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Short-Term Effects of Petroleum Pollutants on Heavy Metal Concentrations in Mangrove Mud Sediments in Iran

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Authors
Navazollah Moradi, *Ph.D.*[1*]
Ommolbanin Bazrafshan, *Ph.D.*[2]

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[1]Assistant Professor, Department of Natural Resources Engineering, Faculty of Agriculture and Natural Resources, University of Hormozgan, Bandar Abbas, Iran.
[2]Professor, Department of Natural Resources Engineering, Faculty of Natural Resources and Agriculture, University of Hormozgan, Bandar Abbas, Iran.

Correspondence
Address: Department of Natural Resources Engineering, Faculty of Agriculture and Natural Resources, University of Hormozgan, Bandar Abbas, Iran.
Phone: +989158263797
Email: nvz.moradi@hormozgan.ac.ir
ORCID: 0000-0002-6588-9440

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ABSTRACT

Aims: This study investigated the short-term effects of diesel and kerosene on heavy metal mobility in mangrove mud sediments (Bandar Abbas, Northern Persian Gulf) and identified element-specific responses under controlled conditions.

Materials & Methods: We contaminated homogenized sediments in a completely randomized design with diesel and kerosene (0 and 4% w/v) and incubated them for 10 days in triplicate (9 units). We extracted elements at a sediment-to-water ratio of 1:5 and measured soluble element concentrations using ICP-OES.

Findings: We classified the elements into three groups based on their response to the pollutants ($P < 0.01$). Group 1 (Vanadium, Lead, Nickel, and Chromium) showed a significant increase in concentration under both pollutants. Group 2 (Tin, Manganese, and Molybdenum) showed a significant decrease upon exposure to petroleum contamination. Group 3 (Tungsten and Copper) displayed divergent behavior, with concentrations decreasing in the presence of diesel and increasing upon exposure to kerosene. Principal component analysis confirmed the three-group classification, with the first two components explaining 99.6% of the total variance. The loading plot clearly separated Group 1 on the negative side of PC1 and Group 2 on the positive side, while PC2 separated Copper and Tungsten, confirming their distnct geochemical behavior.

Conclusion: petroleum contamination, even over the short term, alters heavy-metal dynamics in mangrove mud sediments depending on both element type and pollutant type. These findings underscore the necessity of differentiated metal monitoring and targeted management of petroleum contamination in sensitive coastal ecosystems.

Keywords: Aqueous Extract; Contamination; Hormozgan; HydroCarbon; Mangrove Ecosystems.

CITATION LINKS

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Introduction

Soil contamination by petroleum hydroCarbons and heavy metals is a major environmental concern in many industrial and coastal regions. These two pollutant classes frequently co-occur in areas affected by oil spills, refinery operations, and petrochemical activities. petroleum contamination can introduce persistent organic pollutants into terrestrial and aquatic environments and may influence heavy-metal mobility in surface and subsurface sediments. Due to their well-documented toxicity and persistence, heavy metals are considered potential threats to biota and human health [1].

Although heavy metals occur naturally in marine sediments and soils, anthropogenic activities, including oil extraction, industrialization, and intensive agricultural practices, significantly elevate their concentrations beyond geochemical background levels [2]. This accumulation degrades soil quality, disrupts plant metabolic functions, and contributes to chronic health disorders in humans [3]. For instance, numerous studies have documented that oil spills elevate concentrations of metals such as Lead (Pb), Cadmium (Cd), Nickel (Ni), and Mercury (Hg) in contaminated soils. Research conducted in the Niger Delta has reported substantial increases in Pb and Cd concentrations following crude oil exposure [4]. At the same time, in agricultural lands, applying petroleum -based products and agrochemicals further accelerates heavy metal accumulation [5]. Consequently, by interfering with nutrient uptake mechanisms, these metals restrict plant access to essential elements such as Calcium, Magnesium, and Potassium, thereby impairing crop growth and yield [6]. Moreover, oil spills can compromise groundwater quality and increase public health risks [7], particularly because exposure to heavy metals is associated with respiratory, renal, and cardiovascular disorders [8]. Investigations have shown that petroleum compounds can elevate the concentrations of metals such as Iron (Fe), Pb, and Zinc (Zn) in agricultural soils [9], with these metals subsequently entering the food chain through plant uptake and ultimately affecTing human and animal health [10].

Beyond agricultural systems, petroleum -derived pollution poses a significant threat to sensitive coastal ecosystems, particularly mangrove forests, which provide critical ecosystem services including coastal protection, Carbon sequestration, and biodiversity conservation. Mangrove ecosystems occupy the land–sea interface in tropical and subtropical regions and thrive under saline and brackish conditions. Their complex root systems stabilize coastlines, mitigate erosion, and attenuate storm surges [11]. Although mangroves cover less than 1% of the world's tropical forest area, they support over 1,500 species of flora and fauna, including commercially important fish and endangered species [12]. Their role as Carbon sinks is particularly significant in climate change mitigation [13]. In Iran, the mangrove forests along the southern coasts, particularly in Qeshm and Bandar Abbas, possess substantial ecological and socio-economic value, serving as protective barriers and sustaining the livelihoods of coastal communities. The resilience and multifunctionality of these ecosystems underscore the critical need to investigate how oil pollution alters sediment geochemistry and ecological integrity.

