

Multiple Urban Wastewater Discharge Pathways as Drivers of Water Quality Degradation in the Cotonou Lagoon, Benin

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Abstract This study aimed to evaluate the physicochemical pollution levels in the Cotonou Lagoon, focusing on the dry season, when it receives raw wastewater through various stormwater sewers and drains in the city. Six stations were identified and monthly sampled on the lagoon for this purpose, taking into account the discharge point of the sewers. Temperature, pH, electrical conductivity, dissolved oxygen content, and water transparency of the lagoon waters were measured *in situ*. Turbidity, suspended solids, and nutrient concentrations, including ammonium, nitrites, nitrates, orthophosphates, and sulfates, of the water samples, were determined using molecular spectrophotometry. Through the assessed physico-chemical, the lagoon waters were found to be nutrient-rich, particularly with ammonium and orthophosphates (up to 10 mg L⁻¹ and 0.5 mg L⁻¹, respectively), detected at levels toxic to aquatic life and indicating early risk of eutrophication, despite the high dissolved oxygen levels recorded. The organic pollution index calculated (varying from 2.67 to 4.33), revealed a heterogeneous a moderate organic pollution in most of the lagoon sectors, but a strong and a weak pollution level noticed in other sectors. An effective management of wastewater should be undertaken to significantly reduce the pollution of the lagoon, thereby preventing ecological disasters that may result from eutrophication.

Keywords: Aquatic ecosystem, estuary, pollution, eutrophication, aquatic biodiversity, sanitation

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1. Introduction

The pollution of continental and marine waters is a global concern. Wetlands and coastal lagoons are increasingly subjected to anthropogenic contaminant pressure, driven by rapid urbanisation and population growth [1,2]. This pollution pressure has significant consequences for lagoon ecosystems, which, despite being highly productive and supporting important biodiversity, are extremely fragile and sensitive to external stressors [2,3].

Among the various pollution sources degrading the

water quality of aquatic systems, untreated urban wastewater discharge remains particularly critical [4]. In many developing countries, including those in sub-Saharan Africa and Benin, a substantial share of municipal and domestic wastewater is discharged directly into the environment without adequate treatment [5,6,7,8]. In fact, this issue is widely recognised as a major driver of nutrient enrichment, oxygen depletion, and turbidity in receiving water bodies across Africa and other low-income regions [7,9]. Such unmanaged wastewater discharge can severely impair water quality in receiving surface waters [10].

In Cotonou, the most urbanised town of Benin, no

wastewater collection and treatment systems exist. Large volumes of untreated wastewater are discharged, either directly or via several stormwater drains, into the Cotonou Lagoon, a hydrological man-made channel that links Lake Nokoué to the Atlantic Ocean. The huge input of these nutrient and organic-rich effluents promotes eutrophication risks that making exceptionally vulnerable the Cotonou Lagoon and consequently its neighbouring aquatic environments [9,11,12,13].

This study aimed to assess the contribution of untreated wastewater release to the physico-chemical quality degradation of Cotonou Lagoon waters. It was thus carried out during the dry season, when the lagoon received raw wastewater discharges from several drains and sewers.

2. Material and Methods

2.1. Study Area

This study focused on the waters of the Cotonou Lagoon in Benin, West Africa. The lagoon, extending from north to south, forms a channel approximately 4.5 km long, with an average width of 300 m and depths ranging from 5 to 10 m, connecting Lake Nokoué to the Atlantic Ocean [14] (Figure 1). It serves as the discharge point for stormwater drains and sewers, which are consistently filled with mixed raw wastewater, primarily originating from residential areas, the Dantokpa market, the biggest one in Benin, and a maternity hospital, the "Centre Hospitalier Universitaire de la Mère et de l'Enfant, la Lagune (CHU-MEL)".

