



Heavy metals concentration in soil, surface water, and physicochemical analysis of oilfield wastes of Thar-Jath oilfields, South Sudan

Bior J A^{*1,2}, ¹FozaoK F¹, Tsamo C³, Suh C E⁴

¹Department of Petroleum Engineering, National Higher Polytechnic Institute (NAHPI), The University of Bamenda, P.O. Box 39 Bambili, North West Region, Cameroon

²Department of Chemistry, John Garang Memorial University of Science and Technology, South Sudan

³Department of Agricultural and Environmental Engineering, College of Technology (COLTECH), The University of Bamenda, P.O. Box 39 Bambili, North West Region, Cameroon

⁴Department of Geology, Mining and Environmental Science, Faculty of Science, The University of Bamenda, P.O. Box 39 Bambili, North West Region, Cameroon

Received Date: August 26, 2025; **Accepted Date:** September 10, 2025; **Published Date:** September 23, 2025;

***Corresponding author:** BIOR JAMES AKOI, The University of Bamenda-Cameroon North-west Region, Cameroon. Email: juniorbior25@gmail.com

Abstract

Introduction: Environmental pollution by heavy metals is occurring on a vast and unprecedented scale around the globe, with incessant increase in anthropogenic activities. The release of various organic and inorganic contaminants has continued to rise. Some of these activities include oil industrialization, Agricultural activities, and emission. Among the various categories of pollutants, heavy metals have been identified as one of the priority because they posed deleterious effects on both plants, animals, and the environment. Heavy metals are not biodegraded by microbial activities rather they persist and are transmitted along the food chain with a high degree of bioaccumulation. Although heavy metals are ubiquitous and present in all segment of environment, their concentrations in soil and water continued to rise since soil continued to acts as reservoirs of the metals in the environment. This study provides details on heavy metals in soil and surface water of Thar-Jath oilfields as a results of oilfields wastes.

Method; Eight soils and surface water samples were collected from different sampling points (around the production wells and the oil waste deposition areas of Thar-Jath) in replicate. The concentrations for the heavy metals quantification in soil, and surface water samples were carried out from the vicinity of production wells and the oilfields waste deposition areas at depths of (0-10cm) and (10-30cm). Characterization involving heavy

metal concentrations was carried out using an atomic spectrophotometer (AAS Unicam 969). Exchangeable cations and anions were measured using a flame photometer and UV/Visible spectrometer (Unicam Helios Gamma, UVG 073201; Spectronic 21D). Dissolved Oxygen (APHA-4500 C).

Results: There was a slight significant difference in the mean values of heavy metal concentrations in all the soil and water samples determined. The heavy metals Pb, Cd, Fe, Hg, As, Zn, and Cr concentrations in soil samples exceeded the standard permissible limits. From the results obtained, the production wells and the oilfields waste deposition areas had a direct impact on the concentrations of the heavy metals determined.

Keywords: Concentration, Heavy metals, Oilfield wastes, physicochemical analysis, Surface water

Introduction

Oil and natural gas are major industries in the energy market in the world and play an influential role in the global economy as the world's primary fuel source. The processes and systems involved in producing and distributing oil and gas are highly complex, capital-intensive, and require state-of-the-art technology Schlumberger (2021). The consequences of the global demand for the oil and gas industry's natural resources have increased to meet and satisfy the demand The World Economic

Forum (2012). Exploitation activity of oil and gas would always be with some environmental side effects. Oil spills, damaged land, accidents, fires, and incidents of air and water pollution have all been documented as environmental impacts from the oil production and gas industry at various times and locations. An increase in human activities with a lack of adherence to environmental protection laws has led to the indiscriminate discharge of unwanted substances into the environment. The effect of this oilfields waste discharge results in different forms of pollution in most developing and underdeveloped countries such as South Sudan. Pollution is defined as the release of harmful unwanted materials into the environment that result from the excessive discharge of harmful gases (CO, SO₂, and NO₂) and various forms of waste. These unwanted materials eventually bring out potentially hazardous elements known as “heavy metals” (major and trace) such as arsenic, lead, copper, and cadmium. These metals, when released in concentrations above acceptable levels, become toxic in the air, waters (both ground and surface), stream sediment, and soil, and they invariably enter humans through the food chain GWRAC (1997), Singh (1997). Management skills of these sources and contaminants are challenging unless a concise schedule for the planned wastes and pollutants is in place before development. Since the expense of managing waste and contaminants produced by crude oil and natural gas processing is typically high, responsible companies tend to avoid this cost. Production management is the main factor of the greenhouse effect since unusable gas has been released into the air which can affect the ozone layer Khoei et al., (2018). This also faced threats to the survival of plants and animals in many developed countries' producing communities. However, large quantities of non-hazardous waste are generated through drilling activities, wellbore work, and ongoing production and maintenance operations. Among other sources, non-hazardous waste is also generated through drilling and completions, flow back, foam returns from wellbore works, cement water from well abandonments, fluids from production operations, other fluids with high total suspended solids (TSS), and oil-bearing fluids generated by good work, tank cleaning, and maintenance activities Emilio et al. (2010). In addition, significant quantities of non-hazardous fluids are generated through ongoing field operations such as workovers and stimulation treatments Schlumberger (2021). When agricultural soils and water are polluted, these metals find their way into the soil and become contained without being exposed or washed off Khan et al., 2008, Zhang et al. (2010). From the soil, these metals then move into the groundwater through leaching. Vegetables cultivated in such soils may bioaccumulate the metals easily; thus, becoming a major environmental menace through the food chain and posing risks to public health Ji et al. (2018), Ling et al. (2007), Maslin and Maier (2000), McLaughlin et al. (2000a, 2000b). Soil plays an essential role in the mobility of pollutants such as heavy metals and other essential ecosystem functions (water and nutrient cycling, carbon sequestration, etc.). Due to their adsorption capacity, soils can store and accumulate heavy metals to some extent Sipos (2004). Some environmental factors affect the ability of soil to adsorb heavy metals. Organic and inorganic (such as clay) colloidal soil components are among the most critical environmental factors. In addition, factors such as soil pH, dissolved organic matter, ionic strength, or the type and number

of different metals affect the adsorption capacity of the soil (Shi et al. 2013; Peng et al. 2018). Bradl (2004) and Ming et al. (2016) indicated that mineral and organic colloidal particles of the solid soil phase are the most active soil components in adsorption processes Sipos et al. (2019). Most studies monitoring heavy metal contamination in soil have evaluated total metal concentrations (G.M.S. Abraham et al. (2008); Zhang et al. 2018; Zhu et al. (2019). Total metal concentration is considered a consistent indicator to evaluate the actual long-term enrichment of soil and predict the origin of metals. In addition, soil's potentially available metal content can be a strong indicator of recent metal enrichment C. Celilov et al. (2019); N. Adimalla et al. (2019). Therefore, using datasets of both total and potentially available metal forms and examining their interrelationships can help understand the potential impacts of soil metal content on biological systems and the sources of recent pollution events. These metals are taken up by plants and consequently accumulate in their tissues Ji et al. (2018). Animals that graze on such contaminated plants and drink from polluted waters as well as marine lives that breed in heavy metal polluted waters also accumulate such metals in their tissues and milk, if lactating Ji et al. (2018). Humans are in turn exposed to heavy metals by consuming contaminated plants and animals and this has been known to result in various biochemical disorders. Also, Because of the complex interplay of factors that regulate heavy metal concentrations, many researchers have referred to traditional regression analysis as an inappropriate statistical tool for evaluating the effects of different explanatory variables Fjeld et al. (1994). In such complex situations, path analysis is one of the appropriate approaches. In this approach, explicit assumptions are made about the nature and aspects of causal relationships and the causal effects of explanatory variables are divided into indirect and direct components. S. Cheng (2003) studied Zn⁺² and B adsorption in soils using path analysis. They found that clay and organic carbon (OC) directly affect Zn⁺² adsorption, and cation exchange capacity (CEC) indirectly affects clay. Moreover, the researchers demonstrated the significant direct effect of CEC and OM on the adsorption of boron (B) and the effect of clay over CEC. Using the path analysis model constructed for CEC, they determined the significant direct contribution of clay to CEC, demonstrating the relationship between CEC and the adsorption of Zn⁺² and B. In another study, Fan et al. (2018) used path analysis and X-ray absorption spectroscopy to determine the Zn⁺² sorption capacity in soils. According to correlation and path analysis, pH, clay content, and Fe⁺² extractable with dithionite citrate bicarbonate played a direct role in Zn sorption. They found that pH was the dominant factor. Although numerous heavy metal pollution studies considered various approaches and various parameters have been used, using of soil intrinsic and dynamic characteristics such as texture, pH, organic matter or lime content, which play important role in mobilization or retention mechanisms, behaviors of heavy metal cations (Pb⁺², Cr⁺², Co⁺², Ni⁺², Cd⁺², Cu⁺², Fe⁺², Zn⁺², Mn⁺²) is crucial key particularly for sources of heavy metals and their spatial distribution. Moreover, the present study will also significantly contribute to the literature, as it is the most comprehensive GIS and statistic-geostatistic approach. The objective of this study is to test the hypothesis, that heavy metal concentration spatial distribution in cultivated soils of Thar-Jaath

