

Pollution Levels of Urban Drainage, Stormwater and Wastewater Mixtures Released Into Coastal Waters in Cotonou City (Benin, West Africa)

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Abstract Like developing countries, particularly in Sub-Saharan Africa, Benin still faces limited access to basic and improved sanitation services. However, water consumption and, consequently, wastewater production continue to grow in line with population increases, especially in urban areas. In this context, wastewater is often discharged into the environment untreated, threatening public health and compromising ecosystem integrity. This work assessed the physico-chemical and organic pollution of the mixed wastewater discharged by the storm sewers into Cotonou Lagoon, providing data to efficiently manage effluent treatment. Monthly samples were collected at three sewers outlets (S1, S3 and S3) over an annual cycle. Temperature, pH, electric conductivity (EC) and dissolved oxygen were measured *in situ*, while turbidity, suspended matter (SM), ammoniacal nitrogen, nitrites, nitrates, orthophosphates, sulphates and chemical oxygen demand (COD) were analysed by molecular absorption spectrophotometry standard methods. The Biological oxygen demand (BOD5) was assessed by the oxiTop manometric method. Results showed that the wastewaters were highly mineralised exceeding the recommended limit ($EC > 2.5 \text{ mS cm}^{-1}$), with high turbidity associated with an elevated concentration in SM, reaching 120 mg L^{-1} . They were also loaded with nutrients, particularly nitrogen and orthophosphates out of standards limits, which could contribute to eutrophication in the receiving. Dissolved oxygen levels are consequently low ($< 5 \text{ mg L}^{-1}$), while BOD5 and COD values indicated moderate organic pollution, which was moderately biodegradable according to the biodegradability index (BI) global mean varying from 3.11 (S3) to 4.24 (S1). The studied wastewater quality varied significantly across seasons, with the most polluted yet readily biodegradable wastewater observed during the LDS (BI = 2.31 ± 0.90). Principal component analysis highlighted two main wastewater classes: those enriched in nitrogenous and organic loads with low DO and low BI, which were associated with the LDS and those dominated by phosphorus loads, low pH, particularly linked to the SRS. These findings demonstrate that untreated wastewaters discharged into Cotonou Lagoon carry substantial nutrient and organic loads, underscoring the urgent need for effective wastewater treatment before discharge to preserve lagoon ecosystem integrity.

Keywords: Sewers, sanitation, biodegradability, eutrophication, aquatic ecosystem

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1. Introduction

Worldwide, about 10% of total freshwater consumption is attributed to routine human use, including drinking, sanitation, hygiene, and other domestic purposes [1].

Water consumption continues to grow mainly due to population increase, rapid urbanisation and lifestyle modernisation. Consequently, the volume of wastewater discharged into the environment is rising [2,3,4]. This situation is particularly critical in developing countries, especially in Sub-Saharan Africa, where access to basic and improved sanitation services remains quite limited [5].

In such contexts, inadequate sanitation infrastructure often leads to the direct release of untreated or poorly treated wastewater into freshwater and marine ecosystems, threatening public health and compromising ecosystem integrity [5,6,7].

In Benin, wastewater management remains limited, with most initiatives still at the planning stage and only a few operational sewage treatment plants [8]. Even in Cotonou, the economic capital and most town-planned city, there is no specific wastewater sewer system, and only 32.3% of the population manages wastewater adequately through a self-built system [9]. As a result, large volumes of raw wastewater (from 67.7% of the population) are discharged onto courtyards, streets, or into the gutters and storm sewers [8]. Like other developing cities, at Cotonou, stormwater drains collect uncontrolled rejection, including domestic grey and black wastewater, industrial effluents and solid waste, resulting in a mixture of raw effluent [7] that is directly released into the Cotonou Lagoon, Nokoue Lake and the Atlantic Ocean [10,11], in violation of the guidelines of the World Health Organisation [12] and Benin's standards [13].

This study focused on the case of Cotonou lagoon, which connects Nokoue lake to the Atlantic Ocean, and is permanently impacted by effluent from several main sewers [14,15,16]. Previous studies on wastewater in Cotonou, were mostly sporadic [10,16,17] and did not address temporal variations in physico-chemical and

organic quality. This work thus aimed to assess the physico-chemical and organic pollution level of the mixed wastewater discharged by the main sewers into Cotonou Lagoon over an annual cycle, providing data to guide the planning and design of targeted treatment methods and plants.