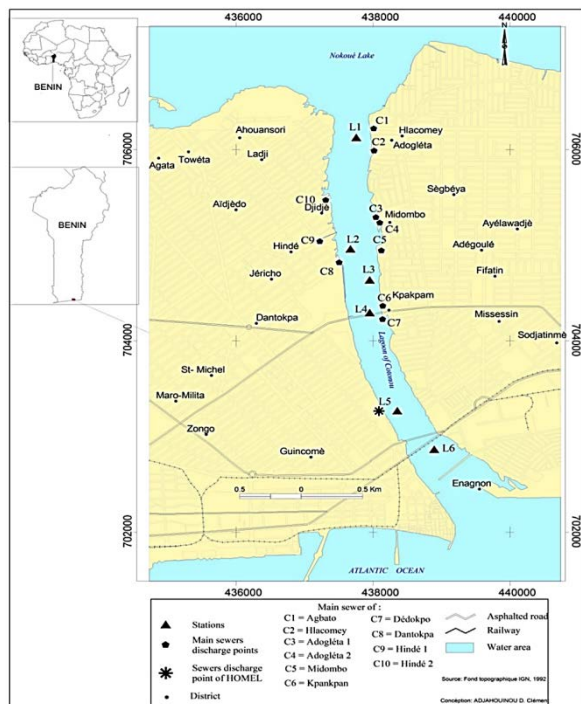


Figure 1. Map of the city of Cotonou showing the sampling stations along the lagoon and the outlets of the main sewers

2.2. Sampling and Analysis Methods

Six stations were selected to cover the entire lagoon

(Table 1 and Figure 1). Sampling was conducted monthly at all these stations throughout the major dry season, from December to March, resulting in a total of four sampling campaigns. During each campaign, all the six stations were sampled on the same day, using a motorised boat, to ensure spatial comparability of the physico-chemical measurements across the lagoon. At each station, a composite sample was collected, resulting from samples taken at three different points in the first few centimetres beneath the water surface. The samples were kept cool until their transfer to the laboratory and stored in a refrigerator at 4°C [15]. During each sampling campaign, some water parameters were measured *in situ*: temperature, pH, and electrical conductivity (EC) using a WTW pH/conduct 340i/SET portable multifunction conductivity meter, dissolved oxygen (DO) content using a WTW oxi 340i/SET portable oxygen meter, and water transparency using a Secchi disk.

In the laboratory, the turbidity and the suspended solids (SS) in the water samples were measured by colourimetry using a HACH DR890 colourimeter. Likewise, ammonium (NH_4^+), nitrites (NO_2^-), nitrates (NO_3^-), orthophosphates (PO_4^{3-}), and sulfates (SO_4^{2-}) were also quantified in these samples using a HACH DR5000 molecular absorption spectrophotometer. The HACH methods used for the analysis of these parameters (Table 2) were adapted from the "Standard Methods for the Examination of Water and Wastewater", approved by the United States Environmental Protection Agency) [16].

Table 1. Situations, characteristics, and geographical locations of sampling stations

Station	Location and characteristic
L1	Ladji - Agbato : Junction area between the lagoon and the Nokoué Lake
L2	Hindé - Djidjè - Sègbeya : Area directly impacted by Sègbeya and Hindé sewers, where manual extraction of lagoon sand is carried out.
L3	Dantokpa - Midombo : Area located between the outlets of the Dantokpa and Midombo sewers, heavily used for canoe transport of people and goods to and from the Dantokpa market.
L4	Kpankpan - Dédokpo : Within the vicinities of the Martin Luther King Bridge and influenced by the Kpankpan and Dédokpo sewers; an area where artisanal fishing is practiced.
L5	Aboki-codji - Tokpa hoho : Area receiving wastewater discharges from dyeing activities and from the maternity hospital.
L6	Akpakpa Dodomey-Placondji : Area close to the junction between the lagoon and the Atlantic Ocean.

Table 2. Summary of HACH methods used for the analysis of assessed physicochemical parameters

Parameters	Analytical Methods
Turbidity	Radiation attenuation method (HACH 8237)
Suspended solids (SS)	Photometric method (HACH 8006)
Ammonium (NH_4^+)	Salicylate method using AmVer reagent for ammonia (HACH 10031)
Nitrite (NO_2^-)	Diazotization method using NitraVer 3 reagent (HACH 8507)
Nitrate (NO_3^-)	Cadmium reduction method using NitraVer 5 reagent (HACH 8039)
Orthophosphate (PO_4^{3-})	PhosVer 3 method (ascorbic acid) (HACH 8048)
Sulfate (SO_4^{2-})	SulfaVer 4 method (HACH 8051)

2.3. Data Analysis

Mean values of the studied parameters, fulfilling the assumptions of normality (Shapiro–Wilk test) and homogeneity of variances (Levene test), were compared among sampling stations using a one-way analysis of variance (ANOVA).