Region and can be successfully predicted on regional level by combining GIS and geostatistics with two models (Enrichment factor-EF and Availability ration-AR). The objective will be carried out by following these steps: i-) to determine the heavy metal concentrations in soil at different depths and surface water, ii-) to evaluate the risk of heavy metal contamination using the laboratory analysis approaches, iii-) to investigate empirical relationships between heavy metals and selected physicochemical soil properties affecting the behavior of heavy metals and to test the explanatory power of a proposed set of causal mechanisms using statistical models.

Materials and Methods

The Study Sites (Thar-jath)

This study was conducted in the Thar-Jath Oilfields of Unity State, South Sudan as shown in Figure 1. Thar-Jath is a town

found on the Unity Plateau in the eastern part of Unity State. The Thar-Jath plateau is located between latitude 8.743947°N and longitude 30.140401°E with an estimated area of 20,591 km² forming the southernmost tip of the Unity State (Figure. 1a). The land-cover includes two main classes: black cotton soil (vertisol), a soil rich in montmorillonite (clay), and wetlands nearby the White Nile European Coalition on Oil in Sudan, (2003). With respect to the geological setting, the study area is inside the Muglad Basin that extends for 120,000 km² from Sudan to South Sudan. The basin is composed of three rift cycles: Early Cretaceous (140–95 Ma), Late Cretaceous (95–65 Ma) and Paleogene (65–30Ma) and is well-known for its hydrocarbon accumulations. The largest oilfields until now discovered are Heglig and Unity (Figure 1b): the first is outside Block 5A and the second adjoins the block. Inside Block 5A we find the Mala and Thar Jath oilfields that are well known for their Nile Blend, a medium low-sulfur waxy crude oil Pedersen et al., (2014).

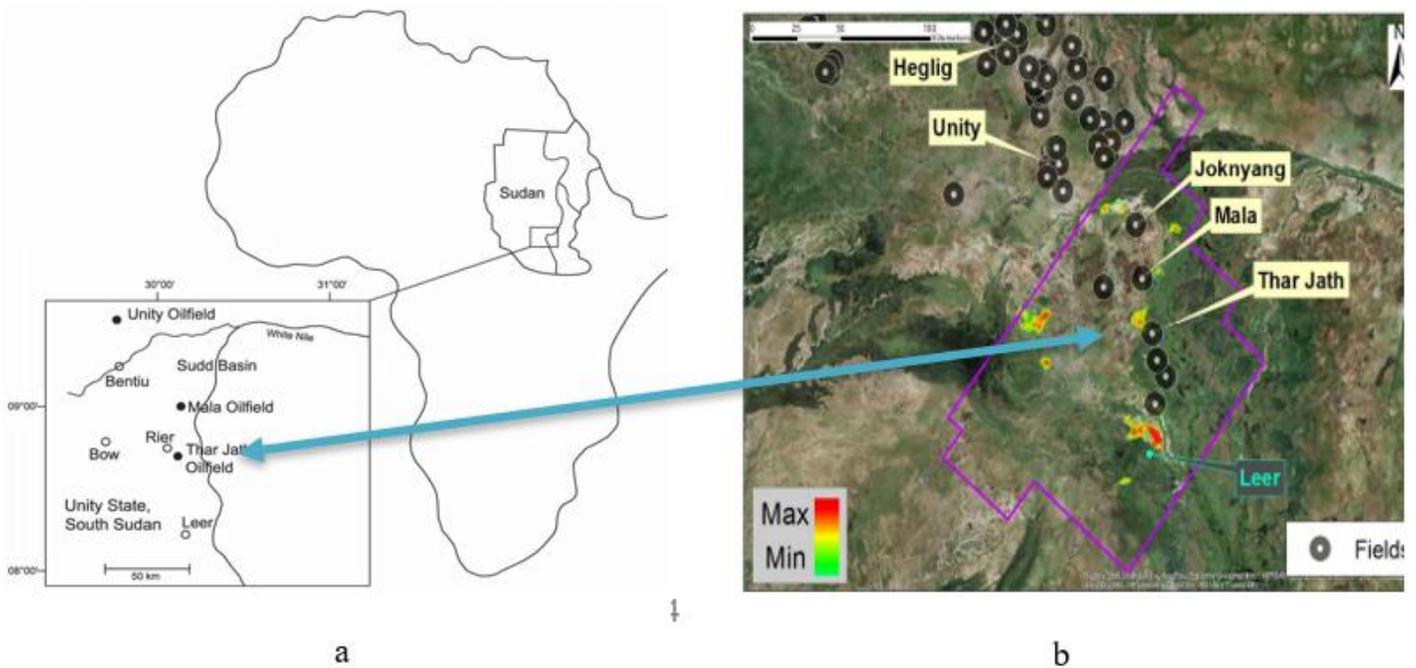


Figure 1: Location of study area in South Sudan (a) location of the studied oilfield, (b) oilfields within the Block 5A licensing block. Oilfields and micro seepage signals detected from remote sensing imagery. The scale minimum (min) and maximum (max) refers to seepages.

