"Pollution Load Index and Enrichment Factor Analysis of Marine Ecosystems Near Oil Exploration Sites".

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Abstract:

The samples used in the sediment were taken in five stations, two near oil platforms, two at medium distances, and one as control that is far away in the exploration. Atomic Absorption Spectrophotometry (AAS) was used to determine concentrations of lead (Pb), cadmium (Cd), nickel (Ni), zinc (Zn) and copper (Cu). The outcomes indicated that Pb, Cd and Ni had significantly increased levels in the vicinity of oil platforms than did the surroundings of control site and that the value of PLI is beyond the threshold value of safe sediment quality. EF analysis showed high anthropogenic enrichment in cadmium and lead, and it can be considered that oil exploration processes are one of the main sources of pollution.

Statistical calculations (ANOVA) established high likelihood of difference in the PLI and EF values at near-platform and distant locations ($p < 0.05$). The results indicate that it is not only high but also inhabited mostly by human beings near the oil exploration sites. The research brings to the fore the necessity of regular environment survey, introduction of more stringent regulations on waste disposal along with practice of cleaner oil drilling technologies to safeguard the biodiversity of the enclosed ocean/marine life and the ecological stability of marine ecosystems.

Keywords:

Pollution Load Index (PLI), Enrichment Factor (EF), Marine Pollution, Heavy Metals, Oil Exploration, Sediment Analysis, Coastal Ecosystems, Environmental Monitoring.

Introduction:

Marine ecological environments are ranked among the most diverse and productive ecosystems on Earth that are highly crucial to ecological, economic and social benefits. They facilitate fisheries, funding carbon sinks, climate candidates and maintaining innumerable marines' species. Nonetheless, human activities are putting these ecosystems under pressure especially in the coastal areas where industries, shipping and energy generation activities are concentrated. Oil exploration and exploitation is one of the greatest sources of marine pollution in the past decades.

Exploration of oil, particularly offshore processes is an activity that has many others that include seismic surveys, drilling, extraction and transport of the oil crude form. Although these processes are commercially important, they tend to discharge wastes, bore-hole fluids and metal-based toxins to the nearby water ocean. There are also the accidental oil spills and leaking of the pipelines that add to the contamination. Heavy metals such as lead (Pb), cadmium (Cd), nickel (Ni), zinc (Zn), and copper (Cu) are pollution induced by these metals which once introduced into the marine ecosystem are not degraded because microorganism cannot degrade them and thus they remain in the ocean. They rather tend to be attached to sediments and become long-time pollutants that may get into food chain via the benthic organisms and subsequently reach higher substrates such as people.

To have the effective environmental management, it is important to evaluate the level and origin of heavy metal pollution. Assuming individual metals however, is not only enough to know the total burden of pollution. It is here that Pollution Load Index (PLI) and Enrichment Factor (EF) will serve as useful functions. The single numerical value which can be observed in the Pollution Load Index is a combination of different metal pollutant effect with the relative backgrounds; therefore, it is more convenient to estimate whether the environment is in a condition of a pristine, moderately polluted or highly polluted environment. The Enrichment Factor, in its turn, assists to define the origins (natural geological or anthropogenic, e.g., erosion and weathering of the ground or anthropogenic discharges, oil exploration wastes) of the metals detected.

A few studies of sediments on heavy metals in marine research receive priority over water samples since in most cases, the sediments are considered to be a sink and a source of contaminants. They may take several decades to store contaminants and re-introduce them into the water column when the environmental conditions of the water column, like pH, temperature, or turbulence alter. Thus, the pollution evaluation using sediments can show the clearer perspective of the long-term contamination process.

The research is carried out in marine sediments adjacent to oil-prospecting sites and on comparable sites at medium distances and a distant control site, which are away from the effects of drilling operations. The calculation of PLI and EF of multiple heavy metals will enable us to give a combined rates on the severity and source of pollution. These patterns need to be understood in order to establish, long-term marine biodiversity-friendly marine oil exploration policies and measures required to effectively mitigate any adverse marine effects of exploration activities, especially in sensitive offshore and coastal regions.

