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HEAVY METAL POLLUTION LINKED TO OIL AND GAS OPERATIONS IN KARAK, PAKISTAN

Asad Zamir[*1], Muhammad Arshad[*2], Basit Ali Shah[3], Afaq Ahmad[4]

[*1] *Department of Chemistry, Government Post Graduate College Karak, Pakistan*
[*2] *Department of Chemistry, University of Malakand, Pakistan*
[3,4] *Department of Chemistry, Government Post Graduate College, Dargai, Pakistan*

[*1] asadzamir000@gmail.com, [2]arshadjan774@gmail.com, [3]basiiialishah@gmail.com, [4]afaqnoorskt4456@gmail.com

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Corresponding Author: *
Asad Zamir,
Muhammad Arshad

Abstract
Oil and gas exploration releases large volumes of drilling waste that often contain toxic heavy metals, posing serious risks to surrounding ecosystems and communities. This study investigated the concentrations of arsenic (As), cadmium (Cd), lead (Pb), mercury (Hg), cobalt (Co), and copper (Cu) in drilling waste (9 samples), soils (36 samples), and drinking water (57 samples) collected around the Nashpa oil and gas plant in Karak, Pakistan. Samples were digested and analyzed using atomic absorption spectrophotometry, and the results were compared against international (WHO, FAO, EPA) and national (Pak-EPA, NEQs) standards. All measured heavy metals exceeded permissible limits in at least one medium. Soil samples showed particularly high enrichment of Cd (36.5 mg/kg), As (60 mg/kg), and Hg (28.5 mg/kg), while drinking water samples contained elevated Hg (13.5 μg/L), Cd (8.15 μg/L), and Cu (362.7 μg/L), far above WHO guidelines. Correlation analysis indicated that drilling waste discharges are the primary source of contamination, with clear pathways into both soil and groundwater. The contamination hierarchies were Cd > Hg > As > Cu > Pb > Co in soils and Hg > Cd > Pb > As > Co > Cu in water. These findings confirm that oil and gas activities in Nashpa have resulted in substantial environmental contamination, with potential risks of bioaccumulation and human exposure via water and agriculture. The study underscores the urgent need for improved waste management practices and regular environmental monitoring to safeguard soil fertility, water quality, and public health in the region.

INTRODUCTION

Heavy Metals

The term "heavy metal" generally refers to transition metals with an atomic mass over 20 and specific gravity above 5 (Budi et al. 2024). In biology, “heavy metals” refers to a series of metals and also metalloids that can be toxic to both plants and animals even at very low concentrations. Here the term “heavy metals” will be for these potentially phytotoxic elements (Rascio and Navari-Izzo 2011).

The term heavy metal refers to any metallic chemical element that has a relatively high density and is toxic or poisonous at low concentrations (Rascio and Navari-Izzo 2011).

Pollution of heavy metals is of excessive concern regarding current environmental awareness, as they are recognized to be toxic, persistent, and can accumulate in the environment over time (Budi et al. 2024). The heavy metals accumulation in the soil is poisonous to it and badly affects soil properties, which could eventually lead to infertility and reduced crop yields (Zhao et al. 2012). It also shows harmful effects in the direction of soil biota by affecting key microbial procedures and declining the number and activity of soil microbes (Zhao et al. 2012). Moreover, the soil accrued with heavy metals could limit the biodegradation of organic chemicals, and heavy metals might enter the food web through biomagnification and induce toxicity in animals and humans (Zhao et al. 2012). The toxicity of heavy metals to microorganisms is well documented (Tyler et al. 1989). At certain concentrations, metals are toxic to higher organisms, microorganisms, and plants (Tyler et al. 1989). Therefore, their presence in wastewater is not only of environmental concern but also sturdily reduces microbial activity badly affecting biological sewer water conduct processes (Tyler et al. 1989). Heavy metals released through drilling wastes can leach into soils and groundwater, leading to contamination of drinking water sources and agricultural fields.

Heavy metals can be classified into two kinds; i.e. carcinogenic and non-carcinogenic (Mohammadi et al. 2019).

Carcinogenic Heavy Metals

Arsenic (As), cadmium (Cd), copper (Cu), lead (Pb), mercury (Hg) and nickel (Ni) are classified as group 1 carcinogens by the International Agency for Research on Cancer and are utilized commercially. In this review, we used molecular pathway analysis to understand the toxicity and carcinogenic mechanisms of these metals (International Agency for Research on Cancer 2023).

Non-Carcinogenic Heavy Metals

The heavy metals Zn, Cu, Mn, and Fe were known to be associated with so many non-carcinogenic related consequences, even though Zn, Cu, and Fe were essential to life (Abd-Elghany et al. 2024).

Heavy-Metal Exposure

All efforts to compare the relative sensitivity of organisms to heavy metals or, conversely, the degree of tolerance to heavy metals displayed by various organisms, are beset by difficulties to define the degree of exposure. Organisms inhabiting the same square meter of the ground, e.g. in a site influenced by heavy-metal deposition, are far from uniformly exposed. Lichens and, in particular, bryophytes have only little chance to avoid the uptake of the deposited metal particulates owing to the surface properties of their tissues (Soltani et al. 2024) .

With only limited uptake through the above-ground biomass, vascular plants are partly protected against the direct or immediate influence of the metals by chemical immobilization mechanisms of the soil. The same mechanisms, however, promote the long-term accumulation of heavy metals in the rhizosphere, which gradually may bring about an increase in the heavy-metal exposure of the plant roots (Notten et al. 2005). Differences between species and populations in the organic compounds utilized of a given substrate are also of importance, owing to the different affinity of compounds for heavy metal ions. The degree of metal exposure at a site is often expressed as the concentration (total or extractable) measured in samples of the soil and calculated as parts per million (ppm) or (mg Kg^{-1}) dry weight (Budi et al. 2024). Comparable values between sites may be obtained in this way only if the volume-to-weight ratio (bulk density) of the soils is similar. This is usually only the case when the proportions of organic matter (humus, litter) in the soils are similar (van WESEMAEL and Veer 1992). Comparing ppm values in soils with greatly differing bulk densities may easily lead to erroneous conclusions as to the heavy-metal exposure of sites. A purely organic soil (e.g., peat or a more horizon) may contain only 8 to 10% of the amount of metal per square meter of the ground compared to a mineral soil at the same ppm value (Shary and Pinskii 2013). This is due to the great density difference between organic and mineral matter. Many studies have been published on heavy metals in the environment containing too limited information of essential soil characteristics to make comparisons with other studies possible.