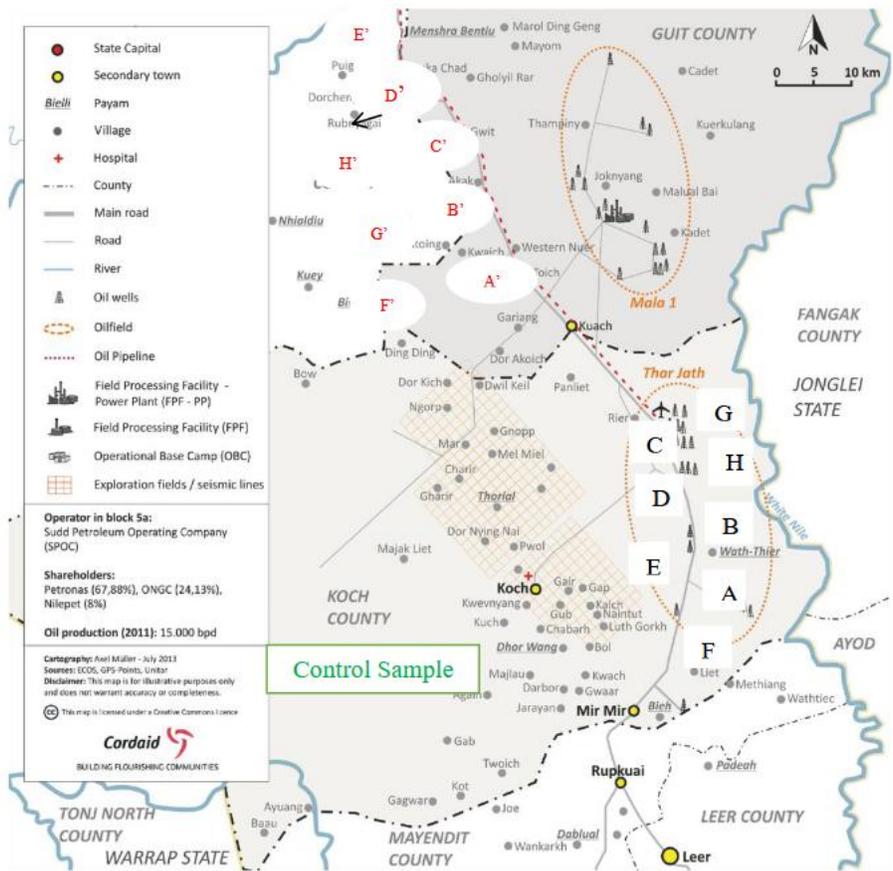


Figure 2: the position of study areas assigned with red (surface water) and black letters (soil samples).

Heavy metal concentrations in soil, surface water, stream sediments, and physicochemical analysis.

Materials

- i. Soil samples at different depths i.e. (0-10cm & at 10-30cm)
- ii. Surface Water samples
- iii. Stream sediments samples

Surface water sampling: Eight surface water samples were collected at different points from A'-G' a long Nam river from

the oil production sites, Oil pipeline, waste decomposition sites and environs in Thar-Jath as shown in Figure 2 using plastic bottles with geographical coordinates and description as presented in Table 1. Before this, the plastic bottles were washed with detergent than with double-distilled water followed by 2 M nitric acid, then double-distilled water again, and finally with sampled water. Two samples were collected from each sampling area in which one sample of 50 mL was mixed with 4 mL of HNO₃ (Nitric acid). The bottles were filled, labeled, sealed tightly, and transported in ice bags to the lab for analysis.

Locations	Geographical Coordinates	Description
A'	8.00°N and longitude 30.00°E	Pipeline leakages and Nam river over flow
B'	8° and 8.25° N 15.15° and 17.50° E	Field processing facilities present
C'	7° and 8.15° N 15.15° and 16.40° E	oil fields is functional in this site
D'	7° and 9.25° N 13.15° and 14.56° E	This area is severely flooded.
E'	10° and 8.25° N 12.15° and 18.30° E	This area is severely flooded as Nam river overflow.
F'	8° and 9.25° N 18.15° and 18.20° E	Fishing, and livestock activities is being practice
G'	8° and 8.25° N 15.15° and 17.50° E	Present of agricultural activities.
H'	8° and 8.15° N 05.45° and 27.10° E	No Pipelines converge in these areas.

Table 1: Surface Water Sampling point's description

Soil sampling: Eight soil samples were collected irregularly at depths not exceeding 30cm in various sampling points with geographical coordinates and description as presented in Table 2

and Figure 2. Portions of soil were decanted and placed into polythene bags using the non-metallic plastic shovel. The samples were appropriately labeled on the spot to avoid mix-ups.

The trowel was rinsed immediately after each collection to avoid contamination of the samples.

Locations	Sub samples	Geographical Coordinates	Description
Control		8.00°N and longitude 30.00°E	No oil production in this area
A	0-10 cm	8° and 7.25° N 15.15° and 17.50° E	Producing wells, drilled wells and the used of additives take place within this area.
	10-30 cm	8° and 7.25° N 15.15° and 17.50° E	
B	0-10 cm	7° and 8.15° N 15.15° and 16.40° E	This site is characterized by oil fields which were abandoned.
	10-30 cm	7° and 8.15° N 15.15° and 16.40° E	
C	0-10 cm	8° and 8.25° N 12.15° and 18.30° E	Sampling at these sites was carried out next to a performing well.
	10-30 cm	8° and 8.25° N 12.15° and 18.30° E	
D	0-10 cm	8° and 8.15° N 05.45° and 27.10° E	There are agricultural farms around these wells from where samples were collected
	10-30 cm	8° and 8.15° N 05.45° and 27.10° E	
E	0-10 cm	7° and 8.25° N 15.15° and 17.50° E	Oilfield waste as a result of leakages at the well heads, and the flow lines.
	10-30 cm	7° and 8.25° N 15.15° and 17.50° E	
F	0-10 cm	8° and 8.25° N 13.15° and 14.56° E	Sampling at these sites was carried out next to a performing well.
	10-30 cm	8° and 8.25° N 13.15° and 14.56° E	
G	0-10 cm	8° and 7.25° N 12.15° and 18.30° E	This site is characterized by oilfields which were abandoned.
	10-30 cm	8° and 7.25° N 12.15° and 18.30° E	
H	0-10 cm	8° and 8.23.15° N 05.45° and 27.10° E	Pipelines (crude oil pipes) converge in these areas.
	10-30 cm	8° and 8.23.15° N 05.45° and 27.10° E	

Table 2: Soil sampling point's descriptions

Pre-treatment Processes

Surface water samples for physicochemical, biological, and heavy metals analysis were collected from 8 purposively selected locations (to ensure full coverage of the study area) in pre-rinsed 1-liter plastic containers after rinsing the containers three times with the water being sampled for the physicochemical analysis. All the samples were labeled appropriately according to the sampling stations, securely sealed, placed in cooler containing ice bags, and were properly conveyed to ensure sample integrity; in the field color and odor were determined using human senses. The samples for the heavy metal analyses were placed in 300 ml plastic containers, and concentrated nitric acid (HNO₃) was added to adjust the pH to preserve the oxidation states of metals and hydrocarbons. Samples for hydrocarbon analysis were collected in pre-treated sample bottles (300 ml) and treated with HCl to avoid oxidation changes of constituents. Biochemical oxygen demand (BOD) samples were collected in 300 ml brown reagent bottles, and sealed to exclude air bubbles APHA (2012). Each sampling point was marked and geo-located using a Geographical Positioning System (Garmin—12GPS). Sampling locations were selected in such a manner as to adequately represent the entire study area. To ensure the integrity of some unstable physiochemical parameters in-situ measurements of temperature, pH, electrical conductivity (EC), dissolved oxygen (DO), total dissolved substance (TDS), turbidity, and total dissolved solids (TDS) was carried out in the field using the HANNA Water Quality Checker in line with the American Public Health Associations Standard for the Analysis of water and wastewater APHA (2012).

Experimental Analysis for Soil; Characterization involving heavy metal concentrations was carried out using an atomic spectrophotometer (AAS Unicam 969). Exchangeable cations

and anions were measured using a flame photometer and UV/Visible spectrometer (Unicam Helios Gamma, UVG 073201; Spectronic 21D). Dissolved Oxygen (APHA-4500 C): The dissolved oxygen (DO) was determined by the Modified Azide or Winkler's method APHA (2012). 80 ml BOD bottle filled with sample. 0.5 ml manganous sulfate (Winkler I) solution and 0.5 ml alkali-iodide-azide reagent (Winkler II) were added, stopper (excluding air bubbles), and mixed by several inversions. After about 10 minutes, 0.5 ml conc. H₂SO₄ was added, re-stopped, and mixed for the complete dissolution of the precipitate.

Experimental Analysis for surface water; The water samples with a known portion of 600ml plastic bottle were collected, diluted with oxygenated, and incubated at 20°C for seven days. At the end of the incubation period, the samples were treated like the DO samples stated above. The detection limit was 2.0 mg/l. Total Alkalinity (API-RP 45) and Chloride (APHA 4500-CL B): were determined by titration analysis; Sulphate (APHA 4500SO42-E/AST MID516) by the turbidimetry method while Phosphate (APHA 4500-PE/ASTM D515). Nitrate, Total Hydrocarbon Content (THC), and PAHs were determined using ASTM D3921 (Extraction/ Spectrophotometry) methods. Heavy metals (Cr, Cu, Pb, Fe, Cd, and Zn,) were determined using an Atomic Absorption Spectrophotometer as described in API-IA 3111B and ASTM D3651.