In the coastal areas of Bandar Abbas, petroleum

pollutants including gasoline, diesel, and kerosene are the primary agents of aquifer contamination, predominantly originaTing from leaks in storage tanks and wastewater discharge channels [14]. Mangrove forests in this region act as natural sinks for heavy metals, supporTing sediment detoxification and maintaining ecological balance [15]. However, crude oil pollution has been shown to elevate the concentrations of metals such as Pb, Cd, Chromium (Cr), and Zn beyond the permissible limits established by the World Health Organization [4]. Driven by increasing maritime traffic, ongoing refinery operations, expanding fuel smuggling, and escalaTing regional tensions in the Persian Gulf, oil pollution in these regions is intensifying. Consequently, investigaTing how petroleum pollutants alter heavy metal dynamics is essential for accurate environmental risk assessment and management.

Despite growing awareness of this issue, a significant knowledge gap remains regarding the short-term effects of oil pollution on mud sediment properties and heavy metal mobility, particularly under saturated conditions. Most previous studies have focused on long-term contamination effects or biodegradation processes, while early-stage environmental responses have received comparatively less attention. Specifically, the acute-phase geochemical behavior of heavy metals following petroleum exposure in mangrove sediments has not been systematically examined, and the differential effects of lighter hydroCarbons such as kerosene versus diesel remain poorly understood. ElucidaTing these early-stage mechanisms is therefore a critical step toward predicting the environmental fate of metals and designing effective remediation strategies for contaminated coastal sediments. In a previous study in the same region, the authors investigated the effects of bio-amendments on soil physicochemical properties under petroleum -contaminated conditions [16]. Building upon those findings, the present study extends this line of research by focusing specifically on the geochemical behavior of heavy metals during the acute phase of petroleum contamination, thereby addressing the identified gap in early-stage environmental responses.

Therefore, the primary objective of this study is to evaluate the impact of short-term exposure to petroleum pollutants (diesel and kerosene) on the geochemical behavior and concentrations of heavy metals in mangrove ecosystem mud sediments under controlled laboratory conditions. The incubation period was intentionally limited to 10 days to capture the acute phase and initial responses of the mud sediment system to hydroCarbon stress, thereby providing valuable baseline data on early environmental processes. By simulaTing saturated moisture conditions consistent with the natural tidal regime, this research provides critical insights into the rapid geochemical changes and metal mobilization resulTing from petroleum introduction into coastal ecosystems. Ultimately, addressing the challenges posed by co-occurring oil and heavy metal pollution requires integrated approaches involving researchers, environmental managers, and local communities. Developing effective remediation and management strategies is essential not only to preserve soil and water quality but also to ensure food security and public health [17]. Future research can build upon this baseline data to investigate long-term pollution effects, predict the fate and transport of heavy metals in mud sediments, and evaluate the efficacy of novel bioremediation methods under real-world tidal conditions.

Materials & Methods

Experimental Design and Mud Sediment Preparation

This study was conducted in five sequential stages, as depicted in the flowchart (Figure 1). To investigate the effects of petroleum pollutants on the concentrations of selected heavy metals in the mud sediment solution of mangrove sediments, Surface samples (0–10 cm depth) were collected from coastal mud sediment in the mangrove forest area (Table 1) of Koolagan, Bandar Abbas, Iran, at distances of approximately 1 to 5 m from the nearest mangrove trees (Figure 2). The samples were directly transferred into 3-kg pots. Following air-drying and homogenization, the mud sediments were prepared for laboratory treatments. The experimental units received separate additions of diesel and kerosene at 4% (w/v) (Table 2).

In contrast, the control was untreated raw mud sediment from the same site, processed identically. The treatments followed a completely randomized design (CRD) with three replicates per treatment, for a total of 9 experimental units (3 treatments × 3 replicates). We selected 4% as a moderate level based on a literature review indicaTing that petroleum contamination studies typically use concentrations ranging from 1% to 8% (w/w). Within this range, we chose 4% because it provides a balanced dose that enables measurable responses without imposing undue stress on the system [16,18].

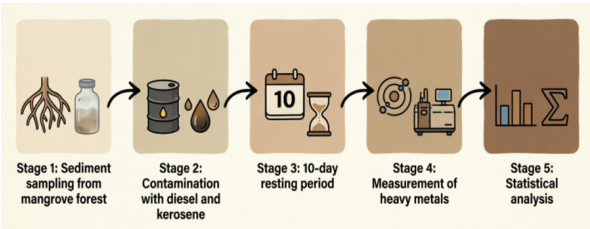

Figure 1) Schematic diagram of the experimental workflow.

Figure 2) Location of the mud sediment sampling site in the mangrove forest.

Incubation Conditions

To stabilize mud sediment conditions, we maintained the pots in a controlled laboratory setTing at the Water and Soil Laboratory of the University of Hormozgan for 10 days at 18–25 °C. Although the mud sediments originated from waterlogged mangrove soils, we maintained the moisture level near field capacity throughout the experiment. This choice ensured controlled, reproducible conditions, as field capacity is a standard reference point in soil-based studies and supports consistent aeration and microbial activity across treatments. We determined field capacity using the pot method: after complete saturation, we allowed gravitational water to drain, and defined the stabilized moisture content as field capacity. After applying the treatments, we covered the mud sediment surface with perforated plastic sheets to minimize evaporation of moisture and volatile petroleum compounds while ensuring adequate ventilation. Throughout the incubation period, we monitored mud sediment moisture gravimetrically. We weighed the pots at 48-h intervals and replenished any water lost to evaporation with deionized water to maintain the target moisture range. We acknowledge that this condition does not fully replicate the natural waterlogged state of mangrove sediments,

Table 1) Selected physicochemical properties of mud sediment used in the study

$EC_{1:5}$ ($dS.m^{-1}$)	$pH_{1:5}$	Organic Matter (%)	Clay (%)	Silt (%)	Sand (%)	Texture
11.42	7.53	1.93	22	70	8	Silt loam

Table 2) Selected physical properties of the Petroleum contaminants

Petroleum Type	Density ($g.cm^{-3}$)	Dynamic Viscosity (cP)*	Kinematic Viscosity (cSt)**	Surface Tension ($dyne,cm^{-1}$)
Kerosene	0.79	1.73	2.19	25.7
Diesel	0.83	5.40	6.50	72.2

Note: cP* = centipoise and cSt** = centistokes

and we have addressed this as a study limitation in the Discussion section.

