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Physicochemical and Environmental Aspects of Effluents from Fish Processing Plants in the Autonomous Port of Dakar (Senegal)

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Abstract

Fish processing plants, which are major water consumers, generate large volumes of effluents consisting of blood, detritus, and other waste, causing pollution at discharge points. This study, conducted at the Autonomous Port of Dakar (Senegal), aims to characterize the effluents from fish processing plants in order to assess their regulatory compliance and their potential impacts on the marine environment. The methodological approach adopted is based on semi-structured interviews with key informants, as well as sample collection and the analysis of physicochemical parameters. Specific water consumption ranges from 0.18 to 4.8 m^3 per ton of treated products, while annual water consumption ranges from 1,144 m^3 to 157,740 m^3. The levels of COD, BOD_5, and suspended solids vary from 2,600 to 50,200 mg/L, 1,100 to 4,000 mg/L, and 50 to 5200 mg/L for TSS confirmed. These effluents are mostly difficult or impossible to biodegrade due to their COD/BOD5 ratios exceeding 5. The annual pollutant loads generated by these different facilities vary from 8.1 and 2,690 tons, depending on the fish processing plant's specialization. These results highlight the need for pretreatment of the studied effluents and pave the way for further research into sustainable management strategies.

Keywords

Autonomous Port of Dakar, Fish Processing Plants, Industrial Effluents, Marine Pollution, Physicochemical Characterization

1. Introduction

In Senegal, industrial activity is mainly located in the Dakar region, specifically in the area of the Autonomous Port of Dakar [1]. In Senegal, the fishing sector plays an important role, representing nearly 3.5% of the national GDP and contributing to the trade balance through the export of fishery products [2]. In 2022, Senegal had nearly 89 processing units approved for export to the European Union, illustrating the vitality of the fisheries sector [3]. Despite their significant contribution to the national economy, these fish processing plants, which are major consumers of water, generate large volumes of effluent rich in oils, fats, suspended solids, etc. [4]. Due to the lack of suitable treatment infrastructure, most of the wastewater from these industrial facilities is discharged directly into the sea without prior treatment [5]. This represents a source of pollution that can alter water quality and impact marine and coastal biodiversity [6].

Aware of these challenges, the State of Senegal has strengthened its legal framework by adopting a new Environmental Code in 2023, which reaffirms the principle of pollution and nuisance control. Furthermore, the national standard NS 05-061 sets the limit values for some physicochemical parameters of wastewater discharges into receiving environments such as surface water, groundwater, and marine waters [7]. This standard is supported by the Interministerial Decree No. 1555 of March 15, 2002, which governs the conditions for its application within the country's territorial boundaries.

Moreover, complementary initiatives, such as the Hann Bay clean-up project, demonstrate recent efforts by state authorities to provide the country with adequate wastewater collection and treatment infrastructure [1]. This project includes, among other things, the construction of a new wastewater treatment plant (WWTP) with a capacity of 25,000 m^3 per day, the connection of industries located in the Hann-Bel-Air industrial zone to this WWTP, and the sanitation of the Autonomous Port of Dakar [8]. This study, which focuses on the physical, chemical and environmental aspects of effluents from fish processing facilities located in the Autonomous Port of Dakar, is being carried out within this framework. It aims to characterize these effluents in order to assess their regulatory compliance and their potential impacts on the coastal environment.

2. Materials and Methods

2.1. Presentation of the Study Area

The study area covers the fishing port of the Port Autonome de Dakar (PAD), also known as the Seydina Limamou LAYE El Mahdi, formerly breakwater 10. It is located in the municipality of Hann-Bel Air, within the PAD and is accessible by road for vehicles and pedestrians via Félix Eboué Avenue (**Figure 1**). Commissioned in 1988, the fishing port covers 24 hectares and includes industrial activities related to the handling, equipping, and processing of fishery products [9]. According to field surveys, eighty-six establishments, including seven located outside the customs zone, fall under the jurisdiction of the Fishing Port Authority, which provides operational oversight.