Results & Discussions

Physicochemical parameters of surface water samples

Physicochemical parameters of water samples from Thar-Jath Oilfields were obtained and recorded as shown in Table 3. The temperature of surface water was observed in the range between 26.28–28.16°C with an average temperature of 27.67°C. This

indicates that the temperature ranges are stable over time. The pH values of the samples ranged from 6.32 which is weak acid to 7.81 with a mean value of 7.19. The total alkalinity was observed between 321–518mg/l. The alkalinity of surface water is continuously increased due to the increase of the pollution load in the downstream from G to H. The high value of alkalinity

indicates the presence of weak acid and strong base as carbonates, bicarbonates, and hydroxides in the water body.

Parameters	A	B	C	D	E	F	G	H	WHO (2013)
Tem (°C)	26.28	27.28	27.27	28.05	28.02	28.18	28.13	28.16	20-30
Ph	7.72	7.25	7.60	6.80	7.35	6.32	7.81	6.70	6.5-9.2
Free CO ₂ (mg/l ⁻¹)	1.82	3.21	5.25	5.85	1.87	5.20	3.09	3.21	Nil
Total alkalinity (mg/l)	321	372	415	470	472	476	486	518	200
Total hardness (mg/l)	280	298	341	391	402	387	412	390	600
Turbidity	2.8	3.15	3.35	3.56	2.74	3.09	3.16	3.02	5
DO (mg/l)	8.54	7.62	7.36	6.69	6.24	5.98	4.75	3.97	-
BOD (mg/l)	18.64	21.85	22.18	25.25	27.21	28.12	29.32	30.01	-
TDS	205.8	120	276	102	72	86	625.36	133.8	500
Conductivity	576	183	423	158	109	132	956	205	1400

N/B: Bold indicates TDS value above permissible limits

Table 3: The physicochemical parameters of surface water sample at different sites.

Metals concentrations in soil and surface water samples

Heavy metal quantification was carried out to ascertain the levels of metal exposure to animals, plants, and humans as a result of petroleum production.

Concentration in (ppm)		
Stations	Pb in Soil (0-10cm)	Pb in Soil (10-30cm)
A	0.282	0.182
B	0.089	0.079
C	0.164	0.154
D	0.003	0.001
E	0.108	0.88
F	0.074	0.064
G	0.002	0.001
H	0.073	0.053

Table 4: Levels of Pb (ppm) from different sampling points (0-10cm) and (10-30cm)

Concentration (ppm)		
Stations	Hg in Soil (0-10cm)	Hg in Soil (10-30cm)
A	0.015	0.005
B	0.002	0.002
C	0.002	0.002
D	0.001	0.001
E	0.003	0.003
F	0.015	0.015
G	0.002	0.002
H	0.002	0.002

Table 5: Levels of Hg (ppm) at different sampling points

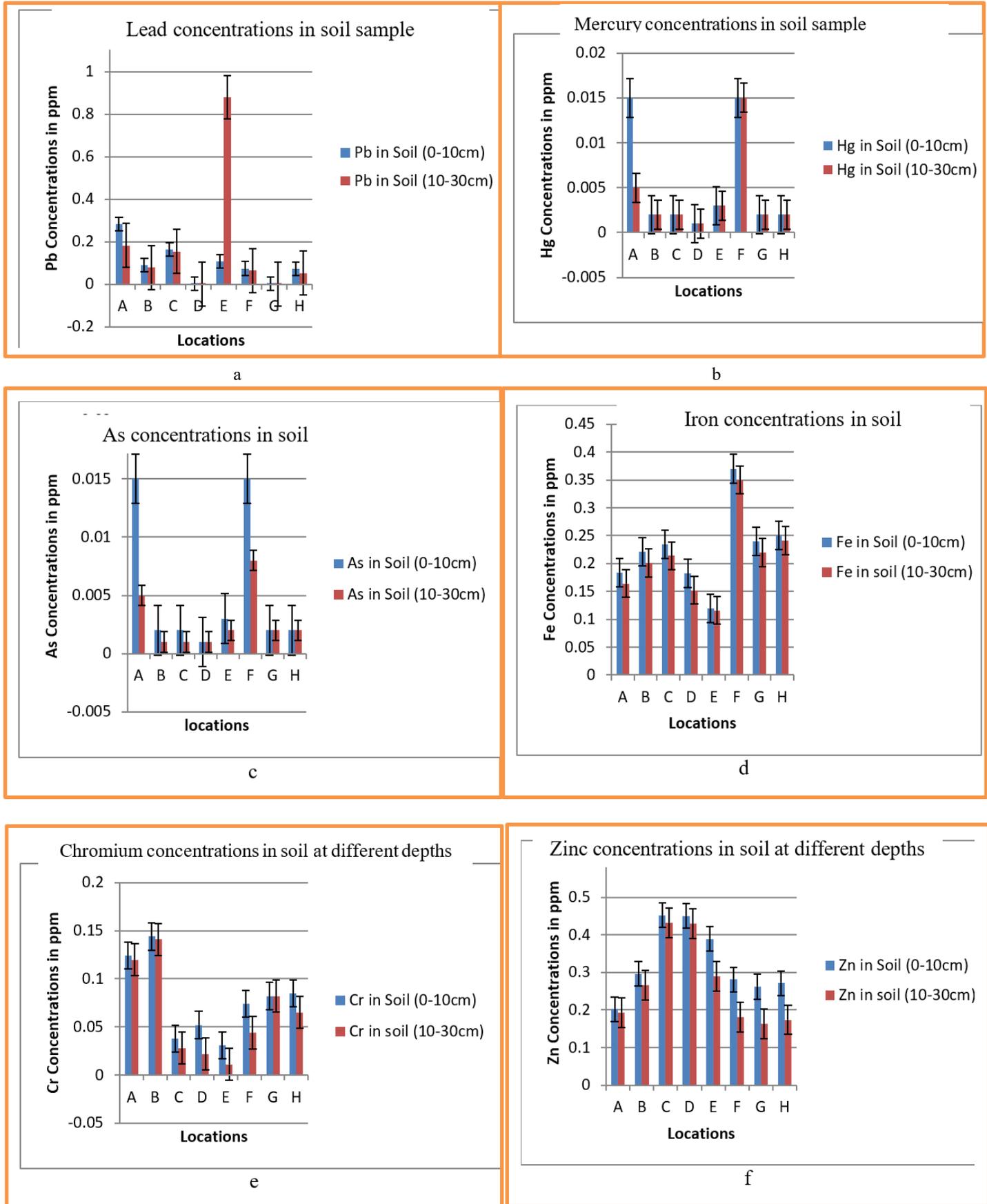


Figure 3: Metals concentrations at different depths

Concentration (ppm)		
Stations	As in Soil (0-10cm)	As in Soil (10-30cm)
A	0.015	0.005
B	0.002	0.001
C	0.002	0.001
D	0.001	0.001
E	0.003	0.002
F	0.015	0.008
G	0.002	0.002
H	0.002	0.002

Table 6: As concentration in soil at different depths (ppm)

Concentration (ppm)		
Stations	Fe in Soil (0-10cm)	Fe in soil (10-30cm)
A	0.184	0.164
B	0.221	0.201
C	0.234	0.214
D	0.182	0.152
E	0.120	0.116
F	0.370	0.35
G	0.240	0.22
H	0.251	0.241

Table 7: Iron concentration in soil at different sampling depths (ppm)