2. Material and Methods

2.1. Study Area

The current study was conducted in Cotonou, the economic capital of Benin, located between latitudes 6°20' and 6°23'N and longitudes 2°22' and 2°30'E. The city is naturally bordered by Nokoué Lake to the north and the Atlantic Ocean to the south, with the two connected by the Cotonou Lagoon (Figure 1). This 4 km-long lagoon serves as the outlet of numerous stormwater drains and sewers, while also receives continuous flows of raw wastewater from various human activities.

Cotonou city is located in a subequatorial climate zone characterised by four distinct seasons: a long dry season (LDS) from December to March, a long rainy season (LRS) from April to July, a short dry season (SDS) from August to September and a short rainy season (SRS) from October to November [18].

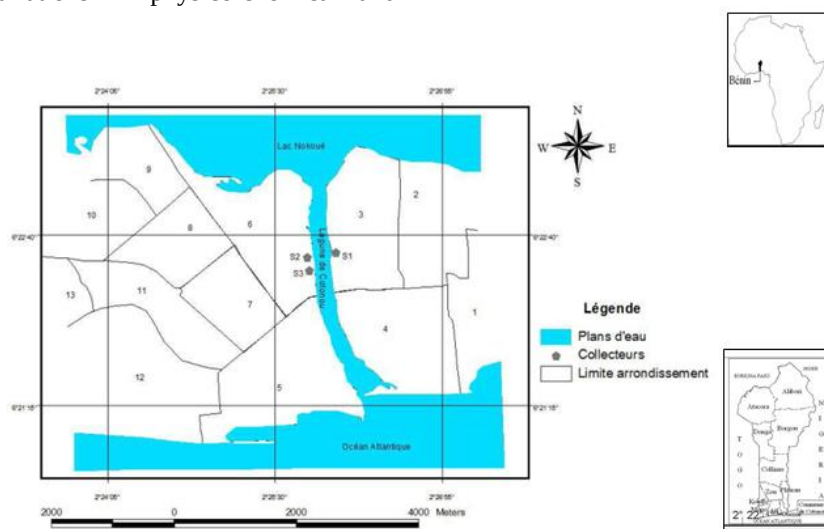


Figure 1. Map of Cotonou city showing stations

2.2. Sampling and Analysis Methods

Table 1. Characteristics of surveyed sewers

Sampling stations	Main sewers	Length	Covered area
S1	T1	1 km	Midombo and vicinity
S2	B	2 km	Gbeto and Dantokpa market
S3	A	4 km	Hindé, Djidjè, Aidjèdo, Jéricho and Gbégamey

Wastewater samples were collected near the discharge points of three main sewers (S1, S2, S3) flowing into Cotonou Lagoon. The sewers were selected based on their size and the level of human pressure on them (Table 1).

Sampling was made monthly throughout an entire year to account for seasonal variations.

Temperature, pH, and electric conductivity (EC) of the studied waters were measured *in situ* using a multiprocessing portable conductivity meter, WTWpH/cond 340i/SET. Dissolved oxygen (DO) was assessed with a portable oximeter, WTW oxi 340i/SET.

Wastewater samples were collected in sterile polyethylene bottles, previously rinsed with sampled water, at midstream of the sewers to minimise edge effects and to obtain representative conditions. Immediately after collection, the bottles were kept in a portable frozen tank, transported to the laboratory on the same day, and stored at 4°C until analysis [19].

Water turbidity and suspended matters (SM) were measured using colourimetric methods with a HACH DR890 colourimeter. Ammoniacal nitrogen (N-NH_3), nitrites (NO_2^-), nitrates (NO_3^-), orthophosphates (PO_4^{3-}), sulphates (SO_4^{2-}), and chemical oxygen demand (COD) were also measured colourimetrically using a molecular absorption spectrophotometer, HACH DR5000. Biological oxygen demand (BOD_5) was determined by the respirometric method with an OxiTop[®] BOD-meter over a five-days incubation period. All analyses were performed according to the "Standard Methods for the Examination of Water and Wastewater", as approved by the United States Environmental Protection Agency (US EPA) (Table 2) [20] following strict QA/QC protocols to ensure data reliability. Field instruments were calibrated before each sampling using manufacturer-recommended standard solutions. Fields blanks, laboratory blanks, and sample duplicates were included at a rate of approximately 10% of total samples to monitor potential contamination and analytical precision.

The biodegradability of the studied waters was assessed by calculating the biodegradability index (BI), defined as the ratio of COD to BOD_5 ($\text{BI} = \text{COD}/\text{BOD}_5$) [19].

