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Ecological and human health impacts of oil spill-induced heavy metal contamination in the Niger delta environment, Nigeria: Post-remedial assessment, risks, and mitigation strategies

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Abstract

The Niger Delta region, nestled along the Gulf of Guinea in Nigeria, presents a complex interplay of ecological and human health challenges stemming from recurring oil spill incidents and the subsequent release of heavy metals into local ecosystems. This study delves into the intricacies of this issue, offering a thorough assessment of post-remedial ecological and human health risks of heavy metal contamination from oil spills in the Niger Delta. The total mean concentrations of Chromium (Cr), Copper (Cu), Lead (Pb) and Zinc (Zn) from ninety-six (96) soils and forty-eight (48) plants samples were evaluated over two seasons for ecological and human health risks of heavy metal pollutants from remediated sites at Aluu, Eziorsu and Owaza in Rivers, Imo, and Abia states respectively. The Ecological Risk Assessment employed the evaluation of different indices, which include the Geo-accumulation Index (Igeo), Index of Ecological Risk Factor (Eri) and Potential Ecological Risk Index (RI) for the surface and sub-surface soil samples during the wet and dry seasons. The Human Health Risk Assessment evaluated the seasonal Average Daily Intake (ADI), Hazard Quotient (HQ), Hazard Index (HI) and the Carcinogenic Risk of exposure to heavy metals in the soils and plants. From the results, the Igeo categorizes the contamination within safe limits at the zero category. The Eri and RI report values below 1, indicating deficient risk levels, emphasizing minimal ecological concerns. However, the ADI values indicate < 30% being < 1, while > 70% being > 8.115, showing many samples exhibit high toxicity risk, with Cu recording the highest values and the Eziorsu site reporting peaks. ADI and HQ values for metal exposure display a considerable risk at Aluu and Owaza, with Pb values of up to 146.77 and 0.964, respectively; in contrast, plant exposure to heavy metals presents safe levels. The HI in soil were all above 100, indicating high human health risk, plant exposure through stems and leaves also reveals potential health hazards, with some sites exceeding safe levels. Regarding carcinogenic risk, Pb and Cr exposure poses a low probability of cancer from plant exposure. However, soil exposure exceeds the USEPA stipulated range of 10-6 to 10-4, warranting attention. Overall, the study's insights underscore the importance of comprehensive post-remediation measures to safeguard the environment and human health.

Keywords: Post-remedial assessment, geo-accumulation, heavy metals, health risk, ecological risk, Niger delta, Nigeria

Introduction

The Niger Delta region of Nigeria, known for its rich biodiversity and vast oil reserves, has unfortunately also become synonymous with a complex web of environmental challenges stemming from oil spill incidents (George *et al*., 2021) [13]. These events, often driven by a combination of industrial activities, operational mishaps, and natural factors, have repeatedly triggered the release of heavy metals into the delicate ecosystems of the region (George *et al*., 2022) [14], and posing significant health risks to human populations and biodiversity in affected regions (Imoobe & Iroro, 2009) [18]. The Niger Delta region has experienced numerous oil spill incidents, leading to the accumulation of organic pollutants and heavy metals in the soil, and despite remediation efforts, ecological and health impacts in the region remain critical and necessitate comprehensive post-remedial assessments (Ahmed *et al*., 2019) [3]. The subsequent contamination of water bodies, soil, and the food chain has raised significant concerns for ecological integrity and the local population's health.

(Olof & Jonas, 2013) [27]. The chemicals and products commonly released into the environment have associated toxic or carcinogenic properties from acute and/or chronic exposure to humans and other organisms (Fentiman & Zabbey, 2015) [12]. The Niger Delta, with its rich biodiversity and dependence on agriculture and fishing, is particularly vulnerable to the adverse effects of heavy metal pollution (Fatoba *et al*., 2016) [11]. These metals, including lead, cadmium, mercury, chromium, arsenic, and nickel, are known to harm the environment and human health (USEPA, 2017) [13]. Understanding the extent of heavy metal contamination and its potential impact on the ecosystem and local communities is vital for designing targeted interventions to mitigate these risks (Sam *et al*., 2016; Zabbey *et al*., 2017) [29, 39].

The aftermath of oil spills in the Niger Delta has been marked by adverse consequences that extend far beyond immediate environmental degradation (Ahmed *et al*., 2019) [3]. The heavy metals liberated during these incidents, including but not limited to lead, mercury, cadmium, and arsenic, possess intrinsic toxicological properties that make them potential threats to both the environment and human well-being (Hart *et al*., 2005) [17]. Ecologically, these metals can disrupt aquatic systems, disturb biodiversity, and propagate through intricate food chains, leading to long-term ramifications that ripple across generations (Imoobe & Iroro, 2009) [18]. The potential health effects on the local populace are equally concerning, who rely heavily on the region's natural resources for sustenance and livelihoods (Zabbey *et al*., 2017) [39].