Stations	Cr in Soil (0-10cm)	Cr in soil (10-30cm)
A	0.124	0.12
B	0.144	0.141
C	0.038	0.028
D	0.052	0.022
E	0.031	0.011
F	0.074	0.044
G	0.082	0.082
H	0.085	0.065

Table 8: Levels of Cr (ppm) at different sampling depths

Stations	Zn in Soil (0-10cm)	Zn in soil (10-30cm)
A	0.202	0.192
B	0.296	0.266
C	0.452	0.432
D	0.450	0.43
E	0.389	0.289
F	0.281	0.181
G	0.262	0.163
H	0.271	0.174

Table 9: Levels of Zn (ppm) at different sampling depths

Table 4 and Figure 3a, shows the concentrations of lead at different soil depth sample, at the depth of 0-10cm A sample have the highest concentration (0.282 ppm) and sample G having the

least concentration (0.002 ppm) and at the depth of 10-30cm, A has highest concentration of 0.182 and G with lowest concentration of 0.001ppm at the depth of 10-30cm. Lead

concentrations in the samples were above the permissible limits WHO (2013). Table 5 and Figure 3b, shows the concentrations of mercury at different soil depth sample, at the depth of 0-10cm A sample have the highest concentration (0.015 ppm) and sample D having the least concentration (0.001 ppm) and at the depth of 10-30cm, F has highest concentration of 0.015 and D with lowest concentration of 0.001ppm at the depth of 10-30cm. Table 6 and Figure 3c, shows the concentrations of arsenic at different soil depth sample, at the depth of 0-10cm A & F sample have the highest concentration (0.015 ppm) and sample D having the least concentration of (0.001 ppm) and at the depth of 10-30cm, F has the highest concentration of 0.008ppm and B, C, & D with the least concentrations of 0-001ppm. Table 7 and Figure 3d, shows the concentrations of iron at different soil depth sample, at the depth of 0-10cm F sample have the highest concentration (0.370ppm) and sample E having the least concentration of (0.120 ppm) and at the depth of 10-30cm, H has the highest concentration of 0.241ppm and G with the least concentrations of

0-22ppm. Table 8 and Figure 3e, shows the concentrations of Cromium at different soil depth sample, at the depth of 0-10cm A sample have the highest concentration (0.144ppm) and sample E having the least concentration of (0.031 ppm) and at the depth of 10-30cm, B has the highest concentration of 0.141ppm and E with the least concentrations of 0-011ppm. Chromium levels in soil and water in this study did not exceed 0.05 ppm limits by (WHO 2013) and South Sudan Standard Bureau Limited SSBL (2021). The sources of Chromium include water erosion of rocks, power plants, liquid fuels, brown and hard coal, and industrial and municipal wastes. Table 9 and Figure 1f, shows the concentrations of Zinc at different soil depth sample, at the depth of 0-10cm C sample have the highest concentration (0.452ppm) and sample A having the least concentration of (0.202 ppm) and at the depth of 10-30cm, C has the highest concentration of 0.432ppm and D with the least concentrations of 0-43ppm.

Concentration in (ppm)	
Stations	Pb in surface water
A'	0.080
B'	0.089
C'	0.141
D'	0.112
E'	0.290
F'	0.023
G'	0.664
H'	0.063

Table 10: Levels of Pb (ppm) concentrations in surface water

Concentration (ppm)	
Stations	Hg in surface water
A'	0.001
B'	0.210
C'	0.310
D'	0.386
E'	0.421
F'	0.023
G'	0.707
H'	0.023

Table 11: Levels of Hg (ppm) at different surface water sampling points

Concentration (ppm)	
Stations	As in Surface Water
A'	0.001
B'	0.210
C'	0.310
D'	0.002
E'	0.210
F'	0.023
G'	0.686
H'	0.023

Table 12: As concentration in surface water samples (ppm)

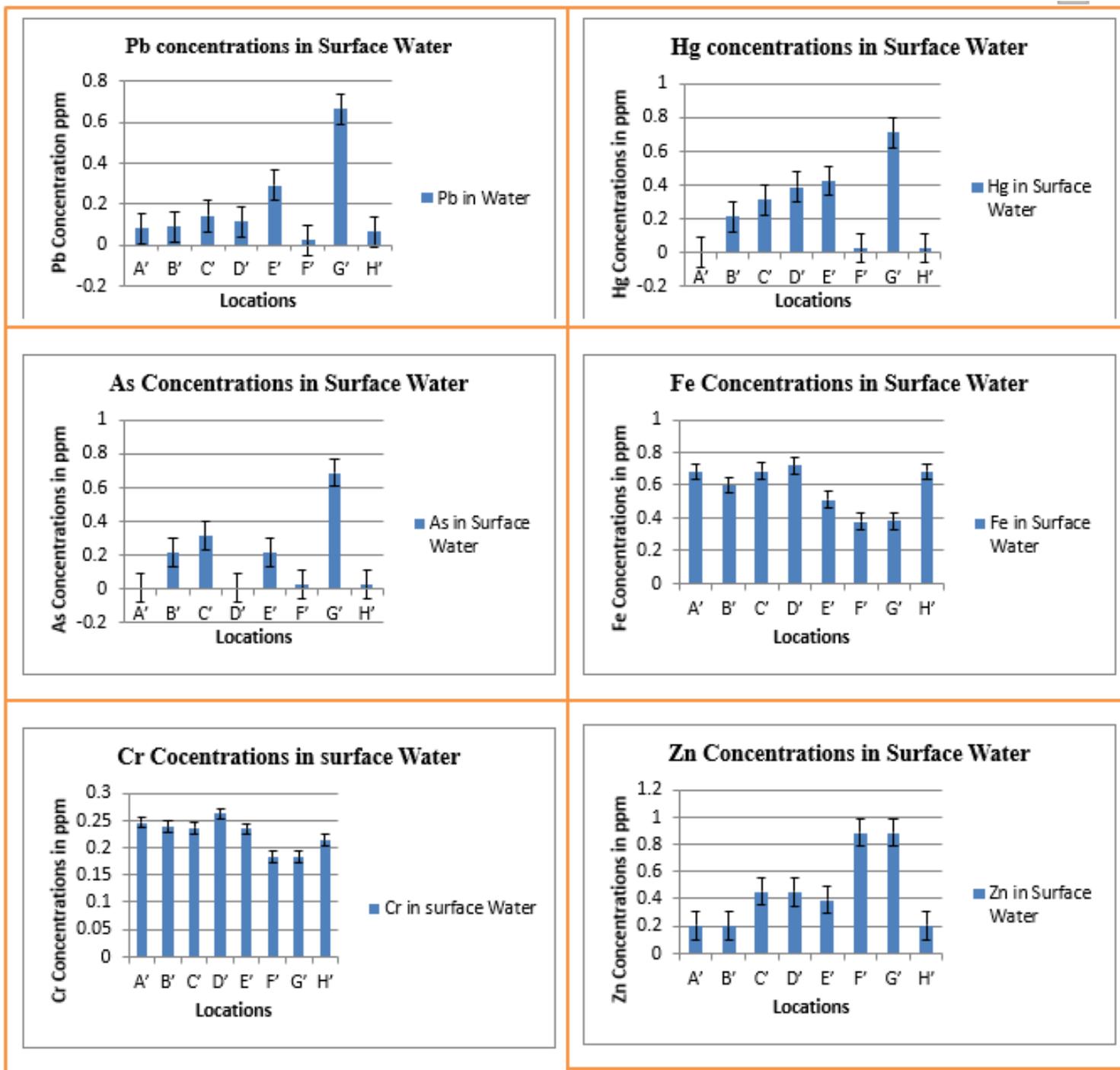


Figure 2: Metals concentrations in surface water in different sampling points

Stations	Concentration (ppm)
A'	0.682
B'	0.601
C'	0.686
D'	0.720
E'	0.510
F'	0.376
G'	0.380
H'	0.683

Table 13: Iron concentration in surface water samples (ppm)