Laboratory Analysis and Extraction

After the 10-day incubation, we collected samples from each treatment to evaluate the impact of petroleum compounds on heavy metal mobility. We air-dried the samples under controlled conditions. Given the saturated, anaerobic conditions characteristic of mangrove habitats, we prepared an aqueous extract at a 1:5 (mud sediment to deionized water) ratio to simulate realistic environmental conditions. We first allowed the suspensions to equilibrate in the laboratory for 24 h. We then shook them for 10 min on an orbital shaker and centrifuged them at 4000 rpm for 5 min. We filtered the supernatant through a 0.45-µm membrane filter to obtain a clear extract for determining water-soluble heavy metals. Elemental analysis was conducted using an inductively coupled plasma optical emission spectrometer (ICP-OES, Model 700, Agilent Technologies, Santa Clara, CA, USA) [19,20]. Elemental analysis was conducted using an inductively coupled plasma optical emission spectrometer (ICP-OES, Model 700, Agilent Technologies, Santa Clara, CA, USA), following the manufacturer's operaTing conditions and calibration procedures [19]. All analyses were performed at the Central Laboratory of the University of Hormozgan. Quality assurance and quality control (QA/QC) procedures included calibration with Oreas 503b certified reference material and analysis of reagent blanks. Digestion recovery ranged from 75% to 90%, with relative standard deviations below 10%. We calculated the limit of detection (LOD) and limit of quantification (LOQ) based on the standard deviation of blank measurements. [21].

Statistical Analysis

We subjected data on concentrations of selected heavy metals in petroleum -contaminated mud sediments to one-way analysis of variance (ANOVA), followed by Duncan's multiple range test for mean comparison. We performed all statistical analyses using SPSS (Version 22.0, IBM Corp., Armonk, NY, USA) at a significance level of $p < 0.01$. We generated graphical representations, including PCA loading plots

and score plots, using Python (Google Colab) with the Matplotlib and Seaborn libraries. We used Microsoft Excel2019 for additional data visualization and basic graphing.

Findings

Analysis of variance revealed that petroleum -derived treatments, specifically diesel and kerosene, exerted highly significant effects ($p < 0.01$) on the concentrations of selected metals in the mud sediment solution, including Chromium (Cr), Lead (Pb), Copper (Cu), Manganese (Mn), Molybdenum (Mo), Nickel (Ni), Tin (Sn), Vanadium (V), and Tungsten (W). These results unequivocally show that petroleum contamination substantially alters the biogeochemical behavior, environmental distribution, and aqueous bioavailability of heavy metals in mangrove forest mud sediments, highlighTing the profound impact of hydroCarbon pollutants on mud sediment solution chemistry (Table 3).

Based on statistical analyses and observed geochemical responses, the studied elements were classified into three distinct patterns under the two Petroleum contaminants. The first group, characterized by a consistent increase, comprised Vanadium, Lead , Nickel, and Chromium, which showed significant concentration increases ($p<0.01$) under both kerosene and diesel (Figure 3). The second group, showing a consistent decrease, included Tin, Manganese, and Molybdenum, whose concentrations declined under both treatments (Figure 4). The third group displayed a divergent response, consisTing of Tungsten and Copper, which increased under kerosene but decreased under diesel (Figure 5).

