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Assessment of Sediment Quality in the Sangomar Marine Protected Area in Senegal Prior to Oil Development

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Abstract

As Senegal embarks on the development of offshore oil resources, there is increasing concern regarding the potential environmental impacts on the adjacent sensitive coastal ecosystems. This study provides a critical baseline assessment of sediment contamination within the Sangomar Marine Protected Area (MPA), focusing specifically on the presence of heavy metals cadmium (Cd), lead (Pb), and mercury (Hg), and polycyclic aromatic hydrocarbons (PAHs), both known for their persistence and toxicity in marine environments. The investigation revealed that most contaminant concentrations remain below internationally recognized ecotoxicological thresholds, suggesting an overall low level of pollution in the area. However, a significant exception was identified at the Bakina station during the 2024 dry season, where cadmium concentrations reached a concerning hotspot value of 37.23 mg/kg, indicating localized pollution that may pose ecological risks. The PAHs contamination profile was dominated by 3- and 4-ring compounds such as fluoranthene, phenanthrene, and anthracene, consistent with pyrogenic sources likely stemming from atmospheric deposition of incomplete combustion products. While the Pollution Load Index (PLI) values generally indicate low to moderate contamination levels, the detection of localized contamination peaks highlights the vulnerability of the MPA, especially given the influence of seasonal hydrodynamics such as upwelling and the proximity of ongoing oil extraction activities. These findings underscore the urgent need for the establishment of comprehensive, long-term, and high-resolution environmental monitoring programs. Such initiatives will be essential to detect early signs of ecological degradation, support adaptive management, and safeguard the rich biodiversity and ecosystem services provided by this critical marine conservation area.

Keywords

HAPs, Heavy Metals, Marine Protected Area, Sediment, Sangomar, Senegal

1. Introduction

Coastal marine ecosystems are areas of high ecological productivity, playing a key role in regulating biogeochemical cycles, supporting biodiversity, and maintaining essential ecosystem services for human societies [1] [2]. Marine sediments are not inert substrates. They host a diverse benthic fauna, ensure nutrient recycling and serve as refuges or spawning grounds for numerous fish species [3] [4]. However, their ability to trap organic and metallic contaminants also makes them potential long-term reservoirs of pollution [5] [6]. Since the discovery in 2014 of the offshore Sangomar oil field, located off the Senegalese coast, a new economic era has opened for the country, with the imminent start of oil exploitation activities scheduled for 2024-2025 [7]. While this prospect shows promise in terms of energy production, there are growing concerns about the preservation of the marine environment, particularly in the Sangomar Marine Protected Area (MPA), which is located directly adjacent to the exploration zone. It is an established fact that offshore oil activities have always been associated with a risk of chronic or accidental pollution. This is especially true when it comes to polycyclic aromatic hydrocarbons (PAHs) and heavy metals such as lead, cadmium, and mercury [8] [9]. PAHs are hydrophobic organic compounds derived from the incomplete combustion of organic matter or petroleum-related activities. Due to their low solubility and strong affinity for organic matter, they have a tendency to accumulate in sediments, where they can persist for extended periods of time [10]. Sediments therefore function as repositories, records and potential sources of PAHs. In the event of physical or chemical disturbances, these compounds may be mobilised into the water column. The toxic effects of PAHs on marine fauna are well documented. These include embryonic developmental disorders, genetic alterations (genotoxicity), immunosuppression, and carcinogenic effects [11]-[14]. Similarly, the presence of heavy metals in the environment is a major concern, due to their ability to bioaccumulate along the food chain. Once absorbed by marine organisms, these metals have been found to disrupt enzymatic processes, induce oxidative stress, and lead to neurotoxic, reproductive, and immunological disorders [15] [16]. Even at low concentrations, they pose a chronic threat to marine biodiversity and the ecological balance of coastal ecosystems. In this context, it is both timely and essential to establish a baseline assessment of sediment contamination in the Sangomar MPA. An evaluation of this kind will allow us to establish current levels of pollutants, especially PAHs and heavy metals, prior to the commencement of offshore oil exploitation. This approach is crucial for distinguishing between pre-existing contamination (natural or anthropogenic) and future impacts directly linked to industrial activities. The findings of this study will therefore contribute to the

development of a robust environmental monitoring system, capable of detecting temporal variations in contamination and supporting the implementation of effective mitigation strategies. The work's primary objective is to underpin sustainable management policies that strike a balance between economic development and the preservation of ecologically sensitive marine environments.

2. Materials and Methods

2.1. Study Area and Sampling Sites

The Sangomar Marine Protected Area (MPA) is located in the heart of the Saloum Delta Biosphere Reserve, a UNESCO World Heritage Site since 2011 due to its outstanding ecological and cultural value [17]. It spans the territories of the municipalities of Palmarin and Dionewar, in the Fatick region of Senegal. Officially established by Decree No. 2014-338 on March 25, 2014, the MPA of Sangomar was created through a participatory process involving strong engagement from local communities. It covers a surface area of 87,437 hectares (Figure 1), making it one of the largest marine protected areas in the country [18]. This protected area is notable for its exceptional biodiversity. It provides habitat for several iconic and threatened species such as marine turtles (Chelonia mydas, Lepidochelys olivacea), coastal dolphins (Sousa teuszii), West African manatees (Trichechus