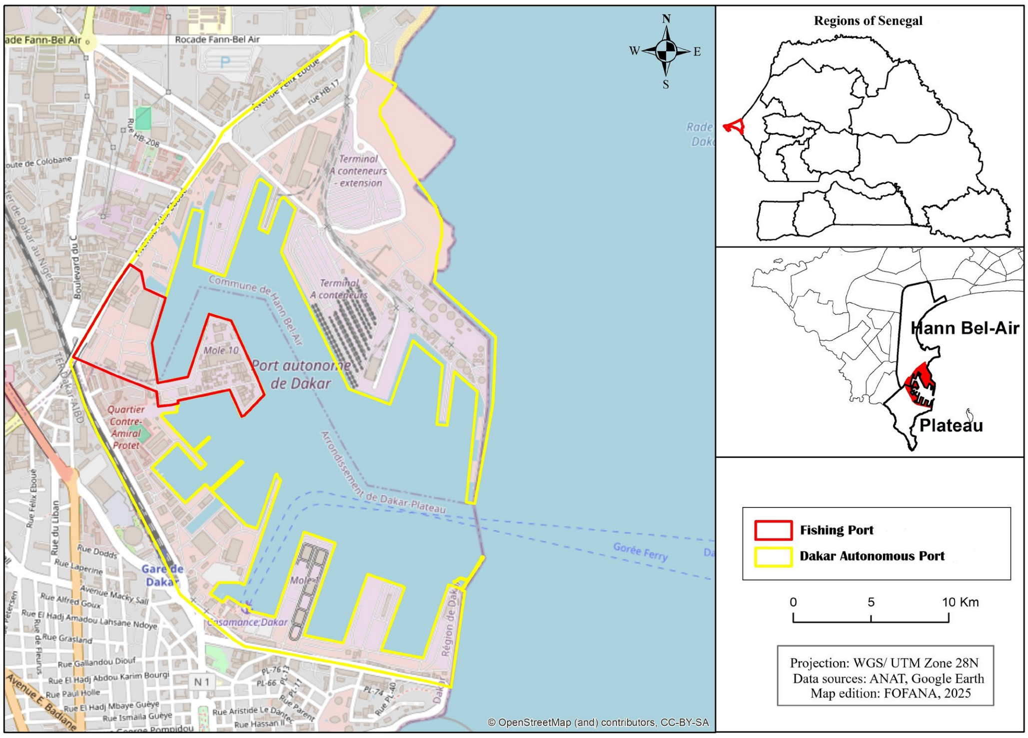

Figure 1. Map showing the location of the study area.

2.2. Methodology

A mixed-methods approach, combining qualitative and analytical methods, was adopted. It is based on semi-structured interviews with key informants, sample collection, and analyses of physicochemical pollution parameters.

2.2.1. Selection of Industrial Facilities for the Study

The *Direction de le Réglementation et du Control Environnemental* (DiREC) (Directorate of Environmental Regulation and Control), in collaboration with the PAD's Environmental Studies Unit, regularly organizes sampling and analysis campaigns for effluents from industrial facilities. These operations are part of DIREC's mandate to ensure compliance with Senegalese standard NS 05-061 regarding wastewater dis-charges [7], in accordance with Law No. 2023-15 of August 2, 2023, establishing the Environmental Code of Senegal.

For this purpose, ten fish processing facilities were selected. Among these, seven were actually visited. These included two canneries and five plants specializing in the production of fresh and frozen products (**Table 1**). The remaining three facilities were not in operation at the period of the study. For this reason, effluent samples were not collected from these facilities.

For confidentiality reasons, the fish processing facilities concerned are identified by the following codes (U = Unit): U1, U2, U3, U4, U5, U6 and U7.

Table 1. Fish processing facilities covered by the study.

Units	Fields	Raw materials	Pre-processing of the wastewater
U1	fresh, frozen	fish, cephalopods, crustaceans	settling tank + rotating screen
U2	cannery	fish	no pretreatment
U3	fresh, frozen	fish	no pretreatment
U4	fresh, frozen	fish, cephalopods, crustaceans	no pretreatment
U5	cannery	sardines, tuna	settling tank + lamellar settling tank
U6	fresh, frozen	fish	no pretreatment
U7	fresh, frozen	fish, cephalopods, crustaceans	no pretreatment

2.2.2. Interviews with Key Informants

A semi-structured interviews were conducted using interview guides to gain a better understanding of the topic through a participatory approach by interviewing various stakeholders. The stakeholders involved are:

- the head of the QHSE department at the Fishing Port Authority;
- the environmental studies officer at the Autonomous Port of Dakar;
- the statistics officer at the Fishing Port;
- the production managers and supervisors of the seafood processing facilities;
- the official from the Directorate of Environmental Regulation and Control responsible for inspecting facilities at the Autonomous Port of Dakar;
- the head of the Wastewater Treatment Department of the Senegalese National Sanitation Utility, who is also responsible for monitoring industrial operators as part of the Hann Bay cleanup project.