A simple method of defining the 'overall' exposure to heavy metals around a defined source of emission, is to use the distance from the source.

The deposition rate usually decreases asymptotically to this distance, provided the topography is not too irregular or the main wind directions too prevailing (Norouzi et al. 2017). When the occurrence and performance of various taxonomic groups have been studied simultaneously in such deposition gradients this is a possible (maybe the only reasonable) way to assess the relative sensitivity of the groups, in a purely 'ecological' sense, to the elements contained in the deposition (Norouzi et al. 2017). This assumes that the ecological niches of these groups do not differ too much and the relative degree of exposure might or should be calibrated against, e.g., deposition measurements at selected points and soil surveys, considering the difficulties stated above.

Oil and Gas Well Drilling

Crude oil (a complex mixture) that occurs naturally, is a mixture of hydrocarbon and non-hydrocarbon compounds (Li et al. 2022). Demand for crude oil has increased intensely as a source of energy and is substantial for production industries (Sun, Wu, and Huang 2024). Several methods of manufacturing, transportation, and refining have been used to fulfill those demands resulting in substantial pollution of the environment. Crude oil products have polluted air, soil, surface water, and groundwater; therefore, there are many ways to human exposure (D'Andrea and Reddy 2014).

Oil and gas well drilling waste discharges contain toxic substances that are potentially harmful to the ecosystem (Ellis, Fraser, and Russell 2012). Drilling waste is one of the largest volumes of waste generated during oil and gas exploration and production activities (Getliff et al. 1998). The presence of heavy metals in drilling waste discharges poses a risk of contaminating the environment (Qaiser et al. 2018a). Oil and gas exploration and production are one of the major and important industrial activities in KP Province, Pakistan (We concentrated only on the Nashpa plant of oil and gas Karak, KP, Pakistan. Waste discharge from oil and gas exploration and production activities has the potential to contaminate the soil, air, surface, and subsurface of water which could lead to serious direct and indirect health problems (Jong et al. 2021). The enhanced environmental degradation due to oil and gas well drilling operations adversely affects the surrounding environmental conditions (Qaiser et al. 2018a). A large number of industries, including oil and gas installations located in Pakistan, are not equipped with or have no centralized waste treatment and specifically liquid waste treatment provisions, and therefore waste is being discharged into drains, pits, and inland areas. Since the scale of oil and gas activities in the region directly determines the extent of this waste generation and contamination, it is important to understand the magnitude of exploration in Pakistan, particularly in Khyber Pakhtunkhwa.

An approximate 143,619.69 km^2 area in Pakistan and 18,890.66 km^2 area (approximately 13.15% of the total area) in KP Province is under oil and gas exploration activities as displayed in Khyber Pakhtunkhwa Board of Investment and Trade (KPBIOT, 2020), Khyber Pakhtunkhwa. The total recoverable crude oil reserves in KP are around 148 billion barrels, while the recoverable natural gas reserves are around 2.321 trillion cubic feet (TCF), and probable crude oil reserves are more than 500 million barrels and probable natural gas reserves are over 9 TCF (KPBOIT, 2020). The province is providing low-risk opportunities for oil and gas exploration due to the higher success ratio of oil and gas wells being drilled. Major reservoirs of oil and gas that have been explored in Karak and Kohat Districts, depict encouraging oil and gas exploration targets in the region. More than 10 oil and gas fields have been discovered in the districts of Kohat and Karak subbasin areas, with an approximate production of 16.279021 billion barrels of crude oil and 1312.07 million cubic feet of natural gas according to Federal Bureau of Statistics, Pakistan (Pakistan Bureau of Statistics, 2021). Nashpa plant of oil and gas is one of the largest sources of oil and gas exploration. The higher success ratio and the encouraging oil and gas production are positive benchmarks for the future oil and gas exploration prospects of KP. This rising trend of oil and gas exploration would also enhance environmental impacts due to the increased oil and gas drilling activities and subsequent waste discharge.

In light of the growing oil and gas exploration activities in Karak, there is a critical need to assess the extent of environmental contamination caused by drilling discharges. The specific objectives of this study were; to analyze concentrations of selected heavy metals (As, Cd, Pb, Hg, Co, and Cu) in drilling waste, surface soils, and drinking water collected around the Nashpa oil and gas plant in Karak; to compare the measured concentrations against national (Pak-EPA, NEQs) and international (WHO, FAO, EPA) permissible limits.

LITERATURE REVIEW

Globally, oil and gas exploration has been identified as a major source of heavy metal pollution, as drilling wastes, cuttings, and produced waters often contain toxic elements such as As, Cd, Pb, Hg, Co, and Cu. These pollutants can leach into soils and groundwater, posing ecological risks and threatening community health near oilfields (Ellis et al., 2012; Jong et al., 2021). Comparisons with international standards (WHO, EPA, FAO) in previous studies have consistently shown exceedances, underscoring the importance of site-specific assessments.

(Orosun et al., 2016) highlight that heavy metal contamination in drinking water has been increasingly linked to industrial activities, particularly mining and smelting, which release toxic metals into nearby water sources. Studies indicate that heavy metals such as lead, cadmium, and arsenic can significantly exceed safety limits, posing serious health risks to communities relying on contaminated water. Industrial activities such as mining and smelting have been shown to significantly elevate heavy metal levels in water sources, posing neurological and developmental risks.

In the study titled *Metal contamination of surface soils of industrial city Sialkot, Pakistan*, (Malik, Jadoon, & Husain, 2010) highlighted that groundwater contamination due to heavy metals poses significant risks to both environmental and public health. The research emphasized the high concentrations of heavy metals such as lead and copper, which were found to exceed permissible limits, indicating a direct threat to water quality. This aligns with the findings in the current study on heavy metal adulteration in soil and water around the Nashpa oil and gas plant, where similar concerns about heavy metal exposure are raised. The commonality in these studies points to a pressing need for comprehensive assessments of heavy metal contamination in various contexts, particularly in industrial and oil extraction regions.

