 30 taxa were distributed among 16 families and 4 orders. The family exhibiting the highest species richness was *Oithonidae* (4 taxa), followed by *Paracalanidae*, *Oncaeidae*, and *Candaciidae* (3 taxa each), and then *Acartiidae*, *Calanidae*, *Temoridae*, *Eucalanidae*, and *Corycaeidae* (2 taxa each). The remaining families were represented by a single species (see **Table 2**).

Table 2. Annual Variation in the Taxonomic Richness of Copepods.

Orders	Family	Genus et species	2020	2021	2022	Total	Percentage %	
Calanoida	Acartiidae	<i>Acartia clausi</i>	338	374	274	986	12.46	
		<i>Acartia danae</i>	30	40	13	83	1.05	
	Aetideidae	<i>Aetideus armatus</i>	24	33	8	65	0.82	77.34
	Calanidae	<i>Calanus minor</i>	12	22	15	49	0.62	
		<i>Calanus helgolandicus</i>	98	103	110	311	3.93	

Continued

		<i>Candacia bipinnata</i>	4	12	6	22	0.28	
	Candaciidae	<i>Candacia aethiopica</i>	5	7	4	16	0.20	
		<i>Candacia armata</i>	4	3	3	10	0.13	
	Centropagidae	<i>Centropage chierchiae</i>	108	203	143	454	5.75	
	Clausocalanidae	<i>Clausocalanus furcatus</i>	4	9	33	46	0.58	
	Eucalanidae	<i>Eucalanus pileatus</i>	128	136	105	369	4.66	
		<i>Eucalanus elongatus</i>	14	18	25	57	0.72	
	Euchaetidae	<i>Euchaeta marina</i>	6	14	8	28	0.35	
		<i>Paracalanus parvus</i>	289	198	246	733	9.26	
	Paracalanidae	<i>Paracalanus scotti</i>	304	598	483	1385	17.50	
		<i>Paracalanus aculeatus</i>	278	220	214	712	9.00	
	Pontellidae	<i>Pontellina plumata</i>	4	9	5	18	0.23	
	Pseudocalanidae	<i>Pseudocalanus elongatus</i>	6	5	5	16	0.20	
		<i>Temora turbinata</i>	37	49	36	122	1.54	
	Temoridae	<i>Temora stylifera</i>	240	198	200	638	8.06	
		<i>Corycaeus africanus</i>	8	16	15	39	0.49	
	Corycaeidae	<i>Corycaeus speciosus</i>	9	18	9	36	0.45	
		<i>Oithona plumifera</i>	19	21	20	60	0.76	
		<i>Oithona brevicornis</i>	9	17	24	50	0.63	14.41
	Oithonidae	<i>Oithona nana</i>	275	458	185	918	11.60	
		<i>Oithona Simplex</i>	10	19	9	38	0.48	
		<i>Oncaea venusta</i>	6	5	3	14	0.18	
	Poecilostomatoidea	<i>Oncaea media</i>	6	8	6	20	0.25	0.86
		<i>Oncaea mediterranea</i>	8	19	7	34	0.43	
	Harpacticoida	<i>Euterpina acutifrons</i>	73	296	217	586	7.40	7.40
		Total	2356	3128	2431	7915	100%	100%

The analysis of the relative abundance of families revealed a marked predominance of Paracalanidae and Acartiidae, contributing respectively 35.76% and 13.51% of the total copepod abundance. Similar observations were made by [15] on pelagic ecosystems in relation to fluctuations in hydrological conditions along the southern Atlantic coast of Morocco.

4.2. Taxonomic Composition

The enumeration of 7 915 individuals revealed a predominance of *Paracalanus scotti* (1385 individuals), *Acartia clausi* (986 individuals), *Oithona nana* (918 individuals), *Paracalanus parvus* (733 individuals), *Paracalanus aculeatus* (712 individuals), *Temora stylifera* (638 individuals), *Euterpina acutifrons* (586 individu-

als), *Centropages chierchiae* (454 individuals), *Eucalanus pileatus* (369 individuals), and *Calanus helgolandicus* (311 individuals). This taxonomic profile closely resembles the community structure described by [16] in their assessment of species diversity and biomass of pelagic copepods in the Ras Kebdana region (Moroccan Mediterranean coast), as well as the findings reported by Kéita [17] on the zooplankton assemblages of the Guinean shelf and their principal ecological features (Bulletin du CERESCOR, No. 14).