2.2.3. Estimation of Water Consumption Volumes

The volumes of water consumed by the all facilities visited were estimated based on semi-structured interviews with technical managers and a review of technical data sheets containing monthly water consumption data. These data were extrapolated to obtain annual averages. Since water is not incorporated into the processed product, the amount of water consumed is considered to be approximately equal to the volume of effluent discharged. Furthermore, it should be noted that six of the seven facilities visited include only water volumes supplied by the public water system in their consumption records. Seawater, although used in certain stages of the process, is often omitted from the measurements. This omission can significantly affect calculations of specific water consumption and effluent volumes.

2.2.4. Effluent Sampling

Sampling campaigns were conducted on July 1 and 2, 2024, between 10:30 a.m. and 2:00 p.m., in accordance with the protocols described in Standard Methods for the Examination of Water and Wastewater [10]. Samples were collected from the tanks storing wastewater from the process of each industrial unit, representing the facility's total discharge. These were grab samples These were grab samples put into 1-liter bottles. The 1-liter polyethylene bottles and the sampling beaker were thoroughly washed with distilled water and then rinsed with the wastewater to be sampled. Two 1-liter bottles were filled using the sampling beaker, immediately sealed, labeled, and placed in a cooler away from light. The samples were then transported to the mobile laboratory parked nearby and stored at 4˚C until analysis.

2.2.5. Determination of Physicochemical Parameters

Temperature (T), pH, electrical conductivity (EC), salinity (S), and total dissolved solids (TDS) are measured in situ using a Palintest® PT162 multiparameter probe. To do this, 200 mL of sample were collected and poured into a 500 mL beaker that had been previously washed and rinsed with distilled water and then with the wastewater to be characterized. Afterward, the dry, clean probe of the powered-on device is immersed in the sample. The device's "Set" button allows you to select the parameter to be measured.

Suspended solids (TSS) were determined in the DIREC mobile laboratory in accordance with French standard NF EN 872 [11]. To help with this process, the wastewater sample is filtered through glass fiber paper, and the filter is then dried in an oven at a specific temperature of 105˚C for 2 hours. The quantity of suspended solids is determined by differential weighing using a highly sensitive balance. The TSS content is calculated in mg/L using the following formula:

$$TSS\left(\text{mg/L}\right)=\frac{m_1-m_0}{V}\times 1000 \quad (1)$$

where:

m_1: is the mass (in g) of the dry filter before filtration,

m_0: is the mass (in g) of the dry filter after wastewater filtration,

V: is the volume (in L) of the sample.

The chemical oxygen demand (COD) was determined in accordance with the French standard NF T90-101 [12]. Thus, 2 mL of distilled water is poured into a reaction Hach tube. This constitutes the blank tube. In other tubes (sample tubes), 2 mL of the sample to be analyzed is poured. These tubes are then mixed and preheated for two hours at 150˚C in the thermal reactor. Once cooled to room temperature, the corresponding COD value is read by inserting the tubes into a Lovibond MD 610 photometer. First, the standard tube is inserted to calibrate the photometer by pressing the "ZERO" button. To read the sample tubes, the "TEST" button is pressed each time. The measurement result is displayed and indicates the COD value in mg O2/L.

To determine the five-day biochemical oxygen demand (BOD_5), the respirometric method was used in accordance with the recommendations of the French standard NF EN ISO 5815-1 [13]. A 157 mL volume of the sample diluted to one-hundredth was taken and poured into the BOD flask containing a magnetic stirrer. To inhibit nitrification, five drops of a specific inhibitor were added to the bottle. Subsequently, 3 to 4 drops of potassium hydroxide solution were added to the BOD bottle's reservoir to absorb the carbon dioxide produced. The BOD sensor heads were screwed onto the BOD bottles. Finally, the BOD vials are placed on the vial holder, which allows for continuous agitation of the samples contained in these vials. The entire setup is incubated at 25˚C in the dark for 5 days. The BOD5 value is displayed directly on the device's screen in mg O2/L.

2.2.6. Evaluation of the Biodegradability of Effluents

To assess the biodegradability of wastewater, the COD/BOD_5 and TSS/BOD_5 ratios were calculated. According to [14], if the ratio:

- COD/BOD5 < 3, the effluent is readily biodegradable;
- 3 < COD/BOD5 < 5, the effluent is moderately biodegradable;
- COD/BOD5 >5, the effluent is difficult to biodegrade or even non-biodegradable.

On the other hand, a high TSS/BOD5 ratio (>1) indicates a high presence of non-biodegradable or mineral matter (sand, silt, etc.), whereas a low ratio (<0.5) suggests a predominance of organic matter favorable to biological processes [15].