In the study by (Esosa Imarhiagbe & Omoregbe Obayagbona, 2020), the environmental impacts of oil-laden drill cuttings were extensively evaluated, highlighting the significant challenges posed by improper disposal practices in oil exploration. The authors emphasize that the biodegradation of drilling waste through natural microbial processes offers a promising avenue for mitigating the adverse effects on both terrestrial and aquatic ecosystems. This research aligns with the focus of the current study on heavy metal contamination from oil and gas operations, as both highlight the pressing need for effective waste management strategies in petroleum-related activities.

The study by (Ofosu et al., 2021) investigated the concentration of heavy metals, including lead, nickel, and iron, in two fish species from an oil drilling area in Ghana, highlighting the significant public health risks associated with their consumption. This research underscores the pressing concern regarding heavy metal pollution in aquatic ecosystems near oil extraction sites, which parallels the concerns raised in the current study about heavy metal adulteration surrounding the Nashpa oil and gas plant in Karak. Notably, the findings from Ghana indicate that heavy metal concentrations in fish can exceed safe consumption limits, thus warranting a comprehensive assessment of similar risks in your study area.

A review by (Riffat et al., 2023) specifically focused on the Federally Administered Tribal Areas (FATA) of Pakistan, where water reservoirs, including both surface and groundwater, are contaminated with toxic metals. The authors revealed that chromium (Cr), cadmium (Cd), copper (Cu), lead (Pb), nickel (Ni), iron (Fe), and manganese (Mn) are among the most hazardous contaminants, and their accumulation in water poses serious health risks. The review highlights that the levels of these contaminants often exceed the acceptable limits set by the World Health Organization (WHO) and the Pakistan Environmental Protection Agency (Pak EPA). This underscores the critical need for proper waste treatment and monitoring to mitigate the adverse effects of heavy metal pollution in the region.

Several of these studies compared observed concentrations with international and national regulatory benchmarks, consistently reporting exceedances and associated risks. However, most investigations in Pakistan have either focused on industrial zones or agricultural regions, without integrating drilling waste, soils, and drinking water into a single assessment. To our knowledge, no comprehensive study has been conducted in the Nashpa oilfield region of Karak, despite its significance as one of the largest oil and gas production sites in Khyber Pakhtunkhwa. This study therefore aims to fill this gap by systematically analyzing heavy metal concentrations in drilling waste, surface soils, and local drinking water, and by evaluating them against WHO, FAO, EPA, and Pak-EPA standards to assess potential ecological and public health risks.

MATERIALS AND METHODS

Study Area Description

The study was conducted in the vicinity of the Nashpa oil and gas plant, located in the Karak District of Khyber Pakhtunkhwa (KP) Province, Pakistan. The exact geographic coordinates of the study site are approximately 33.1216° N latitude and 71.1462° E longitude, as confirmed using Google Maps. The Nashpa plant is one of the largest oil and gas exploration and production facilities in KP, and it plays a significant role in regional energy supply. However, its operations have raised concerns about potential environmental degradation due to untreated waste discharges.

Karak District lies in the semi-arid region of KP and is characterized by limited groundwater resources, making local communities highly dependent on available soil and water for agriculture and domestic use. The Nashpa sub-basin has become an important target area for hydrocarbon exploration, with multiple wells drilled and active production sites. Industrial activities at the Nashpa plant involve drilling, refining, and waste disposal, all of which have the potential to release toxic heavy metals into the surrounding soil and water bodies.

Collection of Samples

Drilling Waste Samples

Drilling waste discharge samples were collected from nine active oil well points located around the Nashpa oil and gas plant. At each point, approximately 1 liter of liquid drilling waste was collected in clean, pre-washed polyethylene bottles. Immediately after collection, the bottles were sealed tightly, labeled (DW1–DW9) as in Figure 1, and placed in plastic bags to avoid leakage or cross-contamination. The samples were preserved in an icebox and transported to the laboratory on the same day to maintain integrity. In the laboratory, all samples were stored at 4 °C prior to analysis. Composite samples were prepared to ensure representativeness, and all procedures strictly followed standard sampling protocols to minimize contamination risks and maintain analytical reliability.

Soil Samples

The heavy metal contaminated soils were collected in plastic bags from 36 different sites (The bags were marked and labeled with S1, S2,... S36 respectively to samples site as in Figure 1) in the research area, and their geographic locations were shown in Figure-1. At each site, 1Kg soil was taken from the surface (0-15 cm). Parts of the soils were sent for DNA extraction directly, and the rest soils were blended and sieved through a 2-mm mesh to remove stones and plant debris for soil property analysis.

Drinking Water Samples

The local tube wells and waste discharge effluent water samples were collected in 1.5 liters PET bottles/containers from different 57 points/sites and their geographic locations were shown in Figure-1. The bottles/containers were clearly marked and labeled for the identification of the sample. The liquid samples after the collection was stored for preservation in an icebox and shifted to a laboratory on an immediate basis for further processing and analysis. In order to attain accuracy and representativeness, composite waste discharge samples were collected from each sampling point.

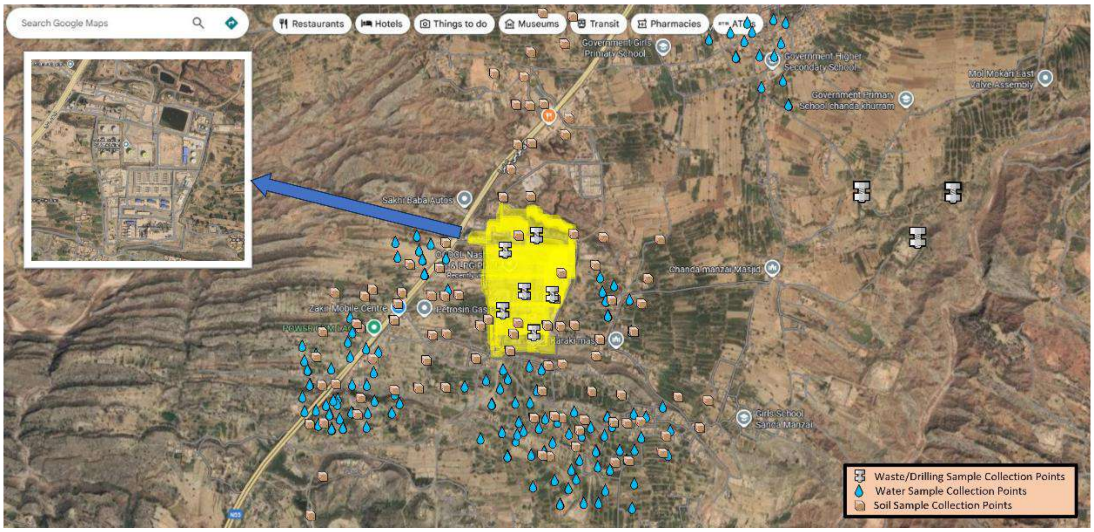


Fig. 1. Identification of sampling points of exposed to Nashpa plant of oil and gas Karak, KP, Pakistan.