Table 2. Summary and references of the methods used for the wastewater quality parameters analysis

Parameters	Methods	References
Turbidity	Radiation attenuation method	APHA method 2130 C: HACH 8237
SM (mg L^{-1})	Photometric method	APHA method 2130 C calibrated against gravimetric determination according to APHA method 2540 D: HACH 8006
N-NH_3 (mg L^{-1})	Salicylate reaction method (Amver reagent)	Adapted from APHA method from SM 4500-NH3 H compatible with US EPA salicylate method 350.1: HACH 10031
N-NO_2^- (mg L^{-1})	Diazotisation-coupling method (Nitraver 3 reagent)	Adapted from APHA method 4500- NO_2^- B: HACH 8507
N-NO_3^- (mg L^{-1})	Cadmium Reduction method (Nitraver 5 reagent)	Adapted from APHA method 4500- NO_3^- E: HACH 8039
PO_4^{3-} (mg L^{-1})	Molybdate-ascorbic acid method (Phosver 3 reagent)	Adapted from APHA method 4500-P E: HACH 8048
SO_4^{2-} (mg L^{-1})	Turbidimetric method (SulfaVer 4 reagent)	Adapted from APHA 4500- SO_4^{2-} E equivalent to US EPA method 375.4: HACH 8051
BOD_5 ($\text{mgO}_2 \text{ L}^{-1}$)	Respirometric Method	APHA method 5210 B
COD ($\text{mgO}_2 \text{ L}^{-1}$)	Reactor Digestion, colorimetric Method. (High range COD Digestion vials)	Adapted from APHA 5220 D: HACH 8000

2.3. Data Analysis

The surveyed wastewater quality parameters were compared among stations and seasons, using one-way analysis of variance (ANOVA 1), after verifying data normality with Shapiro-Wilk test and homogeneity of variance with Levene test, followed by Tukey's HSD post-hoc in case of significant difference. When normality and homogeneity conditions were not fulfilled, the non-parametric Kruskal-Wallis test was carried out followed

by pairwise comparisons using the Mann-Whitney U test in case of need.

A Spearman rank correlation test was carried out to identify the relationship among the studied parameters. Furthermore, a principal component analysis (PCA) was performed to identify the variables that contributed more to the variation in the studied wastewater quality.

All the statistical tests were performed using the statistical software Statistica 6.0 package (StatSoft Inc, Tulsa, USA).

3. Results

The mean values and ranges of the studied parameters recorded at each sampling station are presented in Table 3. Among the analysed parameters, only electrical conductivity (EC) ($H = 14.17$; 0.00), ammoniacal nitrogen (N-NH_3) ($F = 4.05$; $p = 0.03$) and COD ($H = 6.00$; $p = 0.04$) showed significant variations between stations. The highest EC values were recorded at stations S2 and S3. Regarding N-NH_3 , the highest concentration was observed at station S2, while the COD values were higher at stations S1 and S2 compared to station 3.

On the other hand, all the studied parameters exhibited significant seasonal variations ($p < 0.05$) except for EC and orthophosphates, which did not vary significantly among seasons ($p > 0.05$) (Table 4). Overall, the long dry season (LDS) displayed the highest values for most monitored parameters, except for dissolved oxygen (DO) and nitrites (N-NO_2^-).

The Temperature was lower during the short dry season (SDS) compared to the other seasons. pH remained slightly acidic in all the seasons, but was higher and thus closer to neutrality during the long seasons (LDS and LRS) than during the short ones (SDS and SRS). A similar trend was observed for sulphate concentrations. As for the DO, the highest levels were recorded during the SDS and LRS compared to the LDS and SRS. Turbidity and suspended matters (SM) followed an opposite trend, with their lowest mean values recorded during the LDS and SRS.

Regarding nitrogenous compounds, the highest mean concentrations of ammoniacal nitrogen and nitrates were recorded during the LDS, whereas nitrites concentrations peaked during the LRS. Finally, both BOD_5 and DCO values were markedly higher during the LDS compared to the other seasons.

The variation of the biodegradability index (BI) of the studied wastewaters among the sampling stations and across seasons is presented in Figures 2 and 3, respectively. No significant difference was noticed among stations ($F = 1.36$; $p = 0.27$). Nonetheless, the BI values ranged from 1.36 to 7.80 at S1, from 1.31 to 6.29 at S2 and from 1.13 to 9.18 at S3. In contrast, BI varied significantly among seasons ($H = 18.40$; $p = 0.00$). Higher BI values were recorded during the LRS (BI ranging from 1.77 to 9.18) and the SDS (BI ranging from 2.90 to 7.80) compared to the LDS (BI ranging from 1.31 to 4.24) and the SRS (BI ranging from 1.13 to 2.76), indicating a seasonal influence on the biodegradability of the wastewater.