Oil spill affects the physical-chemical properties of the soil, such as temperature, structure, nutrient status and pH (Alabi *et al*., 2019 [4]; Logeshwaran *et al*., 2018) [24]. Petroleum hydrocarbons and heavy metals may find their way into many environments through crops, soil surface and groundwater, where they undergo a redistribution process and are now detected at different concentration levels in the food chain (Hart *et al*., 2005) [17]. The effects of hydrocarbon pollution and contamination may be immediate if man and livestock consume crops planted in spill sites which have accumulated the metals (Ekundayo & Obuekwe, 2000) [10]. Several studies have also indicated that metal pollution (e.g. Pb *et al*.) is responsible for certain diseases of humans and animals, and there is a need for cleaning up oil-contaminated soil (Fatoba *et al*., 2016) [11]. It is crucial assessing areas of contamination, remediate and monitor clean-ups, and final quality evaluation of the remediated soil (Ahmad *et al*., 2019) [3].

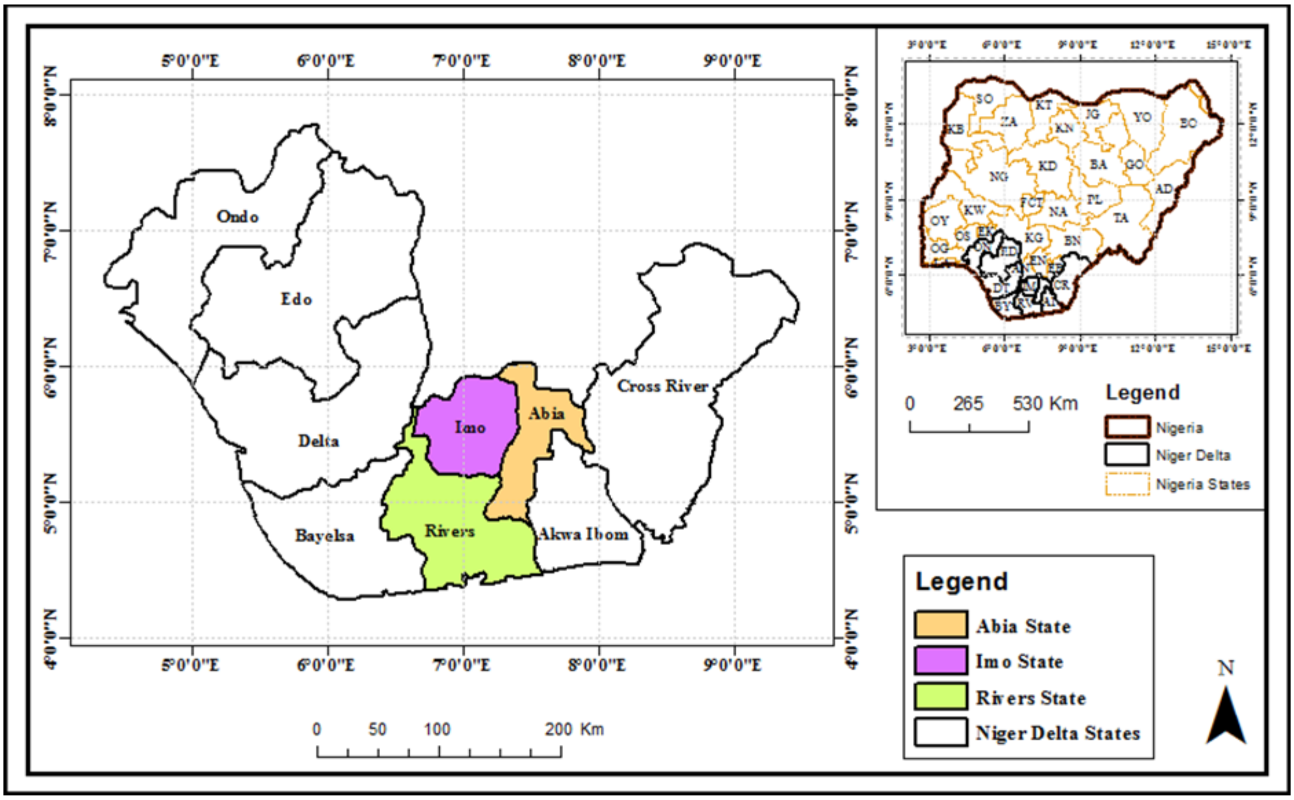

Fig 1: Map showing the Niger Delta States and outlining the study location [13, 14].