Sample Analysis

In order to determine realistic heavy metal contents in samples – specifically in soil samples – prior to analysis acid digestion was strongly recommended for soil samples because heavy metals, mostly in soil, are bonded strongly with mineral matrix Rump H.H (1999). Briefly, air-dried soil (0.5 g) was taken from a thoroughly homogenized soil sample, ground, placed in a conical flask, and 2 ml nitric acid (70%), 3 ml hydrofluoric acid (40%), and 6 ml hydrochloric acid (35%) were added. A transparent solution was attained by refluxing the mixture on a heating plate. The attained solution was cooled to remove excessive hydrofluoric acid, and 15 ml of saturated boric acid was added, after mixing volume was made up to 100 ml with the help of interference-free double de-ionized water Rump H.H (1999). The obtained solution was filtered on Whatman grade 42 paper (Whatman International, UK) and the filtrate was utilized for analytical determination of heavy metals concentration in soil. The water and drilling waste samples were also digested with nitric acid and hydrochloric acid as mentioned above Rump H.H (1999).

Atomic absorption spectrophotometry (AAS) was utilized for determining selected heavy metals (As, Pb, Hg, Cd, Co and Cu) in the affected soil and water samples collected from near around oil and gas Nashpa Plant Karak USEPA 2007. The digested wastewater and soil extract were analyzed after dilution with double-distilled water, where required.

Quality Assurance and Quality Control

Following the sampling guidelines and standard analytical methods Armonk et al. (2013), the concentration of each metal was determined using the standardized analytical conditions and Atomic Absorption Spectrophotometry (AAS) system. The blank was prepared and carried out through the steps of the analytical process in the same way as sample solutions/extracts were prepared for the analytical determination of heavy metals. The precision of the analytical methods, equipment, and accuracy of the results was checked through standard reference material Armonk et al. (2013). The sets of results matched within ±1.0 to ±1.5%.

Data Analysis

The acquired data was processed and statistically analyzed for the statistical parameters through the utilization of IBM SPSS Statistics version 22 software. Basic statistical parameters (mean, median, standard deviation, skewness, minimum, and maximum) were calculated to analyze the data statistically for the selected heavy metals distribution in the affected soil, and local water that are exposed to the Nashpa plant of oil and gas. Item-to-item correlation between studied heavy metals in above mentioned affected terms was also determined statistically, and metal-to-metal correlation matrices were also developed.

Environmental monitoring is essential to evaluate whether waste discharge regulatory frameworks are sufficiently protective (Bakke et al., 2013). In this study, the drilling waste discharge samples collected around the Nashpa oil and gas plant will be analyzed for selected heavy metals (As, Cd, Pb, Hg, Co, and Cu). The mean concentrations obtained will be compared against international and national standards, including FAO/WHO guidelines (Zondo, 2021), the National Environmental Quality Standards of Pakistan (Pak-EPA, 2000), and the Maximum Contaminant Levels (MCL) and Maximum Contaminant Level Goals (MCLG) defined by the U.S. Environmental Protection Agency (EPA, 2018). Similarly, the concentrations of heavy metals in drinking water will be evaluated in relation to WHO guidelines (WHO, 2011) and EPA standards (EPA, 2018), while soil concentrations will be compared with FAO/WHO permissible limits (Zondo, 2021). This comparative evaluation will allow us to determine whether the measured levels of heavy metals exceed acceptable thresholds and to assess the potential risks posed to environmental and human health.

RESULT AND DISCUSSION

Heavy metal accumulation in oil well drilling waste discharge

The analysis of drilling waste discharge collected around the Nashpa oil and gas plant in Karak revealed significant accumulations of toxic heavy metals. The measured concentrations were compared against Maximum Contaminant Level Goals (MCLG), Maximum Contaminant Levels (MCL), and WHO/FAO permissible limits (Bakke et al., 2013; Zondo, 2021; WHO, 2011; EPA, 2018). The mean concentrations, along with statistical parameters, are summarized in Table 1, while visual comparisons are shown in Figures 2–3.

Arsenic (As)

Arsenic concentrations in drilling waste discharge ranged from 2.05–2.58 µg/L, with a mean value of 2.33 µg/L (Table 1). These levels exceeded both WHO (0.1 µg/L) and NEQs (1 µg/L) guidelines table 2, indicating contamination beyond safe thresholds. As is commonly mobilized from drilling fluids and formation rocks, and its presence in high amounts raises serious concerns due to its carcinogenic nature. The statistical data (Table 1) show low variability (SD = 0.29), suggesting consistent As enrichment across sites.

Cadmium (Cd)

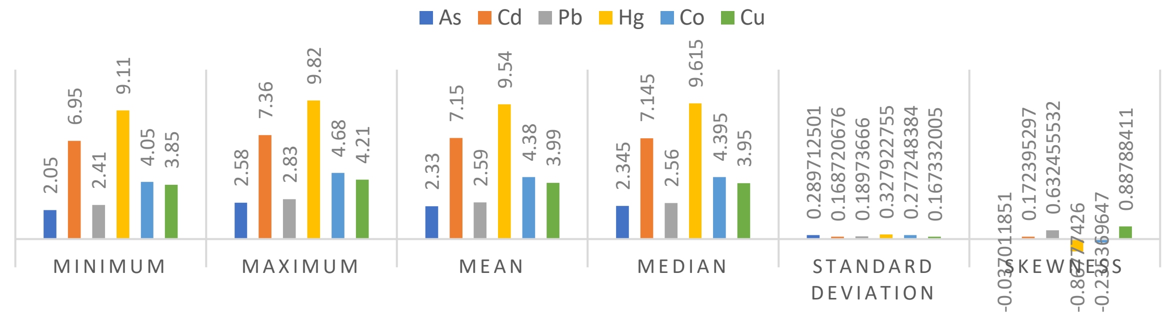
Cadmium recorded a mean value of 7.15 µg/L, with a range of 6.95–7.36 µg/L (Table 1). This was far above the MCL (0.01 µg/L) and WHO permissible limit (0.01 µg/L) table-2. Figure 2 clearly illustrates Cd as also most enriched contaminants after the Hg. The elevated Cd concentrations likely originate from drilling additives and corrosion of drilling machinery. Its high mobility and bioaccumulative nature make it a critical pollutant, posing risks of kidney damage and carcinogenic effects upon chronic exposure.

