JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2026, 27(7), 465–478
https://doi.org/10.12911/22998993/219969
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Received: 2026.03.10
Accepted: 2026.05.15
Published: 2026.06.01

Impact of fish-processing effluents on the microbiological and physicochemical quality of coastal waters in Lévrier Bay, Mauritania

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ABSTRACT

Coastal ecosystems receiving untreated industrial effluents are increasingly exposed to microbiological and organic pollution. This study evaluated the impact of wastewater discharges from fish-processing industries on the seawater quality of Lévrier Bay (northwestern Mauritania). Two sampling campaigns were conducted during the cold and warm seasons at six stations located within the seawater–wastewater mixing zone. Microbiological indicators (total coliforms, *Escherichia coli*, and fecal streptococci), physicochemical parameters (temperature, pH, salinity, electrical conductivity, total dissolved solids, and dissolved oxygen), nutrients (nitrate, nitrite, and phosphate), and organic pollution indicators (BOD_5) were analyzed. Microbiological results revealed severe fecal contamination, with total coliforms reaching 8.8×10^5 CFU/100 mL, E. coli up to 8.5×10^5 CFU/100 mL, and fecal streptococci up to 8.1×10^5 CFU/100 mL. Physicochemical conditions generally remained within natural coastal ranges, with pH (7.53–8.5), salinity (30.43–35.08 PSU), and temperature (21.71–25.83 °C). However, elevated BOD_5 (up to 225 mg/L), phosphate (2.4 mg/L), and low dissolved oxygen (1.78 mg/L) indicated localized organic enrichment and potential hypoxic conditions. Overall, the results demonstrate that untreated industrial discharges from fish-processing industries exert significant microbiological and organic pressure on Lévrier Bay, highlighting the urgent need for wastewater treatment and continuous environmental monitoring to protect this vulnerable coastal ecosystem.

Keywords: Fish-processing wastewater, coastal water quality, microbiological contamination, organic pollution, physicochemical parameters, Lévrier Bay.

INTRODUCTION

Fish processing industries generate large volumes of wastewater characterized by high concentrations of organic matter and biological oxygen demand (BOD). When discharged untreated into surface waters, these effluents can significantly degrade aquatic ecosystems by reducing dissolved oxygen (DO) levels and altering water quality (Gómez-Sanabria et al., 2020). The organic load of fish processing wastewater typically consists of approximately 60% oils and fats, 27% proteins, and 13% a combination of soluble and suspended organic matter (Putra et al., 2020). In addition, seafood processing plants consume substantial quantities of water, mainly for washing raw materials and handling by-products. These facilities are commonly located in coastal regions with abundant water resources and often use more water than is technically required for processing activities (Ben et al., 2007).

Beyond their high organic content, fish processing effluents are also rich in nitrogenous compounds and other biodegradable substances. When released into coastal environments, these nutrients can promote eutrophication, a major environmental problem associated with industrial wastewater discharges (Bhuyar et al., 2021a, 2021b). Eutrophication can lead to excessive phytoplankton growth, altering the ecological balance of aquatic ecosystems. Since phytoplankton communities are highly sensitive to nutrient availability, their diversity and abundance are often used as indicators of environmental quality in coastal waters (Cerino et al., 2019; Zingone et al., 2021).

In addition to their organic and nutrient loads, fish processing effluents also contribute to broader marine pollution problems. Marine pollution caused by anthropogenic activities remains one of the most significant environmental threats to coastal ecosystems and is generally defined as the introduction of substances or energy into the marine environment that may cause harmful effects on marine organisms and ecosystem functioning. Historically, the impacts of wastewater discharges on marine environments were often underestimated due to the assumption that the ocean's dilution capacity would mitigate their effects (Ferraciolli et al., 2018 ; Vallejos et al., 2020).

However, increasing evidence indicates that continuous or large-scale discharges can significantly alter coastal water quality. In particular, the direct release of untreated industrial effluents can modify key physicochemical parameters, including salinity, nutrient concentrations and dissolved oxygen levels, which are essential for maintaining marine life (Anh et al., 2010; Venugopal and Sasidharan, 2020). Such alterations may disrupt ecosystem functioning, promote ecological imbalance, and reduce biodiversity in affected coastal environments (Moncada et al., 2019; Quimpo et al., 2020).

The Mauritanian coastline is one of the world's most productive marine regions, supported by a strong upwelling system that sustains rich fisheries and contributes significantly to the national economy. Highly productive coastal ecosystems like this are, however, particularly sensitive to environmental disturbances. Within this context, Lévrier Bay, located on the western coast of Mauritania, plays a crucial role in the national fishing sector and provides important habitats for marine species reproduction. Over recent decades, the rapid expansion of the fish-processing industry in the region has led to the establishment of nearly 70 factories, including 32 fishmeal and oil plants. While these industries are important for economic development and employment, they are also the main sources of coastal water pollution, discharging untreated effluents rich in organic matter, nutrients, and microbial contaminants directly into coastal waters (Abdel Maleck et al., 2024). Consequently, the combination of Lévrier Bay's exceptional biological productivity and increasing anthropogenic pressures makes it a particularly critical and sensitive area for environmental monitoring and research (Cheikh et al., 2020).