Hence, regular re-assessment of oil spill areas for impacts on the soil and vegetation concerning their hydrocarbon and heavy metal loads is necessary for adequate environmental restoration and human health concerns after remediation (Ahmad *et al*., 2017) [2]. A comprehensive approach is imperative to address the complex challenges arising from heavy metal contamination following oil spills. This study delves into the post-remedial ecological and human health risk assessment of heavy metals originating from oil spills in the Niger Delta. The aim is to assess the extent of ecological disruption and human health risks posed by heavy metal contamination from the selected bioremediated sites. Through rigorous data collection, advanced analytical techniques, and risk assessment methodologies, this research seeks to contribute to the understanding of effective management practices that can safeguard the fragile ecosystems and the well-being of the local communities in the Niger Delta region.

The subsequent sections of this research paper delve into the intricacies of the methodology employed, the outcomes of the risk assessments conducted, and the crucial role of post-remediation monitoring in mitigating the persistent impacts of heavy metal contamination.

Study location

The Niger Delta, positioned in the Gulf of Guinea along the Atlantic Ocean, spans nine coastal states in southern Nigeria. This encompasses six states in the south southern region (Rivers, Delta, Edo, Bayelsa, Akwa-Ibom, and Cross River), one state from the southwestern region (Ondo), and two states from the southeastern region (Abia and Imo). It encompasses approximately 112,000 square kilometres and constitutes 12.0 per cent of Nigeria's total landmass. Historically a prominent palm oil producer, the Niger Delta region boasts a high population density, with an estimated 31 million inhabitants residing in approximately 3000 communities and 186 Local Government Areas within Africa, earning it the distinction of being Africa's most densely populated area (Steiner, 2010) [33].

The region's distinctive character lies in its substantial petroleum activities, directly resulting from its abundant petroleum resources. This has garnered significant international attention due to concerns related to pollution levels. Our research focuses on three pivotal locations across different states within the Niger Delta region, chosen based on historical records of oil spill incidents, logistical accessibility, and security considerations (Steiner, 2010; George *et al*., 2021) [33, 13].

Ukwa West local government area (LGA) is the only oil-producing local government in Abia State. Ukwa West is north bounded by Osisioma local government area, to the north-east by Ugwunagbo local government area and to the east by Ukwa East local government area, all in Abia State. It is also west-bound by Omuma L.G.A., Etche L.G.A. to the southwest, and the south by Oyigbo L.G.A., all in Rivers State. The local government is the only crude oil-producing area in Abia state (George *et al*., 2022) [14].

Ikwerre Local Government Area is in Rivers State, Nigeria; its headquarters is at Isiokpo. The local government area has many petroleum hydrocarbon deposits; it contains 92 oil wells producing an estimated 100,000 barrels daily. The local government hosts several multinational oil-producing and servicing companies and many other industries and establishments. Aluu is a community in the Ikwerre Local government area that hosts different oil and gas pipelines, including the Rumuekpe-Nkpoku flowline close to the Aluu community, Obio-Akpor Local Government Area in Rivers State (George *et al*., 2022, George *et al*., 2021) [14, 13].

Owaza clan seats along the east bank of Imo River at a point not quite far from where it empties into Opobo Creek, emptying into the Atlantic Ocean. The clan comprises four autonomous communities: Isi Etitioha, Ipu West, Igiri-Ukwu and Etitioha, all oil-bearing communities. Reports show that Owaza's OML 11 is the largest oil-producing oil mining lease on the land where Shell Petroleum Development Company SPDC operates. Owaza people are predominantly farmers, with subsistence agriculture being the primary practice, while small forms of commercial farming are also done (Okonkwo, 2011) [26].

Eziorsu is a South-bound community of Oguta Lake with a population estimated at 14,560 according to the 1991 census. It is one of the Oil and Gas producing communities in Imo State, the second largest producing community in Oguta L.G.A. In addition, the Eziorsu community is the major stable food producer in the state, with produce including yam, cassava, maize and palm oil (Okonkwo, 2011) [26].

Methodology

Heavy metal risk assessment

To effectively assess the health risk associated with human exposure to heavy metals, the Bioaccumulation Factor (BAF) of metals in biota samples will first be determined using the Equation of Inoti *et al*. (2012) [19].

$$BAF = \frac{\text{Concentration in crop}}{\text{Concentration in soil}} \qquad (1)$$

Ecological risk assessment of heavy metals

To determine the degree of pollution, geochemical indices, including the Geo-accumulation Index (Igeo), index of ecological risk (Eri), and potential ecological risk index (RI), were derived.