Correlation analysis between physico-chemical parameters revealed significant positive and negative

relationships among many variables, as shown in Table 5.

The PCA results indicated that the first two principal components (F1 and F2) together explain 81.39% of the variance in the measured parameters, with contributions of 53.75% and 27.64% for F1 and F2, respectively (Figure 4a). The projection of the water quality parameters in the factorial design (F1-F2) (Figure 4.a), highlights a strong positive correlation of Turbidity (0.94), SM (0.98), N-NH₃ (0.99), N-NO₃⁻ (0.96) and BOD₅ (0.97) with F1, whereas

the DO (0.81) and the BI (-0.81) are correlated negatively with this component. For F2, only PO₄³⁻ (0.80) displays a positive correlation, while pH (-0.80), N-NO₂⁻ (-0.81) and SO₄²⁻ (-0.94) are negatively correlated.

When seasons are considered as groups (Figure 4.b), the LDS and SDS exhibit positive and negative correlations with the component F1, respectively, whereas the LRS and SRS show negative and positive correlations with F2, respectively.

Table 3. Mean values ($\pm$ standard deviation) of physico-chemical parameters of the Cotonou wastewaters at sampled stations, with corresponding ranges

Parameters	S1	S2	S3	Range		Discharge standards limit values [13]
				Min	Max	
Temperature (°C)	31.23 $\pm$ 2.92	29.67 $\pm$ 1.71	28.60 $\pm$ 1.05	27.00	37.50	-
pH	6.31 $\pm$ 0.90	6.47 $\pm$ 0.64	6.42 $\pm$ 0.75	4.32	7.49	6-9
EC (mS cm ⁻¹)	1.17 $\pm$ 1.40 ^b	4.19 $\pm$ 4.22 ^a	4.38 $\pm$ 6.01 ^a	0.14	20.800	-
DO (mg L ⁻¹)	2.73 $\pm$ 2.31	2.15 $\pm$ 1.72	2.66 $\pm$ 2.24	0.17	6.84	-
Turbidity (NTU)	61.20 $\pm$ 41.20	64.08 $\pm$ 32.23	59.00 $\pm$ 35.30	11.00	160.00	-
SM (mg L ⁻¹)	42.25 $\pm$ 32.78	55.92 $\pm$ 33.14	50.30 $\pm$ 37.70	4.00	120.00	35
N-NH ₃ (mg L ⁻¹)	6.08 $\pm$ 3.80 ^b	11.33 $\pm$ 6.96 ^a	6.33 $\pm$ 3.89 ^b	0.00	24.00	10*
N-NO ₂ ⁻ (mg L ⁻¹)	0.13 $\pm$ 0.20	0.36 $\pm$ 1.23	0.11 $\pm$ 0.34	0.00	4.27	-
N-NO ₃ ⁻ (mg L ⁻¹)	1.39 $\pm$ 0.55	7.06 $\pm$ 7.44	2.78 $\pm$ 1.89	0.40	25.30	-
PO ₄ ³⁻ (mg L ⁻¹)	1.33 $\pm$ 0.78	1.79 $\pm$ 0.90	1.41 $\pm$ 0.89	0.16	3.52	1-2**
SO ₄ ²⁻ (mg L ⁻¹)	47.67 $\pm$ 19.32	92.20 $\pm$ 97.60	90.30 $\pm$ 70.10	0.00	292.00	-
BOD ₅ (mg O ₂ L ⁻¹)	58.70 $\pm$ 51.50	76.20 $\pm$ 46.60	47.50 $\pm$ 26.97	11.00	195.00	25
COD (mg O ₂ L ⁻¹)	178.30 $\pm$ 87.20 ^a	202.80 $\pm$ 130.60 ^a	107.10 $\pm$ 34.70 ^b	59.00	488.00	125

For the same parameters, different superscript letters indicate significant differences among stations ($p < 0.05$).