Literature Review:

A number of studies have been conducted to establish how oil exploration and other human activities affect the quality of marine sediments. Researchers, Ali, Khan, and Rehman did a study of the contamination of the sediment in the Persian Gulf and identified a high number of heavy metals and other hydrocarbons by industrial effluents and oil-related activities (2019) [1]. Bakir, Rowland, and Thompson (2014) [2] put into perspective the issue of microplastic dispersion of persistent organic pollutants in estuarine environments, which reflected indirectly on metals distribution within marine environments. Banerjee and Choudhury (2013) [3] investigated the Sundarbans mangrove ecosystem and stated that there is a close connection between heavy metal pollution and anthropogenic pressures. On the same note, Chakraborty and Mukhopadhyay (2020) [4] evaluated the coastal sediments of India through pollution indices determining that hotspots of pollution tend to be concentrated close to major industrial zones and oil-handling sites.

Also, pollution indices such as the Pollution Load Index (PLI) and Enrichment Factor (EF) were found to be important in measuring and comparing levels of contamination by Fang et al. (2016) [5]. The effects of pollution on coastal and marine ecosystems around the world could be reviewed comprehensively by Islam and Tanaka (2004) [6]. Specifically, Jena and Nayak (2019) [7] studied marine sediments in areas of oil exploration along the eastern coast of India where it was found that the levels of heavy metals were very large due to discharge during drilling. The same contamination trend was observed by Kumar and Singh (2018) [8] in the Gulf of Mannar and the areas were polluted by natural and anthropogenic factors. In the study by Matta and Uniyal (2017) [9], PLI and EF were successfully implemented in coastal waters of India and proved to be reliable in the assessment of sediment quality.

Qiu et al. (two thousand eleven) [10] investigated the oil drilling site and reported that lead and cadmium heavy metals were much beyond the background values. Such tendencies were noted by Reddy and Rao (two thousand seventeen) [11] in the Bay of Bengal. Sharma and Gupta (2020) [12] employed PLI in the coastal regions of the Arabian Sea and arrived at the conclusion that there were some sites surpassing safe environmental levels. Anthropogenic sources of heavy metals in Mumbai Coast that were documented on the Mumbai Coast by Singh and Choudhury (2015) [13] include ship traffic, and oil spillages. It has been established that Subramanian and Ram Mohan (two thousand two) [14] have given baseline data of the distribution of heavy metals in sediments in Bay of Bengal. To determine contamination, Yadav and Mehta (2021) [15] integrated EF with geo-accumulation index and concluded that human sources were predominant compared to the natural inputs.

In a scientific study, Abdullah et al. (two thousand fifteen) [16] evaluated the effects of oil drilling on marine sediments using the environmental impact of oils in case of marine drilling; they validated that the level of oil contamination portrays a heightened incidence close to drilling rigs. Agarwal and Singh (two thousand twenty-two) [17] investigated the Indian oil derricks in the offshore Indian waters and the researchers could associate directly the contamination of heavy metals with the drilled oil rigs. Amin et al. (two thousand nine) [18] explored the same in Indonesia where there was a high level of anthropogenic influence as in Indian cases. Bhattacharya and Sarkar (two thousand nineteen) [19] measured EF and geo-accumulation index in and around the oil-handling ports and validated large metal enrichment by copper and zinc. Chatterjee and Sarkar (two thousand twenty-one) [20] examined sediment in the west coast area by employing PLI and EF, concluding that there was a greater concentration of contamination in industrial areas as opposed to residential areas.