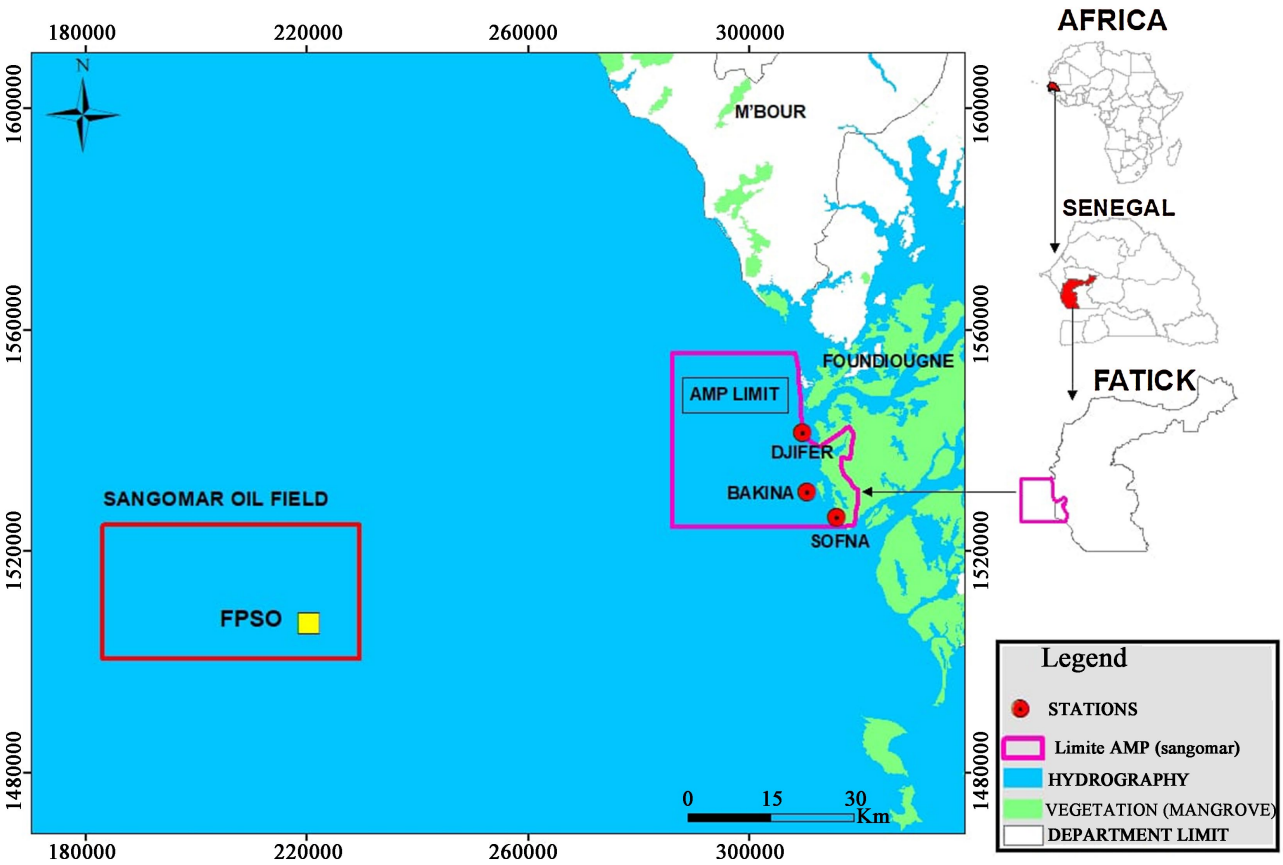

Figure 1. Location of the Sangomar Marine Protected Area and the sampling stations.

senegalensis), as well as a wide range of waterbirds. Over 90 species of fish have also been recorded in the area, underscoring its remarkable fisheries richness [19]. The ecosystems within this MPA are equally diverse, comprising mangroves, seagrass beds, mudflats, tidal channels, and relic forests. Together, they form a highly productive yet fragile ecological mosaic [20].

2.2. Sampling

Sediment samples were collected from three key stations within the Sangomar Marine Protected Area (MPA): Bakina, Djiffer, and Sofna. These sites were selected based on their accessibility and ecological significance within the MPA (**Figure 1**). In fact, they represent the main fishing grounds in the area. Sampling was conducted at low tide during both the dry and rainy seasons of 2023 and 2024, using a Van Veen grab sampler. Immediately after collection, samples were placed in coolers with ice to preserve their physicochemical integrity. They were then transported to the laboratory for further analysis.

2.3. Chemical Analysis

2.3.1. Heavy Metals

For the calibration of the atomic absorption spectrometer (AAS110), analytical standards of Pb, Cd, and Hg were used. For each sample, 0.5 g of dry sediment was digested with 15 mL of 65% nitric acid, 3 mL of hydrochloric acid, and 0.5 mL of perchloric acid in Pyrex graduated flasks, to which 6 mL of 1% nitric acid was also added. The resulting solution was diluted and adjusted to 50 mL with 0.1 N acidified water, and metal concentrations were measured using graphite furnace atomic absorption spectrometry (AAS110). Mercury (Hg) was quantified using cold vapor atomic absorption spectrometry (CV-AAS). Calibration standards were prepared for each element to ensure instrument accuracy. A spiked sample was used to calculate the recovery rate of each metal, with the spiking concentration falling within the calibration range. All concentrations are reported in mg/kg dry weight. The limits of quantification (LOQ) for Pb, Cd, and Hg were 0.05, 0.005, and 0.01 mg/kg, respectively.