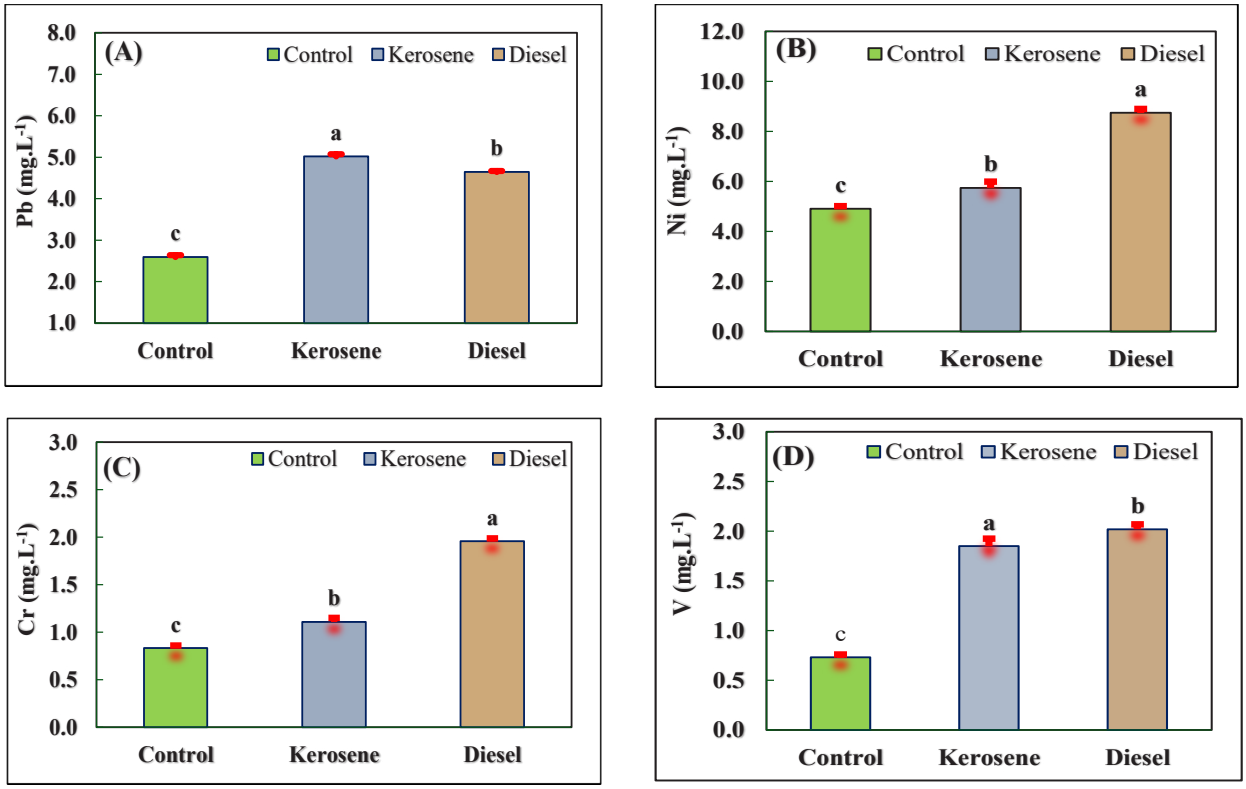

Figure 3) Impact of Petroleum contaminants (diesel and kerosene) on the soluble concentrations of selected heavy metals in mangrove mud sediment: (A) Lead (Pb), (B) Nickel (Ni), (C) Chromium (Cr), and (D Vanadium (V). Error bars represent standard deviations. Different lowercase letters denote statistically significant differences at $p < 0.01$ as determined by Duncan's multiple range test.

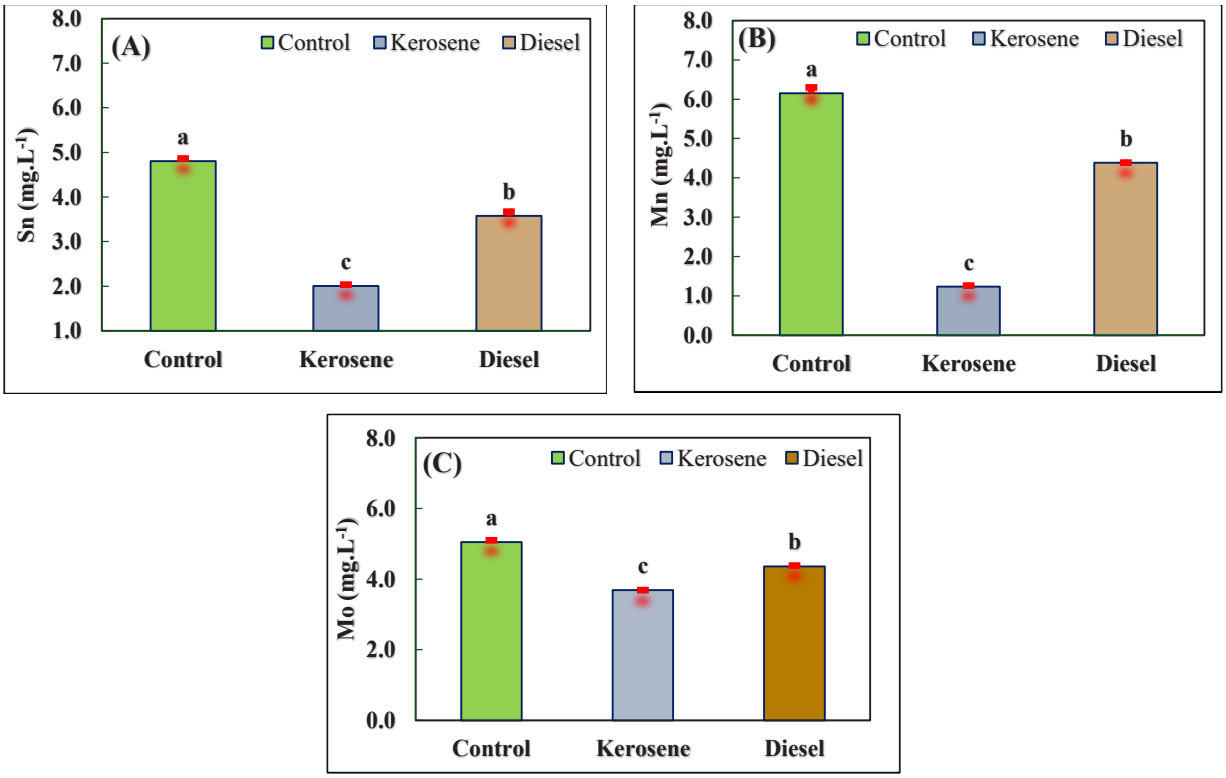

Figure 4) Impact of Petroleum contaminants (diesel and kerosene) on the soluble concentrations of selected heavy metals in mangrove sediment: (A) Tin (Sn), (B) Manganese (Mn), and (C) Molybdenum (Mo). Error bars represent standard deviations. Different lowercase letters denote statistically significant differences at $p < 0.01$ as determined by Duncan's multiple range test.

Table 3) Analysis of variance (ANOVA) results evaluaTing the effects of Petroleum pollutants on the concentrations of selected heavy metals.

Sources of Variations	Mean Square									
	df	Cr	Cu	Mn	Mo	Ni	Pb	Sn	V	W
Treatment	2	0.849**	0.332**	16.129**	1.254**	9.942**	4.248**	5.278**	1.465**	1.369**
Error	8	0.001	0.007	0.012	0.002	0.027	0.002	0.004	0.003	0.004
CV (%)		2.43	3.83	2.79	1.02	2.54	1.11	1.82	3.57	1.74

Note: ** indicates significance at the 1% level.