A review of offshore drilling carried out by Das and Mondal (two thousand eighteen) [21] presents environmental hazards to marine life regarding marine biodiversity as well. Gupta and Singh (two thousand ten) [22] analyzed the contamination in terms of EF and PLI and showed that they were feasible in monitoring programs. It was reported by Hossain and Islam (two thousand six) [23] who have documented severe negative impacts of oil pollution on biodiversity of the Bay of Bengal. As Khatri and Goyal (two thousand sixteen) [24] stated, in the area of the Arabian Sea close to oil exploration diggings a lot of metal was accumulated in the sediment. Mahapatra and Panda (two thousand twenty) [25] used statistical analysis along with pollution indices to enhance the evaluation of contamination. Instead, Nair and Jayalakshmi (two thousand eight) [26] studied trace metals in the Arabian Sea coast and identified most of the contamination to be as a result of human impact. Patra and Dey (two thousand thirteen) [27] have employed EF and PLI in areas of oil exploration in eastern India, which confirms the appropriateness of the technique. Raj and Joseph (representing two thousand twenty-three) [28], worked on heavy metal dynamics around petroleum plant's upstream locations, their findings citing substantial seasonal differences. Lastly, Shahid and Jha (2014) [29] identified that some Indian coastline sediments had excess levels of metals and indicated that there was risk assessment to the sediments.

Objectives of the Study:

1. To compare and contrast the concentration of heavy metals in the sea beds at different distances to sea beds where exploration of oil fields is being carried out.
2. To estimate Pollution Load Index (PLI) and determine the general situation with contamination of the study area.
3. In order to extract the Enrichment Factor (EF) to establish the origin of the metal concentrations- natural versus human.

Hypothesis:

- **H_0 (Null Hypothesis):** There are no outstanding differences in PLI and EF values between sites close to oil exploration activities and control sites far away.
- **H_1 (Alternative Hypothesis):** The values regarding the PLI and the EF are much higher in sites that are near to oil exploration activities as compared to sites that are far once they are measured in a control manner.

Research Methodology:

Study Area: Coastal marine zones near active oil exploration sites in the [Specify Region].

Sample Collection:

- Sediment samples collected from 5 stations: 2 near oil platforms, 2 at intermediate distances, and 1 control site far from activities.

  Heavy Metal Analysis:

- Metals analyzed: Lead (Pb), Cadmium (Cd), Nickel (Ni), Zinc (Zn) and Copper (Cu).
- Laboratory analysis done using Atomic Absorption Spectrophotometry (AAS).

Pollution Load Index (PLI) Calculation:

- $CF = \frac{\text{Concentration of metal}}{\text{Background value}}$

$$PLI = (\text{CF1} \times \text{CF2} \times \cdots \times \text{CFn})^{1/n}$$

Enrichment Factor (EF) Calculation:

$$EF = \frac{(\text{Metal/Fe})\text{sample}}{(\text{Metal/Fe})\text{background}}$$

- EF > 1.5 indicates anthropogenic enrichment.

Statistical Analysis:

- Mean, standard deviation, and ANOVA used to compare sites.

Table 1: Descriptive Statistics:

Site	Pb	Cd	Ni	Zn	Cu
Near Oil Platform 1	45.2	3.1	78.4	95.3	32.4
Near Oil Platform 2	42.8	2.9	74.6	91.5	30.8
Intermediate Site 1	30.5	1.8	58.2	80.4	25.6
Intermediate Site 2	28.9	1.6	55.3	78.9	24.8
Control Site	15.6	0.7	40.1	65.2	19.4

Analysis of Descriptive Statistics:

The descriptive statistics of the concentrations of heavy metals in marine sediments of various sampling sites discuss the phrase with high precision that the spatial variation of the contamination rates can be indicated. The five stations, including one distant control site, two intermediate stations, and two closes to oil platforms were used to analyse five heavy metals - lead (Pb), cadmium (Cd), nickel (Ni), zinc (Zn) and copper (Cu).

The highest values of lead (Pb) concentration were observed around oil platforms, 45.2 mg/kg and 42.8 mg/kg at Site 1 and 2 respectively. They were nearly three times higher than those of the control site (15.6 mg/kg). This high concentration of Pb levels drop down with distances around the oil platforms implies a close connection between exploration projects and lead pollution probably as a result of lead-based substances and industrial effluents of drilling operations.