2.2.7. Regulatory Compliance Assessment

Physicochemical parameters analyses are compared to the regulatory limits set by the Senegalese standard NS 05 061 on wastewater discharges [7]. Thus, the discharge limits into the natural environment (**Table 2**) and the limits prior to connection to a wastewater treatment plant (**Table 3**) are taken into account.

Table 2. Limit values for selected parameters for wastewater discharges into the natural environment [7].

Parameters	Legal limit values
Temperature	≤30˚C
pH	5.5 ≤ pH ≤ 9.5
Total Suspended Solids (TSS)	50 mg/L
BOD5	40 mg/L if load > 30 kg/day 80 mg/L if load < 30 kg/day
COD	100 mg/L if load > 100 kg/day 200 mg/L if load < 100 kg/day

Table 3. Limit values for certain effluent parameters for discharge into a sewer system leading to a wastewater treat-ment plant [7].

Parameters	Legal limit values
TSS	600 mg/L if load > 15 kg/day
BOD5	800 mg/L if load > 15kg/day
COD	2000 mg/L if load > 45 kg/day

In the absence of detailed information on daily flow rates, the upper limits of the regulatory thresholds for COD and BOD_5 applicable to discharges into the natural environment were adopted. This approach allows for the uncertainties associated with variations in discharge volumes and frequencies, in accordance with the precautionary principle.

Furthermore, Senegalese legislation provides for a fee payable by any facility discharging effluents into the natural environment, whether or not it has a wastewater treatment plant. This fee is set at 180 CFA francs (~0.26 USD) per kg of pollutant load in accordance with Interministerial Decree No. 1555 of March 15, 2002, establishing the conditions for applying Standard NS 05-061 on wastewater discharges [7]. The calculation of the pollutant load in mg/L is performed using the following basic formula (2):

$$X\left(\text{mg/L}\right)=\left(\text{TSS}-50\right)+\left[\left(\text{COD}-200\right)+2\left(\text{BOD}_5-80\right)\right]/3 \tag{2}$$

The pollutant load, when multiplied by the daily volume of discharged effluent, gives the pollutant load in kilograms per day (kg/d) [7].

This value is then extrapolated to an annual load using the following formula (3):

$$\text{Annual load } (t/\text{year}) = X * \text{ Annual volume } (\text{m}^3) * 10^{-3} \tag{3}$$

This annual load is used to calculate environmental royalties [7].

2.2.8. Quality Assurance and Quality Control

Quality assurance and quality control procedures were implemented throughout the analytical process to ensure the reliability and reproducibility of the results. The measuring instruments (pH meter, conductivity meter, and spectrophotometer) were calibrated daily, using appropriate calibration solutions and verified with certified standards. Analytical blanks (distilled water) and control samples were included to monitor the risk of contamination and verify the reproducibility of the measurements. Samples with concentrations exceeding the analytical range of the instruments were appropriately diluted and then reanalyzed. Each parameter was measured in duplicate to improve the accuracy and reliability of the results.

2.2.9. Data Analysis

Data normality was assessed using the Shapiro-Wilk test. The data are considered normal if the p-value is greater than 0.05. Since some variables do not follow a normal distribution, Spearman's correlation was used to establish the correlation matrix. Statistical analyses and graphs were performed using the R software within the RStudio interface [16].

3. Results and Discussions

3.1. Water Consumption in the Fish Processing Facilities

The volumes of water consumed and the production levels of the various facilities are shown in **Table 4**. The annual water consumption of the different seafood processing plants varies significantly. It ranges from 1,144 m³ for U5 to 157,740

m^3 for U2. Specific consumption that is, the ratio of annual water consumption to annual production, ranges from 0.18 m^3 to 4.38 m^3 of water per ton of processed product.

Table 4. Water consumption and effluent discharge volumes.

Units	Type of processing	Water Consumed (m^3/year)	Production (t/year)	Ratio (m^3/t)
U1	fresh, frozen	19.734	11.500	1.72
U2	cannery	157.740	36.000	4.38
U3	fresh, frozen	2.340	nf	nd
U4	fresh, frozen	1.170	12.960	0.18
U5	cannery	47.300	16.500	2.87
U6	fresh, frozen	1.144	nf	nd
U7	fresh, frozen	131.560	nf	nd

The specific water consumption figures found for canning facilities U2 and U5 are lower than those reported by [17], who estimated between 9 and 15 m^3 of water for canning one ton of sardines. Benyakhlef *et al.* [4] reported ratios of around 35 m^3 per ton for a cannery in Morocco. However, they included in their water balance ancillary operations such as facility cleaning and domestic uses, which require a significant amount of water. In fresh/frozen fish processing facilities, ratios of about 1.72 and 0.18 m^3 per ton of processed product are also lower than those reported in the literature. For example, [18] reported values of 6.1 m^3 of water per ton of processed product in a fish processing plant in Brazil. However, they noted that 20% of this water consumption is used for defrosting the cold storage room and flushing the cooling towers, and is therefore not directly related to processing. This could explain the significant differences observed compared to our study. These results show a variability in specific water consumption depending on the type of plant, the nature and quantity of processed products, equipment, etc., as highlighted [19].