2.3.2. PAHS

For the analysis of priority PAHs defined by the USEPA, a modified QUECHERS extraction method (AOAC protocol) was used, following the procedure described by Pule *et al.* (2012). Extracts were analyzed using gas chromatography coupled with mass spectrometry (GC/MS) on a Varian model 1200 system. The chromatographic column used was a DB-5MS (30 m × 0.25 mm × 0.25 µm). Injections were performed in splitless mode, with a volume of 1 µL. The injector and source temperatures were set at 295˚C and 280˚C, respectively. Scanning was performed over a mass range of 50 - 500 m/z. Helium was used as the carrier gas at a constant flow rate of 1 mL/min. PAH quantification was performed using the Selected Reaction Monitoring (SRM) method. All reagents and standards were supplied by Sigma-Aldrich.

2.3.3. Quality Assurance and Quality Control

A rigorous quality assurance and control protocol was implemented for both PAHs and heavy metals. For PAHs, three test samples were obtained from a homogenized reference sample to verify measurement accuracy. One of these samples was spiked with 1 µL of a 2000 µg/mL PAH standard mix, representing the 16 priority PAHs defined by the USEPA, while the other two were left unspiked. This allowed the calculation of recovery rates. The detection limit (LOD) for PAHs was set at 40 ng/g dry weight. For trace metals, a multi-element calibration was performed using mono-elemental standard solutions (SCP Sciences). To ensure instrument stability and analytical precision, standards were injected after every third sample.

2.4. Pollution Indices

In this study, three commonly used indices were applied to assess the degree of sediment contamination: the Contamination Factor (CF), the Pollution Load Index (PLI), and the Geoaccumulation Index (Igeo).

2.4.1. Contamination Factor (CF)

This index assesses the contamination level of a specific element by comparing its measured concentration in the sediment to a natural or background reference value. It provides a direct estimate of the extent to which sediments have been enriched by a particular contaminant [21]. For this study, the background values used are 100 mg/kg for lead (Pb), 2 mg/kg for cadmium (Cd), and 1 mg/kg for mercury (Hg). These values allow for the interpretation of contamination levels according to the following classification: CF < 1 indicates low contamination; 1 ≤ CF < 3, moderate contamination; 3 ≤ CF < 6, considerable contamination; and CF ≥ 6, very high contamination (Recommendations concerning work and operations involving potentially contaminated aquatic sediments - V2 - 06/2013 - Annexes).

$$\mathrm{FC} = \frac{\text{concentration of the trace element in the sediment}}{\text{concentration of references}} \tag{1}$$

2.4.2. Pollution Load Index (PLI)

The Pollution Load Index provides a synthetic measure of sediment quality by integrating the contamination factors (CF) of multiple metals. It offers an overall view of contamination levels and allows for comparisons between different sites [22] [23]. A PLI value greater than 1 indicates overall sediment pollution, whereas a value below 1 suggests that the site is unpolluted.

$$\mathrm{PLI} = \left(CF_1 \times CF_2 \times CF_3 \times \cdots \times CF_n\right)^{\frac{1}{n}} \tag{2}$$

2.4.3. Geoaccumulation Index (Igeo)

The Geoaccumulation Index (Igeo) is used to assess the degree of heavy metal enrichment in sediments, while accounting for natural variations in background concentrations [24]. This index distinguishes between natural geogenic inputs

and anthropogenic contamination. It is calculated by comparing measured concentrations with background values, typically derived from pre-industrial sediments or established geochemical reference baselines. The use of threshold values from the Environmental Protection Agency (USEPA) ensures a rigorous and standardized pollution assessment [25] [26]. The Igeo is calculated using the following formula:

$$\text{Igéo} = \log 2\left(\frac{C_n}{1.5B_n}\right) \tag{3}$$

where, C_n is the measured concentration of element n, B_n is the background concentration of the same element, and 1.5 is a constant correction factor accounting for natural background matrix variability.

3. Results

3.1. Heavy Metal Concentrations in Sediments

Lead concentrations were generally low throughout the study period (**Figure 2**), compared to the reference values provided in the Recommendations concerning works and operations involving potentially contaminated aquatic sediments - V2 - 06/2013 - Annexes. During the 2023 dry season, no detectable levels of lead