EC: Electric conductivity; DO: Dissolved oxygen; SM: Suspended matter; BOD: Biological oxygen demand; COD: Chemical oxygen demand

*Threshold for Kjeldahl nitrogen; ** Threshold for total phosphorus

Table 4. Seasonal mean values ($\pm$ standard deviation) of physico-chemical parameters of Cotonou wastewaters

Parameters	LDS	LRS	SDS	SRS	F	H	Significativity
Temperature (°C)	29.90 $\pm$ 2.32 ^a	30.308 $\pm$ 2.294 ^a	27.30 $\pm$ 0.24 ^b	31.28 $\pm$ 1.34 ^a	4.55	-	S
pH	6.89 $\pm$ 0.17 ^a	6.56 $\pm$ 0.57 ^a	5.69 $\pm$ 1.05 ^b	5.69 $\pm$ 0.44 ^b	-	14.30	S
EC mS cm ⁻¹)	5.27 $\pm$ 6.13	3.21 $\pm$ 3.95	1.09 $\pm$ 0.48	1.34 $\pm$ 1.42	-	4.46	NS
DO (mg L ⁻¹)	1.34 $\pm$ 1.15 ^b	3.787 $\pm$ 2.33 ^a	4.07 $\pm$ 1.12 ^a	0.78 $\pm$ 0.11 ^b	-	12.25	S
Turbidity (NTU)	96.08 $\pm$ 28.92 ^a	30.42 $\pm$ 17.30 ^c	46.00 $\pm$ 17.09 ^{bc}	69.50 $\pm$ 20.89 ^{ab}	18.36	-	S
SM (mg L ⁻¹)	83.50 $\pm$ 24.54 ^a	23.17 $\pm$ 17.66 ^c	26.670 $\pm$ 17.60 ^{bc}	56.80 $\pm$ 26.00 ^{ab}	18.26	-	S
N-NH ₃ (mg L ⁻¹)	12.25 $\pm$ 6.38 ^a	5.42 $\pm$ 3.50 ^{bc}	3.50 $\pm$ 1.87 ^c	8.67 $\pm$ 3.08 ^{ab}	-	13.89	S
N-NO ₂ ⁻ (mg L ⁻¹)	0.01 $\pm$ 0.01 ^b	0.55 $\pm$ 1.22 ^a	0.10 $\pm$ 0.19 ^{abc}	0.00 $\pm$ 0.00 ^{bc}	-	10.62	S
N-NO ₃ ⁻ (mg L ⁻¹)	7.06 $\pm$ 7.25 ^a	1.63 $\pm$ 1.35 ^b	2.03 $\pm$ 1.35 ^{ab}	3.05 $\pm$ 3.04 ^{ab}	-	8.41	S
PO ₄ ³⁻ (mg L ⁻¹)	1.58 $\pm$ 0.69	1.15 $\pm$ 0.74	1.99 $\pm$ 1.23	1.61 $\pm$ 0.86	1.43	-	NS
SO ₄ ²⁻ (mg L ⁻¹)	89.10 $\pm$ 70.10 ^a	114.60 $\pm$ 80.30 ^a	17.67 $\pm$ 12.29 ^b	35.33 $\pm$ 21.08 ^b	4.19	-	S
BOD ₅ (mg O ₂ L ⁻¹)	98.100 $\pm$ 44.70 ^a	39.40 $\pm$ 34.80 ^b	37.33 $\pm$ 22.08 ^b	52.330 $\pm$ 21.50 ^b	6.89	-	S
COD (mg O ₂ L ⁻¹)	215.70 $\pm$ 112.40 ^a	144.60 $\pm$ 85.70 ^{ab}	172.80 $\pm$ 94.80 ^a	83.00 $\pm$ 22.58 ^b	3.05	-	S

For the same parameters, different superscript letters indicate significant differences among seasons ($p < 0.05$).

EC: Electric conductivity; DO: Dissolved oxygen; SM: Suspended matter; BOD: Biological oxygen demand; COD: Chemical oxygen demand

S: Significant; NS: No significant

Table 5. Spearman's rank correlation matrix of the physicochemical parameters of Cotonou wastewaters.

Variables	Temp	pH	EC	DO	Turb	SM	NH3	NO2	NO3	PO4	SO4	BOD	COD	BI
Temp	1.00													
pH	0.20	1.00												
EC	-0.05	0.36	1.00											
DO	-0.40	-0.41	-0.46	1.00										
Turb	0.18	0.26	0.31	-0.67	1.00									
SM	0.21	0.23	0.39	-0.65	0.96	1.00								
N-NH ₃	0.35	0.24	0.27	-0.54	0.66	0.66	1.00							
N-NO ₂ ⁻	-0.06	0.05	-0.36	0.40	-0.43	-0.47	-0.56	1.00						
N-NO ₃ ⁻	-0.21	0.07	0.15	-0.20	0.40	0.43	0.41	-0.23	1.00					