All elements in the first group (Pb, Ni, V, and Cr) increased significantly ($P < 0.01$) in soluble concentration after exposure to both kerosene and diesel, compared with the control (Figure 3). However, the extent of these increases varied considerably by metal and petroleum contaminant. In the kerosene treatment, Vanadium showed the largest increase (153.4%), followed by Lead (93.8%), Chromium (33.7%), and Nickel (9.4%). In the diesel treatment, Vanadium again showed the greatest increase (176.7%), while Chromium (136.1%), Nickel (78.4%), and Lead (79.5%) also increased substantially. Notably, kerosene had a stronger effect on Lead mobility, whereas

diesel more prominently influenced the concentrations of Nickel, Chromium, and Vanadium. All differences between the two petroleum treatments were statistically significant ($P < 0.01$).

Conversely, the elements in the second group showed a uniform decline in mud sediment solution concentrations under both hydroCarbon contamination treatments (Figure 4). Compared to the control, the application of kerosene and diesel significantly reduced ($p<0.01$) the mobility of Tin (Sn)(2.01 and 3.58 $mg.L^{-1}$), Manganese (Mn)(1.23 and 4.38 $mg.L^{-1}$), and Molybdenum (Mo)(3.69 and 4.36 $mg.L^{-1}$). In kerosene-amended mud sediments, concentrations of these elements decreased by factors of 2.39, 5.00, and 1.37 relative to the control, respectively, whereas diesel contamination resulted in corresponding reductions of 1.34-, 6.65-, 1.41-, and 1.16-fold, respectively. Comparative analysis showed that Tin and Manganese depletion was more pronounced under kerosene exposure, whereas Molybdenum showed greater sensitivity to diesel contamination, demonstraTing element-specific responses to hydroCarbon type. The third group (Tungsten and Copper) showed the most complex geochemical behavior, as these elements responded differently depending on the hydroCarbon applied (Figure 5). Notably, kerosene contamination induced a marked increase in the concentrations of Tungsten (4.27 $mg.L^{-1}$) and Copper (2.52 $mg.L^{-1}$), whereas diesel treatment resulted in a significant decrease in their concentrations (Tungsten: 2.72 $mg.L^{-1}$; Copper: 1.74 $mg.L^{-1}$). The results indicate that under kerosene exposure, both metal concentrations increased significantly ($p < 0.01$), showing an approximately 10% increase relative to the control samples. Conversely, in diesel-contaminated samples, metal concentrations decreased substantially, with reductions of about 30% for Tungsten and 24% for Copper.

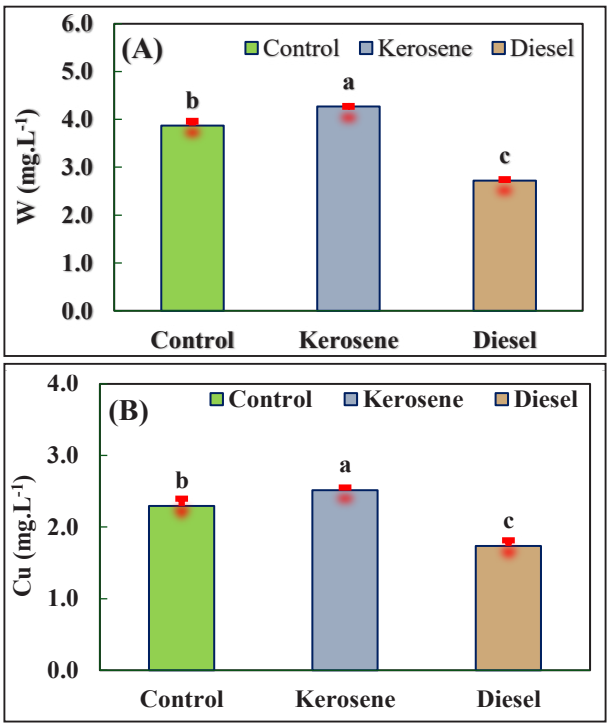

Figure 5) Impact of petroleum contaminants (diesel and kerosene) on the soluble concentrations of selected heavy metals in mangrove sediment: (A) Tungsten (W) and (B) Copper (Cu). Error bars represent standard deviations. Different lowercase letters denote statistically significant differences at $p < 0.01$ as determined by Duncan's multiple range test.

The triangular heatmap shows pairwise Pearson correlation coefficients (r) for nine heavy metals (Cr, Cu, Mn, Mo, Ni, Pb, Sn, V, and W), calculated from their soluble concentrations across all treatments (control, diesel, and kerosene) (Figure 6). The color scale, from light brown (negative correlation) to dark brown (positive correlation), indicates the direction and strength of the relationships, with darker colors reflecTing stronger associations. Group 2 metals (Sn, Mn, and Mo) showed strong positive correlations ($r = 0.99–1.00$), confirming their similar geochemical

behavior under petroleum contamination. Group 1 metals (Pb, Ni, V, and Cr) showed moderate to strong positive correlations (r = 0.32–0.99), except for Pb–Ni (r = 0.32). In contrast, Tungsten (W) and Copper (Cu) exhibited a strong negative correlation (r = -0.87), indicaTing divergent geochemical behavior between these two elements. The matrix is presented in a lower-triangular format for better clarity, and all coefficients were calculated using Pearson's method. Tungsten and Copper exhibited a strong negative correlation (r = -0.87), indicaTing that these two metals respond differently to petroleum contamination. This finding supports their classification as a separate group with divergent behavior.