4.3. Abundance Patterns

Copepod abundance increased markedly during August (rainy season), reaching a first peak of 20265 ind/m² at Station S1, followed by a second peak of 20123 ind/m² at Station S2. Conversely, a pronounced decline was observed during the dry season in January, with abundance reaching a minimum of 1 120 ind/m² at Station S7 (Table 3). These seasonal dynamics are consistent with the observations of [18] regarding zooplankton variability in Lake Geneva (Figure 2).

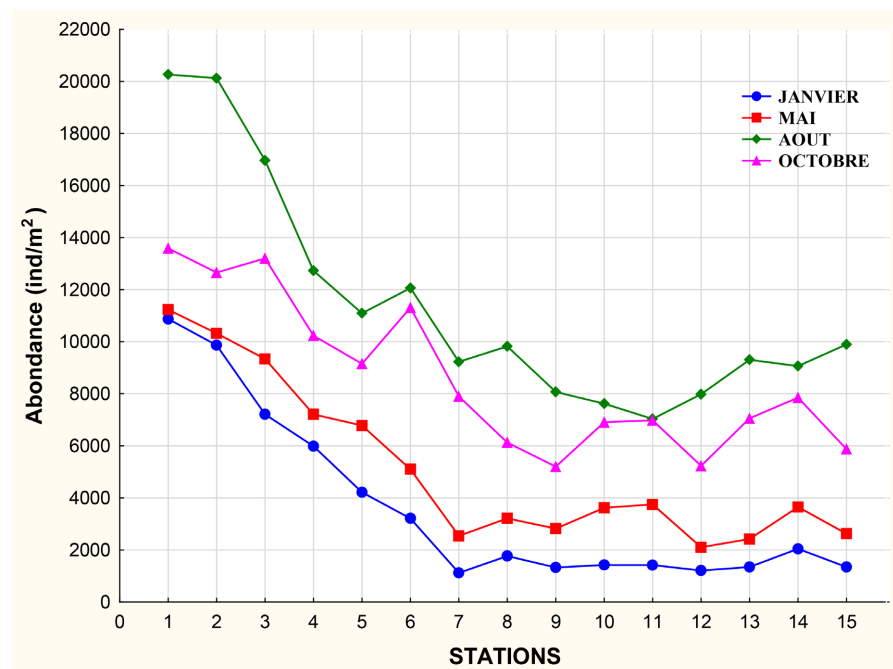


Figure 2. Spatiotemporal variation of abundance across sampling stations.

Table 3. Distribution of abundance within copepod assemblages.

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15
January	10873	9867	7210	5987	4214	3210	1120	1765	1326	1425	1422	1210	1345	2045	1344
May	11230	10320	9340	7210	6782	5099	2542	3215	2820	3620	3750	2104	2420	3652	2623
August	20265	20123	16966	12727	11091	12062	9230	9820	8070	7620	7034	7985	9307	9064	9897
October	13585	12658	13204	10236	9152	11310	7897	6126	5200	6907	6980	5232	7054	7852	5874

4.4. Shannon Diversity Index

The Shannon diversity index (H'), which typically ranges from 0 to 5, is widely used as a metric to assess ecosystem complexity. Values below 2 generally indicate limited heterogeneity and may reflect ecological imbalance, whereas values above 2 are suggestive of a more balanced and presumably more stable biological community.

In the present study, the Shannon diversity index (H') varied between 1.97 and 2.97 bits per individual (see **Table 4**). The maximum value (2.97) was recorded in January at station S1, while the minimum value (1.97) was observed in May at station S12. This range highlights a notable degree of diversification within the copepod assemblages under investigation. These findings are consistent with previous studies. For instance, [19] reported comparable values in Lake Kaby (Bongouanou, Côte d'Ivoire), with a maximum Shannon index of 2.72 bits per individual during the rainy season and a minimum of 1.94 bits per individual during the dry season. Similarly, [16] documented a maximum value of 3.49 in December in their study of species diversity and biomass of pelagic copepods in the Ras Kebdana region (Mediterranean coast of Morocco), with the lowest indices recorded during summer, reaching 1.69 in July (**Figure 3**).