Stations	Cr in surface water
A'	0.246
B'	0.238
C'	0.236
D'	0.262
E'	0.234
F'	0.183
G'	0.183
H'	0.213

Table 14: Levels of Cr (ppm) from different sampling points

Stations	Zn in surface water
A'	0.202
B'	0.200
C'	0.452
D'	0.450
E'	0.389
F'	0.886
G'	0.886
H'	0.203

Table 15: Levels of Zn (ppm) from different sampling points

Lead concentration in surface water were determine in Table 10 and Figure 4a, its indicated that samples G has highest value of (0.664ppm) and sample F has least concentration of (0.023 ppm). Sample G exceeded the standard value Khan et al. (2008). Suggestion that, Lead contamination of the surface water may be the result of entry from petroleum effluents, old plumbing, household sewages, agricultural run-off, and mining activities as well as human and animal excreta. In Table 11, the concentrations of Mercury in surface water samples analyzed varied enormously with a minimum and maximum mean value between 0.001-0.706 ppm in surface water samples and plotted Figure 4b. Mercury toxicity depends on the chemical form of ingestion. Inorganic forms of mercury cause spontaneous abortion, congenital malformation, and gastrointestinal disorders Hakanson et al. (1980). Poisoning by its organic forms, which include monomethyl and dimethyl mercury presents stomatitis, neurological disorders, and total damage to the brain and CNS and is also associated with congenital malformation soil Khan et al. (2008). Arsenic concentrations Table 12 in surface water samples plots in Figure 4c were determined and the means of the samples recorded showed that samples A and D have a minimum value of 0.001 ppm while sample G had the highest mean value of 0.686 ppm in the surface water sample B (0.015 ppm) and F (0.015 ppm) contains the highest concentrations of Arsenic and D (0.001 ppm) contain the least amount. Among all the samples analyzed, A and D showed negative compliance with the WHO (2013) acceptable limit (0.01 ppm) for Arsenic levels in the water while all samples determined for Arsenic in soil samples showed positive compliance, falling below the acceptable limit of 1.50 ppm. Studies show that agents of denudation, leaching, or mining activity may be responsible for the high concentration in the water sample obtained from point G. The levels of Iron in the different surface water samples analyzed were extremely high as

sown in Table 13 and Figure 4d. The minimum and maximum mean values in water were seen in samples F and D to be 0.376 and 0.726 ppm, respectively. Sample F (0.367 ppm) has the highest concentration of Fe in soil. In all water samples for Fe concentrations, sample F was found to be above the 0.30 ppm permissible limit for Iron in both soil and water samples set by WHO (2013) and the South Sudan Standard Bureau Limited SSBL (2020). The level of Iron could be the result of clay deposits in the area. Iron is an essential element to the human body, hence higher iron concentration does not pose a serious threat to human health although high concentration is associated with Tetanus Xie et al. (2016). Zinc concentrations determined in the different surface water samples in Table 15 and Figure 4f showed mean values distributed across the various samples analyzed to have minimum and maximum values of 0.202 and 0.886 ppm, respectively. All samples analyzed for Zinc concentrations in soil were below the permissible limit in soil. The high concentrations of Zinc in water samples F and G indicate translocation either by leeching or erosion of the element Islam et al., (2016). Soil and water levels of industrial activities, such as mining, coal and waste combustion, and steel processing ((Islam et al., 2016)). Comparing the levels of the heavy metals analyzed in soil samples and surface water samples, no significant difference ($p < 0.05$) in concentrations of lead between soil and water in sample B while soil samples A, and C had significant differences ($p < 0.05$) in lead levels than water samples. The decreased concentrations determined in the various soil samples could be due to their transformation into various mobile forms before ending in the environment. Zinc determined in this study interestingly revealed that samples A, C, D, and E, have equal mean values in both surface water and soil samples while samples B have higher values for Zinc in soil than surface water, and samples F and G have much higher values of Zinc in water

compared to those analyzed in soil samples. The levels of these metallic elements at much higher levels in surface water samples compared to soil can be attributed to mining and anthropogenic activities as well as transportation by erosion and other agents of denudation or leached into aquifers and eventually into streams, rivers, and other water sources downstream thereby leading to contamination. This study is similar to other findings on heavy metals mobility in soils with a contradiction in the case of Zn and Hg. Asmoay et al. (2019) reported that Zn and Fe have high mobility compared Pb, Hg, and As metals in the soil. According to Gilli et al., (2018), the mobility of Hg is influenced by the chemical forms of Hg, as different Hg species exhibit vastly different environmental behaviors and toxicities.

The control showed significant heavy metals concentrations of 0.001-0.182, 0.001-0.005, 0.001-0.008, 0.22-0.241, 0.43-0.432, for Pb, Hg, As, Fe, and Zn respectively. Though this site was far from other points as evident from geographical coordinates, it has been cultivated for many years before being abandoned. Except for site, A (10-30cm), all other sites involved agricultural activities and mainly farming. Depending on the type of fertilizer used, they all have the potential to add heavy metals to the soil as evidenced from. This may account for the concentration of heavy metals obtained in this study, especially from sites with agricultural activities. Other sources of heavy metals in agricultural soils include irrigation with municipal wastewater and Industrial wastewater which introduces Zn, Cu, Ni, Pb, Cd, Cr, As, and Hg in the soil, as well as atmospheric deposition from mining metal smelting and refining, manufacturing processes, transport, and waste incineration: primarily Srivastava et al., (2017). By comparing the results obtained in the study to standard values of heavy metals in agricultural soils, it can be observed that only Cu and Hg exceed those standards. The standards are grouped under threshold and permissible limits. These limits are applied worldwide to measure the heavy metal contents in agricultural soils Adagunodo et al. (2018). The threshold limit is used to checkmate the minimum toxicity in all soil's environment. The permissible limit applies to agricultural soils. If the values of the heavy metals exceed the permissible limit, such soil is regarded as contaminated soil for agricultural

activities Adagunodo et al. (2018). It is either associated with health risk (hr) or ecological risk (er). Equally comparing the concentrations of Heavy metals in Thar-Jath soils with other agricultural soils not close to oil field activities and agricultural soils around oil fields can be seen that results obtained in this study were similar to other studies with very low values for Pb and Ni.

Sample distribution and metal concentrations across depth and land cover types

Sample distribution and metal concentrations across depth and land cover types Sample locations in the laboratory used for analysis were primarily in Thar-Jaath (Figure 1) and few sampling localities are in proximity to towns or areas of settlements. The dataset also contained very few (< 10) samples located in the continuous Thar-Jaath zone; the bulk of sample locations were located in discontinuous and sporadic permafrost. Metal concentrations were summarized in Table 16. Metal concentrations varied between sampling depth intervals of 0–10 cm, 10–30 cm, and below 30 cm for all metals except As (Figure 3). While Ni concentrations are highest above 10 cm ($\chi^2 = 63.38$, $p < 0.001$; Kruskal-Wallis multiple comparisons of means and Fisher's Least Significant Difference tests for all comparisons reported here) Pithan Fand Mauritsen T. (2014), Cr, Hg, and Pb have higher concentrations at depth Romanovsky VE et la. (2007). Concentrations are highest in the 10–30 cm depth interval for Cr ($\chi^2 = 43.14$, $p < 0.001$) and Pb ($\chi^2 = 11.39$, $p = 0.003$) and below 30 cm for Hg ($\chi^2 = 6.68$, $p = 0.035$). Metal concentrations also varied between land cover types (Figure 3) Jorgenson MT et al. (2010). Wetland sites had the lowest concentration of both As and Pb ($\chi^2 = 99.76$, $p < 0.001$; $\chi^2 = 11.91$, $p < 0.001$). Forested sites had higher concentrations of Cr and Ni and lower concentrations of Hg than other vegetated land cover types. Oil production-impacted soils have higher concentrations of all metals except Ni, for which oil production-impacted sites and forested sites had comparable concentrations ($p < 0.001$ for all) Schuur EAG et al. (2015).