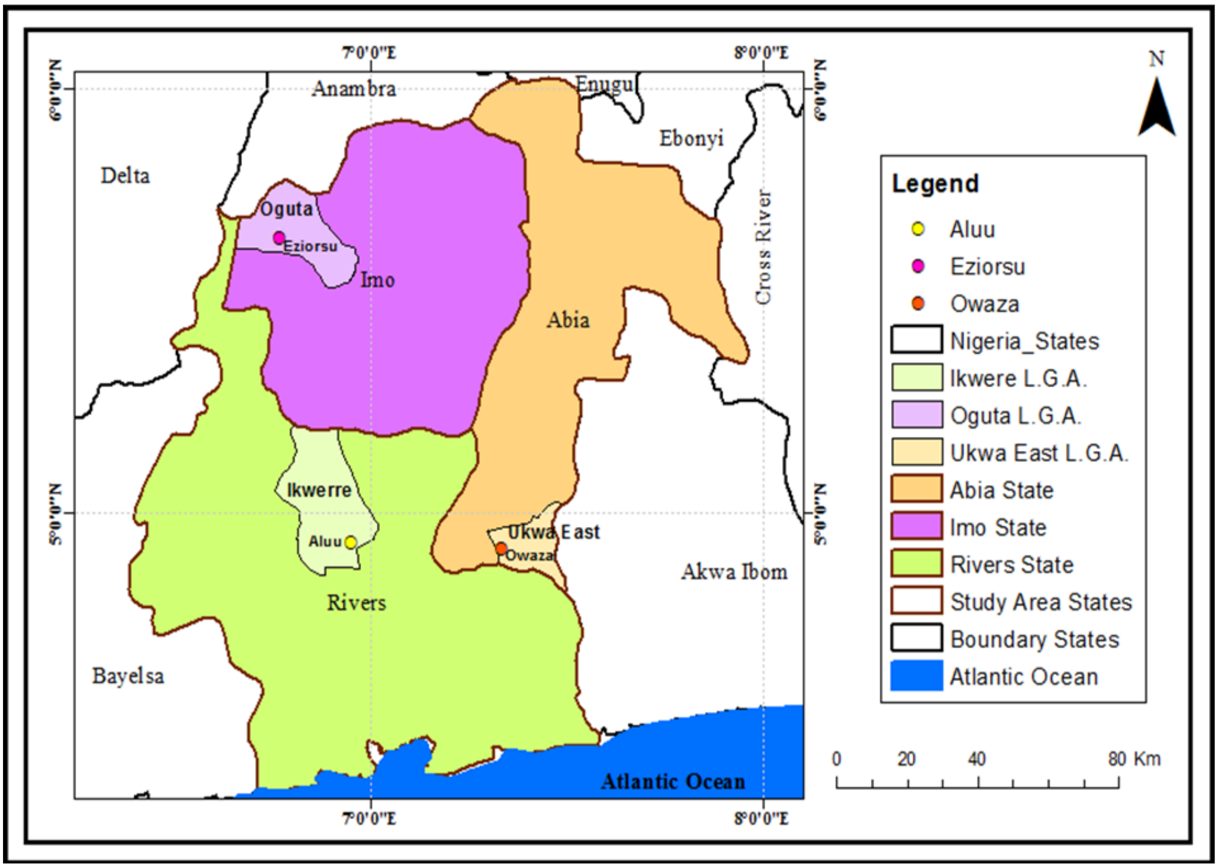

Fig 2: Map Showing Study Area and Sampling Points [13; 14]

The geo-accumulation index (Igeo)

The Geo-accumulation Index (Igeo) indicates the extent of metal accumulation in the soil compared to a reference standard. It is used to ascertain the environmental implication of soil pollutant (heavy metals) levels. This index is useful as an indicator of the presence and intensity of anthropogenic contamination (Kolawole *et al*., 2018) [22]. It is calculated using the following Equation:

$$Igeo = log2(Cn/1.5Bn) \tag{2}$$

Cn = metal concentration in the soil, and Bn is the value of the geochemical background for the element.

Index of ecological risk factor (Eri)

Eri was calculated using the following Equation.

$$\boldsymbol{Eri} = Ti \times \frac{Cn}{Cref} \tag{3}$$

Ti = toxic-response factor for metal. (Hakanson, 1980) [15].

Potential ecological risk (RI)

Potential ecological risk (RI) is used to assess the degree of ecological risk caused by increased levels of heavy metals in an environmental media. The index is calculated as the sum of ecological risk factors indexes (Eri) for specific metals in a sample. (Hakanson, 1980) [15].

$$\boldsymbol{RI} = (Eri1 + Eri2 + Eri3 + Eri4 + Eri5 \ldots Erin) \tag{4}$$

Table 1: Ecological risk levels according to (Zhi-Jie *et al*., 2012) [41].

Er i	RI	Level of ecological risk
Eri < 40	RI<94	Low ecological risk
40 ≤ Er i<80	94 ≤ RI≤<188	Moderate ecological risk
80≤Er i <160	188 ≤ RI<376	Considerable ecological risk
Eri≥ 160	RI ≥ 376	Very high ecological risk

Human health risk assessment of heavy metals

To effectively assess the human health impact associated with human exposure to heavy metals from the post-remediated soil sites, the following indices will be utilized:

The average daily intake of metals (ADI), The hazard Quotient (HQ) and hazard Index (HI) for a quantitative description of non-carcinogenic and Carcinogenic Risk (CR) for health risks associated with carcinogenic metal carcinogenic risks related to human exposure to heavy metals from the previously remediated sites under study (Ogunlaja *et al*., 2019) [25].