These relatively low specific water consumption values, compared to those reported in the literature, should be interpreted with caution. They could be explained by a need to optimize water requirements. Conversely, they could also be linked to two methodological omissions in the water balance. The first omission results either from deliberate misrepresentation or a lack of technical means to accurately measure water consumption. In fact, some facilities underestimate their actual water consumption in order to reduce the amount of pollution tax they have to pay, while others do not have reliable flow meters. This may affect the representativeness of the collected data and constitute a regulatory constraint regarding the environmental compliance of effluents, as noted by Mokhtar *et al.* [20]. The second omission concerns the non-inclusion in the water balance of related operations that consume large amounts of water, such as cleaning floors and equipment, water usage in bathrooms and social areas, and defrosting cold storage rooms, among others. Although these processes are peripheral, they can contribute significantly to total water consumption. It should also be noted that the initial washing of fish, cooling and transport of raw materials, which are often carried out using seawater, constitute a significant source of water consumption that is generally not quantified [21].

3.2. Physicochemical Characteristics of Wastewater

3.2.1. Physical Parameters

The main results of the parameters measured in situ are presented in **Table 5**.

Table 5. Physical parameters of effluents from the fish processing facilities.

Parameter	Mean	Median	Standard deviation	Minimum	Maximum
Temperature (˚C)	27.56	25.80	4.34	21.50	33.50
pH	7.49	7.40	0.45	6.84	8.31
Conductivity	1257.14	1067.00	507.70	731.00	2150.00
Salinity	502.29	420.00	209.62	288.00	875.00
TDS	906.86	757.00	382.71	515.00	1600.00

The temperature of the effluents ranges from 21.5˚C to 33.5˚C. In all industrial facilities, it does not exceed the tolerance range of 30˚C ± 5˚C established by Senegalese law [7]. The pH, meanwhile, shows very little variation, with a standard deviation of 0.48. The measured values, ranging from 6.8 to 8.31, all comply with the NS 05-061 standard. The measured electrical conductivity, salinity, and TDS exhibit high variability, reflecting significant heterogeneity in the effluents depending on the processes and the nature of the processed products, as noted by Katsara *et al.* [22]. Furthermore, a perfect correlation ($r = 1$) was established between these three parameters, indicating that they vary in strict proportion to one another. This interdependence allows, in accordance with the observations of DeLisle *et al.* [23], for the use of just one of these indicators to assess the overall ionic load of the effluents. In this case, electrical conductivity ranges from 731 to 1,650 µS/cm with a standard deviation of nearly 357 µS/cm. This reflects a moderate dispersion around the mean. By comparison, Cristóvão *et al.* [24] reported an initial conductivity of 7,900 µS/cm in their study on wastewater treatment at a fish cannery in Portugal. In Morocco, Benyakhlef *et al.* [4] reported conductivities ranging from 3,870 to 7,900 µS/cm in fish processing plants. In summary, comparison with these international studies allows us to classify the effluents from the PAD's fish processing facilities as moderately ion laden, thereby ruling out the use of seawater in the processes.

3.2.2. Organic Parameters

The analysis of organic parameters, specifically concentrations of suspended solids (SS), COD and BOD_5 is a critical step in assessing the quality of industrial effluents, particularly in the fisheries sector. Figure 2 provides a graphical representation of the total suspended solids (TSS) values for various effluents. These total suspended solids (TSS) levels range from 50 mg/L for U3 to 5,200 mg/L for U4. With the exception of U3, all effluents exceeded the discharge limit for release into the natural environment, which is 60 mg/L. The effluents from U4 even exceed the regulatory threshold of 600 mg/L for TSS for a connection to a wastewater treatment plant by more than eight times.