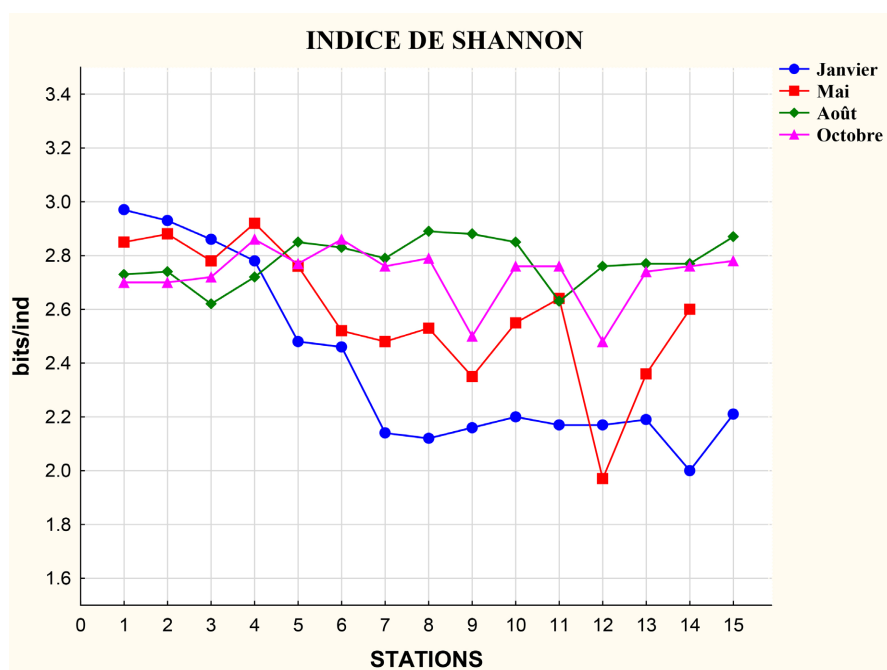


Figure 3. Distribution of Shannon diversity indices across sampling stations.

Table 4. Distribution of Shannon diversity indices within copepod assemblages.

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15
January	2.97	2.93	2.86	2.78	2.48	2.46	2.14	2.12	2.16	2.2	2.17	2.17	2.19	2.00	2.21
May	2.85	2.88	2.78	2.92	2.76	2.52	2.48	2.53	2.35	2.55	2.64	1.97	2.36	2.60	2.36
August	2.73	2.74	2.62	2.72	2.85	2.83	2.79	2.89	2.88	2.85	2.63	2.76	2.77	2.77	2.87
October	2.70	2.70	2.72	2.86	2.77	2.86	2.76	2.79	2.50	2.76	2.76	2.48	2.74	2.76	2.78

4.5. Evenness Index

The Evenness Index further highlights the recurrent equilibrium of the ecosystem, with a minimum recorded value of 0.81. The extreme values ranged from 0.81, observed at stations S1, S2, and S3 during the months of August and October, to 0.97 at station S15 in January (Table 5; Figure 4). These values indicate a well-balanced distribution of individuals among species, since they fall within the interval $0.80 < E < 0.97$, which characterizes a community in equilibrium.

Table 5. Distribution of evenness indices within copepod assemblages.

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15
January	0.87	0.86	0.86	0.87	0.87	0.89	0.95	0.92	0.94	0.94	0.92	0.96	0.95	0.92	0.97
May	0.86	0.86	0.87	0.87	0.86	0.86	0.90	0.88	0.91	0.87	0.88	0.90	0.89	0.88	0.89
August	0.81	0.81	0.81	0.82	0.85	0.85	0.85	0.86	0.86	0.86	0.86	0.85	0.84	0.84	0.85
October	0.81	0.81	0.81	0.86	0.84	0.86	0.85	0.87	0.86	0.86	0.86	0.86	0.85	0.85	0.87