Several studies conducted in Mauritania have investigated chemical contamination in marine environments, particularly focusing on trace metals in fish, sediments, and bivalves (Sidoumou et al., 1992; Dartige 2006; M'Hamada et al., 2011; Wagne et al., 2013; Legraa et al., 2019; Cheikh et al., 2020 and Yehdih et al., 2022). More recently, Moulay Ely et al. (2023), examined the environmental impact of wastewater discharges from fishmeal plants. However, these studies provide limited information on the specific effects of wastewater generated by fish freezing and processing activities. In particular, no study has yet evaluated the combined microbiological and physicochemical impacts of fish-processing wastewater on the quality of coastal waters in Lévrier Bay.

Concerns regarding the environmental status of Lévrier Bay were further heightened in April 2023, when a massive fish stranding event was reported along its coastline. This event primarily affected the black mullet (*Mugil capurrii*) and raised serious concerns about the potential influence of untreated industrial wastewater discharged into the marine environment (IMROP, 2023). Such incidents highlight the urgent need to better understand the relationship between industrial wastewater discharges and the deterioration of coastal water quality in this ecologically and economically important region.

In this context, the present study aims to evaluate the microbiological and physicochemical quality of coastal waters potentially affected by industrial fish-processing effluents in Lévrier Bay. Particular emphasis is given to the seawater-wastewater mixing zone through the analysis of key microbiological indicators, including total coliforms, *Escherichia coli* and Enterococci, in conjunction with major environmental parameters such as pH, salinity, electrical conductivity,

BOD_5, temperature, dissolved oxygen, total dissolved solids, nitrites, nitrates and phosphates.

In this study, we aimed to assess the microbiological and physicochemical quality of coastal waters potentially impacted by industrial fish-processing effluents in Lévrier Bay, with a focus on the seawater–wastewater mixing zone. Key microbiological indicators, including total coliforms, *Escherichia coli*, and Enterococci, were analyzed alongside major environmental parameters such as pH, salinity, electrical conductivity, BOD_5, temperature, dissolved oxygen, total dissolved solids, nitrites, nitrates, and phosphates.

MATERIALS AND METHODS

Description and location of the study area

Sampling was conducted in June and September 2023 at six sites across Lévrier Bay (Figure 1, Table 1). Four sites (S1, S2, S3, S4) were located in the Bountiya zone, hosting all fishmeal and oil factories as well as artisanal processing activities. Two additional sites (S5 and S6) were positioned near the discharge points of fish processing and freezing plants. Sites were selected based on accessibility and potential exposure to industrial effluents.

None of the selected sites had previously undergone an assessment for fishing industry discharges. This study provides the first evaluation of direct, untreated wastewater discharges from fish processing industries on receiving coastal waters in Lévrier Bay, a region of both ecological and economic importance.

Sampling and sample collection

Water samples were collected at a depth of 30–50 cm to characterize effluents from the factories. Two samples per site were taken, 20 meters apart: one at the discharge point and the other approximately about 50 meters downstream.

Physicochemical samples were collected in 500 mL plastic bottles pre-cleaned with 10% HCl and rinsed with distilled water. Microbiological samples, were collected aseptically in sterile 250 mL glass bottles with ground stoppers, leaving a small air space to facilitate microorganism resuspension. All samples were stored at 4 °C and transported promptly to the laboratory for analysis.

Microbiological analyses employed the membrane filtration method (0.45 µm). Membranes were incubated on selective media: Total coliforms (TC) and *Escherichia coli* (*E. coli*) on chromogenic agar (CCA) at 36 °C for 24 h (ISO 9308-1:2014), and fecal streptococci (FS) on Slanetz and Bartley medium at 36 °C for 44 h (ISO 7899-2:2000). Results were expressed as colony-forming units per 100 mL (CFU/100 mL).

For each sample, potential of hydrogen (pH), total dissolved solids (TDS), salinity, electrical conductivity (EC), and temperature of waters (T °C) were measurements in-situ using a calibrated Hanna Multiparameter HI9829-01042 (Hanna Instruments, ROMANIA). In the laboratory, dissolved oxygen (DO) was measured using the Winkler titration method (Winkler 1888) and biochemical oxygen demand (BOD_5) was determined using an Oxitop-I IS6 manometric system (Xylem Analytics, WTW) in a thermostatically controlled Oxitop Box at 20 °C, following DIN EN 1899-2, and manufacturer instructions (Xylem Analytics – WTW 2017). Nutrient (nitrite, nitrate, and phosphate) were quantified with a DR 2800 spectrophotometer (Hach Lange www.hach.com) following standard protocols.