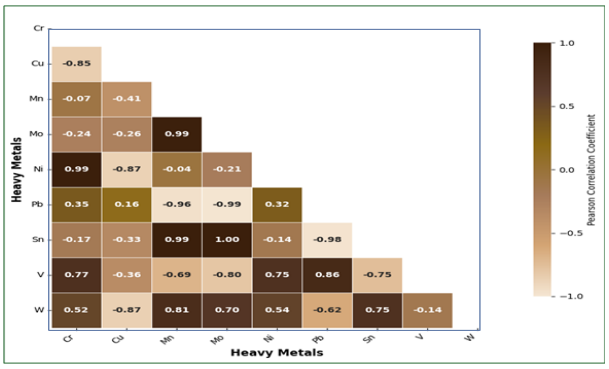

Figure 6) Pearson correlation matrix of soluble heavy metal concentrations in petroleum -contaminated mangrove mud sediments. The lower triangular matrix displays Pearson correlation coefficients (r) among nine heavy metals: Chromium (Cr), Copper (Cu), Manganese (Mn), Molybdenum (Mo), Nickel (Ni), Lead (Pb), Tin (Sn), Vanadium (V), and Tungsten (W). The color gradient represents the strength and direction of the correlations, ranging from strongly negative (lightest shade, r = −1.0) to strongly positive (darkest shade, r = 1.0).

We performed principal component analysis (PCA) to validate heavy-metal grouping (Figure 7). The first two principal components explained 99.6% of the total variance (PC1: 58.4%, PC2: 41.2%). The loading plot clearly separated Group 1 (Pb, Ni, V, Cr) on the negative side of PC1 and Group 2 (Sn, Mn, Mo) on the positive side. PC2 separated Copper (Cu) and Tungsten (W), confirming their distnct geochemical behavior. These results support the threegroup classification derived from ANOVA and correlation analyses.

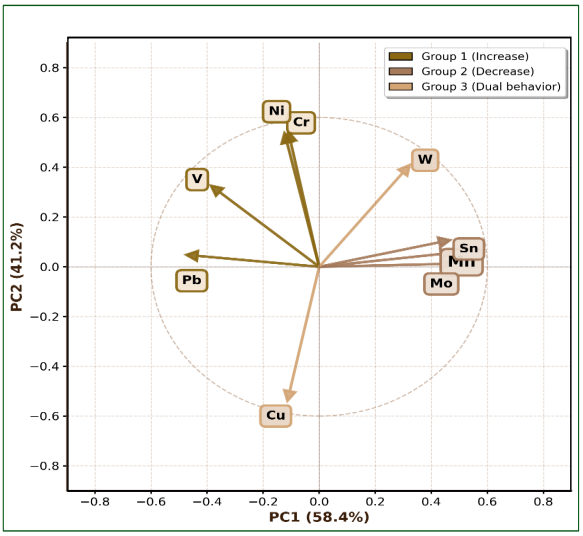

Figure 7) Principal component analysis (PCA) loading plot of soluble heavy metal concentrations in petroleum -contaminated mangrove mud sediments from Bandar Abbas, Iran. The plot displays the loadings of nine heavy metals: Chromium (Cr), Copper (Cu), Manganese (Mn), Molybdenum (Mo), Nickel (Ni), Lead (Pb), Tin (Sn), Vanadium (V), and Tungsten (W) on the first two principal components (PC1 and PC2). PC1 and PC2 account for 58.4% and 41.2% of the total variance, respectively (cumulative variance = 99.6%). Vector length and direction indicate each metal's contribution to the principal components and its relationships with other elements. The dashed circle represents the correlation circle. Vectors are color-coded by the metals' temporal behavior: Group 1 (dark brown, increase), Group 2 (medium brown, decrease), and Group 3 (light brown, dual behavior).

Discussion

Heavy metals in mangrove sediments respond differently to petroleum contamination, depending on the hydroCarbon type and the chemical nature of each element. In this study, we observed three distnct patterns of change in metal

concentrations during incubation. Based on these observations, and supported by ANOVA, correlation analysis, and principal component analysis (PCA), the metals were grouped into three categories: those that increased (V, Pb, Ni, and Cr; $p < 0.01$), those that decreased (Sn, Sc, Mn, and Mo; $p < 0.01$), and those that showed contrasTing behavior depending on the contaminant (W and Cu). The consistency of results across three independent statistical approaches confirms that this classification is robust and reflects real geochemical differences rather than random variation. These findings highlight that the type of petroleum product plays a key role in shaping metal mobility in coastal sediments. The observed differential behavior among elements may be attributed to interactions with petroleum derived dissolved organic matter (DOM), possible shifts in redox potential (Eh), and competitive adsorption mechanisms. These processes operate under the saturated, anaerobic conditions commonly reported in mangrove sediments, where organic matter quality and mineralogy control metal mobility [22,23]. Furthermore, chemometric analyses in oil-contaminated areas show that each element exhibits a distnct geochemical response, highligh Ting the complexity of metal fate in coastal wetlands and the need for element-specific evaluations rather than treaTing them as a homogeneous group [24]. The concentration increases observed for the first group of elements (V, Pb, Ni, and Cr) primarily originate from their inherent occurrence within petroleum matrices. These metals, particularly V, Ni, and Pb, are natural constituents of crude oil that are not entirely removed during refining processes [25], resulTing in their direct mobilization into the mud sediment pore water upon contamination. Beyond this direct input, the organic compounds present in diesel and kerosene can form soluble complexes with various heavy metals, facilitaTing their release from the solid mud sediment phase into the aqueous phase. Previous research has shown that these hydroCarbon-derived compounds act as ligands, forming stable complexes with metals like Pb and significantly increasing their solubility in environmental systems [26].