Only nitrites (NO_2^-), nitrates (NO_3^-), and orthophosphates (PO_4^{3-}) concentrations did not satisfy the conditions of normality and homoscedasticity. Consequently, the mean values of these parameters among stations were compared using the non-parametric Kruskal–Wallis test. The significant difference was set at the threshold of 0.05.

A principal component analysis (PCA) was performed to identify the variables that highlight better the lagoon's waters quality.

All the above-mentioned statistical analyses were performed using the Statistica 6.0 package (StatSoft Inc., Tulsa, USA).

Based on the mean concentration of ammoniacal nitrogen, nitrites and orthophosphates recorded, the Organic Pollution Index (OPI) was calculated according to methods proposed by Leclercq [17] (Table 3), to evaluate the organic pollution level of the lagoon waters in each sampled stations.

Table 3. Limit of Organic pollution index (OPI) [17]

Class	NH_4^+ (mg L^{-1})	NO_2^- ($\mu\text{g L}^{-1}$)	PO_4^{3-} ($\mu\text{g L}^{-1}$)	Class range	Organic pollution levels
5	<0.1	<5	<15	4.6-5.0	Null
4	0.1- 0.9	6-10	16-75	4.0-4.5	Weak
3	1-2.4	11-50	76-250	3.0-3.9	Moderate
2	2.5-6	51-150	251-900	2.0-2.9	Strong
1	>6	>150	>900	1.0-1.9	Very strong

3. Results

The range and the mean values of the studied parameters are presented in Table 4. No parameter showed

a significant difference among sampled stations ($P > 0.05$).

The Principal Component analysis of the physico-chemical parameters indicated that 71.80% of the total variance is explained by the first two principal components (F1 and F2), which contribute to 42.65% and 29.15%, respectively (Figure 2). On the correlation circle (Figure 2a), the axe 1 (F1) was strongly and positively correlated with temperature ($r = 0.90$), EC ($r = 0.95$), salinity ($r = 0.97$), NH_4^+ ($r = 0.75$) and NO_2^- ($r = 0.58$) whereas it was negatively correlated with the DO level ($r = -0.88$). Hence, axis 1 highlights a pollution-mineralisation gradient opposing warm, saline, nutrient-rich, oxygen-poor waters (positive scores) to cooler, more oxygenated and less mineralised waters (negative scores). The axis 2 (F2) showed strong positive correlations with SM ($r = 0.81$), PO_4^{3-} ($r = 0.75$) and SO_4^{2-} ($r = 0.88$) while transparency ($r = -0.94$) and pH ($r = -0.58$) displayed negative correlations. Based on these correlations, axis 2 defines a turbidity-phosphate-sulfate gradient, contrasting acidic, particulate, and phosphate-enriched waters with clearer and less disturbed waters.

The distribution of stations on the factorial plane (Figure 2b) shows clear spatial differentiation. The station L6 was positioned on the positive side of the axis F1, corresponding to waters characterised by higher salinity, ammonium and temperature and lower dissolved oxygen. Conversely, L1 negatively correlated with F1 but positioned positively on F2, corresponding to water highly concentrated in phosphate and sulfate, but with a significant DO level.

On the other hand, the station L2 plots negatively on the axis F2, associated with high transparency and low nutrient concentrations, especially for orthophosphates and sulfates, indicating less impacted conditions. The stations L3, L4 and L5 occupy intermediate positions towards the two axes, reflecting transitional water quality between polluted and less impacted areas of the lagoon.

The OPI calculated varied from 4.33 to 2.67, revealing that the lagoon presented a spatial heterogeneous level of organic pollution varying from weak to strong (Figure 3).

Table 4. Minimum, maximum, and mean values of the physico-chemical parameters of the Cotonou lagoon waters

Parameters	Range		Mean±SD	F	H	P-value	Significativity
	Min.	Max.					
Temp ($^{\circ}\text{C}$)	28.00	29.60	29.00±0.39	0.15	-	0.98	NS
pH	7.60	8.40	7.97±0.20	0.39	-	0.85	NS
EC (mS cm^{-1})	23.90	52.100	43.19±10.31	0.24	-	0.94	NS
Sal (g/L)	14.60	34.50	27.86±7.22	0.28	-	0.92	NS
DO (mg L^{-1})	6.88	10.51	8.49±0.98	0.47	-	0.79	NS
Transp (cm)	48.00	140.00	103.13±32.27	0.05	-	1.00	NS
Turb (NTU)	3.00	25.00	10.08±6.16	0.09	-	0.99	NS
SS (mg L^{-1})	1.00	12.00	4.46±3.27	0.19	-	0.96	NS
NH_4^+ (mg L^{-1})	0.00	10.00	1.71±3.03	0.46	-	0.80	NS
NO_2^- (mg L^{-1})	0.00	0.09	0.01±0.03	-	5.85	0.32	NS
NO_3^- (mg L^{-1})	0.00	13.20	2.03±3.37	-	2.54	0.77	NS
PO_4^{3-} (mg L^{-1})	0.00	0.50	0.16±0.15	-	3.98	0.55	NS
SO_4^{2-} (mg L^{-1})	43.00	3500.00	1343.83±1093.99	0.02	-	1.00	NS