Variables	Temp	pH	EC	DO	Turb	SM	NH3	NO2	NO3	PO4	SO4	BOD	COD	BI
PO ₄ ³⁻	-0.01	0.07	0.13	-0.21	0.14	0.11	0.39	-0.53	0.22	1.00				
SO ₄ ²⁻	0.08	0.48	0.52	-0.18	-0.10	0.02	0.13	-0.03	0.12	-0.17	1.00			
BOD	0.28	0.43	0.38	-0.65	0.77	0.69	0.66	-0.40	0.24	0.27	0.01	1.00		
COD	0.11	0.58	0.22	-0.34	0.41	0.32	0.35	0.00	0.01	0.29	0.04	0.61	1.00	
BI	-0.29	0.02	-0.29	0.49	-0.61	-0.60	-0.53	0.51	-0.28	-0.05	0.02	-0.67	0.14	1.00

Values in bold are the significant correlation coefficients at the threshold of 0.05

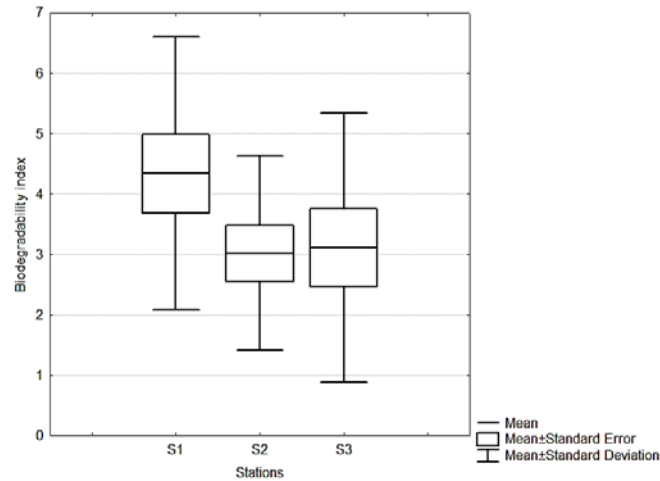


Figure 2. Variation of the biodegradability index of the studied wastewaters among the sampling stations

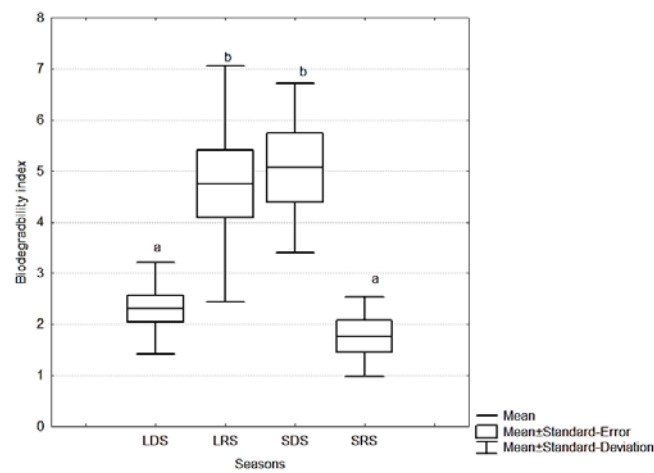
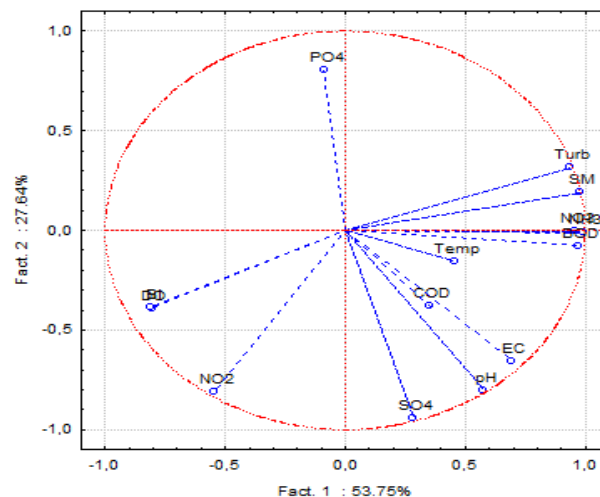


Figure 3. Seasonal variation of the biodegradability index of studied wastewaters (a,b: significant difference at 0.05 threshold)



(a)