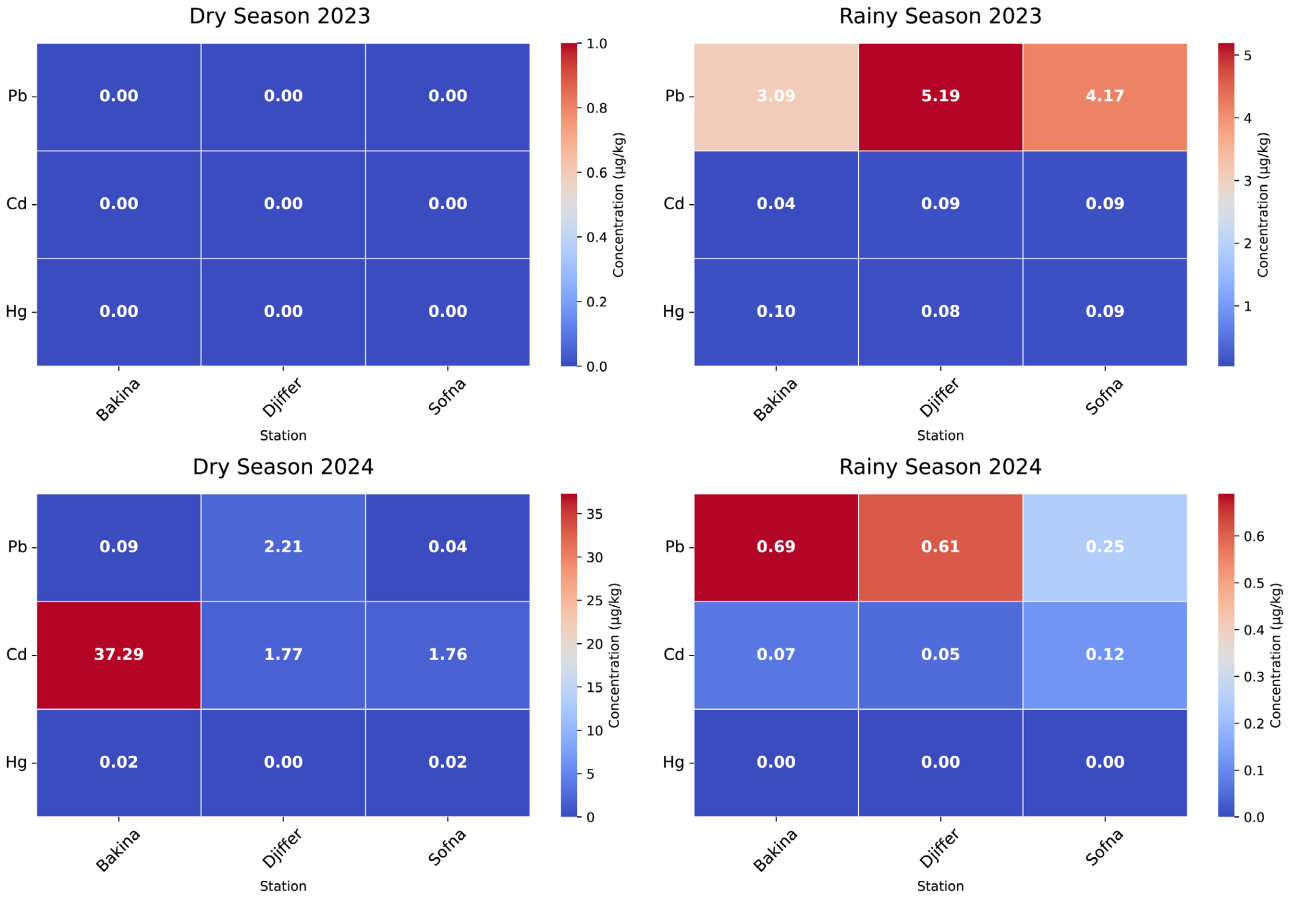

Figure 2. Spatio-temporal variations in Pb, Cd, and Hg concentrations in sediments within the Sangomar MPA.

were measured at any of the three stations. In contrast, during the rainy season of the same year, moderate levels were recorded, ranging from 3.09 mg/kg at Sofna to 5.19 mg/kg at Bakina, indicating relatively uniform but limited contamination. In 2024, concentrations measured during the dry season ranged from 0.04 mg/kg at Sofna to 2.21 mg/kg at Djiffer, reflecting a significant decrease compared to the previous year. This downward trend continued during the 2024 rainy season, with concentrations ranging from 0.25 mg/kg at Sofna to 0.62 mg/kg at Bakina, while Djiffer recorded a value of 0.09 mg/kg. Cadmium exhibited marked variability, particularly in 2024. In 2023, no detectable concentrations were observed during the dry season, and levels recorded during the rainy season remained very low, ranging from 0.023 mg/kg at Djiffer to 0.09 mg/kg at Bakina. In contrast, a dramatic increase was observed in the dry season of 2024, with a maximum value reaching 37.23 mg/kg at Bakina, suggesting severe localized pollution. At Djiffer and Sofna, concentrations remained more moderate, at 1.77 mg/kg and 1.76 mg/kg, respectively. The rainy season of 2024 showed a clear decrease in cadmium levels, ranging from 0.012 mg/kg at Sofna to 0.069 mg/kg at Bakina. This decline could be attributed to the dilution effect of freshwater inputs during the rainy season, combined with potential transport or dispersion of contaminants. Mercury concentrations remained low and relatively stable across all sampling campaigns. Values ranged between 0 and 0.1 mg/kg, with no significant variation between seasons or stations, indicating a low and consistent level of contamination—likely stemming from diffuse sources and only minimally influenced by seasonal hydrological changes.