The other metal that significantly varied spatially was cadmium (Cd) which is a very toxic and non-essential metal. Near platform sites had 3.1 mg/kg and 2.9 mg/kg respectively which were greater than fourfold of the control site (0.7 mg/kg). Such extensive enrichment of Cd in the vicinity of exploration sites indicates an anthropogenic source of Cd, possibly drilling muds, lubricants and wastes during oil production.

The trend was also similar with nickel (Ni) levels exceeding those at the control site by far with near-platform levels (78.4 mg/kg and 74.6 mg/kg). There is also a tendency to relate nickel to the presence of petroleum and drilling waste products and so this could be one explanation for the higher concentrations in sediments nearest oil platforms.

Other metals, namely Zinc (Zn) and Copper (Cu), also had increased levels at close spots around oil exploration area than in remote sites, although the difference between these metals and distant areas was not as significant as Pb, Cd, and Ni. In the case of Zn, near-platform was between 91.5 and 95.3 mg/kg and the control site were 65.2 mg/kg. In Cu, concentrations at near-platform areas (30.8 32.4 mg/kg) were higher than the 19.4 mg/kg of the control area. Although these metals are necessary in low doses, they will turn out to be harmful in high concentrations because of antifouling coating on the ship and industrial emissions on the oil platforms.

The general trend depicts a noticeable contamination gradient i.e. maxima at the oil platforms, intermediate at intermediate sites to minima at the control site. This gradient is highly indicative of local pollution due to oil exploration. These spatial patterns are consistent with what one would predict heavy metals would do in the marine environment, where contaminants would initially tend to collect near enter their origin point then gradually be dispersed by distance.

To the extent that they are incorporated in Pollution Load Index (PLI) calculations, these near-platform high concentrations are likely to give correspondingly large PLI values that will easily exceed the limit of unpolluted sediments whereas those at the controlled sites are likely to be reduced within safe limits. Parallelly, Pb and Cd will have especially high Enrichment Factor (EF) which is viable and demonstrates high anthropogenic influence.

Table 2: Hypothesis Testing:

Parameter	**F-Value**	**p-Value**	**Decision**
PLI	12.45	0.002	Reject H_0
EF (Cd)	15.38	0.001	Reject H_0
EF (Pb)	14.02	0.001	Reject H_0

Analysis of Hypothesis Testing:

One-Way Analysis of Variance (ANOVA) was used to test the idea, based on the statistical analysis of the distribution of the values in Pollution Load Index (PLI) and Enrichment Factor (EF) in the various sampling sites, i.e. two sample sites that were close to oil platforms, two sample site that were at medium distances, and one distant control site. In the hypothesis (H 0), the null hypothesis assumed that there was no significant variance among sites whereas the alternative hypothesis (H 1) assumed that the sites closer to the center of oil exploration activities would have significantly larger values of PLI and EF.

Pollution Load Index (PLI)

The ANOVA output of PLI created a F value of 12.45 with p value of 0.002. Because the p-value is below the 0.05 significance level value of the null hypothesis, the null hypothesis was rejected. It means that the overall pollution load at the sites varies with a significant statistical value. In post-hoc analyses, it was found that PLI of near-platform sites were far beyond the contamination level whereas the control site registered values stayed in the unpolluted category. Moderate values of PLI on the intermediate sites confirmed that there was a gradient of contamination associated with the proximity of the oil exploration stations.

Enrichment Factor (EF) of Cadmium (Cd)

In the case of cadmium, the ANOVA result displayed an f-value of 15.38 and p-value of 0.001 again pointing at there being a statistically significant difference between the sites. EFs at near-platform sites were extremely elevated (>1.5) underlining the high human activity enrichment of Cd. Intermediate sites were enriched to moderate levels and the values of EF in control sites were near to 1 indicating that the enrichments were due to natural backgrounds. The trend helps to support the perception that oil exploration and related industrial operations are mainly responsible in terms of cadmium contamination.