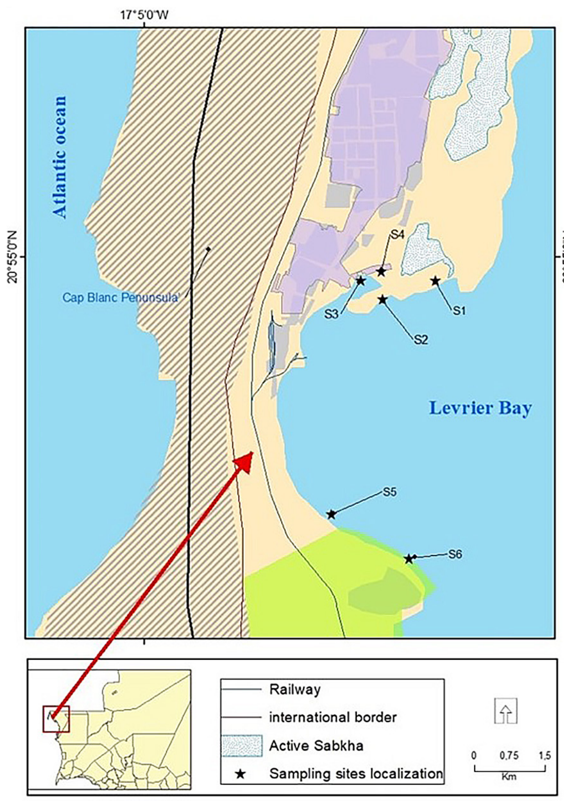

Figure 1. Geographic location of the sampling stations in Lévrier Bay

Table 1. Geographical coordinates of the sampling stations

Stations	Geographic coordinates	
S1	20°54'31"N	17°02'17"W
S2	20°54'44"N	17°01'41"W
S3	20°54'44"N	17°02'32"W
S4	20°54'50"N	17°02'18"W
S5	20°52'04"N	17°02'52"W
S6	20°51'34"N	17°01'59"W

Statistical analysis

Differences among sites were considered significant at $p < 0.05$. Principal component analysis (PCA) was applied to:

- Visualize correlations between variables and environmental gradients.
- Identify the contribution of environmental parameters t the abundance of fecal indicator bacteria.

All statistical analyses were performed using R software.

RESULTS AND DISCUSSION

Bacteriological parameters

The microbiological analysis of seawater samples collected during the cold and warm seasons revelated very high bacterial counts, indicating severe fecal contamination (Table 2). Maximum concentrations reached 8.8×10^5 CFU/100 mL for total coliforms, 8.5×10^5 CFU/100 mL for *Escherichia coli*, and 8.1 x 10^5 CFU/100 mL for fecal streptococci.

Enumeration of total coliforms indicated markedly elevated levels compared to typical coastal seawater. The highest TC concentrations were observed at stations S1, S5 and S6 reaching 8.8×10^5 and 8.1×10^5 CFU/100 mL, respectively. The lowest values were recorded at station S1 during the warm season 1.4×10^3 FCU/100 mL and at stations S3 and S4 during the cold season 5.8×10^3 and 2.5×10^4 CFU/100 mL, respectively (Figure 2). These results indicate a clear gradient of contamination from discharge points to more distant sampling locations.

Escherichia coli concentrations followed a similar spatial pattern, with the highest counts measured at stations S6 and S5 during the cold season, reaching 8.5×10^5 and 8.3×10^5 CFU/100 mL, respectively. The lowest values were detected at station S1 in the warm season 6×10^2 CFU/100 mL and at stations S3 and S4 in the cold season 8×10^2 and 1×10^3 CFU/100 mL, respectively (Figure 3). This result highlights the strong influence of untreated industrial discharges on microbial water quality.

Fecal streptococci concentrations were highest at station S6, with 8.1×10^5 CFU/100 mL in the cold season and 3.6×10^5 CFU/100 mL in the warm season. The lowest concentrations, 0.5 CFU/100 mL, were recorded at station S1 and S4 during the cold season (Figure 4). Overall, the spatial distribution of FS closely mirrored that of total coliforms and *E. coli*, confirming the substantial microbiological impact of direct discharges from fish-processing facilities on Lévrier Bay.

Determination of the source of fecal contamination

The source of fecal contamination was evaluated using the quantitative ratio R = TC/FS according to (Borrego and Romero, 1982). Based on this