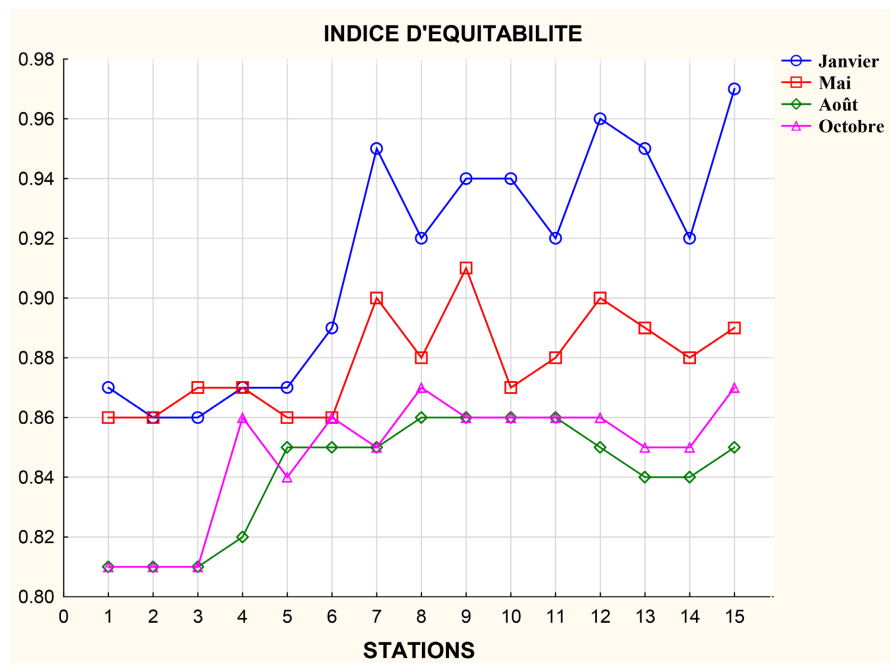


Figure 4. Distribution of evenness indices across sampling stations.

Comparable observations were reported by [20] in fishponds located in Bertoua (Eastern Cameroon), where Pielou's Evenness Index revealed a relatively homogeneous distribution of individuals across the studied assemblages. The recorded values were broadly similar to those obtained in the present study, except for the Côte d'Azur pond ($E = 0.65$) and the Mopa pond ($E = 0.70$). Likewise, [21] in their study of the Kondi stream (Douala, Cameroon), found that the Evenness Index varied between 0.48 (station K3, April 2012) and 1.0 (station K1, October 2011 and February 2012). In that case, station K1, with a mean value of 0.91 ± 0.1 , supported a community with the most evenly distributed individuals among species.

4.6. Principal Component Analysis (PCA) of the Physicochemical Characteristics of the Tinguilinta Estuary (Rio Nunez) during the Dry Season

Principal Component Analysis (PCA) of the physicochemical parameters of estuarine waters during the dry season revealed that the first two axes, F1 (41.45%) and F2 (19.21%), together account for more than half of the total variance (60.66%) associated with the environmental variables under investigation. Examination of the correlation circle (**Figure 5**) indicates a strong negative correlation between axis F1 and eight physicochemical parameters: Total Dissolved Solids (TDS, $r = -0.94$), Salinity ($r = -0.90$), Electrical Conductivity (EC, $r = -0.89$), pH ($r = -0.66$), Temperature ($r = -0.66$), Dissolved Oxygen (DO, $r = -0.66$), Nitrate (NO_3^- , $r = -0.57$), and Turbidity (Tu, $r = -0.32$). In contrast, only Nitrite concentration (NO_2^- , $r \approx 0.32$) exhibited a positive correlation with axis F1. Axis F2 showed a positive correlation with Phosphate (PO_4^{3-} , $r = 0.76$) and a negative correlation with Suspended Solids (SS, $r = -0.82$).