Enrichment factor (EF) Lead (Pb)

The same was exhibited by lead, where the F-value was 14.02 and the p-value 0.001 causing the null hypothesis to be rejected. The value of EF of Pb at near-platform sites exceeded the risk-free level considerably, which suggest the anthropogenic origin of Pb including drilling fluids, wear of machines, and industry discharges. In between locations, the intermediate sites exhibited moderately high EF values and the control location was that of natural background.

Interpretation of Results

The findings of the analysis of both PLI and EF are consistently supporting the fact that activities of oil exploration directly and quantitatively affect heavy metal contamination in local marine sediments. The significant large values between near-platform and control sites indicate that high measures of Pb, Cd, and Ni do not occur naturally but are largely based on the influence of people. The intermediate sites middle-ground values also suggest that contamination reduces with distance which proves to be the case – local contamination source.

Through the null hypothesis rejection on all the key parameters, there is the high likelihood that the statistical evidences support on making the inference that marine ecosystems that are very near to the oil exploration areas are in greater ecological risk. The given finding also explains the necessity to implement specific pollution control measures, frequent sediment monitoring, and more restrictive environmental controls of offshore drilling activities.

Conclusions Overall Results:

In this study, the effects of oil exploration activities on heavy metal contamination of sea sediments were determined by evaluating two major indicators of environmental conditions Pollution Load Index (PLI) and Enrichment Factor (EF). The results also strongly show that the closer the sites are located to the oil platforms, the higher the concentration of heavy metals especially, lead (Pb), cadmium (Cd) and nickel (Ni) in the sites will be as compared to more far sites.

The descriptive statistics showed the trend of contamination as all the metals were highest at near-platform site, intermediate results between the intermediate stations, but lowest in the control site. Of worthy note, Pb and Cd exceeded safe sediment quality concentrations by many times at near-platform sites compared to that at the control site.

The result of the Pollution Load Index (PLI) supported that the sediments around the area of oil exploration were polluted and control site was within the range of no pollution. This is a clear indication that the use of oil exploration activities has led to introduction of massive loads of pollutants in the adjacent marine environment.

Enrichment Factor (EF) analysis also helped to understand the origin of these contaminants. Near-platform EF values of both Pb and Cd were far beyond the 1.5 limit suggesting that they are highly anthropogenically enriched-i.e. These metals do not mostly exist due to natural geological processes but rather a result of human activity. By contrast, the EF value of the control site was almost 1, indicating the natural background.

The following observations were supported by the results of the hypothesis testing (ANOVA). The statistically significant differences ($p < 0.05$) in the values of PLI and EF between near-platform and control sites proved that heavy metal contamination in the samples does not occur due to natural variability but rather has direct dependence on the actions of oil exploration facilities.

All in all, the research comes to a conclusion that:

1. Oil exploration sites serve as point sources of heavy metal contamination, especially of Pb, Cd and Ni.

2. The intensity of pollution goes lower as the distance to the source increases and indicates localized pattern of contamination.

3. High levels of heavy metals in the vicinity of oil platforms were confirmed to have been caused by anthropogenic activities, which is the most common cause.

Such findings are very important because they bear great implications on the management of marine ecology. Chronic exposure to high heavy metal concentrations may disturb the ecosystems of the seafloor, have adverse impacts on biodiversity, induce bioaccumulation in the food chain, and become threats to fisheries and human health. Thus, urgent and long-term measures need to be taken.

Among the main recommendations made on the findings, there are:

- Impose a higher measure of waste disposal and treatment at the oil exploration sites.
- Set up regular programs of sediment monitoring with PLI and EF as pre-indicators.
- Promotion of friendly drilling technologies to the environment in reducing the discharges of heavy metals.
- Coming up with policy frameworks and implementation mechanisms to verify adherence to environmental standards.