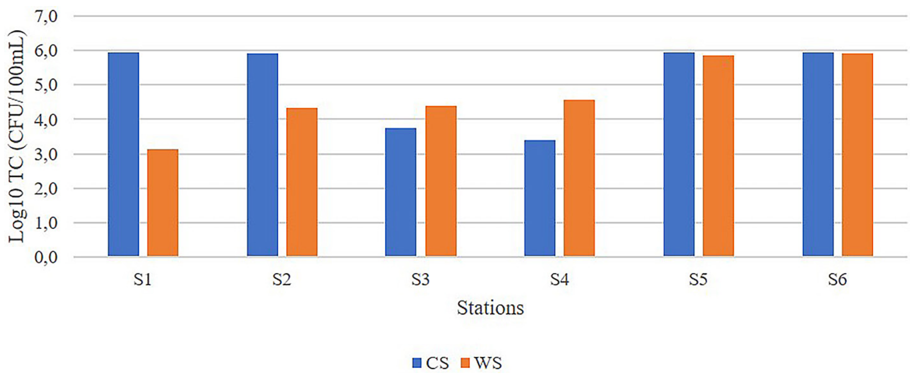

Figure 2. Log_{10} values of total coliforms in cold and warm seasons

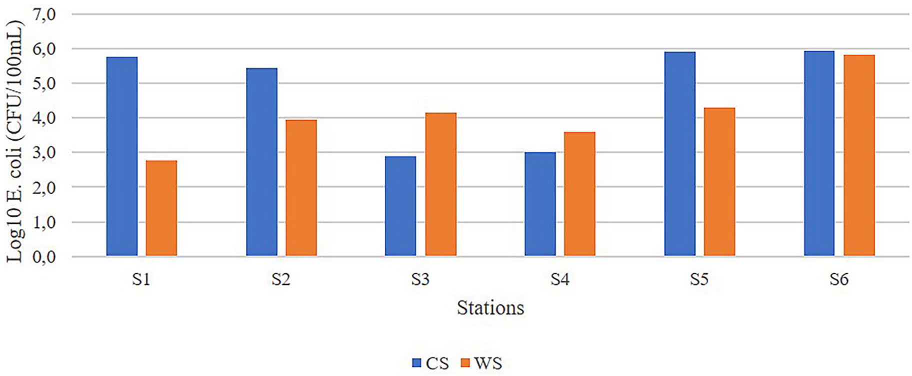

Figure 3. Log_{10} values of Escherichia coli in cold and warm seasons

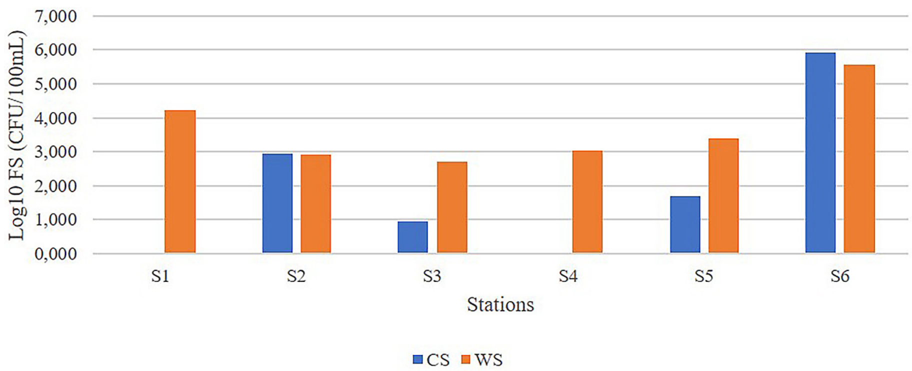

Figure 4. Log_{10} values of fecal streptococci in cold and warm seasons

Table 2. Microbiological parameters of seawater samples (CFU/100 mL)

Station	Season	TC	*E. coli*	FS
S1	Cold	8.8×10^5	5.8×10^3	0.5
S1	Warm	1.4×10^3	6×10^2	1.7×10^4
S2	Cold	8.4×10^5	2.7×10^5	900
S2	Warm	2.2×10^4	9×10^3	800
S3	Cold	5.8×10^3	800	9
S3	Warm	2.5×10^4	1.4×10^4	500
S4	Cold	2.5×10^4	1×10^3	0.5
S4	Warm	3.8×10^4	4×10^3	1100
S5	Cold	8.8×10^5	8.3×10^5	51
S5	Warm	7.3×10^5	2×10^4	2400
S6	Cold	8.0×10^5	8.5×10^5	8.1×10^5
S6	Warm	8.1×10^5	6.6×10^5	3.6×10^5

criterion, contamination is classified as primarily animal ($R < 0.7$), uncertain ($1 < R < 2$), primarily human ($2 < R < 4$), or clearly human ($R > 4$). The calculated ratios for all sampling stations (Table 3) indicate that fecal contamination in Lévrier Bay is predominantly of human origin. These findings suggest that untreated wastewater from fish processing industries represent the main source of microbial contamination in the coastal waters of the Bay.

Physicochemical parameters

Before being discharged into the natural environment, wastewater must comply with established standards to protect the receiving environment from all forms of pollution. The physicochemical characteristics of coastal seawater samples collected from Lévrier Bay are summarized in Tables 4 and 5. Table 4 presents the descriptive

Table 3. Origin of fecal contamination in seawater samples

Period	CT/SF	Origin of the contamination
S1	51.85	Human origin
S2	507.06	Human origin
S3	60.51	Human origin
S4	36.80	Human origin
S5	656.87	Human origin
S6	1.38	Human origin

statistics of the measured parameters, while Table 5 shows the spatial and seasonal variations observed at the different sampling stations during the cold and warm seasons.

Water temperatures ranged from 21.71 to 25.83 °C, remaining below 30 °C threshold commonly recommended for wastewater discharges. pH values were slightly alkaline, varying between 7.53 to 8.5. Dissolved oxygen concentrations ranged from 1.78 to 7.27 mg/L, with a median value of 2.77 mg/L. Electrical conductivity (EC) values were between 47.72 to 53.19 mS/cm, while total dissolved solids (TDS) were elevated, with a median value of 25.89 g/L. Salinity ranged from 30.43 to 35.08 PSU, with a maximum of 34.24 PSU, reflecting typical marine conditions in the study area.

Nutrients analyses revealed median concentrations of 0.884 mg/L for nitrate (NO_3^-), 0.036 mg/L for nitrite (NO_2^-) and 0.36 mg/L for phosphate (PO_4^{3-}). BOD_5 reached a maximum value of 225 mg/L, with a median of 56 mg/L, indicating significant organic loading in the coastal environment.