Metal	Number of observations	Range (mg kg ⁻¹)	Mean ± SD (mg kg ⁻¹)	Median (mg kg ⁻¹)	IQR (mg kg ⁻¹)	US average (mg kg ⁻¹)
As	961	0.39–14900	188 ± 1120	11.0	7.0–20.0	6.6 ± 19.6
Cr	1072	1.0–350	59.2 ± 38	56.0	33.3–78.0	37 ± 89
Hg	800	0.01–6090	30.4 ± 0.06	0.06	0.04–0.09	0.04 ± 0.17
Ni	1073	2.0–702	44.6 ± 61	28.3	19.0–41.6	18.5 ± 54.4
Pb	1081	2.0–720	21.1 ± 41.1	13.0	9.0–19.0	22.2 ± 46.6
IQR = interquartile range; first quartile–third quartile						
^a Values from Smith et al., 2013, Geochem and Mineralogical Data for Soils of the Conterminous US, USGS Data Series 801						

Table 16: Summary of metals concentrations.

Concentrations of As, Cr, Hg, Ni, and Pb in mine-impacted areas of Thar-Jaath were especially elevated (Figure 3), likely due to heavy metal air pollution from oil production, waste deposition and subsequent wet/dry deposition onto soils Neitlich PN et al. (2001-2006). However, soils with metals concentrations that exceed average values from the contiguous Thar-Jaath were found to be distributed across the study region and are not isolated to production-impacted sites or sites with close proximity to sources of anthropogenic contamination. The proportion of samples with elevated concentrations were comparable when calculated with and without mine-impacted sites, indicating that the small number (n < 20 for all metals) of mine-impacted sites did not disproportionately impact the proportion of samples with

elevated concentrations. This suggests that “pristine” soils in Thar-Jaath (i.e. those from outside areas with heavy anthropogenic disturbance) can also contain elevated levels of heavy metals which may be released through warming and thaw. Aside from anthropogenic contamination, heavy metals in soils can be derived from lithogenic pools that become distributed across surface environments through natural biogeochemical cycles and near-surface processes (i.e. erosion, weathering, pedogenesis) Reimann C and Caritat P De (2005). Furthermore, the bias towards surficial soils as shown in (Figure 3) impedes distinguishing if elevated concentrations are a result of background levels or from surface contamination.

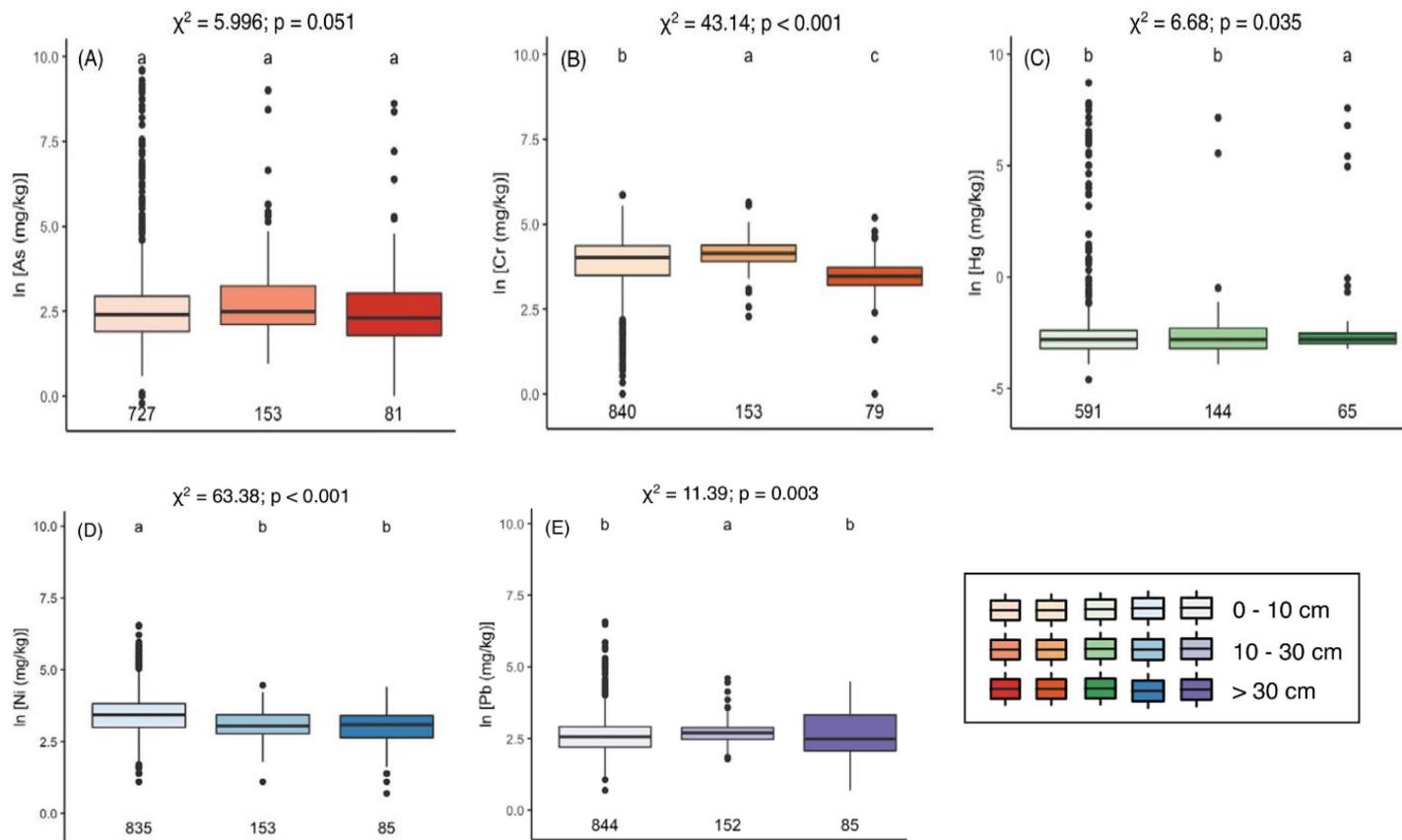


Figure 3. Metal concentrations by sample depth. Concentrations of As (A), Cr (B), Hg (C), Ni (D), and Pb (E) across binned sampling depths. All concentrations are displayed on a natural log scale. Chi-squared test statistic and alpha value results of the Kruskal-Wallis tested used to determine differences by depth for each metal are reported above each plot, DF = 2 for all. Letters above boxes represent groups determined by the Fisher’s Least Significant Difference test. Numbers below boxes represent the number of observations from each source for each metal.

Conclusion

Results of the study show that, surface water and soil contaminated by heavy metals poses a significant threat to human health and the environment. Mercury, lead and arsenic are well documented for their toxicity, which affects neurological functions, organs systems and cancer risks. Heavy metals

contaminated soil and surface water must be remediated to mitigate these risks. Developing new biosorbents improve approach for improving monitoring and assessment strategies to better understood the long-term effects of heavy metals contamination and assess the effectiveness of remediation efforts. Overall, addressing the challenges posed by heavy metals contamination requires a multi-disciplinary approach and the public to ensure the protection of human health and the environment. Results of this study show that critical attention must be given to sites at the depth of (0-10cm) as well as other activities in other sites that can contaminate the soils and surface water.

Acknowledgements

The support for this research was made possible through a capacity building competitive grant training the next generation

of scientists provided by the Carnegie Cooperation of New York through the Regional Universities Forum for Capacity Building in Agriculture (RUFORUM).

GTA Grant; Grant# RU/2024/GTA/CCNY/05).