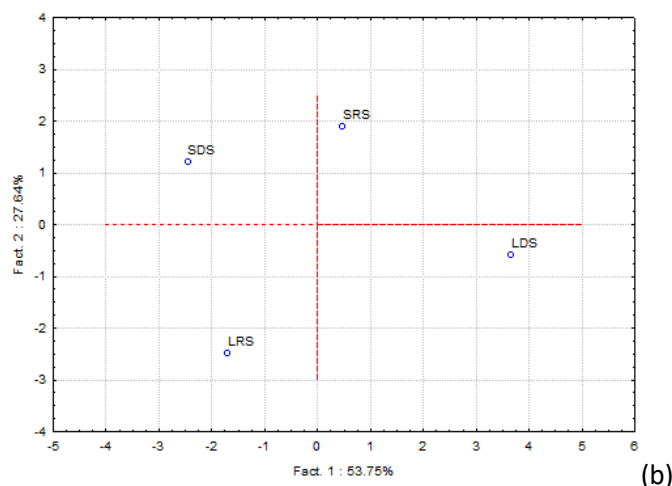


Figure 4. Projection of physico-chemical parameters (a) and sampling seasons (b) in factorial design (F1-F2)

4. Discussion

The wastewaters discharged through storm sewers into the Cotonou Lagoon showed relatively similar quality across the different outlets, although some seasonal variations were noticed.

The mean temperature values are within the recommended limit of 30°C, as specified by wastewater discharge standards [21,22,23]. These values were comparable to those reported for raw wastewater in Abidjan, Côte d'Ivoire [24] and in Adétikopé, Togo [25]. With respect to pH, the investigated effluents were slightly acidic, in contrast to the pH values reported for wastewaters reported in Abidjan, Côte d'Ivoire [24], Ouargla, Algeria [26], Oujda [27] and Ben Sergao at Agadir [28], Morocco, as well as Abomey-Calavi, Benin [29], which were globally alkaline. Nevertheless, on average, the recorded pH values fell within the permissible range of 6 to 9, set by effluent release guidelines [13, 30], during the LDS and LRS but exceeded this range during the SDS and SRS. Based on this pH range, the studied effluents are therefore more favourable to the survival and growth of microorganisms involved in the degradation of organic loads during the LDS and LRS [31,32].

The recorded EC values exceeded the recommended limit of 2.5 mS cm⁻¹, indicating that the prospected wastewaters are highly mineralised, as commonly reported for urban effluents in Africa [33,34,35,36,37]. Dissolved oxygen (DO) levels were low and generally below the 5 mg L⁻¹ threshold required for aquatic life protection, a trend also observed in urban effluents [38]. Accordingly, the studied effluents appear unfavourable both to the degradation of organic loads and to the survival of aquatic fauna [39]. Furthermore, this low oxygen level, combined with the temperature above 20°C [19], may promote the development of anaerobic microorganisms, particularly sulphite-reducing bacteria [14]. These microorganisms can generate hydrogen sulphide (H₂S) from sulphur compounds, producing the unpleasant odours frequently associated with the effluents [40,41]. A wide turbidity was registered for the studied wastewaters. Turbidity showed a strong positive correlation with suspended matter (SM) concentration ($r = 0.96$), which reached 120 mg L⁻¹, almost four times higher than the threshold of 35 mg L⁻¹

set by Beninese standards [13]. This high SM load, generally due to both organic and inorganic particles [42], considerably reduces water transparency and, consequently, impairs photosynthetic activity, decreasing dissolved oxygen levels [27,39,42,43]. This is further highlighted by the significant negative correlations observed between DO and turbidity ($r = -0.67$) as well as between DO and SM ($r = -0.65$). The discharge of such wastewater, heavily loaded with SM, could therefore trigger similar effects in the receiving aquatic ecosystem by reducing primary production. Additionally, high SM concentrations can directly impair fish respiration by clogging their gills [19].

All the aforementioned parameters (EC, turbidity, SM and OD) highlight the unsuitability of the studied effluents for direct discharge into the environment without prior treatment. This is further supported by the concentrations of nutrient parameters. In fact, although nitrogenous minerals were found in low concentrations in the wastewater, they still pose a potential threat to the receiving environment. In particular, during the LDS and SRS, the release of the effluents with nitrogen levels exceeding 10 to 15 mg L⁻¹ [13,44], could lead to significant ecological and public health impacts [46,47]. Among the nitrogenous species monitored, ammonia nitrogen showed the highest concentrations, likely due to the low DO levels (negatively correlated with the ammonia concentration, $r = -0.54$), which create quasi-anaerobic conditions unfavourable to oxidation reactions in the studied waters [47]. Since ammonia nitrogen is toxic for fish in its unionised form (NH₃) [48,49,50], its high concentration in the investigated wastewaters represents a potential hazard to the biota of the receiving ecosystem. Orthophosphates concentrations were slightly above the discharge limit for phosphorus into sensitive environments (1-2 mg L⁻¹) [13]. When combined with the nitrogen level, the recorded phosphorus concentrations suggest that effluent release could increase the risk of eutrophication events in the Cotonou lagoon [51,52,53]. In addition, the high sulphate concentrations recorded (exceeding 20 mg L⁻¹ and reaching up to 292 mg L⁻¹) may also indirectly contribute to eutrophication in the receiving ecosystem by promoting sulphate reduction and subsequent phosphorus release from sediments [54]. Elevated sulphate levels can also exert direct adverse

effects on aquatic organisms, including disruptions in osmoregulation, reproduction and embryonic development [55,56].