Microbiological parameters

The present study provides a comprehensive assessment of the microbiological and physicochemical quality of coastal waters in Lévrier Bay. Analyses revealed pronounced spatial and seasonal variations in both bacterial contamination and physicochemical parameters across sampling stations. These variations are strongly linked to the discharge of untreated effluents from fish-processing facilities along the bay, highlighting the role of anthropogenic activities in shaping water quality.

Microbiological analyses confirmed extensive fecal contamination. TC counts ranged from 5.8×10^3 to 8.8×10^5 CFU/100 mL, while *Escherichia coli* concentrations varied between 6×10^2 and 8.5×10^5 CFU/100 mL across cold and warm seasons. These consistently high levels indicate continuous microbial loading and suggest that contamination is chronic rather than episodic. Seasonal differences, including higher bacterial counts in the cold season, may reflect hydrodynamic conditions, microbial survival rates, or temporal fluctuations in industrial discharge. The persistent presence of TC and *E. coli* at these concentrations poses significant public health risks for recreational water users and local seafood consumers.

Comparable contamination patterns have been reported in other coastal environments affected by untreated industrial and domestic effluents. For instance, Libyan coastal waters exhibited elevated TC and *E. coli* concentrations under similar anthropogenic pressures (Al-Ghobeini and Murad, 2025; Ayitey et al., 2025; McLellan et al., 2024). The co-occurrence of high TC and *E. coli* counts in Lévrier Bay underscores the significant contribution of fish-processing effluents to fecal pollution. These findings reinforce the urgent need for effective wastewater treatment and management strategies to protect the ecological integrity of the bay and mitigate associated public health risks.

Table 4. Descriptive statistics of physicochemical parameters

Parameter	Minimum	Median	Maximum	±SD
pH	7.53	8.08	8.50	0.327
Dissolved oxygen (mg/L)	1.78	2.77	7.26	2.202
Conductivity (mS/cm)	47.72	51.74	53.19	1.453
TDS (g/L)	23.41	25.96	26.60	0.829
Salinity (PSU)	30.43	34.24	35.08	1.462
Temp (°C)	21.71	24.01	25.83	1.169
Phosphate (mg/L)	0.17	0.36	2.40	0.612
Nitrate (mg/L)	0.44	0.884	3.09	0.764
Nitrite (mg/L)	0.01	0.04	0.09	0.028
Biochemical oxygen demand (mg/L)	0.10	56	225	71.034

Table 5. Physicochemical parameters measured at the sampling stations during the cold and warm seasons in Lévrier Bay

Station	Season	Temp (°C)	pH	DO (mg/L)	EC (mS/cm)	TDS (g/L)	Salinity (PSU)	BOD_5 (mg/L)	NO_3^- (mg/L)	NO_2^- (mg/L)	PO_4^{3-} (mg/L)
S1	Cold	21.7	8.50	2.61	51.64	25.88	34.11	0.6	0.88	0.04	0.17
S1	Warm	24.9	8.38	6.66	52.70	26.35	34.78	84	1.77	0.03	0.40
S2	Cold	22.9	8.48	2.72	51.72	25.89	34.07	84	0.88	0.01	0.21
S2	Warm	25.11	7.53	3.34	52.56	26.33	34.68	0.5	3.09	0.06	0.64
S3	Cold	22.8	8.27	2.63	52.72	26.03	34.56	0.2	0.44	0.01	0.22
S3	Warm	25.0	7.80	6.76	51.45	25.72	33.81	56	0.88	0.04	0.52
S4	Cold	23.6	8.13	1.78	51.76	25.88	33.90	0.5	0.44	0.01	0.38
S4	Warm	25.83	8.02	6.99	52.21	26.12	34.36	0.5	1.33	0.08	0.38
S5	Cold	24.0	7.95	2.11	50.87	26.15	34.50	0.1	1.77	0.01	0.28
S5	Warm	24.0	8.16	2.83	53.19	26.60	35.08	113	0.44	0.04	0.34
S6	Cold	23.3	7.79	2.18	47.72	23.41	30.43	125	0.88	0.08	2.40
S6	Warm	24.5	7.60	7.26	50.47	25.24	31.11	56	0.88	0.09	0.18

Fecal streptococci (FS) are robust indicators of fecal contamination due to their persistence in aquatic environments. In Lévrier Bay, FS concentrations ranged from 0.5 to 8.1×10^5 CFU/100 mL across cold and warm seasons, confirming substantial fecal pollution consistent with total coliform and *E. coli* patterns. These values indicate chronic microbial contamination linked to untreated fish-processing effluents.

Similar trends have been reported in coastal studies elsewhere: for instance, in China, 41–46% of recreational water samples exceeded regulatory standards for enterococci, with higher concentrations observed nearshore and during rainfall events (Ming et al., 2020; U.S. EPA, 2012). This highlights the combined influence of anthropogenic inputs and environmental factors on microbial water quality, consistent with our observations of persistently elevated FS levels in Lévrier Bay.