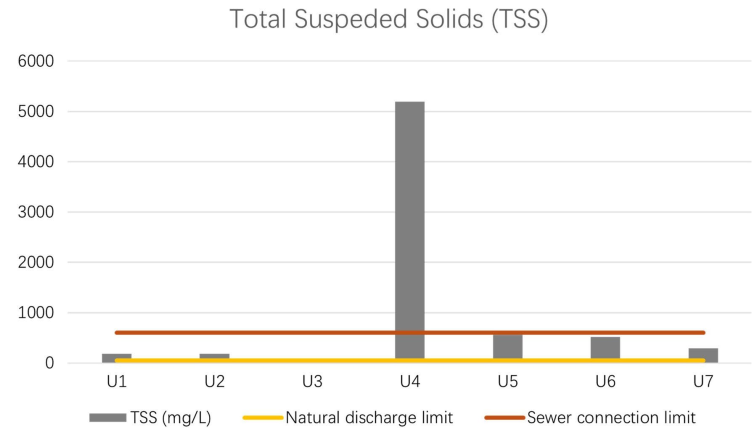

Figure 2. Suspended solids concentration in effluents from fish processing facilities.

The high variability of effluents from the seafood processing industry in terms of suspended solids has been documented in the literature. Indeed, Anh *et al.* [25] reported suspended solids concentrations ranging from 150 to over 22,000 mg/L in effluents from seafood processing plants, depending on the nature of the product processed and the processes used. Benyakhlef *et al.* [4] also found high TSS concentrations of approximately 1,295 mg/L. These high TSS levels can impact wastewater treatment equipment and facilities, as well as cause siltation issues in coastal environments [26].

The COD values (Figure 3) significantly exceed the discharge limits for discharge into the natural environment (200 mg/L) and those for discharge into a sewer connected to a municipal wastewater treatment plant (2,000 mg/L).

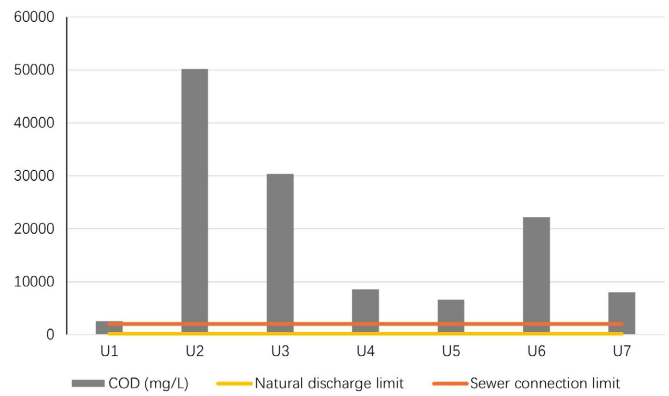

Figure 3. COD concentration in effluents from fish processing facilities.

The effluent from cannery U2 has the highest COD level, at 50,200 mg/L. The effluent with the lowest COD levels comes from plants U1 and U5. These two industrial units are equipped with specific pretreatment systems: a rotary screen for one and a lamellar clarifier for the other. Consequently, the low COD lev-els could be attributed to the more or less effective retention of most organic solid particles, thereby contributing to the reduction of COD in the final effluents. The very high COD values, especially for the U2 cannery, indicate significant organic pollution. Indeed, in canneries, cooking processes release proteins, fats, and organic residues into the water, while canning process results in losses of oil, brine, and organic fragments, significantly increasing the organic load of the effluents, as noted by Katsara *et al.* [22]. These high values are comparable to those observed by Venugopal and Sasidharan [17], in the range of 11,000 mg/L for effluents from a tuna cannery and 13,180 mg/L for effluents from a general fish processing plant.

The BOD_5 levels measured in the effluents from the various facilities are substantially higher than the limit set by the Senegalese standard, which is 80 mg/L for direct discharge into the natural environment and 800 mg/L for discharge into a sewer leading to a centralized wastewater treatment plant [7]. They range from 1,100 to 4,000 mg/L depending on the processing methods (**Figure 4**), indicating a high organic load.

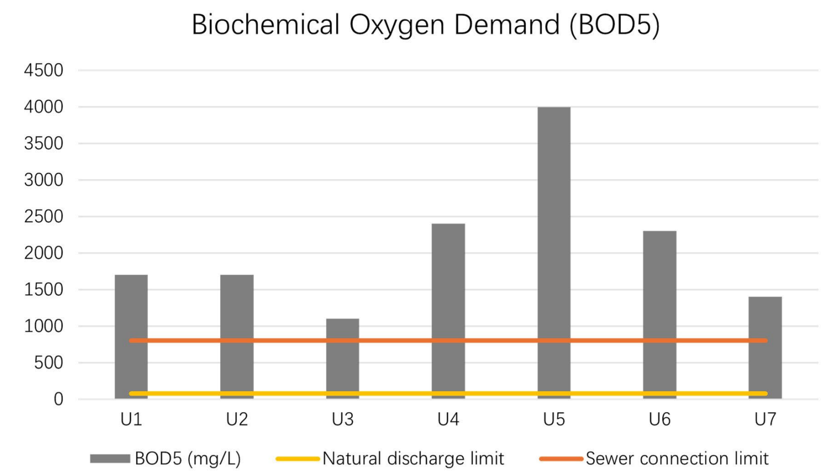

Figure 4. BOD_5 levels of various effluents.