3.2. Assessment of Heavy Metal Pollution Levels

3.2.1. Contamination Factor and Pollution Load Index

The results indicate low to moderate levels of contamination, with the exception of a localized cadmium pollution peak (**Figure 3**). Lead (Pb) showed very low contamination factors (CF) across all stations, ranging from 0.01 to 0.03, indicating no significant contamination. The same applies to mercury, whose CF values were also very low (between 0.02 and 0.03), suggesting a negligible presence in

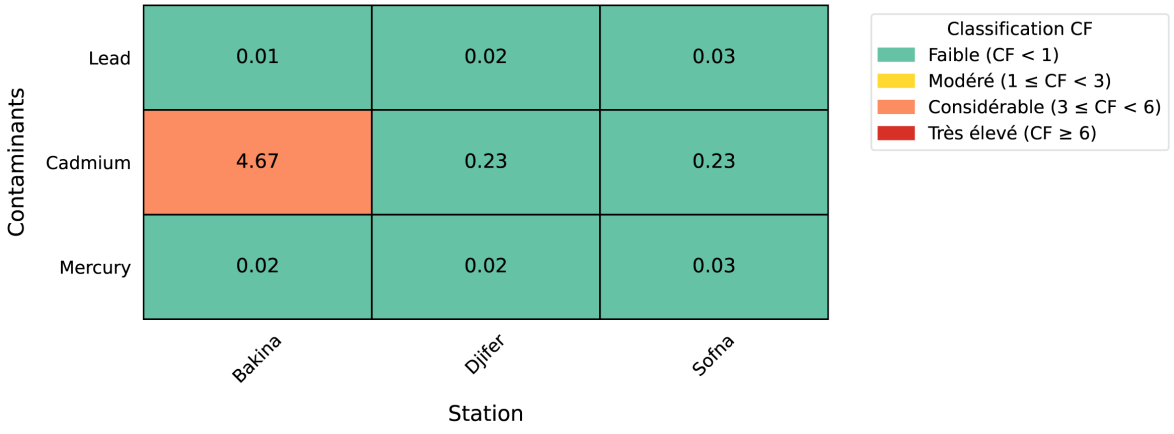

Figure 3. Spatial distribution of the contamination factor within the Sangomar MPA.

the sediments. In contrast, cadmium (Cd) displayed a concerning level at the Bakina station, with a CF reaching 4.67. This value stands in stark contrast to those observed at Djiffer and Sofna, where Cd CFs remained below 0.23.

The Pollution Load Index (PLI), calculated for the stations of Bakina, Sofna, and Djiffer (see Table 1), yielded respective values of 0.03 for Bakina, and 0.01 for both Sofna and Djiffer. All these values are well below the critical threshold of 1 (PLI < 1), indicating no significant overall pollution at the studied sites. Nevertheless, the Bakina station stands out with a slightly higher PLI compared to the other two sites, suggesting a more pronounced influence of contaminants, particularly cadmium, as revealed by the contamination factor analysis. Table 2: Pollution Load Index (PLI) calculated at each sampling station.

3.2.2. Assessment of Pollution Degree Using the Geoaccumulation Index

Analysis of the geoaccumulation index (Igeo) values reveals spatial heterogeneity in metal pollution (Figure 4 and Table 2). Contamination levels vary depending on both the sampling station and the specific trace metal considered. At Bakina, the Igeo for cadmium reaches 1.3, corresponding to a moderate pollution level. In contrast, the indices calculated for lead (Igeo = −16.5) and mercury (Igeo = −3.8) indicate no pollution, as the measured concentrations are well below geochemical background values. At Sofna, Igeo values are −0.6 for mercury, −4.7 for cadmium, and −12.7 for lead, also reflecting an absence of contamination for all analyzed metals. Similarly, at Djiffer, the indices are −3.7 for mercury, −7.6 for cadmium, and −19.3 for lead, confirming a non-contaminated state at this station. Overall, the results indicate an absence of lead (Pb) contamination across all stations, as evidenced by the strongly negative Igeo values. Cadmium (Cd) shows

Table 1. Pollution Load Index (PLI) calculated at each sampling station.

	Stations		
	Bakina	Sofna	Djiffer
PLI	0.03	0.01	0.01

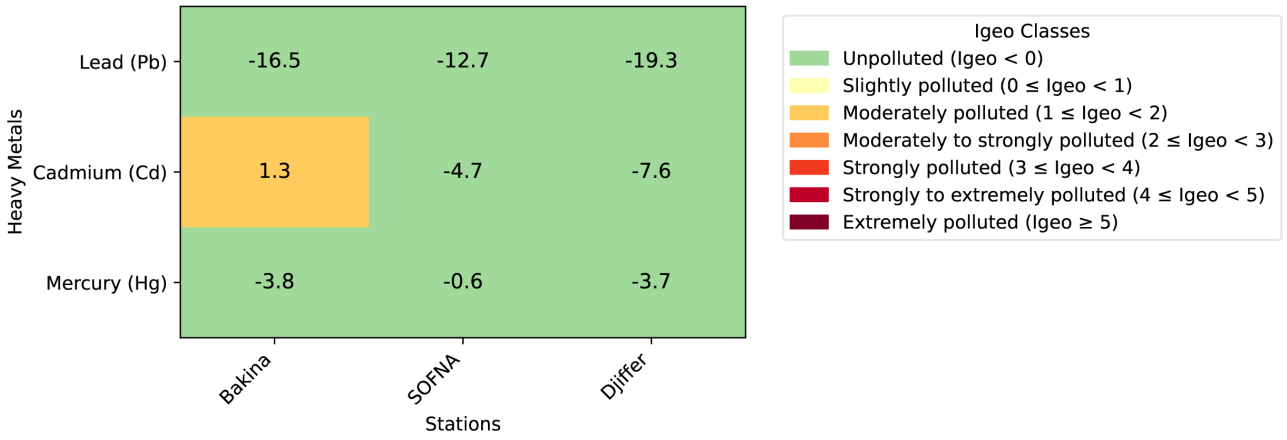

Figure 4. Spatial distribution of geoaccumulation index within Sangomar MPA.