Average daily intake of heavy metal (ADI)

The estimated daily intake of metals will be calculated using the relationship stipulated by (Kacholi & Sahu, 2018) [20].

$$ADIing = \frac{Cn \times IR \times EF \times ED}{BW \times AT} \tag{5}$$

Where

ADIing is the average amount of metals taken in daily mg/kg-day,

Cn: is the concentration of heavy metal in mg/kg for soil.
IR: the ingestion rate, IR mg/day
EF: Exposure frequency,
ED: Exposure duration in years,
BW: body weight of the exposed person (kg),
A: Average time.1

Table 2: Exposure parameter used for the health risk assessment through different exposure pathways for soil

Parameter	Unit	Child	Adult
Body weight (BW)	Kg	15	70
Exposure frequency (EF)	Days/ years	350	350
Exposure duration (ED)	Years	6	30
Ingestion rate (IR)	mg/ day	200	100
Average time (AT) for carcinogens	Days 3	65 x 70	66 x 70
Average time (AT) for non-carcinogens	Days	365 x ED	366 x ED

Hazard quotient (HQ)

The hazard quotient is also referred to as the Non-Carcinogenic Risk. The hazard quotient is the probability of exposed persons suffering adverse effects. As shown in Equation, it is a quotient of the Average Daily Intake of exposed metals divided by the chronic reference dose (RfD) in mg/kg-day of a specific heavy metal.

$$HQ = \frac{ADI}{RfD} \tag{6}$$

Where

ADI is the Average daily intake of metals.
RfD is the oral reference dose.
When *HQ* < 1, metal contamination is still within safe limits.
HQ≥1 can cause disease (Chary *et al*., 2008) [9].

Hazard index

The hazard is an index of the hazard quotient; when the value exceeds 1 (one), there is a probability of adverse effects from exposure to non-carcinogenic effects (Caspah *et al*., 2016) [8].

$$HI = \sum HQ1 + HQ2 + HQ3 + HQ4 + HQ5 + HQ6 + \mathrm{HQn} \tag{7}$$

Where

HQ1= hazard Quotient for the heavy metal 1,
HQ2= hazard Quotient for the heavy metal 2,
HQ3 = hazard Quotient for the heavy metal 3,
HQ4= hazard Quotient for the heavy metal 4, etc.

Carcinogenic risk assessment for carcinogens (CSF)

This is the probability that an individual exposed to carcinogenic metals will develop cancer over a lifetime (Bello *et al*., 2019; Kamunda *et al*., 2016) [6, 21].

Carcinogenic risk is calculated as following relationship for lifetime cancer risk is:

$$\mathrm{CSF} = ADI \times CSF \tag{8}$$

Where

ADI =the average daily intake.

CSF =cancer slope factor, expressed in (mg/kg/day)-1. According to USEPA. (2011), when the cancer risk (CR) ranges are greater than 10−6 or 10−4; metal concentrations can be considered hazardous to health. (Rahman *et al*., 2019; Torres *et al*., 018) [28, 35].

Results and discussion

The ample assessment of heavy metal contamination within the Niger Delta region during both wet and dry seasons has yielded insightful results that shed light on the potential ecological and human health risks associated with these contaminants. The data extracted through various indices and methodologies provide a comprehensive understanding of the extent of contamination and offer valuable insights into the potential impacts on both the environment and human populations.

Table 3: Reference doses (RfD) in (mg/kg-day) and cancer slope factors (CSF) for the different heavy metals (Kamunda *et al*., 2016) [21].

Parameter	Oral RfD	Ingestio CSF	Reference
Pb	0.0036	0.00850	Luo *et al*., (2012)
Cr (IV)	1.5	0.500	Caspah, (2016); DEA, (2010); U.S.EPA, (2011)
Cu	0.04	-	DEA, (2010) & U.S.EPA, (2011)
Zn	0.3		DEA, (2010)

Index of geoaccumulation for surface soil in wet season

During the wet season, the Index of Geoaccumulation (Igeo) was employed to assess the accumulation tendencies of chromium, copper, lead, and zinc within the surface soils of the study areas. The results unveiled distinct patterns for each metal. Cr concentrations (mg/kg) in the study area during this period exhibited a range extending from 0.001 (Control and Eziorsu) to 0.000 (Owaza and Aluu). Notably, copper's distribution ranged from 0.009 (Control) to 0.021 (Eziorsu). In contrast, the Igeo values for Pb across the study area remained uniform at 0.001 during the wet season, consistent across all sample stations. Noteworthy is the variation in Igeo values for zinc, with the lowest value recorded in the Control (0.003), while Eziorsu demonstrated the highest calculated Igeo value of 0.009, as depicted in Figure 3.