The higher FS concentrations during the cold season may reflect enhanced microbial survival under lower temperatures, while lower concentrations during the warm season could result from increased microbial die-off or dilution by coastal mixing. Overall, the concurrent high counts of FS, TC, and *E. coli* indicate that untreated wastewater significantly degrades the microbiological quality of the bay, posing risks to public health and emphasizing the need for wastewater treatment prior to discharge.

Physicochemical parameters

Water temperature is an important environmental parameter influencing biological activity and chemical process in marine ecosystems. In the present study, temperatures ranged from 21.71 to 25.83 °C, reflecting typical thermal conditions of coastal waters in Mauritanian upwelling systems. The relatively small seasonal variation observed between the cold and warn periods may be related to the moderating influence of oceanic circulation in Lévrier Bay. The relatively high temperatures have already been reported in the bay and attributed at different stages of fishmeal production, including cooking, pressing, and drying (Abdel Maleck et al., 2024).

Similar temperatures have been observed in other coastal environments subject to upwelling, such as on the Moroccan coast (Rafiq et al., 2022b). Although locally elevated, the measured temperatures remain below the critical threshold of 30 °C set for coastal waters and can be compared to those reported by (Ndiaye et al., 2025) during the same period.

The pH levels recorded in this study were slightly alkaline, ranged from 7.53–8.5, wish is consistent with the neutral pH range observed in marine waters. Such values are typical of coastal ecosystems where seawater buffering capacity regulates pH fluctuations. However, slight decreases in pH at certain stations located near discharge points may reflect localized inputs of organic matter associated with industrial effluents from fish-processing activities.

Similar pH ranges have been reported in Dakhla Bay (7.8–8.3) by (Anhichem and Benbrahim, 2020a). According to (Chaouay et al., 2016), pH influences metal solubility, water alkalinity, and microbial metabolism, and therefore significantly affects seawater quality. In addition, photosynthetic activity by phytoplankton and algae may increase pH through the uptake of dissolved carbon dioxide (Gandaseca et al., 2011).

Overall, the pH values measured for the physiological functioning of plants and multicellular animals in coastal waters, suggesting that the coastal waters of Lévrier Bay are not currently affected by significant acidification processes (Gandaseca et al., 2011).

Dissolved oxygen is essential for the physiological functioning of aquatic organisms and plays a key role in the biogeochemical cycling of organic matter and nutrients in coastal ecosystems (Testa and Malkin, 2024). When DO concentrations fall below 4–5 mg/L, aquatic organisms may experience physiological stress (Dey, 2017).

In the present study, DO concentrations varied considerably among sampling stations, ranging from 1.78 mg/L at station S4 during the cold season to 7.26 mg/L at station S6 during the warm season. The lowest values were recorded near wastewater discharge areas, suggesting increased oxygen consumption linked to microbial degradation of organic matter. This decrease is directly linked to the high organic load of wastewater, which enhances microbial respiration and increases oxygen consumption. Such reductions in DO are commonly associated with elevated organic loading and may indicate the onset of localized eutrophication. Under the hypoxic conditions, sensitive fish species may experience physiological stress, potentially leading to abnormal behavior, mortality, or occasional stranding events in shallow coastal areas.

Electrical conductivity reflects the ability of dissolved salts and other inorganic substances present in water to conduct an electrical current. In the marine environments, average conductivity values generally range between 24 and 47.6 mS/cm (Rafiq et al., 2022a). In this study, the measured values ranged from 47.72 recorded at station 6 to 53.19 mS/cm at station 5, with a median of 51.74 mS/cm. Compared to other coastal ecosystems, such as Agadir Bay, where a conductivity of 55.4 mS/cm has been reported (Chaouay et al., 2016), the obtained results are of the same order of magnitude. This elevated conductivity reading suggest significant salinity and reflects the excellent conductivity of the waters in this study area.

Salinity is a fundamental parameter of the marine environment, reflecting the concentration of dissolved salts, mainly sodium chloride, in seawater. It plays an important role in many oceanographic processes, including stratification, water mass circulation, and the distribution and dynamics of biological communities (Pawlowicz, 2017). During the present study, salinity showed moderate variability, ranging from 30.43 to 35.08 PSU observed at stations 6 and 5 respectively. They indicate relative stability in the salinity regime, despite the proximity of industrial fish production and processing units. The relativity stable salinity conditions may also be influenced by regional oceanographic processes, particularly the coastal upwelling system that characterizes the Mauritanian shelf. Moreover, Comparable salinities have already been reported in the bay, particularly during episodes of harmful algal blooms (Ndiaye et al., 2025), suggesting that these saline conditions could be a permissive factor in the development of such events. in these places.

TDS represent the overall concentration of dissolved substances in water and constitute an important parameter for assessing water quality (Ferdous et al., 2019). In the present study, TDS values ranged from 23.41–26.6 g/L at stations 6 and 5 respectively, wish in consistent with the mineral content typically observed in marine environments. These concentrations reflect the naturally high ionic composition of seawater, primarily controlled by dissolved salts such as sodium, chloride and sulfate (Reddy et al., 2020). The relatively limited spatial variation in TDS observed among sampling sites suggests that local industrial discharges did not significantly alter the mineral composition of the coastal waters. This contrasts with the pronounced variability observed for dissolved oxygen and organic parameters, indicating that the impact of anthropogenic activities in the study area is primarily reflected in biological and organic pollution rather than in the mineral load of the water.