Table 2. Müller's classification for the geoaccumulation index (Müller, 1981).

Class	Value	Pollution Intensity
0	Igeo ≤ 0	Unpolluted
1	0 < Igeo < 1	Unpolluted to moderately polluted
2	1 < Igeo < 2	Moderately polluted
3	2 < Igeo < 3	Moderately to heavily polluted
4	3 < Igeo < 4	Heavily polluted
5	4 < Igeo < 5	Heavily to very heavily polluted
6	Igeo > 5	Very heavily polluted

moderate contamination limited to the Bakina station, while the Sofna and Djiffer stations display no signs of pollution. Regarding mercury (Hg), negligible contamination is observed at Bakina and Djiffer, whereas the Sofna station exhibits an Igeo of −0.6, corresponding to the "uncontaminated to slightly contaminated" category according to Müller's classification.

3.3. PAHs Concentrations in Sediments

Analysis of PAH concentrations in sediments from the Bakina, Djiffer, and Sofna stations for the years 2023 and 2024 revealed significant spatiotemporal variations in both molecular profiles and contamination intensity (**Figure 5**). During the 2023 dry season, all three stations exhibited marked contamination dominated by fluoranthene, with concentrations reaching 966 µg/kg at Sofna, 938 µg/kg at Djiffer, and 898 µg/kg at Bakina. Phenanthrene was also detected but at considerably lower concentrations (12 to 18 µg/kg). No other PAHs were quantified during this period. In the 2023 rainy season, a notable shift in the PAH profile was observed. At Bakina, fluorene became the predominant compound (71.2 µg/kg), accompanied by trace amounts of phenanthrene (4 µg/kg). At Djiffer, only fluorene was detected at very low concentrations (1.1 µg/kg), while no PAHs were quantified at Sofna. The 2024 dry season was characterized by a general decrease in PAH concentrations compared to the previous year. At Bakina and Djiffer, only low amounts of phenanthrene (3.12 - 3.36 µg/kg) and anthracene (6.23 - 6.71 µg/kg) were detected. No PAHs were identified at the Sofna station. During the 2024 rainy season, the contamination profile was dominated by phenanthrene and anthracene. Bakina recorded the highest concentrations (8 µg/kg for each compound), whereas Djiffer and Sofna exhibited more modest levels, ranging from 4 to 6 µg/kg. It is noteworthy that fluoranthene, which was abundant in 2023, was completely absent in 2024.

Assessment of PAHs pollution levels

The contamination factors (CF) calculated for PAHs in the sediments of Bakina, Sofna, and Djiffer reveal notable spatiotemporal variations depending on the compounds and seasons (**Figure 6**). During the dry season, fluoranthene concentrations