F: ANOVA test statistic; H: Kruskal–Wallis test statistic; NS: Non-significative; $p < 0.05$ indicate statistical significance

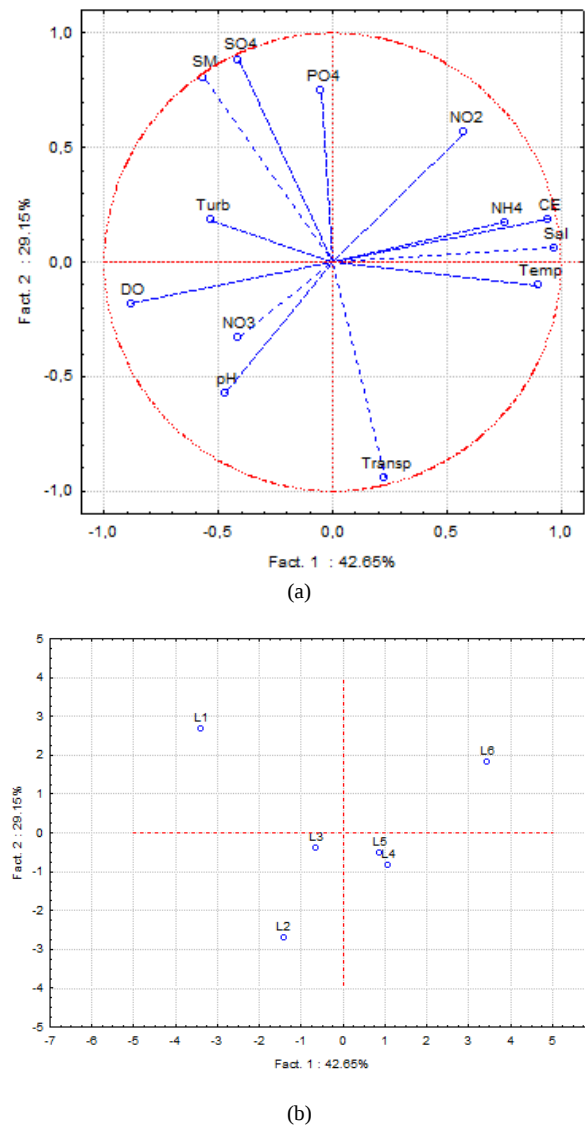


Figure 2. Projection of water quality variables (a) and sampled stations (b) in the factorial plane (F1-F2)

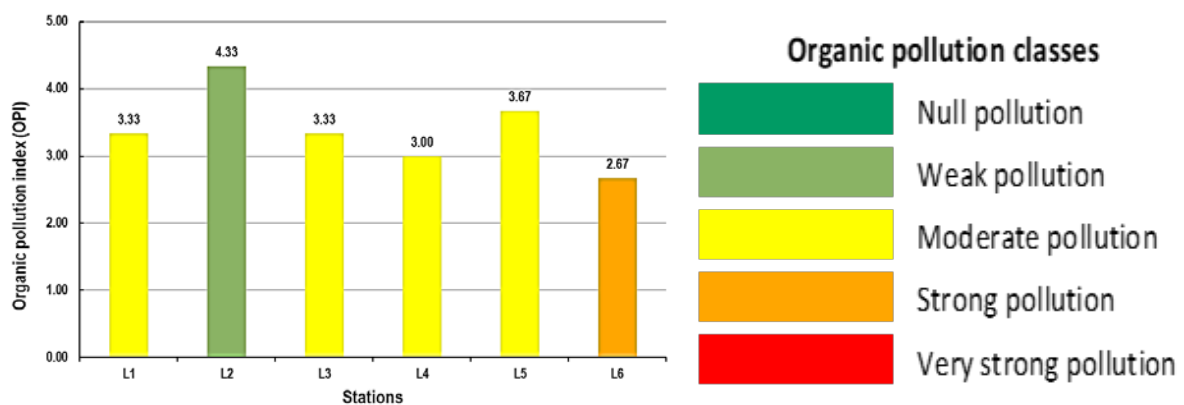


Figure 3. Organic pollution level of the different sampling stations on the Cotonou lagoon