Table 1. Statistical parameters of selected Heavy metal concentrations in the drilling waste discharge (µg/L)

Parameters	As	Cd	Pb	Hg	Co	Cu
Minimum	2.05	6.95	2.41	9.11	4.05	3.85
Maximum	2.58	7.36	2.83	9.82	4.68	4.21
Mean	2.33	7.15	2.59	9.54	4.38	3.99
Median	2.345	7.145	2.56	9.615	4.395	3.95

Standard deviation	0.289712501	0.168720676	0.18973666	0.327922755	0.277248384	0.167332005
Skewness	-0.037011851	0.172395297	0.632455532	-0.86777426	-0.23536964	0.88788411

Fig-2: relative comparasions of statistical parameters of selected heavy metals (µg/L) in drilling waste discharge.



Lead (Pb)
Lead concentrations varied from 2.41-2.83 µg/L, with a mean of 2.59 µg/L as in table 1. Although Pb values did not exceed the FAO/WHO soil reference limit of 100 µg/L, they were above the NEQs limit of 0.1 µg/L for water (Table 2). Pb contamination is associated with lubricants, drilling equipment, and rock cuttings. The relatively moderate variability (SD = 0.18) indicates widespread low-to-moderate Pb accumulation, which nonetheless poses risks due to its persistence and neurotoxic effects.

Mercury (Hg)
Mercury levels in drilling waste were found to be extremely high, ranging from 9.11-9.82 µg/L, with a mean of 9.54 µg/L. This far exceeded the MCL (0.5 µg/L) and WHO guideline (0.1 µg/L). The statistical data (Table 1) highlight Hg as the most variable contaminant (SD = 0.32). Mercury is highly toxic and persistent, and its presence at such elevated levels suggests severe environmental threats. Once released into aquatic systems, Hg can transform into methylmercury, which bioaccumulates in food chains, amplifying risks to local communities.

Table 2. Relative comparison of mean values of heavy metal concentrations in the drilling waste discharge to MCLG, MCL and WHO (µg/L)

Chemicals	CASRN Number	FAO/WHO	NEQs	Mean
Arsenic (As)	7440-38-2	0.1	1	2.33
Cadmium (Cd)	7440-43-9	0.01	0.01	7.15
Lead (Pb)	7439-92-1	0.065	0.1	2.59
Mercury (Hg)	7487-94-7	0.1	0.5	9.54
Cobalt (Co)	7440-48-4.	0.05	1	4.38
Copper (Cu)	7440-47-3	0.017	1	3.99

Cobalt (Co)
Cobalt concentrations ranged between 4.05-4.68 µg/L, with a mean of 4.38 µg/L(Table 1). While Co is an essential micronutrient, the recorded levels exceeded the MCLG of 0.05 µg/Land NEQs (1µg/Lµg/L). Elevated Co may originate from natural mineralization and drilling equipment wear. Excessive Co can disrupt soil microbial

communities and potentially bioaccumulate in crops, leading to ecological imbalance.

Copper (Cu)

Copper concentrations averaged 3.99 µg/L, with a range of 3.85-4.21 µg/L(Table 1). These values exceeded WHO permissible limits (0.017 µg/L), though they remained below the FAO/WHO soil reference of 100 µg/L. Figure 3 shows Cu enrichment across all discharge sites, likely due to corrosion of drilling machinery and use of Cu-containing additives. Although less toxic than Cd and Hg, excess Cu interferes with soil fertility and microbial activity.

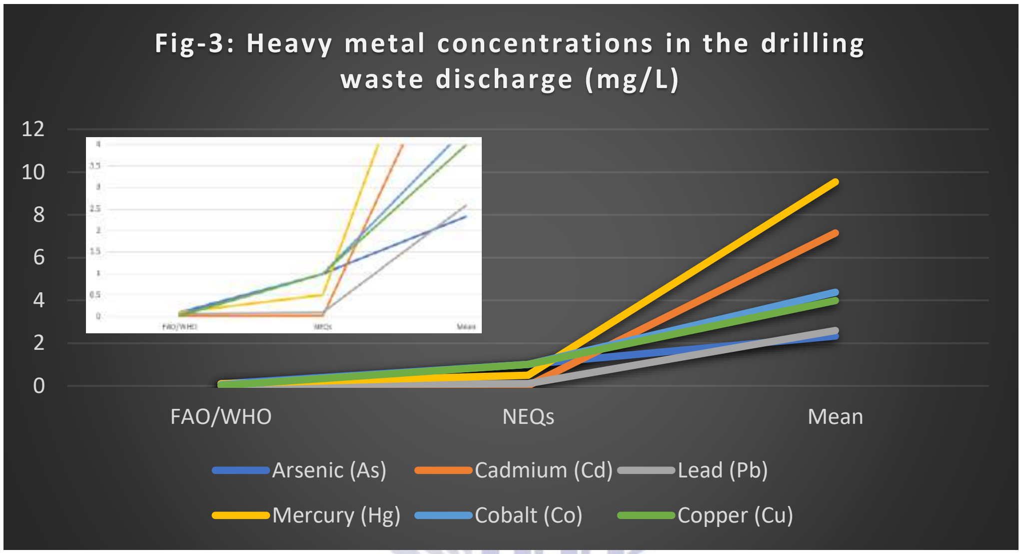


Fig-3: Heavy metal concentrations in the drilling waste discharge (mg/L)

Comparative Evaluation with Standards

The comparative evaluation (Table 2; Figure 3) revealed that all six metals exceeded WHO and NEQs permissible levels. Cd, Hg, and As showed the most critical exceedances, while Pb, Co, and Cu exceeded some but not all reference limits. The order of enrichment was:

Hg > Cd > As > Co > Cu > Pb

This enrichment hierarchy confirms that drilling wastes are a major source of heavy metal contamination, consistent with global studies on oil and gas exploration sites.