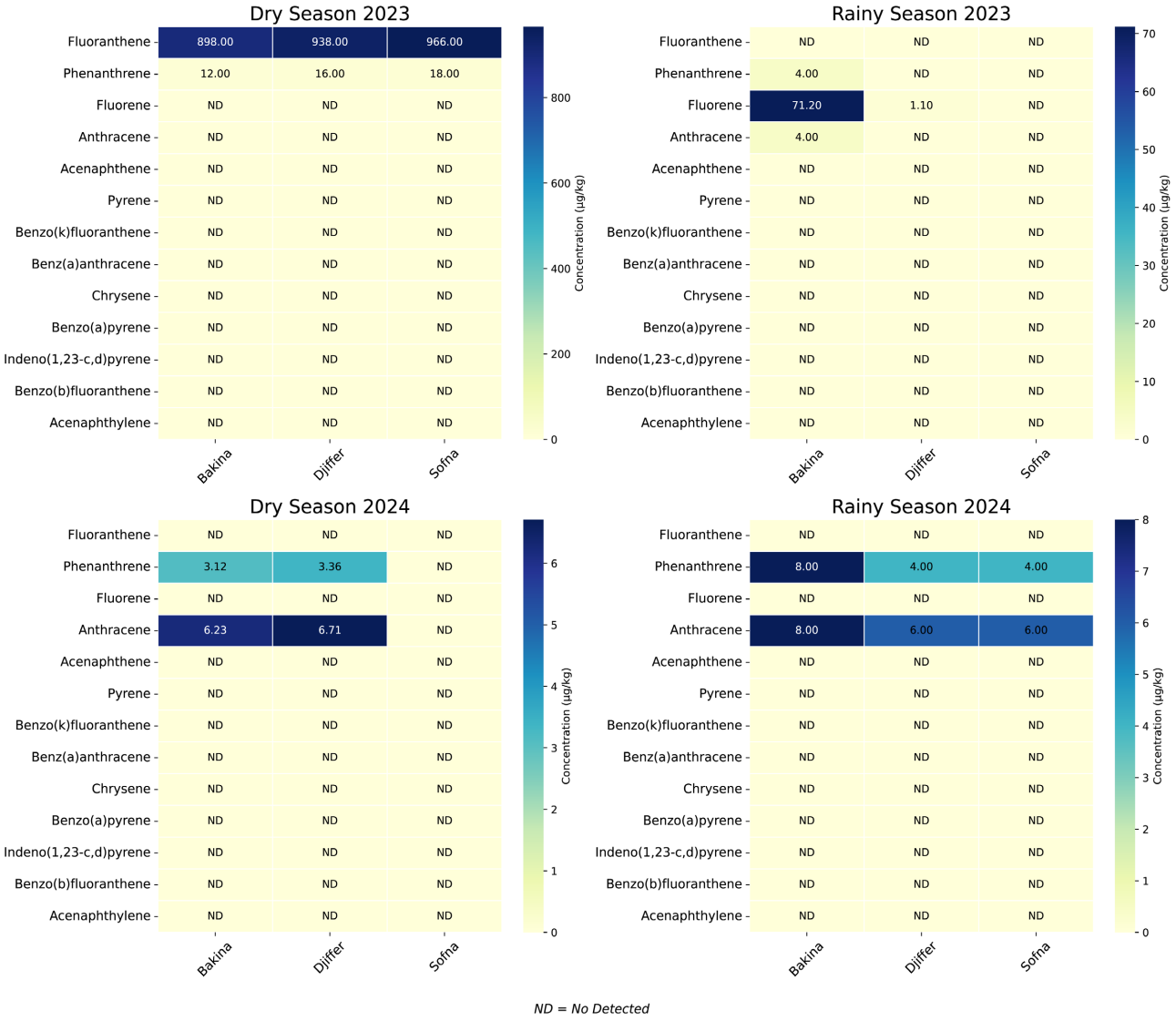

Figure 5. Spatio-temporal variations of HAPs concentrations in sediments within Sangomar MPA.

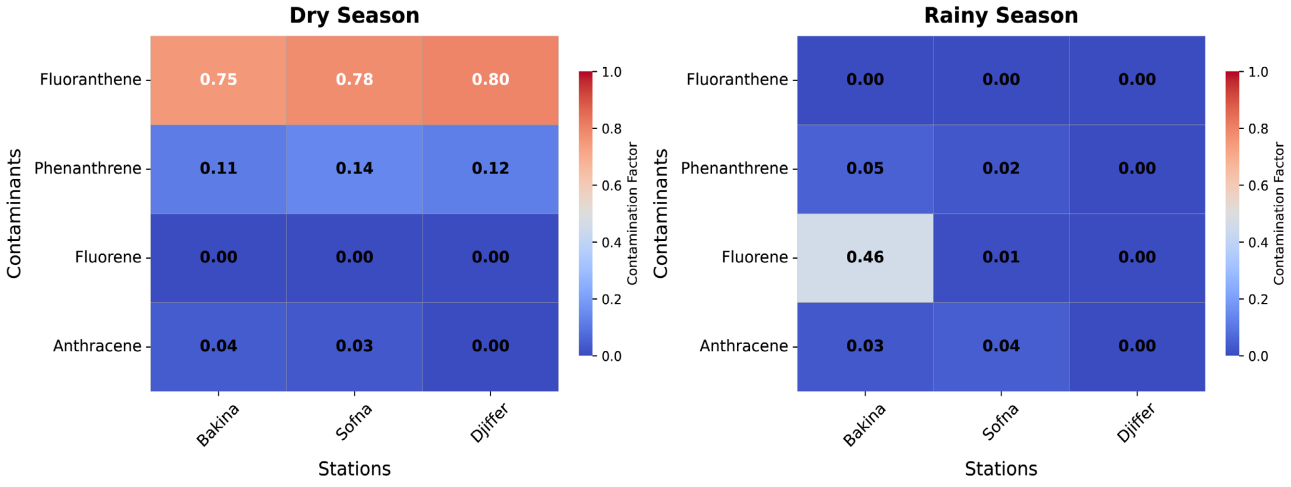

Figure 6. Spatial distribution of contamination factor of PAHs within the Sangomar MPA.

were relatively consistent across the three stations, with CF values of 0.75 at Bakina, 0.78 at Sofna, and 0.80 at Djiffer. Although fluoranthene was the most abundant compound during this period, all values remained below the contamination threshold (CF < 1), indicating the absence of significant pollution. Phenanthrene CF values were slightly lower: 0.11 at Bakina, 0.14 at Sofna, and 0.12 at Djiffer, also reflecting limited presence in the sediments without exceeding levels of environmental concern. Fluorene was completely absent during the dry season (CF = 0 at all stations), indicating no contamination by this compound at that time. Anthracene showed very low CFs: 0.037 at Bakina, 0.030 at Sofna, and no detection at Djiffer (CF = 0), suggesting negligible contamination. In the rainy season, the contamination profile shifted considerably. Fluoranthene was not detected at any station (CF = 0), which may be attributed to increased dilution, more rapid biodegradation, or changes in contamination sources. Phenanthrene was detected only at Bakina (CF = 0.05) and remained undetected at Sofna and Djiffer. Fluorene showed a relatively high value at Bakina (CF = 0.46), suggesting moderate contamination, while it remained very low at Sofna (CF = 0.007) and was not detected at Djiffer. Lastly, anthracene was quantified at Sofna (CF = 0.03) and Bakina (CF = 0.04), but was absent at Djiffer (CF = 0).