3.2.3. Biodegradability of Effluents

The assessment of the biodegradability of the various effluents is based on an analysis of the COD/BOD_5 and SS/BOD_5 ratios. These ratios are presented in **Table 6**. According to the scale developed by Rodier *et al.* [14], the effluents from U1 and U5 are readily biodegradable, while those from U4 are moderately biodegradable. In contrast, the effluents from U6 and U7 are difficult or even non-biodegradable because they contain a high refractory organic load that is resistant to biological treatment processes. The effluents from U2 and U3, however, have very high ratios (29.5 and 27.6, respectively), indicating a highly non-biodegradable form of pollution. This low biodegradability of the effluents can be explained by the use of additives, brine, acetic acid and sulfites to ensure the quality as well as the microbiological and organoleptic stability of the products as mentioned by Cristóvão *et al.* [24].

Table 6. Biodegradability and particulate load of effluents.

Units	COD/BOD$_5$	Biodegradability	TSS/BOD$_5$	Particulate Load
U1	1.53	readily biodegradable	0.10	organic matter
U2	29.53	biodegrade or even non-biodegradable	0.10	organic matter
U3	27.64	biodegrade or even non-biodegradable	0.04	organic matter
U4	3.58	moderately biodegradable	2.17	high presence of non-biodegradable or mineral matter
U5	1.65	readily biodegradable	0.14	organic matter
U6	9.65	biodegrade or even non-biodegradable	0.23	organic matter
U7	5.71	biodegrade or even non-biodegradable	0.21	organic matter

Furthermore, all effluents have an TSS/BOD$_5$ ratio below 1, with the exception of effluent U4, for which this ratio is 2.2. This indicates that this effluent has a high concentration of poorly biodegradable solids [15]. It therefore requires physical pretreatment such as AOPs prior to any biological or chemical treatment [27].

3.2.4. Exploration of Inter-Parameter Relationships in Pollution Levels of Different Effluents

To better understand the relationships between the various parameters measured in the effluents, a correlation matrix (**Figure 5**) was made. Several relationships among the physicochemical parameters were identified.

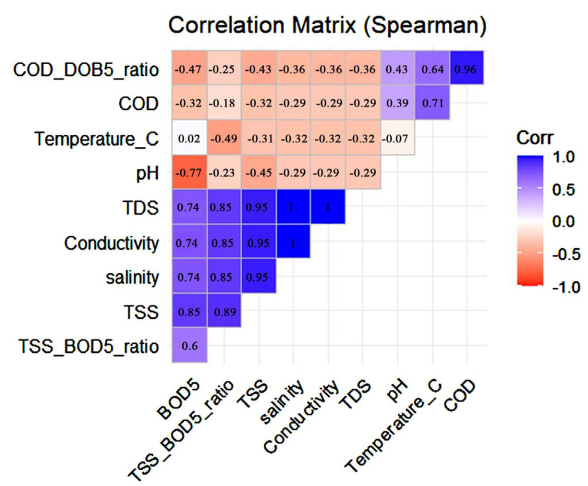

Figure 5. Correlation matrix of the various parameters studied.

A strong and significant positive correlation was observed between temperature and COD ($\rho = 0.93$, $p = 0.003$), suggesting an association between temperature and organic matter load. This relationship is supported by the work of Yapo *et al.* [28], who demonstrated that the increase in temperature enhances the degradation of the carbon fraction of organic matter, thereby increasing COD. Similarly, a strong and significant positive correlation was observed between the COD/BOD_5 ratio and temperature ($\rho = 0.86$, $p = 0.014$). Given that higher COD/BOD_5 ratios generally indicate lower biodegradability, this positive association may suggest a decrease in the relative biodegradability of organic matter with increasing temperature. However, this relationship should be interpreted cautiously given the small sample size. This observation is consistent with the work of Venugopal and Sasidharan [17]; who emphasize that high temperatures promote rapid biodegradation but can also intensify the production of toxic byproducts such as ammonia, hydrogen sulfide, and amines; thereby reducing biological activity.