Heavy metal accumulation in surface soils and their characteristics

The concentrations of arsenic (As), cadmium (Cd), lead (Pb), mercury (Hg), cobalt (Co), and copper (Cu) in surface soils surrounding the Nashpa oil and gas plant and statistical parameters are summarized in Table 3 and figure 4, while relative comparison of mean concentration of selected heavy metals with WHO/FAO are shown in Table 4 and visualized in Figures 5. The measured concentrations clearly demonstrate that drilling waste discharges have led to substantial heavy metal enrichment in the local soils.

Table 3. Statistical parameters of selected heavy metals (mg/Kg) in soil.

Parameters	As	Cd	Pb	Hg	Co	Cu
Minimum	13	17	12	23	11	68
Maximum	89	52	61	38	42	102
Means	60	36.5	43.5	28.5	22.5	78.75
Median	69	38.5	50.5	26	18.5	72.5
Standard deviation	32.7618	14.4799	22.4277	6.702	13.4784	15.6498
Skewness	-1.47422	-0.80634	-1.35022	1.651823	1.568261	1.883365

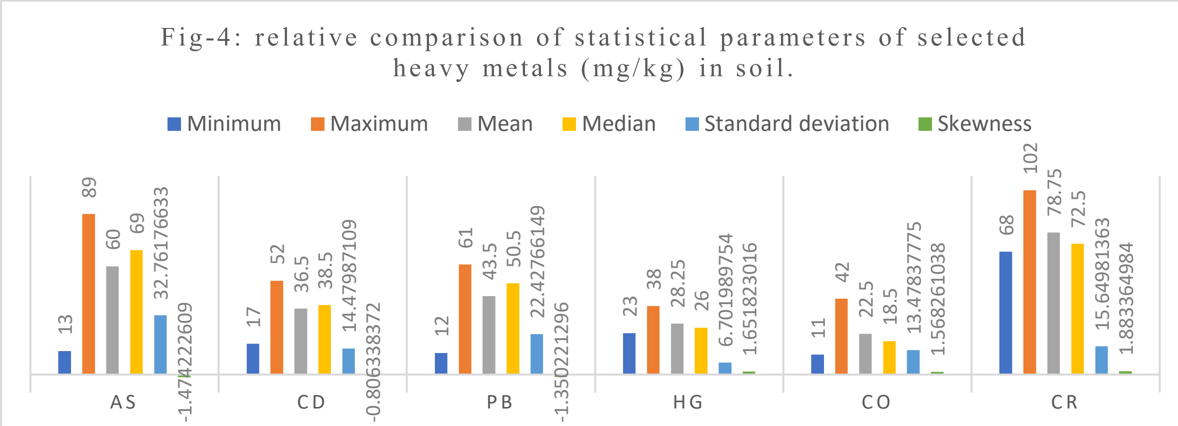
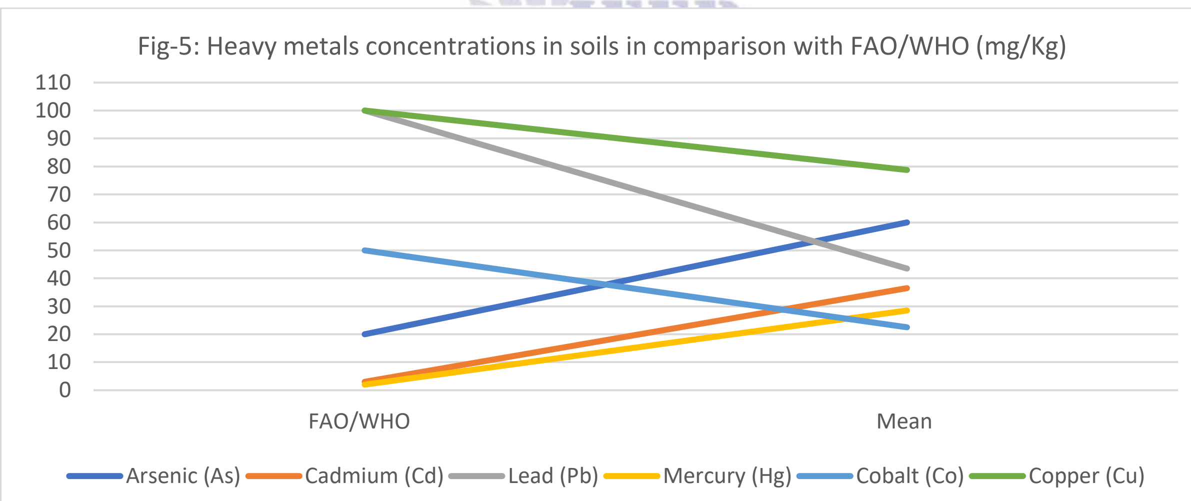


Table-4: Heavy metals concentrations in soils in comparison with FAO/WHO (mg/Kg)		
Metal	**FAO/WHO**	**Mean**
Arsenic (As)	20	60
Cadmium (Cd)	3	36.5
Lead (Pb)	100	43.5
Mercury (Hg)	2	28.5
Cobalt (Co)	50	22.5
Copper (Cu)	100	78.75



Arsenic (As)

Arsenic concentrations in soils ranged from 13–89 mg/kg, with a mean value of 60 mg/kg (Table 3). Compared with the FAO/WHO recommended limit of 20 mg/kg, the measured mean value was approximately three times higher (Table 4, Figure 5). This strong enrichment indicates significant anthropogenic input, likely from drilling muds and fluid releases. Arsenic enrichment in soils poses a severe risk for groundwater leaching and eventual food chain contamination.

Cadmium (Cd)

Cadmium concentrations were notably elevated, ranging between 17–52 mg/kg, with a mean of 36.5 mg/kg (Table 3). These values were more than tenfold higher than the FAO/WHO guideline of 3 mg/kg (Table 4, Figure 5). The high Cd enrichment in soils aligns with its elevated levels in drilling waste discharge, suggesting a clear pathway of contamination. Given Cd's high mobility, its presence in soils creates a high risk of uptake by crops, with direct implications for human health.