Results indicate that petroleum contamination substantially elevates heavy metal concentrations in the mud sediment solution, with kerosene exhibiTing a markedly stronger effect on metal solubility than diesel. This difference likely stems from variations in chemical structure, molecular weight, and polarity between the two hydroCarbons. Kerosene contains intermediate-molecular-weight hydroCarbons and a higher proportion of aromatic and aliphatic compounds, which interact more readily with heavy metals and enhance their solubility and mobility in the sediment-water system [27]. The specific chemical structure of kerosene components enables them to act as more effective solvents for heavy metals, facilitaTing the formation of stable metal-organic complexes. In contrast, diesel consists predominantly of higher-molecular-weight hydroCarbons with longer Carbon chains, exhibiTing lower polarity and, consequently, a reduced capacity to mobilize heavy metals [21].

Furthermore, polar compounds and impurities in kerosene, particularly sulfur- and nitrogen-containing heterocycles, further enhance metal solubility by acTing as effective ligands that increase metal mobility in the aqueous phase [28]. These findings align closely with previous research

highlighTing the critical role of hydroCarbon pollutants in altering heavy metal dynamics in contaminated environments. For instance, significant increases in Ni, Pb, and Cd concentrations have been reported in saturated paddy soils in Salem, India [29], which aligns with the current study's observations. Similarly, documented increases in Pb, Cd, and Zn concentrations in the presence of crude oil [30], along with the accumulation of Pb, Cd, Ni, and Hg following oil spills [31], underscore the redistributive nature of petroleum pollutants in mud sediment systems. Given their high persistence and bioaccumulation potential, these metal accumulations pose ongoing threats to public health and ecosystem integrity and require rigorous monitoring and remediation strategies.

In the second group, Tin (Sn), Manganese (Mn), and Molybdenum (Mo) exhibited a consistent decrease in concentration. Statistical analyses showed that concentrations of these elements in mud sediment solutions from diesel- and kerosene-contaminated mud sediments were significantly lower than in the control samples. The extent of this reduction varied by both element type and contaminant; specifically, Sn and Mn showed greater reductions under kerosene treatment, whereas Mo experienced more pronounced decreases under diesel treatment. This pattern likely stems from changes in sediment physicochemical conditions, particularly shifts in redox potential (Eh) and surface adsorption mechanisms, after introducing petroleum pollutants. These hydroCarbons appear to reduce the solubility and bioavailability of these elements, thereby decreasing their aqueous-phase concentrations.

This reduction pattern aligns with findings from previous studies in natural and agricultural environments, including petroleum -based mulching applications, where hydroCarbon presence led to decreased metal mobility [32]. Furthermore, the observed decline in Sn and Mo concentrations is consistent with recent findings in mangrove forests, where dissolved Mo decreased significantly along the land-sea gradient [22]. Although the ecosystem examined in the present study differs from mulched environments or natural zonation gradients, the similar pattern suggests that hydroCarbon-induced geochemical alterations affecTing heavy metals may transcend ecosystem-specific boundaries.

The mechanisms governing dissolved metal dynamics in the present study, particularly the roles of redox conditions and organic matter, align with previous findings showing that complex interactions among redox potential, organic matter dynamics, and mineralogical transformations create distnct geochemical micro-environments [22]. The observed decrease in dissolved metal concentrations may also reflect shifts in oxidation states that promote precipitation or enhanced adsorption of these elements onto the solid phase of the mud sediment. Furthermore, the pronounced heterogeneity in heavy-metal responses to petroleum contamination confirms that local micro-environments conditions strongly govern dissolved-metal mobility. Consequently, these findings indicate that petroleum pollution substantially alters the biogeochemical behavior of heavy metals in mangrove ecosystems, highlighTing the need for comprehensive, long-term investigations to evaluate their implications

for the sustainable conservation of these sensitive environments.

The third group, comprising Tungsten (W) and Copper (Cu), showed the most complex geochemical behavior, with starkly divergent response patterns depending on the hydroCarbon contaminant. Upon exposure to kerosene, the aqueous concentrations of both metals increased markedly relative to the control, indicaTing enhanced solubility and bioavailability. In sharp contrast, diesel contamination substantially depleted these metals in the mud sediment solution. These opposing trends underscore the distnct mechanisms by which kerosene and diesel govern the geochemical mobility and environmental fate of specific trace elements in mangrove mud sediments.

One plausible mechanism for the increased concentration of these metals in the kerosene treatment involves competition between petroleum -derived organic compounds and metal ions for adsorption sites on sediment particles [34]. Such competition may displace metal ions into the mud sediment solution, thereby enhancing their solubility. However, this mechanism alone cannot account for the decreased metal concentrations observed in the diesel treatment, suggesTing that other factors, including differences in the chemical composition and physical properties of the two pollutants, play critical roles.

Recent findings in mangrove forests partially explain the divergent behavior of W and Cu, showing that dissolved metal concentrations vary significantly and depend strongly on redox conditions, organic matter content, and mineralogical transformations [22]. Under strongly anoxic conditions, decreases in dissolved metal concentrations are typically attributed to the sequestration of metals into insoluble sulfide phases. Although the present study did not directly measure redox potential, the similar decrease in Cu in the diesel treatment suggests that petroleum contamination may induce localized anoxic conditions, leading to metal immobilization. Observational data from this study indicated that kerosene exhibited a higher evaporation rate than diesel[34], a physical property that may play a critical role in determining metal fate. Kerosene's faster evaporation likely leads to a more rapid reduction of the oil film covering the mud sediment surface, thereby facilitaTing greater Oxygen diffusion into the sediment. This may maintain relatively oxidizing conditions favorable for the solubility of metals such as Cu and W. In contrast, the slower evaporation of diesel, attributed to its heavier hydroCarbon chains and higher viscosity [35], creates a more persistent cover on the mud sediment surface. This restricts Oxygen diffusion, enhancing local anoxic conditions, which could stabilize metals in the solid phase and consequently decrease their concentrations in the mud sediment solution.