Nutrient concentrations and biochemical oxygen demand provide valuable information on the degree of organic enrichment and anthropogenic influence in coastal environments. In the nitrogen cycle, nitrite is a phase that lies in between nitrate and ammoniacal nitrogen, which generally explains its low concentration in aquatic environments (Aydın, 2013). In the present study, nitrite concentrations varied between 0.01–0.09 mg/L at station 3 and 6 respectively. Although levels remain low overall, the maximum value recorded could reflect increased bacterial activity or incomplete nitrification, possibly induced by organic inputs, particularly those from fish processing plant discharges. A similar situation has been reported in Taza, Morocco, where elevated nitrite concentrations in surface waters have been correlated with recent contamination, depletion of dissolved oxygen and reduction of nitrates by organic matter (Abouabdallah et al., 2023).

The presence of nitrates in water can indicate a recovery process following organic pollution, as they represent the end product of nitrogen oxidation. This transformation is generally carried out by nitrifying bacteria, which play an essential role in the biological treatment of nitrogen-enriched water (Sanoja-López et al., 2025). During our study, nitrate concentrations ranged from 0.44 to 3,09 mg/L. The highest values could reflect the influence of industrial discharges, particularly those from fish processing plants, which are rich in nitrogenous organic matter. In coastal environments, such concentrations may also result from the nitrification of ammonium from these discharges. This implies that the environment was enriched with organic matter at the sites where the highest values were recorded. This organic matter is progressively converted to nitrite and eventually nitrate in the presence of dissolved oxygen and nitrifying bacteria. This situation is probably linked to continuous wastewater inputs, as observed in the coastal waters of Dakhla, Morocco (Anhichem and Benbrahim, 2020b).

Phosphates, mainly originate from urban and domestic sources. They are generally the limiting factor in eutrophication processes, as their concentration directly influences the primary productivity of the environment (Cramer, 2010). In combination with nitrates, their excessive presence can stimulate phytoplankton blooms, leading to eutrophication and subsequent oxygen depletion. Phosphate concentration showed a wider variability, reaching a maximum of 2.4 mg/L at station S6 during the cold season. Elevated nutrient concentrations in coastal waters are commonly associated with inputs of organic matter and nutrient-rich effluents from industrial activities related to fish processing, as well as untreated domestic discharges. Similar observations have been reported in Dakhla Bay, where elevated phosphate levels have been linked to significant anthropogenic pressure (Anhichem and Benbrahim, 2020b). In Lévrier Bay, the observed nutrient enrichment is likely related to the discharge of untreated wastewater from fish-processing industries located along the coastline. These industrial activities generate large quantities of organic residues and nutrient-rich effluents that can significantly alter the chemical composition of receiving waters. Similar increases in nitrate and phosphate concentrations have been reported in coastal environments affected by seafood-processing industries and urban wastewater discharges.

Biochamical oxygen demand (BOD_5) reflects the amount of oxygen required for microbial decomposition of biodegradable organic matter in water (Boughou et al., 2018). In the present study, BOD_5 values showed substantial variability, ranging from (0.1–225 mg/L), with median of 56 mg/L. Such elevated levels indicate a significant input of biodegradable organic matter into the coastal waters. The highest values were observed at stations located near discharge points, particularity S5 and S6, suggesting strong influence of industrial effluents. High BOD_5 levels are commonly associated with wastewater rich in organic residues, which enhances microbial activity and increases oxygen consumption in aquatic environments. Such conditions may lead to hypoxia or anoxia, causing stress or mortality in aquatic organisms and disrupting ecological balance. Although these values remain lower than those previously reported in the bay (Abdel Maleck et al., 2024), they largely exceed typical thresholds for natural waters and may lead to oxygen depletion and ecological disturbances if such inputs persist (Penn et al., 2009).

Multivariate analysis of physicochemical and microbiological parameters

Following the detailed discussion of the microbiological results which appear too elevated, it is crucial to explore how these microbial indicators are related to the measured physicochemical parameters. Multivariate statistical analysis, such as PCA, provides a comprehensive overview of the complex interactions among these variables, highlighting the main environmental factors influencing water quality in Lévrier Bay. This statistical approach acts as a bridge between the microbiological and physicochemical data, revealing correlations and dissociations between the different parameters.