Lead (Pb)

Lead levels in soils varied from 12–61 mg/kg, with a mean of 43.5 mg/kg. Although these concentrations remained below the FAO/WHO permissible limit of 100 mg/kg, they were still elevated compared to natural background values (Table 4). Pb enrichment can be attributed to lubricants, drilling fluids, and corrosion of well pipes. Chronic accumulation of Pb in soils, even below the safety threshold, remains a concern due to its non-biodegradable nature and potential transfer into plants.

Mercury (Hg)

Mercury in surface soils ranged from 23–36 mg/kg, with a mean of 28.5 mg/kg (Table 3). This value was over 14 times higher than the FAO/WHO reference of 2 mg/kg (Table 4). Hg contamination in soils is particularly concerning given its ability to volatilize and contaminate both terrestrial and aquatic systems. Figure 5 shows a narrow range of values, indicating uniform distribution of Hg across the sampling sites. Such elevated levels represent a major ecological and public health hazard.

Cobalt (Co)

Cobalt concentrations ranged between 11–42 mg/kg, with a mean of 22.5 mg/kg (Table 3). These levels were below the FAO/WHO permissible limit of 50 mg/kg (Table 4). However, enrichment above natural background values suggests anthropogenic contributions from drilling activities. While Co is an essential trace element, its excessive accumulation may disrupt soil microbial activity and reduce soil fertility.

Copper (Cu)

Copper levels were the highest among all measured metals, ranging from 68–102 mg/kg, with a mean of 78.75 mg/kg (Table 3). Although the mean value did not exceed the FAO/WHO permissible limit of 100 mg/kg(Table 4, Figure 5), it approached the threshold, indicating strong enrichment likely derived from drilling fluid additives and corrosion of drilling equipment. Elevated Cu levels may lead to phytotoxicity and reduced microbial diversity in soils.

Statistical Interpretation of Soil Data

The statistical parameters (Table 3; Figure 4) revealed significant variability among metals. As, Cd, and Pb showed strong negative skewness, indicating dominance of higher concentrations across the majority of samples. Hg, Co, and Cu displayed positive skewness, reflecting localized hotspots of elevated contamination. The standard deviations for As (32.7 mg/kg) and Pb (22.4 mg/kg) indicate considerable variability, while Hg displayed a narrower distribution (SD = 6.7 mg/kg), suggesting more uniform deposition.

Comparative Evaluation with Standards

Figure 5 compares soil heavy metal concentrations with FAO/WHO permissible limits. The results indicate that Cd, As, and Hg far exceeded international safety thresholds, while Cu approached the limit. Pb and Co were within permissible ranges but still showed enrichment compared to background levels. The contamination hierarchy in soils was:

Cd > Hg > As > Cu > Pb > Co

This order differs slightly from the drilling waste pattern, highlighting how certain metals (Cd, Hg, As) persist more strongly in soils due to their geochemical properties.

Heavy metal concentrations in surface and underground drinking water

Drinking water samples (tube wells and pressure pumps) collected around the Nashpa oil and gas plant revealed heavy metal contamination above permissible levels. The descriptive statistics are presented in Table 5 and Figure 6, while comparison with WHO and USEPA (MCL/MCLG) standards is shown in Table 6 and Figure 7.

Table 5. Statistical parameters of selected Heavy metal concentrations in the drinking water (µg/L)

Parameter	As	Cd	Pb	Hg	Co	Cr
Minimum	10.94	5.18	9.89	9.27	115.82	221.11
Maximum	17.87	12.1	17.56	16.92	163.99	413.92
Mean	14.58	8.15	12.97	13.54	134.63	362.74
Median	11.755	8.16	12.97	13.49	130.37	278.965
Standard deviation	3.234161406	2.869018415	3.255225287	3.405704773	20.6158	89.23883
Skewness	1.854053935	0.476084178	0.604312469	-0.238807359	1.236479	0.801263

Fig-6: Statistical parameters of selected heavy metal concentrations in the drinking water (µg/L)

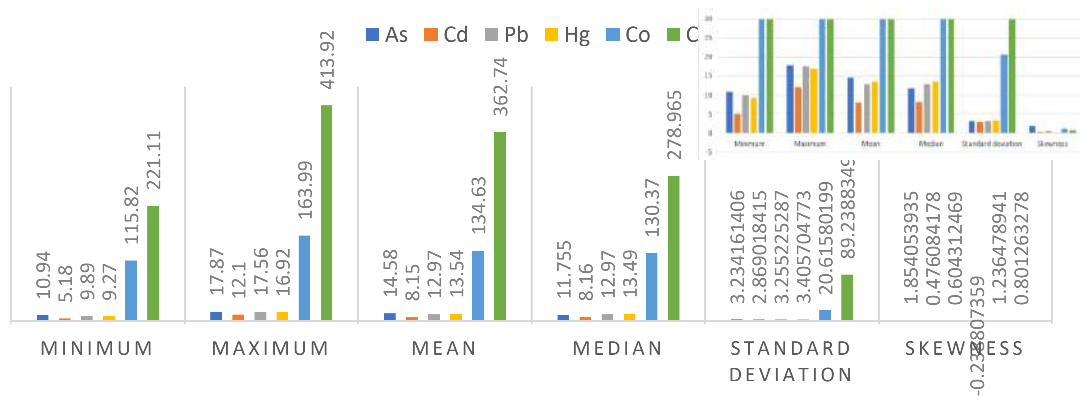


Table-6 : Heavy metal concentrations in the drinking water to MCLG, MCL and WHO (µg/L)

Chemicals	MCLG (µg/L)	MCL (µg/L)	WHO (µg/L)	Mean (µg/L)
Arsenic (As)	0	10	10	14.58
Cadmium (Cd)	5	5	3	8.15
Lead (Pb)	0	15	10	12.97
Mercury (Hg)	2	2	6	13.54
Cobalt (Co)	1	107	100	134.63
Copper (Cu)	100	100	200	362.74

Arsenic (As)

Arsenic concentrations in drinking water ranged between 10.94—17.87 µg/L, with a mean of 14.58 µg/L (Table 5). While this mean value is exceed the WHO and EPA permissible limit of 10 µg/L, its detection across all samples indicates a persistent contamination source. Chronic rich-level As exposure has direct concerning to chronic diseases due to its cumulative carcinogenic effects.