4. Discussion

4.1. Heavy Metal Contamination in Sediments: Spatiotemporal Dynamics

The low concentrations of lead (Pb) and mercury (Hg) measured at all stations over the two years of the study indicate a relatively unremarkable situation regarding metal contamination. These results are consistent with findings from other less industrialized West African coastal areas, such as Côte d'Ivoire and Ghana, where the absence of heavy industry or oil ports limits direct anthropogenic inputs [27] [28]. In contrast, the exceptionally high cadmium (Cd) concentration recorded at the Bakina station during the 2024 dry season (37.23 mg/kg) constitutes a significant anomaly. This value, coupled with a contamination factor (CF > 4) and a geoaccumulation index (Igeo = 1.3), points to moderate to strong, localized, and likely recent pollution. Similar peaks have been linked elsewhere to point-source inputs such as untreated wastewater discharges, intensive use of lead acid batteries or phosphate fertilizers rich in Cd, or atmospheric deposition from distant urban or industrial zones [29]-[31]. Alongside these potential anthropogenic factors, the influence of the natural upwelling phenomenon—particularly active along the Senegalese coast during the dry season—should be considered. This oceanographic process brings deep waters, often rich in dissolved trace elements including cadmium, to the surface. These natural inputs can enrich the water column with Cd, especially in shallow coastal zones, before transfer to surface sediments [32] [33]. The sharp decrease in Cd concentrations observed during the rainy season supports a dilution effect caused by precipitation and runoff, a process well documented in tropical coastal environments [34] [35]. Global pollution indices (PLI

< 1) confirm the absence of diffuse contamination at the site scale, but the Bakina case illustrates that localized pollution hotspots, potentially hidden in overall averages, can pose serious micro geographical threats.

4.2. PAH Profiles and Sources: Seasonal and Spatial Influences

The contamination profile by polycyclic aromatic hydrocarbons (PAHs) is dominated by 3- and 4-ring compounds (fluoranthene, phenanthrene, anthracene), with concentrations exceeding 900 µg/kg at some sites during the 2023 dry season. This profile, typical of a pyrogenic origin, suggests predominantly atmospheric inputs related to the incomplete combustion of biomass, wood, or fossil fuels, as observed in other African coastal areas exposed to bushfires or diffuse urban pollution [36]-[38]. The rainy season is characterized by lower concentrations, a shift in PAH composition (domination of fluorene and phenanthrene in 2023, then anthracene in 2024), and the notable absence of fluoranthene. These changes may be explained by dilution through runoff, enhanced degradation of PAHs under more Toxic conditions, or sediment redistribution driven by stronger hydrodynamic flows [39]-[41]. Although calculated contamination factors for PAHs generally remain below 1, indicating low to moderate pollution, the predominance of high molecular weight compounds such as fluoranthene remains concerning due to their environmental persistence and chronic toxicity, particularly to benthic fauna [42] [43].

4.3. Environmental Implications and Management Perspectives

The results suggest an overall moderate pollution status in the Sangomar MPA. However, the presence of localized contamination peaks—especially for Cd and PAHs—highlights a particular vulnerability during the dry season, a period marked by reduced mixing dynamics, increased evaporation, and greater water mass stability. This situation warrants increased attention in the context of the Sangomar oil field exploitation, located approximately 70 km from the MPA. Operated by Woodside Energy and PETROSEN, the project surpassed its production targets as early as 2024, with over 16 million barrels extracted [44]. Although compliant with international standards, offshore oil production carries risks of accidental spills [45]. Coastal currents, particularly upwelling and littoral drift, may facilitate the migration of these pollutants toward the coast, threatening sensitive zones such as mangroves, seagrass beds, marine turtle nesting areas, and fish spawning grounds [46] [47]. Chronic effects on long-lived, bioaccumulative species—such as demersal fish, seabirds, and coastal cetaceans—include endocrine disruption, reduced reproductive success, immunosuppression, and larval mortality [42] [48] [49]. In this context, we recommend strengthening seasonal monitoring of contaminants in sediments and the water column, integrating molecular biomarkers and isotopic analyses to trace sources and understand transfer mechanisms [50] [51], and employing hydrodynamic dispersion models to anticipate potential impact zones. Finally, the coexistence of oil exploitation and marine conservation requires inte-

grated environmental governance, involving local communities, environmental authorities, and industrial operators to ensure transparent and adaptive monitoring [52].

5. Conclusion

The analyses conducted in the Sangomar Marine Protected Area highlight an overall well preserved environmental state, characterized by low to moderate contamination levels for most heavy metals and PAHs. However, the detection of localized pollution, particularly cadmium at the Bakina station, as well as seasonally elevated concentrations of certain PAHs during the dry season, underscores the site's vulnerability to increasing environmental pressures. The identification of a potential link between coastal upwelling and cadmium enrichment in sediments reminds us that natural processes can act synergistically with anthropogenic sources, complicating environmental risk management. Furthermore, the molecular profiles and spatiotemporal dynamics of PAHs indicate a predominance of atmospheric pyrogenic inputs, intensified during the dry season. In view of the offshore oil development in the immediate vicinity, it is imperative to implement a continuous and integrated monitoring strategy, including seasonal tracking of contaminants, the use of advanced analytical tools (biomarkers, isotopes), and predictive hydrodynamic models to anticipate at-risk areas. Finally, inclusive environmental governance involving institutional, scientific, industrial, and community stakeholders is a key lever to ensure the harmonious coexistence of oil exploitation and the conservation of this ecosystem. Nevertheless, the study is subject to certain limitations, notably the number of sampling campaigns and the absence of replicates during sample collection, which may affect the statistical robustness of the results. Furthermore, the analysis did not take into account certain emerging contaminants. It is important to note that these factors limit the scope of the conclusions. This highlights the need for complementary approaches to refine the environmental baseline and enhance the capacity to detect future environmental disturbances.

Conflicts of Interest

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

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