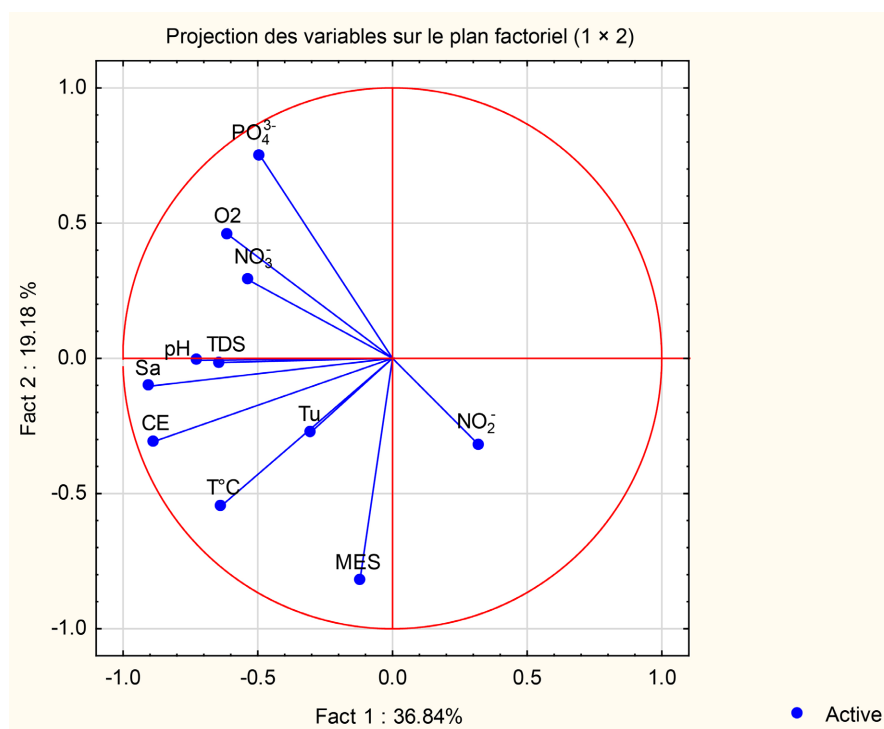


Figure 5. Correlation circle of variables in the factorial plane defined by F1 and F2.

Principal Component Analysis (PCA) on axes F1 and F2 reveals a contrast between two groups of stations. On the one hand, stations S12, S11, and S15, characterized by high concentrations of dissolved substances and reduced turbidity, suggest mineralization of natural or anthropogenic origin. On the other hand, stations S1, S5, S6, S7, S8, and S9, showing low overall mineralization but an enrichment in nitrites, indicate recent pollution or incomplete degradation of nitrogen compounds. Stations S2, S13, and S14, with high phosphate concentrations, high-

light pollution of residential or agricultural origin. Finally, stations S3, S4, and S10, dominated by Suspended Matter (SM), reflect significant organic pollution. (Figure 6).

These findings are consistent with those reported by [22] for surface waters of the Moulouya River (Eastern Morocco), where high PO_4^{3-} and suspended solid concentrations were similarly identified as indicators of organic pollution of domestic origin.

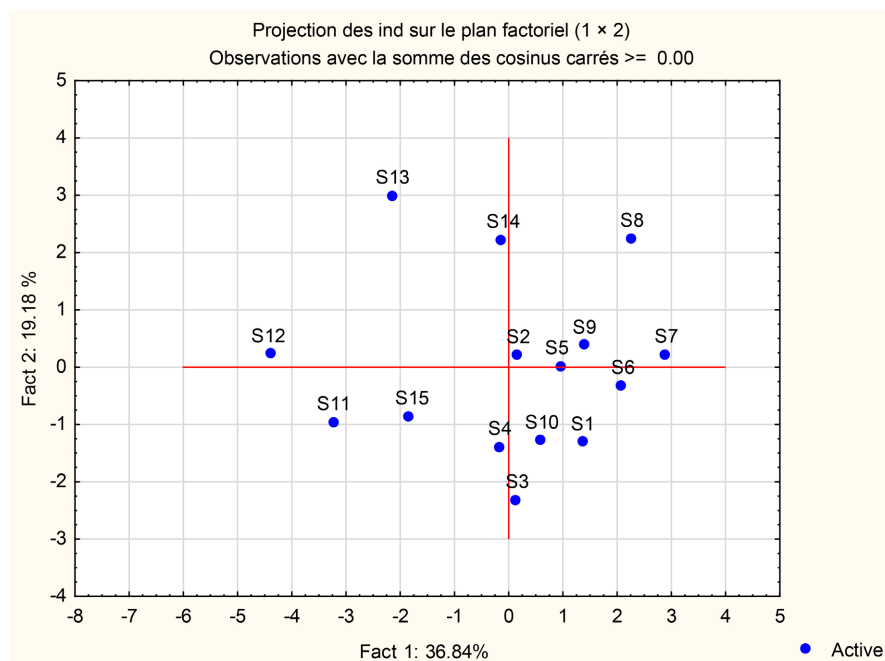


Figure 6. Representation of sampling stations on the F1-F2 factorial plane.