4. Discussion

The water temperatures recorded during the study period are consistent with the typical dry season thermal regime described for southern Benin and its coastal lagoons [18]. Similar dry season temperature ranges have been reported for the waters of Nokoué Lake [19,20],

Ahémé Lake [21] in Benin, and the Ologe Lagoon in Nigeria [22,23], confirming that the values noticed in Cotonou Lagoon fall within the regional trend.

The slightly alkaline pH recorded is also typical of many West African coastal areas, including the lagoons of Fresco and Aby in Côte d'Ivoire, where the surface waters frequently remain above neutrality [24,25,26]. In these lagoons, seasonal changes in pH are closely linked to

salinity and the intensity of marine intrusion: high-salinity conditions during the dry season generally correspond to more alkaline waters, whereas periods dominated by continent inflow and low salinity are associated with slightly lower pH [26,27]. Accordingly, the alkaline character of the Cotonou Lagoon waters during the study period can reasonably be attributed to their high salinity ($27.86 \pm 7.22 \text{ g L}^{-1}$). Furthermore, the pH values were within the acceptable range (6.5 to 8.5) to protect water and aquatic organisms from contamination and favourable for fish (6.5 to 9) [29].

The high salinity recorded resulted from the predominance of marine water intrusion and limited freshwater inflow in the dry season, reinforced by strong evaporation [30]. This salinity level was reflected in very elevated electrical conductivity values ($>1000 \text{ }\mu\text{S cm}^{-1}$), which indicated strong mineralisation of the lagoon waters [15]. This is consistent with the strong positive relationship generally reported between salinity and electric conductivity in tropical lagoons and estuarine systems, where both these parameters respond to the balance between seawater intrusion, freshwater inflow and evaporation [26,28].

The lagoon waters were highly oxygenated, with an average dissolved oxygen concentration of 8.49 mg L^{-1} , which is more than the double of the minimum threshold of 4 mg L^{-1} generally recommended for the protection of aquatic life in warm waters [29]. Such elevated DO values reflect favourable environmental conditions that promote the aerobic degradation of organic matter by microbial communities. The high oxygenation is supported by the low turbidity of the water column, which enhances light penetration and thereby favours photosynthetic activity, particularly by phytoplankton. Similar observations were reported in the Grand-Lahou Lagoon (Côte d'Ivoire), where high DO concentrations were associated with low turbidity levels [31].

The low suspended solids (SS) concentrations recorded in the studied lagoon waters, which are in line with the low turbidity, further confirm the favourable conditions contributing to the elevated DO levels. The suspended solids present in the Cotonou Lagoon predominantly originate from wastewaters discharged through the urban sewer networks that are often highly enriched in SS during the long dry season [13] as well as from refuse accumulating along the lagoon's banks.

Nitrogen and phosphorus nutrients are key nutrients to monitor the surface water quality. Although essential for aquatic organisms, excess inputs of these elements are major drivers of eutrophication and ecosystem degradation [32,33]. In the studied waters, nitrates, the most oxidised form of inorganic nitrogen, displayed the highest concentrations. This pattern is consistent with the high availability of dissolved oxygen and the slightly alkaline pH recorded, both of which fall within the optimal ranges ($5\text{--}10 \text{ mg L}^{-1}$ and $7\text{--}8$, respectively) for nitrification reactions [34]. The concentrations of the oxidised nitrogen species (nitrites and nitrates) remained below the chronic toxicity thresholds of 0.02 mg L^{-1} and 3.6 mg L^{-1} , respectively, set for the protection of aquatic life in brackish or saline waters [29]. In contrast, ammonium concentrations largely exceeded the limit value of 0.5 mg L^{-1} established for the protection of aquatic organisms in

brackish or saline waters [29], highlighting a significant input of reduced nitrogen into the lagoon.