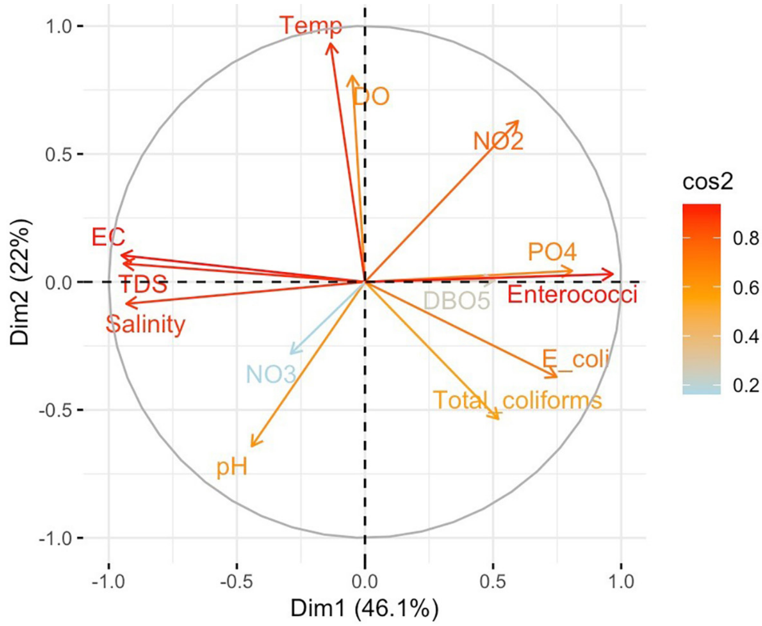

Figure 5. Principal component analysis of microbiological and physicochemical parameters in Lévrier Bay

Table 6. Pearson correlation coefficients between microbiological and physicochemical parameters in Lévrier Bay

Variables	pH	DO	EC	TDS	Salinity	Temp	PO4	NO3	NO2	DBO5	TC	*E. coli*	FS
pH	1	0.93*	0.88*	0.85*	0.91*	-0.63*	-0.71*	-0.04	-0.69*	-0.78*	-0.78*	-0.79*	-0.76*
DO		1	0.83*	0.85*	0.84*	-0.66*	-0.71*	-0.05	-0.70*	-0.82*	-0.78*	-0.78*	-0.75*
EC			1	0.98*	0.91*	-0.54	-0.58*	-0.12	-0.51	-0.60*	-0.70*	-0.69*	-0.66*
TDS				1	0.90*	-0.49	-0.53*	-0.10	-0.52	-0.62*	-0.71*	-0.70*	-0.67*
Salinity					1	-0.62*	-0.67*	-0.04	-0.66*	-0.75*	-0.75*	-0.74*	-0.71*
Temp						1	0.71*	0.01	0.67*	0.74*	0.74*	0.74*	0.73*
PO4							1	0.11	0.85*	0.92*	0.93*	0.90*	0.87*
NO3								1	-0.10	-0.03	0.03	0.01	0.03
NO2									1	0.86*	0.87*	0.82*	0.80*
DBO5										1	0.96*	0.92*	0.89*
TC											1	0.99*	0.91*
E. coli												1	0.89*
FS													1

Note: * In bold the correlation is significant at 0.05.

The PCA (Figure 5) demonstrates a clear grouping of variables along the first principal component, which clusters microbial indicators together with organic pollution markers such as biochemical oxygen demand (BOD_5), phosphates, and nitrites – reflecting the substantial organic and fecal load from untreated effluents.

Conversely, parameters related to water mineralization, including electrical conductivity, TDS, and salinity, are strongly correlated with each other but negatively correlated with microbial contamination indicators. This suggests that microbial pollution is not necessarily accompanied by increased mineral load. The second principal component highlights seasonal or hydrological variations, where temperature and dissolved oxygen co-vary, while nutrients and pH show more complex relationships.

These observations are reinforced by the correlation matrix (Table 6), which shows statistically significant ($p < 0.05$) positive correlations between organic and microbiological pollution parameters, alongside negative correlations with mineral-related variables and salinity.

CONCLUSIONS

This study provides an integrated assessment of the impacts of untreated industrial wastewater from fish processing plants on Lévrier Bay. Microbiological analyses revealed consistently elevated fecal contamination, with total coliforms reaching 8.8 × 10^5 CFU/100 mL, Escherichia coli up to 8.5 × 10^5 CFU/100 mL, and fecal streptococci up to 8.1 × 10^5 CFU/100 mL, indicating chronic microbial pressure on the coastal environment. Physicochemical parameters largely remained within natural coastal thresholds, pH (7.53–8.5), salinity (30.43–35.08 PSU), and temperature (21.71–25.83 °C) but localized elevated BOD_5 (up to 225 mg/L) and phosphate concentrations (up to 2.4 mg/L), combined with low dissolved oxygen (as low as 1.78 mg/l), indicate localized hypoxia and organic enrichment. These finding highlight that effluents impose both biological and chemical stress on the bay, exceeding the ecosystem's self-purification capacity. The integrated analysis of microbiological and physicochemical indicators demonstrates a clear linkage between industrial discharges and ecosystem degradation. Continuous inputs of microbial and nutrients contaminants threaten water quality, aquatic life, and public health. To reduce coastal water pollution in Lévrier Bay, it is essential to implement wastewater treatment systems tailored to remove organic and microbial loads, enforce stricter environmental regulations for industrial discharges, and establish continuous environmental monitoring programs to track water quality and detect early signs of contamination. Proactive management of these measures will help preserve the bay's ecological integrity and maintain its role as a productive marine ecosystem.

Acknowledgements

We intend to express our gratitude to Dr. Aly Yahya Dartige, Director General of ONISPA, for his unwavering support throughout the development and completion of this work. We also thank Dr. Moulaye Mohamed Wagne, Head of the LEMMC at IMROP in Nouadhibou, for his technical assistance.

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