4.7. Principal Component Analysis (PCA) of the Physicochemical Characteristics of Tinguilinta Estuary (Rio Nunez) Waters during the Rainy Season

Principal Component Analysis (PCA) revealed that the first two principal components, F1 (explaining 62.60% of the variance) and F2 (explaining 11.23% of the variance), together accounted for 73.83% of the total variability observed in the environmental parameters. The variable correlation circle (Figure 7) highlights a strong inverse association between F1 and five physicochemical parameters: turbidity ($r \approx -0.92$), nitrites (NO_2^-) ($r \approx -0.92$), nitrates (NO_3^-) ($r \approx -0.63$), suspended particulate matter (SPM) ($r \approx -0.62$), and phosphates (PO_4^{3-}) ($r \approx -0.57$). Conversely, F1 exhibited strong positive correlations with five other variables, namely electrical conductivity (EC) ($r = 0.97$), dissolved oxygen (DO) ($r = 0.97$), salinity ($r = 0.95$), pH ($r = 0.81$), and total dissolved solids (TDS) ($r = 0.63$). With respect to the second component (F2), only temperature (T, °C) showed a negative correlation ($r \approx -0.67$).

Axis F1 reveals a contrast between sites most affected by human activities (S12, S13, S14, S15: characterized by high concentrations of nitrites, phosphates, sus-

pended matter, and turbidity) and sites with lower anthropogenic influence, associated with better oxygenation (S1, S2, S3: correlated with higher salinity, electrical conductivity, and total dissolved solids). Stations S4 and S11 occupy an intermediate position (low concentrations of suspended matter), while stations S5 to S10 are distinguished along Axis F2 due to their geographical location in deeper or thermally cooler areas (**Figure 8**).

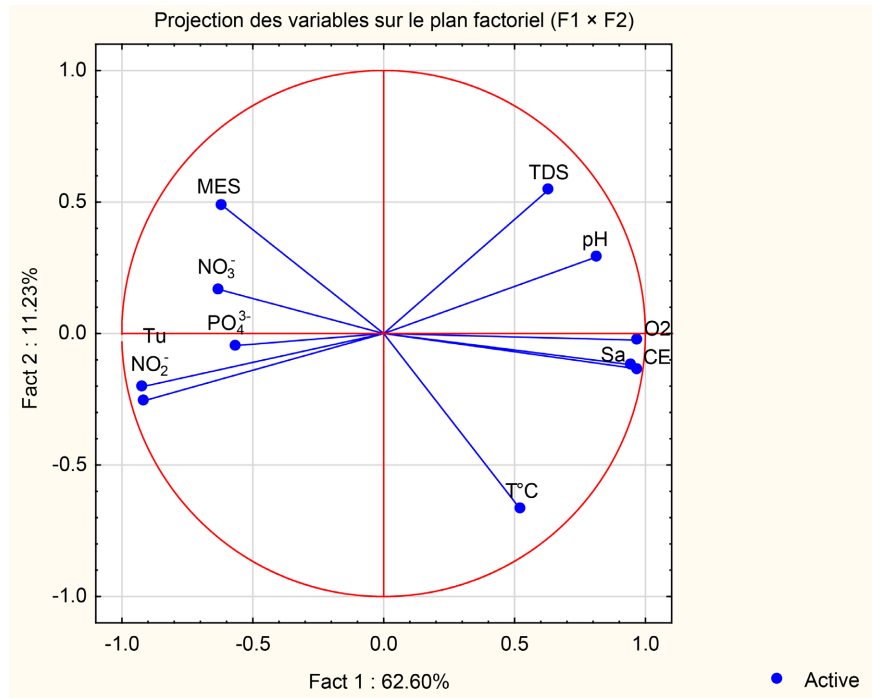


Figure 7. Correlation circle of variables in the factorial plane defined by F1 and F2.