Orthophosphates levels were also markedly elevated, exceeding both the chronic toxicity threshold of 0.03 mg L^{-1} [29] and the minimum concentration of 0.05 mg L^{-1} known to trigger eutrophication in aquatic environments [4,33]. Consequently, the lagoon appears to exhibit early symptoms of eutrophication, comparable to those documented in the Biétry Estuarine Bay (Abidjan, Côte d'Ivoire), where orthophosphates levels of a similar magnitude have been observed [35]. The substantial ammonium and orthophosphates load recorded can be attributed, in part, to the continuous discharge of untreated urban wastewater, particularly from multiple sewer outlets around the lagoon, which release nutrient-rich effluents that become even more concentrated during the long dry season [13]. This represents a potential ecological risk for the lagoon ecosystem. High ammonium levels may be directly toxic for fish and aquatic invertebrates by impairing, respiration and osmoregulation, particularly under warm and saline conditions [32,33]. Furthermore, excessive phosphate enrichment promotes eutrophication, stimulating algal proliferation, reducing water transparency, and ultimately leading to oxygen depletion during organic matter degradation [4,36]. Such conditions are known to cause fish stress or mortality, habitat degradation, and progressive biodiversity depletion [1,2].

The PCA highlights two dominant processes shaping the lagoon's hydrochemical structure: a salinity-mineralisation gradient (F1) and a turbidity-phosphates-sulfates gradient (F2).

The relatively high temperature, salinity and electrical conductivity, combined with elevated ammonium levels on Axis 1, indicate the joint influence of urban wastewater inputs and saline water intrusion on the lagoon water quality. The negative correlation of DO with this same axis further reflects oxygen depletion in response to elevated organic and nutrient inputs from sewer discharges, a common feature in eutrophying coastal systems [13,33,36]. Comparable eutrophication patterns have been observed in Lagos Lagoon [37].

Axis 2 emphasises the influence of phosphates, sulfates, and suspended solids on the quality of the lagoon waters. These pollutants are discharged into the lagoon at high concentrations through the sewer outlets [13]. Phosphates most likely originate from detergent-rich household wastewater, whereas sulfates may derive from industrial effluents, as similarly reported for other coastal wetlands [38,39]. The negative correlation of pH and transparency with this axis further highlights the acidic and turbid conditions of areas receiving large particulate and nutrient loads.

Spatially, the ordination reveals a distinct heterogeneous pollution gradient: -i- L1 and L6 appear as the most degraded sectors, affected by both urban pressures and marine intrusion near the ocean outlet; -ii- L3, L4 and L5 experience intermediate conditions; and -iii- L2 indicates comparatively better water quality. This spatial pattern is in accordance with the organic pollution gradient noticed with L6 presenting the poorest quality and L2 the best, while the remaining stations showed moderate levels.

These findings confirmed that the Cotonou Lagoon was globally subjected to eutrophication pressure, driven largely by heavily polluted effluent inflows during the dry season [13], when hydrodynamic renewal is limited, like other tropical coastal ecosystems [38,40].

Beyond ecological impacts, eutrophication and organic pollution observed in the Cotonou Lagoon may also have important public health concerns. Elevated inputs of organic matter and nutrient from untreated wastewater favour high microbial activity in the receiving surface water. Chronic exposure to such contaminated waters, either directly or through consumption of fishery products, may increase the risk of waterborne diseases and long-term health effects [6,33].

5. Conclusions

This prospective assessment of the physico-chemical characteristics of the Cotonou Lagoon during the dry season revealed a general deterioration of the water quality, even though certain parameters, such as pH, turbidity, transparency, dissolved oxygen, and suspended solids, remain within acceptable limits. The most critical signs of degradation arise from elevated concentrations of nutrients, particularly nitrogen and phosphorus-based nutrients, whose levels were sufficient to impair aquatic life and act as key precursors to eutrophication. Furthermore, the results highlight a clear organic pollution gradient across the lagoon, with the most degraded sectors located near major wastewater inflow points and the lagoon mouth, where the combined influence of untreated urban effluents and marine intrusion intensifies pollutant accumulation. Intermediate zones exhibited moderate organic loading, while only one upstream sector displayed better conditions. Based on this spatial pattern, it may be concluded that organic polluted and nutrient-rich wastewater discharges are the dominant drivers shaping the lagoon's current ecological state. Further study using biotic indicators and including all the hydrological season is needed to highlight the real ecological alteration level of the lagoon.

Wastewater management policies should be respected by significantly reducing the uncontrolled discharges from the population and implementing effective treatment to mitigate eutrophication risks and preserve the ecological integrity of this vulnerable coastal ecosystem.

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