The assessment of organic load and the wastewater biodegradability requires the determination of both BOD₅ and COD [19,57]. In this study, the mean values obtained for these two parameters were lower than those generally reported for urban effluents in other cities such as Abomey-Calavi in Benin [29], Abidjan in Côte d'Ivoire [24], Biskra in Algeria [42], Blantyre in Malawi [58], Sidi Kacem [59] and Sidi Yahia [60] in Morocco.

The moderate BOD₅ and COD levels recorded may partly reflect dilution by stormwater in the combined sewer system sampled, particularly during the rainy seasons when the lowest values were observed [61]. Nevertheless, both BOD₅ and COD exceeded the limit of 25 mg O₂ L⁻¹ and 125 mg O₂ L⁻¹, respectively, recommended by the Beninese discharge standards [13]. These parameters are critical for selecting a suitable wastewater treatment method, since they are used to assess the biodegradability index (BI), defined as the COD/BOD₅ ratio [19,35]. The BI mean values recorded at the sampling stations ranged between 3 and 5, indicating that the studied wastewaters are moderately biodegradable and can therefore be treated using biological processes [19]. This suggests that the accumulation of organic pollutants from the effluents in the receiving water body may be limited, depending on the self-purification capacity of the lagoon.

Biodegradability, however, varied significantly across seasons ($p < 0.05$). Wastewaters were readily biodegradable during the LDS and SRS ($BI < 3$), moderately biodegradable during the LRS ($3 < BI < 5$), and poorly biodegradable during the SDS ($BI > 5$). Seasonal variations in BI closely reflected changes in BOD₅, as shown by their negative correlation ($r = -0.67$). The highest BOD₅ values, comparable to those reported for the household greywater in Cotonou [17], corresponded to the lowest BI and were recorded in the LDS and the SRS. This indicates a strong domestic wastewater contribution, rich in biodegradable matter, likely linked to continuous household effluent discharges into drains and sewers in Cotonou. In contrast, very low BOD₅ levels associated with the highest BI were noticed during the LRS and SDS, suggesting a predominance of non-biodegradable inputs, probably coming from the industrial effluents [17], various solid wastes leachates, or petroleum hydrocarbons discharged into the urban sewers [62].

The PCA results highlighted the correlation among parameters and helped further characterise the studied wastewaters across seasons. The first principal axis (F1) reflected high concentrations of biodegradable organic matter and nitrogenous loads coupled with low DO and low BI values, particularly characterising the LDS. The second axis (F2) pointed up effluents with elevated phosphorus loads and low pH, especially during the SRS. Accordingly, two main classes of wastewater could be distinguished in the surveyed sewers: (i) those enriched in nitrogenous and organic loads, and (ii) those dominated by phosphorus-related pollution. From a treatment perspective, these PCA results call for a seasonal operational strategy consisting of prioritize biological nitrogen removal during dry seasons and, focusing on

phosphorus control during rainy seasons.

5. Conclusion

The results of this study revealed that the mixed wastewaters released into Cotonou Lagoon through storm sewers are highly mineralised with relatively high nitrogen and phosphorus content, turbid and loaded with suspended matters. They contain an important organic load which is moderately biodegradable. The pollution level of the effluents varied across seasons, with the most polluted yet readily biodegradable waters recorded during the LDS. On the other hand, wastewater quality was mainly influenced by mineral and organic pollutants, as well as DO levels during dry seasons, whereas, in rainy seasons, it was much more determined by pH and phosphorus. Most of the monitored quality parameters exhibited some values above discharge standards. These findings highlight the urgent need for seasonally adapted treatment of these effluents prior to their discharge into coastal waters, in order to prevent eutrophication driven ecological imbalance and biodiversity decline. Furthermore, the moderate range of BOD₅ and COD characterising the studied wastewater, partly due to stormwater mixture, suggests the design of a separate collection system in order to concentrate the organic load required for treatment system operation.

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