Cadmium (Cd)

Cadmium was detected at very high concentrations, ranging from 5.18—12.10.1 µg/L, with a mean of 8.15 µg/L. This exceeded both the WHO guideline of 3 µg/L and the EPA/NEQs limit of 5 µg/L (Table 6). Figure 7 illustrates that Cd is one of the most enriched metals in drinking water. Given Cd's strong bioaccumulation potential, its presence in drinking water represents a critical public health concern.

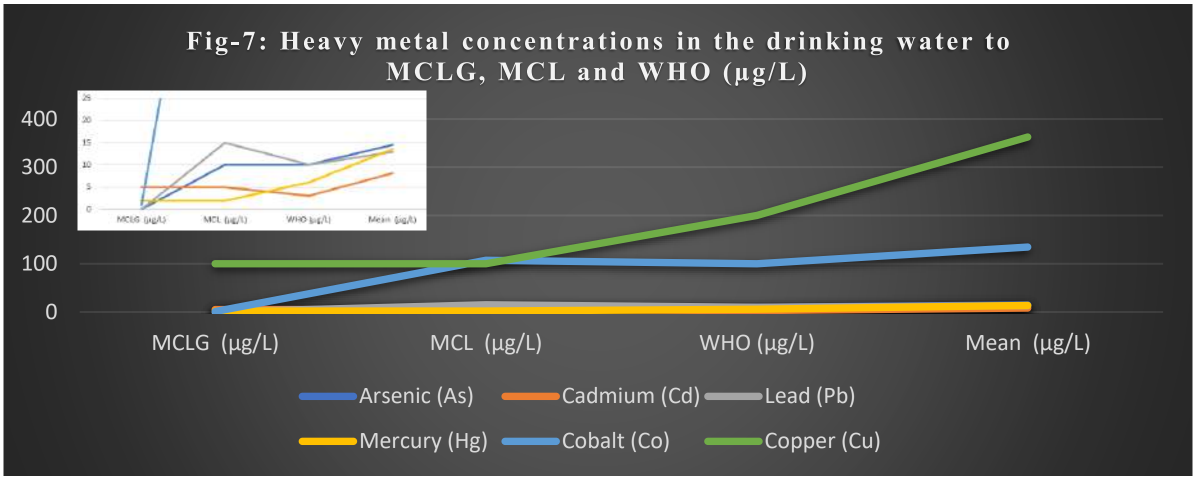


Fig-7: Heavy metal concentrations in the drinking water to MCLG, MCL and WHO (µg/L)

Lead (Pb)
Lead concentrations varied between 9.89—17.56 µg/L, with a mean of 12.97 µg/L. These values exceed the WHO limits 10 µg/L and low than EPA limits of 15 µg/L, but their detection indicates anthropogenic input. Pb contamination likely originates from leaching of drilling wastes into groundwater aquifers. Even at sub-threshold levels, Pb is of concern due to its neurotoxicity, particularly for children.

Mercury (Hg)
Mercury concentrations in drinking water ranged widely, from 9.27—16.92 µg/L, with a mean of 13.54 µg/L (Table 5). These values exceeded the WHO guideline (6 µg/L) and EPA limit (2 µg/L) by a significant margin (Table 6). Figure 8 shows Hg as one of the dominant contaminants. The presence of Hg at such elevated levels suggests strong input from drilling wastes. Given Hg's high toxicity and tendency to form methylmercury, this represents a serious ecological and health hazard.

Cobalt (Co)
Cobalt concentrations were measured between 115.82—163.99 µg/L, with a mean of 134.63 µg/L (Table 5). These values exceeded the MCLG of 1 µg/L, though they were within the broader WHO/NEQs permissible range (100–107 µg/L). Elevated Co may affect soil-water interactions and contribute to bioaccumulation in aquatic organisms, although its concentrations were not as alarming as Cd or Hg.

Copper (Cu)
Copper concentrations ranged from 221.11—413.92 µg/L, with a mean of 362.74 µg/L. These levels are well exceeds the WHO permissible limit of 200 µg/L, MCLG 100 µg/L and MCL100 µg/L limits (Table 6).

Statistical Interpretation of Water Data
The statistical parameters (Table 5; Figure 6) reveal moderate variability in most metals, with higher deviations observed for Hg (SD = 3.40 µg/L) and Co (SD = 20.6 µg/L), suggesting localized hotspots of contamination. Skewness values indicate positive skew for As, Cd, and Pb, meaning most samples had concentrations below the mean but a few sites showed much higher values. Negative skew for Hg indicates more consistent contamination across sites.

Comparative Evaluation with Standards

Figure 6 and 7 illustrate the comparison of mean concentrations with WHO and EPA standards. The analyzed heavy metals significantly exceed the strictest regulatory standards. Specifically, Arsenic (As), Cadmium (Cd), Lead (Pb), Mercury (Hg), Cobalt (Co), and Copper (Cu) all show mean values that are higher than their respective MCLG and WHO limits, with the most pronounced exceedances seen for Cobalt (Co) at 134.63 μg/L (compared to MCLG of 1 μg/L) and Copper (Cu) at 362.74 μg/L (compared to WHO limit of 200 μg/L), indicating a potential risk to water quality and public health. The contamination hierarchy in drinking water was:

Hg > Cd > Pb > As > Co > Cu

CONCLUSION

The present work is concerned with the estimation and detection of the concentration of some heavy metals (As, Pb, Cd, Cu, Hg and Co) in soil, and water that are exposed to Nashpa plant of oils and gas Karak. The water which is excreted or waste product of the plant contains very high concentrations of heavy metals. This water is a hazard to the animals, plants and soils fertility. Both underground and surface water was heavy metal-contaminated. Both kinds of water are dangerous to plants and animals' lives. The lives of people who are living near to Nashpa plant of oil and gas in the range of 3Km; are in danger because these people are much more exposed to various carcinogenic heavy metals (As, Pb, Cd, Cu, Hg and Co) that are explored during the exploration of oil and gas. The estimated metals were measured by atomic absorption spectrophotometer.

Although this study did not include direct biomonitoring of exposed populations, the elevated concentrations in soil and water suggest a high probability of human exposure through drinking water and crop uptake pathways.

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