Igeo for sub-surface soils during wet season

A graphical representation of the Igeo values for chromium, copper, lead, and zinc can be observed in Figure 4. The Igeo values for chromium in the sub-surface soil within the study area during the wet season exhibited a range from Eziorsu (0.001) to Control, Owaza, and Aluu (0.000), respectively. The copper Igeo values ranged from Eziorsu (0.023) to Control (0.012). For lead, the Igeo values ranged from Eziorsu (0.002) to Control, Owaza, and Aluu (0.001). Additionally, the Igeo values for zinc in the sub-surface soil samples ranged from Eziorsu (0.008) to Control (0.03).

Igeo for surface soil samples in dry season

The Igeo values for chromium, copper, lead, and zinc in surface soil during the dry season are depicted in Figure 5. The Igeo values for chromium in the surface soil samples during the dry season within the study area were uniformly registered at 0.001. The copper Igeo values ranged from Eziorsu (0.030) to Control (0.012). The lead Igeo values spanned from Control, Eziorsu, and Aluu (0.002) to Owaza (0.001). Meanwhile, the zinc Igeo values ranged from Eziorsu (0.011) to Control (0.005).

Igeo for sub-surface soil samples in dry season

The Igeo for Cr, Cu, Pb, and Zn in sub-surface soil during the dry season within the study area is presented as follows. The Igeo values for chromium in the sub-surface soil samples during the dry season ranged from Eziorsu (0.003) to Aluu (0.000). Copper exhibited a range from Control (0.015) to Eziorsu (0.033). The lead Igeo values spanned from Eziorsu (0.002) to Control, Owaza, and Aluu (0.001).
Lastly, the Igeo values for zinc in sub-surface soil samples during the dry season ranged from Control (0.004) to Eziorsu (0.010), as shown in Figure 6.

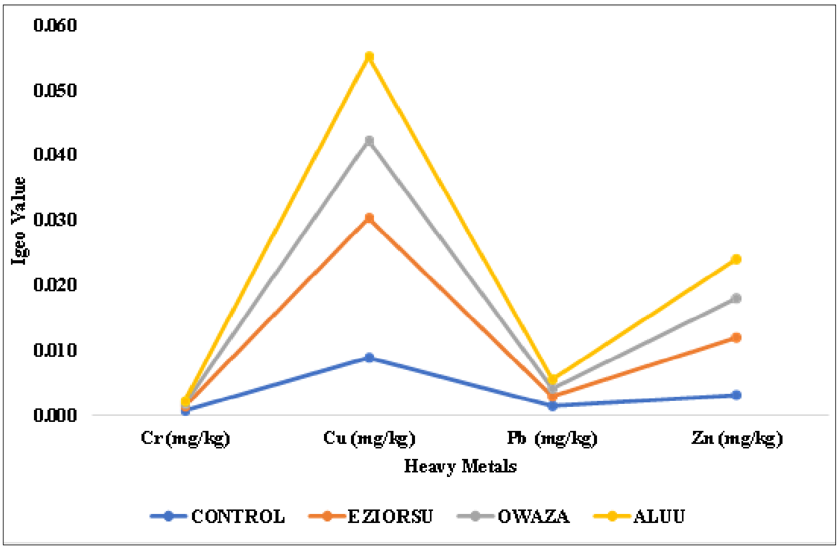

Fig 3: Igeo of surface soil from the study area during the wet season.

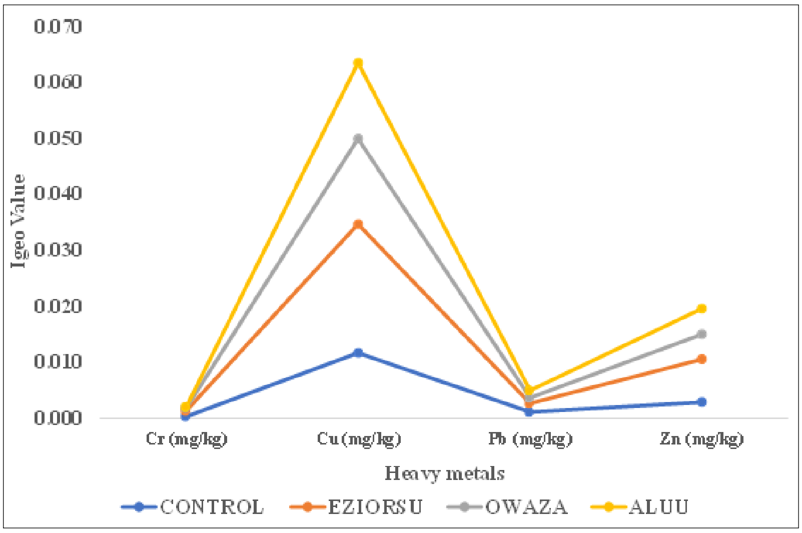

Fig 4: Igeo of sub-surface soil from the study area during the wet season.