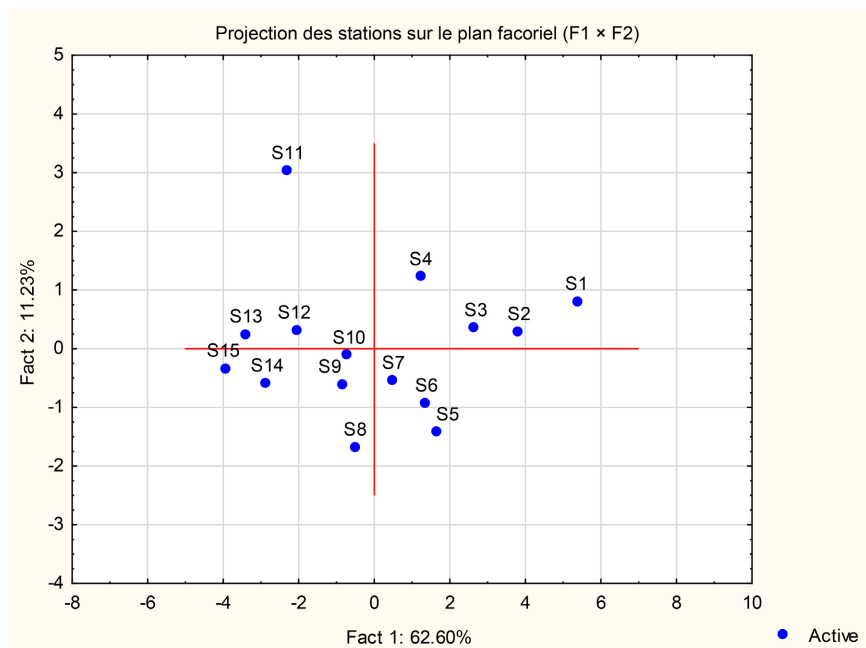


Figure 8. Representation of sampling stations on the F1-F2 factorial plane.

Comparable findings were reported by [23] in their assessment of the physico-chemical quality of the Merzeg River (peri-urban area of Casablanca, Morocco). Their results similarly showed that elevated concentrations of dissolved oxygen, pH, and electrical conductivity reflect mineralized and well-oxygenated waters, generally associated with reduced anthropogenic influence.

4.8. Redundancy Analysis (RDA)

Influence of physicochemical parameters on the distribution of aquatic copepod communities in the Tinguilinta River estuary (Rio Nunez)