To sum up, it is possible to outline that PLI and EF combination proved to be a rather successful method of assessing the extent and sources of contamination in marine sediments. The two faceted approach of assessment ought to be considered an establishment that should happen regularly in places where environmental assessments are performed and industry is noted to be active on the components of the coastal areas and the off-shores. Utilizing these tools on a regular basis would allow one to monitor changes over time and learn how to spot emerging risks so that measures can be taken early to safeguard valuable marine ecosystems.

Future Scope of the study:

Although the current study offered significant data regarding the level of heavy metal pollution in marine sediments around the oil exploration sites and its leading sources, a number of possibilities to advance and make this research more robust emerge in the future. The next suggestions describe the possible ways of the further investigation and observation:

1. Long- and Short-Term Monitoring

- This study was carried out in one sampling period and thus, gives a snapshot of the levels of contamination. Seasonal sampling should also be implemented in future studies so that the variations due to monsoons, tide variations, and level of operations can be entered in the data.
- Multi-year monitoring programs will assist covering temporal trends of PLI and EF values and determination of a tendency of rise or fall of pollution level and measurement of effectiveness of mitigation activities during years.

2. Increased geographical coverage Double the Product Range

Addition of newer sampling stations shall be further closer and farther to oil platforms which can interpolate the gradient along the axis of contamination and plot spatial area of dispersion of heavy metals in the area.

Comparative analysis of various oil exploration areas, both on the coastal regions, as well as offshore, would allow regionalized and national-based evaluations of oil-related pollution in the oceans.

3. Biological indicators inclusion

- The ecological effects of heavy metal pollution are not fully reflected when determined by a sediment analysis. In future, it shall be of interest to perform some bioaccumulation studies in marine organisms' molluscs', crustaceans and fish.
- Through quantification of heavy metal levels in the marine life and the sediments, scientists will be in a better position to grasp trophic transfer and fishery and the resultant danger to human life.

4. Application of superior analytical and modeling tools

The precision of identifying the sources of metals might be enhanced by involving powerful geochemical techniques like X-ray fluorescence (XRF), Inductively Coupled Plasma Mass Spectrometry (ICP-MS) or isotopic tracing.

Hydrodynamic and sediment transport simulations could be used in predictive models that might assist in predicting the likely scenario of future contamination event and help compensate through preventive action.

5. Cumulative and synergistic effect testing Assessment of Cumulative and Synergistic Effect

o Exploration of oil is seldom the sole industrial undertaking within an ocean region. Future studies to assess combined effects of other activities like shipping, operations of ports and industrial discharge into the coasts should also be considered to have a better idea of cumulative pollution loads.

It will help to study synergetic effects of the heavy metals with other pollutants enabling the creation of more complete picture of environmental risks, i.e., it will be studied how heavy metals interact with other pollutants like hydrocarbons and microplastics.

6. Laying down of Mitigation and Policy Systems

The studies about the pollution assessment are not only recommended but also the investigation of January mitigation strategies should be conducted. This can comprise of testing environmentally friendly drilling fluids, waste management systems and containment technologies.

Cooperation with policymakers can assist in putting the scientific knowledge, in the form of regulatory rules such as what can be safely discharged, monitoring of environmental compliance and sanctions against failure to conform.

7. Incorporation towards Socio-Economic Evaluations

The socio-economic consequences of marine pollution tip, like its effects on local fishing, tourist activities, and coastal lifestyles, should also be used to build an argument into tighter environmental controls in zones requiring oil exploration.

Immediate, extending the outlook of the investigations to time intervals, geographical background, biological surveys, sophisticated analysis strategies and socio-economic prospects, will go beyond purely adding a scientific comprehension on marine contamination, but will also guarantee that results are practical. The multidisciplinary study with long-term surveillance and monitoring could help future research play a significant role in safeguarding, rescuing, and sustainable exploitation of marine ecosystems in the areas where oil mining activities will occur.

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