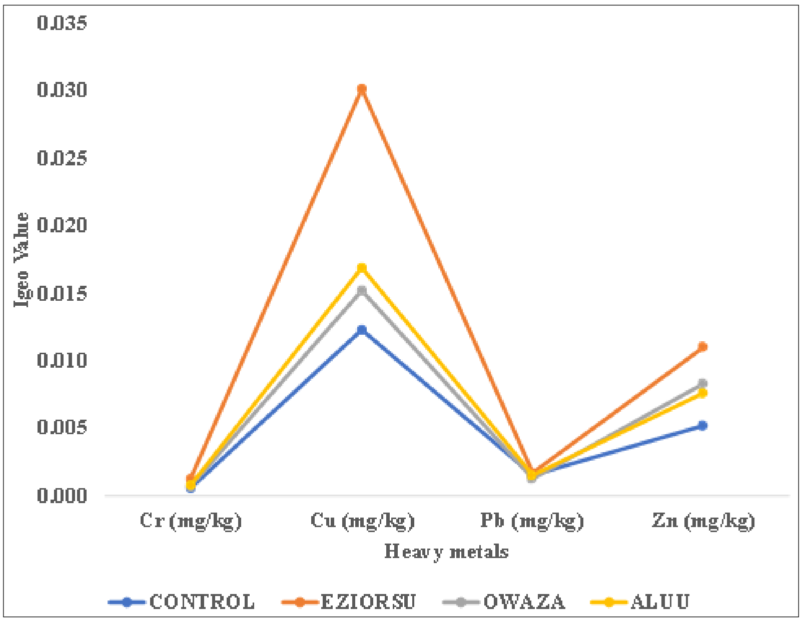

Fig 5: Igeo of surface soil from the study area during the dry season.

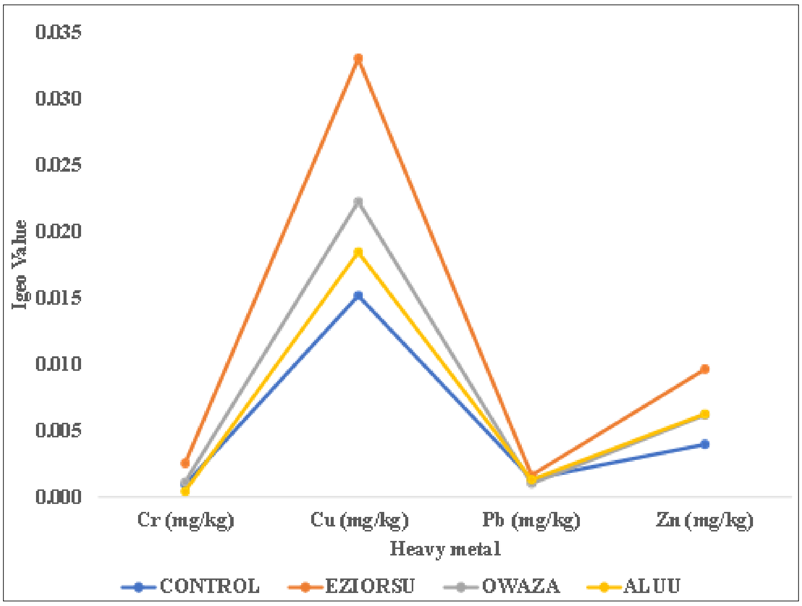

Fig 6: Igeo of sub-surface soil from the study area during the dry season.

The result of the Geo-accumulation index (Igeo) for Cr, Cu, Pb, and Zn in the study area for both surface and sub-surface soil in the wet and dry seasons is presented in Figures 3 to 6. All the data here are in the zero category, indicating that soil from the ex-post remediated sites is not polluted according to the assessment index. This result agrees with the findings of Simeon and Friday (2017) [31], who also reported values within the zero categories from their research on the index model's assessment of heavy metal pollution in soils within selected abattoirs in Port Harcourt. The results of the present study agree with the studies of Haris *et al*. (2017) [16], who studied the Geo-accumulation index and contamination factors of heavy metals (Zn and Pb) in urban river sediment. These results are below those of Kolawole *et al*. (2018) [22]., who reported the Igeo value of unpolluted to moderately polluted in their study.

Index of ecological risk factor (eri) for surface and sub-surface soils in wet season.