Author Contributions

Prof. FOZAO KENNEDY FOLEPAI, Prof. TSAMO CORNELIUS facilitated and conceptualized the whole research process and write-ups construction; Prof. CHEO EMMANUEL SUH edited and proofread the final paper; BIOR J. AKOI conducted the research, analyzed the data, and wrote the paper; all authors approved the final revision of the paper.

Declarations

Conflict of interest on behalf of all authors; the corresponding author states that there is no conflict of interest.

References

1. Adagunodo, T.A. Sunmonu, L.A, Emeter, M.E. (2018). Heavy metals' data in soils for agricultural activities, Data in Brief 18:1847–1855,
2. APHA, (American Public Health Association), Standard Methods for the Examination of Water and Wastewater, 20th edition, American Water Works Association and Water Environmental Federation, Washington, 1998
3. Bradl, H.B. (2004) Adsorption of Heavy Metals on Soils and Soil Constituents. *Journal of Colloid and Interface Science*, 277, 1-18.
4. C. Celilov *et al.* (2019). Determination of the spatial distribution for erodibility parameters using different interpolation methods: Ilgaz National Park Soils, Turkey *Turk J Agric Res* (2019)
5. Emilio Lèbre., La Rovere. Jacqueline. Barboza Mariano., (2010) “Environmental impacts of the oil Industry” Energy Specialist at National Petroleum Agency of Brazil Professor at Energy Planning Program, Federal University of Rio de Janeiro, Brazil
6. E. Fjeld *et al.* (1994). Influence of environmental factors on heavy metal concentration in lake sediments in southern Norway indicated by path analysis *Can. J. Fish. Aquat. Sci.* (1994)
7. European Coalition on Oil in Sudan “The Legacy of Lundin, Petronas and OMV in Block 5A, Sudan 1997 – 2003,” Report, ECOS, (2010).
8. Gilli, R. S, Karlen, C, Weber, M, Rüegg, J, Barmettler, K, Biester, H, Boivin, P. and Kretzschmar, R. (2018). Speciation and Mobility of Mercury in Soils Contaminated by Legacy Emissions from a Chemical Factory in the Rhône Valley in Canton of Valais, Switzerland, *Soil Syst.*
9. G.M.S. Abraham *et al.* (2008). Assessment of heavy metal enrichment factors and the degree of contamination in marine sediments from Tamaki estuary, Auckland, New Zealand *Environ. Monit. Assess.* (2008)
10. Hakanson, L., (1980). An ecological risk index for aquatic pollution control a sedimentological approach. *Water Res.* 14, 975–1001.
11. H. Ming *et al.* (2016). Competitive sorption of cadmium and zinc in contrasting soils *Geoderma* (2016)
12. Islam M. S. Ahmed M. K. Habibullah-Al-Mamun M. Hoque M. F. 2015a, Preliminary assessment of heavy metal contamination in surface sediments from a river in Bangladesh. *Environmental Earth Sciences* 73 (4), 1837–1848.
13. Islam M. S. Ahmed M. K. Raknuzzaman M. Habibullah-Al-Mamun M. Islam M. K. 2015b Heavy metal pollution in surface water and sediment: a preliminary assessment of an urban river in a developing country. *Ecological Indicators* 48, 282–291.
14. Ji, Y., Wu, P., Zhang, J., Zhang, J., Zhou, Y., Peng, Y., Zhang, S., Chai, G., Gao, G., (2018). Heavy metal accumulation, risk assessment and integrated biomarker responses of local vegetables: a case study along the Le'an River. *Chemosphere* 361–367.
15. Jorgenson MT, Romanovsky V, Harden J, Shur Y, Donnell JO, Schuur EAG, et al. (2010). Resilience and vulnerability of permafrost to climate change. *Can J For Res.* 2010; 1236:1219–36.
16. Khan, S., Cao, Q., Zheng, Y.M., Huang, Y.Z., Zhu, Y.G., (2008). Health risks of heavy metals in contaminated soils and food crops irrigated with wastewater in Beijing, China. *Environ.*
17. Khoei, Javanshir, Arash. (2018). Application of physical and biological methods to remove heavy metal, arsenic and pesticides, Malathion, and diazinon from water. *Turk. J. Fish. Aquatic. Sci.* vol. 19, 21– 28, 1.
18. L. Peng *et al.* (2018). Kinetics of heavy metal adsorption and desorption in soil: developing a unified model based on chemical speciation *Geochim. Cosmochim. Acta* (2018)
19. N. Adimalla *et al.* (2019). Assessment of heavy metal (HM) contamination in agricultural soil lands in northern Telangana, India: an approach of spatial distribution and multivariate statistical analysis *Environ. Monit. Assess.* (2019)
20. Neitlich PN, Ver Hoef JM, Berryman SD, Mines A, Geiser LH, Hasselbach LM, et al. Trends in spatial patterns of heavy metal deposition on national park service lands along the Red Dog Mine haul road, Alaska, 2001–2006.
21. Pedersen, A. and Bazilian, M., “Considering the impact of oil politics on nation building in the Republic of South Sudan,” *The Extractive Industries and Society* 1, 163-175 (2014).
22. Pei Xu, Guyu Peng, Lei Su, Yongqiang Gao, Lei Gao, Daoji Li (2018). Microplastic risk assessment in surface waters: A case study in the Changjiang Estuary, China
23. Peter Sipos (2004). Geochemical factors controlling the migration and immobilization of heavy metals as reflected by the study of soil profiles from the Cserhát Mts. January 2004

24. Pithan F, Mauritsen T. (2014). Arctic amplification dominated by temperature feedbacks in contemporary climate models. *Nat Geosci.* 2014; 7:181–4.
25. Reimann C, Caritat P De. Distinguishing between natural and anthropogenic sources for elements in the environment: regional geochemical surveys versus enrichment factors. *Sci Total Environ.* 2005; 337:91–107.
26. Romanovsky VE, Smith SL, Christiansen HH. (2007). Permafrost Thermal State in the Polar Northern Hemisphere during the International Polar Year 2007–2009: a Synthesis. *Permafr Periglac Process.* 2010; 116:106–16.
27. S. Cheng (2003). Heavy metal pollution in China: origin, pattern and control *Environ. Sci. Pollut. Res.* (2003)
28. Schlumberger. *Oilfield Glossary.* (2021).
29. Schuur EAG, McGuire AD, Grosse G, Harden JW, Hayes DJ, Hugelius G, et al. (2015). Climate change and the permafrost carbon feedback. *Nature.* 2015; 520:171–9.
30. Srivastava, V., Sarkar, A., Singh, S., Singh, P., de Araujo ASF, and Singh, R.P. (2017). Agroecological Responses of Heavy Metal Pollution with Special Emphasis on Soil Health and Plant Performances. *Front. Environ. Sci.* 5: 64.
31. The World Economic Forum (2012). “Energy for Economic Growth. Energy Vision Update”; the World Economic Forum: Cologny, Switzerland, 2012.
32. World Health Organization (2013). *International Drinking Water Standards.*
33. Wei, J., Duan, M., Li, Y., Nwankwegu, A.S., Ji, Y., Zhan, J., (2019). Concentration and pollution assessment of heavy metals within surface sediments of the Raohe Basin, China. *Sci. Rep.* 9, 13100, 2019.
34. Xie, Y., Fan, J., Zhu, W., Amombo, E., Lou, Y., Chen, L., Fu, J., (2016). Effect of heavy metals pollution on soil microbial diversity and bermudagrass genetic variation. In: *Frontier Plant Sciences Journal*, 31 May 2016.
35. Z. Zhang *et al.* (2018). Assessment of heavy metal contamination, distribution and source identification in the sediments from the Zijiag River, China *Sci. Total Environ.* (2018).

Citation: Bior J A, Fozao K F, Tsamo C, Suh C E (2025) Heavy metals concentration in soil, surface water, and physicochemical analysis of oilfield wastes of Thar-Jath oilfields, South Sudan. *Adv Agri Horti and Ento: AAHE-226*