Another key factor explaining this behavioral difference is pollutant viscosity [36]. In multiphase systems such as water-oil-sediment mixtures, viscosity plays a crucial role in phase separation and directly influences mass transfer and material distribution across different phases (Table 2). Because of its heavier hydroCarbon chains, diesel has a higher kinematic viscosity (approximately 3–8 $mm^2.s^{-1}$) than kerosene (approximately 1.2–2.5 $mm^2.s^{-1}$), which contains shorter hydroCarbon chains [29]. When oil viscosity is high, the mass transfer of heavy metals between phases is restricted, leading to greater accumulation of these metals within the oil phase or specific mud sediment layers. Conversely, the

lower viscosity of kerosene (Table 2) allows greater mobility within the mud sediment matrix, providing more opportunity for heavy metal transfer to the aqueous phase. This results in wider pollutant dispersion throughout the surrounding envIron ment and their subsequent entry into the mud sediment aqueous extracts. The pronounced heterogeneity observed in W and Cu responses further confirms that dissolved metal dynamics depend strongly on local micro-environmental conditions, reinforcing the critical interplay among redox potential, organic matter, and mineralogical transformations in altering metal behavior [22].

A point to consider is that the incubations were carried out at field capacity, a choice made to maintain controlled and reproducible conditions across all treatments. While this is a common and accepted practice in soil-based studies, it does not fully reproduce the permanently waterlogged conditions typical of mangrove sediments. As a result, the redox chemistry and metal solubility observed here may not entirely reflect those in natural, flooded environments. Keep this in mind when interpreTing the results, especially when redox-sensitive mechanisms are invoked. Future work comparing both moisture regimes would help confirm the patterns reported here.

From an environmental perspective, both scenarios present distnct ecological concerns. Because of its lower viscosity and ability to enhance metal solubility, kerosene disperses pollutants over wider areas, extending associated ecological risks. Conversely, diesel's higher viscosity (Table 2) and the resulTing decrease in dissolved metal concentrations typically lead to pollutant accumulation near the spill site, resulTing in more persistent, localized environmental impacts. Although previous studies have reported elevated concentrations of heavy metals, including Fe, Pb, Mn, Zn, and Cu, in petroleum -contaminated sediments [9], the findings of the present study indicate that this mobilization response is highly conTingent upon the specific type of petroleum pollutant, the prevailing physicochemical conditions, and the intrinsic geochemical characteristics of each metal.

Mangrove forests are among the most productive coastal ecosystems, providing essential habitat and nursery grounds for a wide variety of commercially important species, including fish, shrimp, and crabs [37]. As a result, the sediments of these ecosystems play a fundamental role in suppor Ting coastal food webs and, ultimately, human nutrition in many coastal communities. The observed changes in metal mobility within the sediment matrix, therefore, have broader ecological implications beyond simple geochemical alteration. Although this study did not directly measure metal concentrations in biota or assess human health risks, the mobilization of heavy metals into pore water suggests a potential increase in metal bioavailability to benthic organisms. Once metals enter the food web through uptake by invertebrates and small fish, they can be transferred to higher trophic levels, including commercially harvested species [38]. Previous studies conducted in the Persian Gulf region have documented heavy metal bioaccumulation in fish and shellfish, indicaTing that sediment contamination can indeed affect seafood quality [39]. This potential pathway highlights the importance of the findings for coastal management and underscores the need for future research that directly investigates bioaccumulation and associated health risks.

Conclusion

This study showed that diesel and kerosene affect heavy metal dynamics in saturated mangrove mud sediments differently, depending on hydroCarbon type and metal. The measured elements fell into three response patterns: Group 1 (V, Pb, Ni, Cr) increased; Group 2 (Sn, Mn, Mo) decreased; and Group 3 (W, Cu) decreased under diesel but increased with kerosene. These divergent behaviors likely reflect differences in chemical composition and interactions with the sediment matrix.

The observed mobilization of heavy metals into pore water suggests increased metal availability, which may affect sediment quality. Although we did not assess toxicity and bioaccumulation, the observed trends could inform future risk assessments. Identifying pollution sources and understanding transport mechanisms remain key research priorities, along with investigaTing the specific roles of kerosene and diesel components in metal behavior under saturated conditions.

Based on these findings, we recommend: (1) preventive measures to minimize oil spills into coastal waters; (2) integrated remediation strategies combining biological approaches (e.g., planTing tolerant mangrove species) with non-biological techniques; and (3) stricter enforcement of environmental regulations to prevent contaminant transfer through the food web, particularly via fish and shrimp. These actions would help mitigate ecological and public health risks in coastal ecosystems.

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Authors' Contributions

Both authors contributed equally to this work. **N Moradi** and **O Bazrafshan:** Jointly conceived and designed the study, performed the experiments, analyzed the data, and wrote the manuscript. Both authors reviewed and approved the final version of the manuscript.

Ethical Permission

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Conflict of Interest

The authors declare no conflict of interest.

AI Use Declaration

The authors have used AI (Qwen 3.6) in 2026 for language ediTing to improve the readability of the work and Figure 1. The authors have reviewed and edited the output and take full responsibility for the publication's content.

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