Furthermore, conductivity, salinity, and TDS showed strong positive correlations with TSS ($\rho = 0.92$ for each parameter) and BOD_5 ($\rho = 0.77$ for each parameter), indicating that the more saline and conductive effluents tended to exhibit higher suspended solids and organic loads. These observations are consistent with the work of Alotaibi *et al.* [29], who demonstrated that high salinity levels in industrial effluents can influence biological treatment performance. A strong negative association was observed between pH and BOD_5 ($\rho = -0.72$), although this relationship was not statistically significant ($p = 0.068$). This could reflect the sensitivity of biological activity to the acidity and alkalinity of the environment. This trend may reflect the sensitivity of biological processes to pH conditions. Previous studies, such as Kokina *et al.* [30], have reported that pH variations can affect nitrification and consequently influence BOD_5 levels.

3.2.5. Estimation of the Depollution Tax Based on Pollutant Load

The annual quantities of pollutant loads discharged are estimated to range from about 10 to nearly 3,000 tons (**Table 7**). Effluent U6 has the lowest pollutant load, while U2 has the highest.

Table 7. Annual pollution emissions and pollution tax.

Units	Pollutant load X (t/an)	Estimated fee charged (FCFA)
U1	40.5	7,290,000
U2	2690	484,200,000
U3	24.4	4,392,000
U4	8.1	1,458,000
U5	281.5	50,670,000
U6	10.2	1,836,000
U7	489.4	88,092,000
Aggregate	3544.1	637,938,000

These amounts of pollutants are associated with environmental royalties estimated to range from about 1.46 million to about 484 million CFA francs per year, depending on the volume of water consumed and the pollutants generated. The estimated annual total for these seven industrial facilities amounts to 637.9 million CFA francs per year. This amount represents nearly 0.7% of the total cost of the Hann Bay cleanup project, estimated at 93 billion CFA francs according to ONAS [8]. Compared to the budget for the Hann Bay cleanup project, this amount seems negligible. However, it could contribute significantly to the operation of the wastewater treatment plant.

This fee is based on the "polluter pays" principle, as defined by Dreyfus [31] as a mechanism designed to make polluters responsible for the cost of the environmental damage they cause. However, as Drobenko [32] points out, the implementation of this principle can become a mere accounting formality without any real incentive to change industrial practices or invest in pollution control solutions, particularly when the calculation methods are opaque or offer little incentive. In this regard, concrete efforts have been undertaken, particularly at the PAD fishing port, where certain businesses have received assistance in acquiring equipment for the pretreatment of their wastewater as part of the Hann Bay cleanup project. This approach, which combines tax incentives and technical support, aims to strengthen environmental compliance while taking into account the operational capacities of economic actors.

4. Conclusion

The seafood processing industry consumes significant amounts of water. The purpose of this study was to characterize the effluents from seafood processing plants in the PAD, with a view to assessing their regulatory compliance as well as their potential impacts on the coastal environment. The relatively low specific water consumption figures observed may be due to the exclusion of certain ancillary operations from the water balance, such as equipment cleaning, deicing, and intermittent discharges. Furthermore, levels of total suspended solids (TSS), chemical oxygen demand (COD), and biochemical oxygen demand in five days (BOD_5) were found to far exceed national standards for discharges into the natural environment or for connection to a wastewater treatment plant. These effluents, which are heavily loaded with organic matter, can have negative impacts on marine and coastal ecosystems, particularly through the consumption of dissolved oxygen and the disruption of benthic communities. Furthermore, their high pollutant load can compromise the performance of wastewater treatment facilities, particularly in light of their planned connection to the outfalls of the Hann Bay cleanup project. This study thus highlights the need to collect and pretreat these effluents before any discharge into the marine environment or into public infrastructure. In this context, the implementation of the environmental tax can serve as an incentive to encourage industrial operators to improve the quality of their effluents and to plan for their connection to the system with a view to long-term compliance.

However, the assessment of compliance must be viewed with caution. It depends on sampling conditions, seasonal variability, and the analytical methods used. The results presented here provide robust but not absolute indications, which need to be supplemented by regular monitoring and additional analyses to accurately reflect the actual environmental impact.

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Author Contributions

Conceptualization, IF, EMS and MLD; methodology, IF, EMS and MLD; software MLD; validation, EMS and MLD; formal analysis, IF and MLD; investigation, IF and MLD; resources, MLD; data curation, IF and MLD; writing—original draft preparation, IF; writing—review and editing, EMS. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

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

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