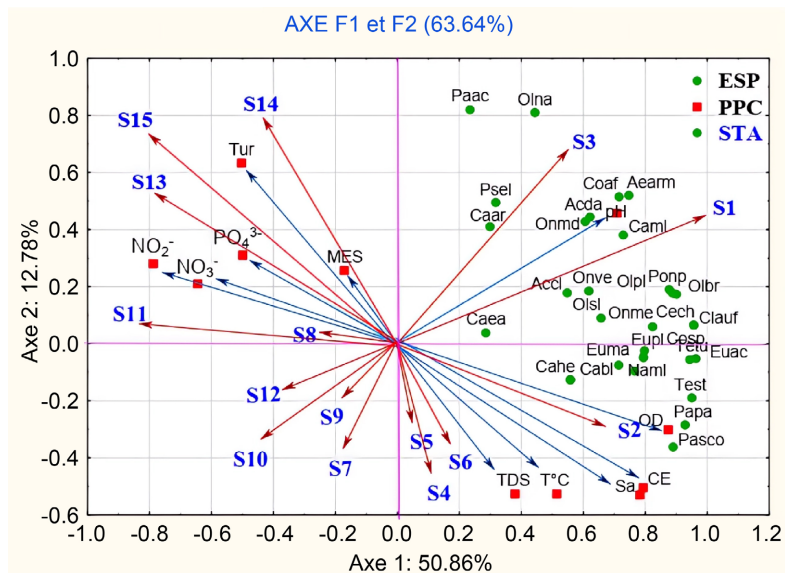


Figure 9. Redundancy Analysis (RDA) of the dominant copepod species in the aquatic environments of the Tinguilinta River estuary and their relationships with environmental variables recorded across sampling stations from January 2020 to December 2022. Biological variables: Pasco: *Paracalanus scotti*, Papa: *Paracalanus parvus*, Accl: *Acartia clausi*, Acda: *Acartia danae*, Oina: *Oithona nana*, Oibr: *Oithona brevicornis*, Oipl: *Oithona plumifera*, Paac: *Paracalanus aculeatus*, Test: *Temora stylifera*, Tetu: *Temora turbinata*, Euac: *Euterpina acutifrons*, Cech: *Centropages chierchiae*, Eupi: *Eucalanus pileatus*, Cahe: *Calanus helgolandicus*, Cami: *Calanus minor*, Nami: *Nanocalanus minor*, Euma: *Euchaeta marina*, Clauf: *Clausocalanus furcatus*, Oisi: *Oithona simplex*, Aearm: *Aetideus armatus*, Cosp: *Corycaeus speciosus*, Onve: *Oncaea venusta*, Ome: *Oncaea media*, Omed: *Oncaea mediterranea*, Ponp: *Pontellina plumata*, Cabi: *Candacia bipinnata*, Caea: *Candacia aethiopica*, Psel: *Pseudocalanus elongatus*, Coaf: *Corycaeus africanus*, Caar: *Candacia armata*. Environmental variables: PO_4^{3-} : Phosphate; NO_3^- : Nitrates; NO_2^- : Nitrites; Tur: Turbidity; MES: Suspended matter; pH: Hydrogen potential; $T^\circ\text{C}$: Temperature; Sa: Salinity; CE: Electrical conductivity; OD: Dissolved oxygen; TDS: Total dissolved salts. Sampling sites: S1: Station 1, S2: Station 2, S3: Station 3, S4: Station 4, S5: Station 5, S6: Station 6, S7: Station 7, S8: Station 8, S9: Station 9, S10: Station 10, S11: Station 11, S12: Station 12, S13: Station 13, S14: Station 14, S15: Station 15.

The RDA analysis reveals a clear distinction between different types of stations (Figure 9):

- Highly altered stations (S8, S9, S10, S11, S12, S13, S15): characterized by high

nutrient concentrations and significant turbidity, leading to the absence or substantial reduction of zooplankton, suggesting a toxic effect.

- Relatively preserved stations (**S1, S2, S4, S6**): displaying well-oxygenated waters and high mineralization, conditions favorable to a high diversity of copepods (30 taxa).
- Stations with an intermediate level of impact (**S3, S5, S14**): showing a decrease in suspended matter, which favors the presence of certain sensitive copepods, potentially indicative of an improvement in environmental quality.
- Oligotrophic stations (**S5, S7**): characterized by low levels of total dissolved solids and nutrient scarcity, limiting zooplankton development.

Overall, the RDA results demonstrate that conductivity, temperature, salinity, pH, and dissolved oxygen are the key variables influencing copepod distribution. Similar patterns have been reported by [24] in four coastal rivers of southeastern Côte d'Ivoire and by [25] in the waters of the Upper Bandama River (Côte d'Ivoire).

5. Conclusions

The present study conducted in the Tinguilinta River estuary enabled the identification of 30 copepod taxa, predominantly dominated by the order *Calanoida* (20 species). Among the families recorded, *Paracalanidae* and *Acartiidae* were the most abundant, representing 35.76% and 13.51% of the total, respectively.

Principal Component Analysis (PCA) of the physicochemical and biological data revealed correlations among the different environmental parameters and facilitated the delineation of spatial zonation in estuarine water quality. Through a spatiotemporal physicochemical approach, water analyses distinguished stations S1, S2, S4, and S6 as relatively less impacted, exhibiting higher species richness and the abundance of several tolerant zooplankton (copepod) species. In contrast, stations S8, S9, S10, S11, S12, S13, and S15 were characterized by unfavorable environmental conditions. Stations S3, S5, and S14 appear to function as indicators of habitats undergoing ecological restoration.

Finally, redundancy analysis (RDA) identified temperature, dissolved oxygen, conductivity, salinity, and pH as the primary factors influencing copepod distribution. Overall, the study highlights the ecological significance of this biodiverse estuarine ecosystem and underscores the urgent need for its protection against anthropogenic threats.

Due to the limited number of study sites, the short monitoring period, and the partial taxonomic scope, the conclusions of this study should be considered preliminary. To further deepen the understanding of the ecological dynamics of the Tinguilinta estuary, it is recommended to:

- Expand and Diversify Sampling Stations: Broadening the sampling network will better account for the spatial heterogeneity of the estuary.
- Implement Annual Monitoring with Monthly Frequency: More comprehensive temporal monitoring will allow for the assessment of seasonal variations

and the quantification of the impact of environmental parameters.

Integrate Other Zooplankton Compartments and Environmental Variables: Including additional zooplankton groups and considering more environmental variables will provide a more complete picture of trophic interactions and the factors influencing community structure.

Conflicts of Interest

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

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