The Eri for chromium, copper, lead, and zinc in surface soil during the wet season within the study area yielded the following results. Chromium Eri values ranged from Owaza and Aluu (0.004) to Control (0.007). Copper's Eri values varied from Control (0.220) to Eziorsu (0.535). Lead Eri values spanned from Owaza (0.030) to Eziorsu (0.037), while zinc's Eri values ranged from Control (0.015) to Eziorsu (0.044), as documented in Table 4. In the sub-surface soil, the Eri for chromium ranged from Aluu (0.002) to Eziorsu (0.010). Copper's Eri ranged from Control (0.291) to Eziorsu (0.573). Lead Eri values spanned from Owaza (0.025) to Eziorsu (0.038), and zinc's Eri values were between Control (0.014) and Eziorsu (0.038), according to Table 5.

Table 4: Index of ecological risk factor (Eri) of surface soils in the wet season

Parameter	Tr	Control	Eziorsu	Owaza	Aluu
Cr	2	0.007	0.006	0.004	0.004
Cu	5	0.220	0.535	0.297	0.323
Pb	5	0.035	0.037	0.030	0.035
Zn	1	0.015	0.044	0.030	0.030

Table 5: Index of ecological risk factor (Eri) of sub-surface soils in the wet season

Parameter	Tr	Control	Eziorsu	Owaza	Aluu
Cr	2	0.003	0.010	0.005	0.002
Cu	5	0.291	0.573	0.380	0.338
Pb	5	0.029	0.038	0.025	0.033
Zn	1	0.014	0.038	0.022	0.023

Index of ecological risk factor (eri) for surface and sub-surface soils in the dry season

The Eri index of chromium within the study area ranged from 0.006 for the control location to 0.013 for Eziorsu. In the context of copper, the Eri values extended from 0.306 (Control) to 0.751 (Eziorsu), while for lead, the range encompassed values from 0.032 (Owaza) to 0.042 (Eziorsu). For zinc, the Eri index spanned from 0.026 (Control) to 0.055 (Eziorsu), as documented in Table 6. In the sub-surface soil during the dry season, the ecological risk factor for chromium presented a range from 0.004 (Aluu) to 0.025 (Eziorsu). Concerning copper, the Eri values ranged from 0.378 (Control) to 0.823 (Eziorsu), while lead displayed values between 0.025 (Owaza) and 0.041 (Eziorsu). In parallel, the zinc Eri values extended from 0.020 (Control) to 0.048 (Eziorsu), as delineated in Table 7.

Table 6: Index of ecological risk factor (Eri) of surface soils in the dry season

Parameter	Tr	Control	Eziorsu	Owaza	Aluu
Cr	2	0.006	0.013	0.007	0.004
Cu	5	0.306	0.751	0.379	0.421
Pb	5	0.038	0.042	0.032	0.038
Zn	1	0.026	0.055	0.041	0.038

Table 7: Index of ecological risk factor (Eri) of sub-surface Soils in the dry season

Parameter	Tr	Control	Eziorsu	Owaza	Aluu
Cr	2	0.008	0.025	0.013	0.004
Cu	5	0.378	0.823	0.556	0.468
Pb	5	0.028	0.041	0.025	0.039
Zn	1	0.020	0.048	0.030	0.041

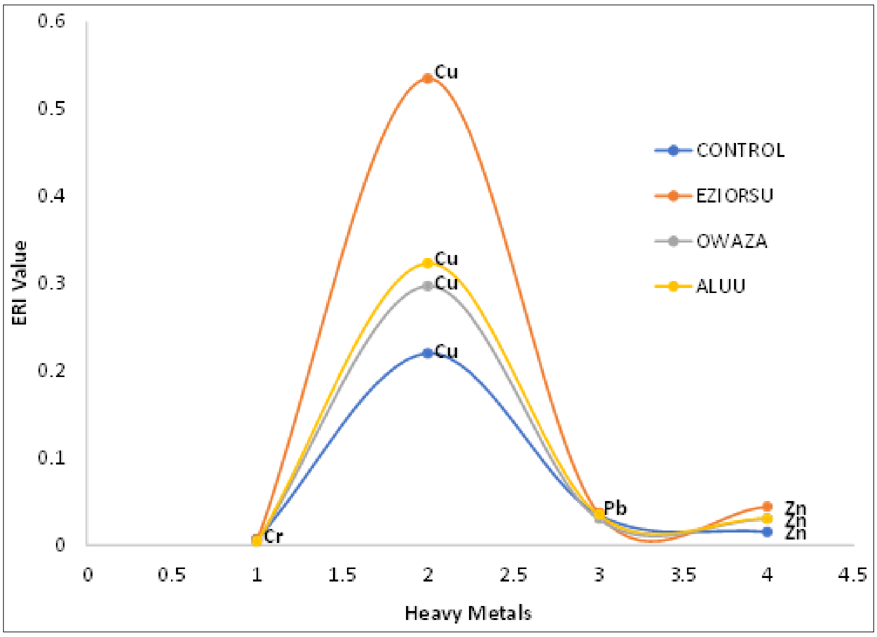

Fig 7: Index of ecological risk factor (Eri) surface soils in the wet season.

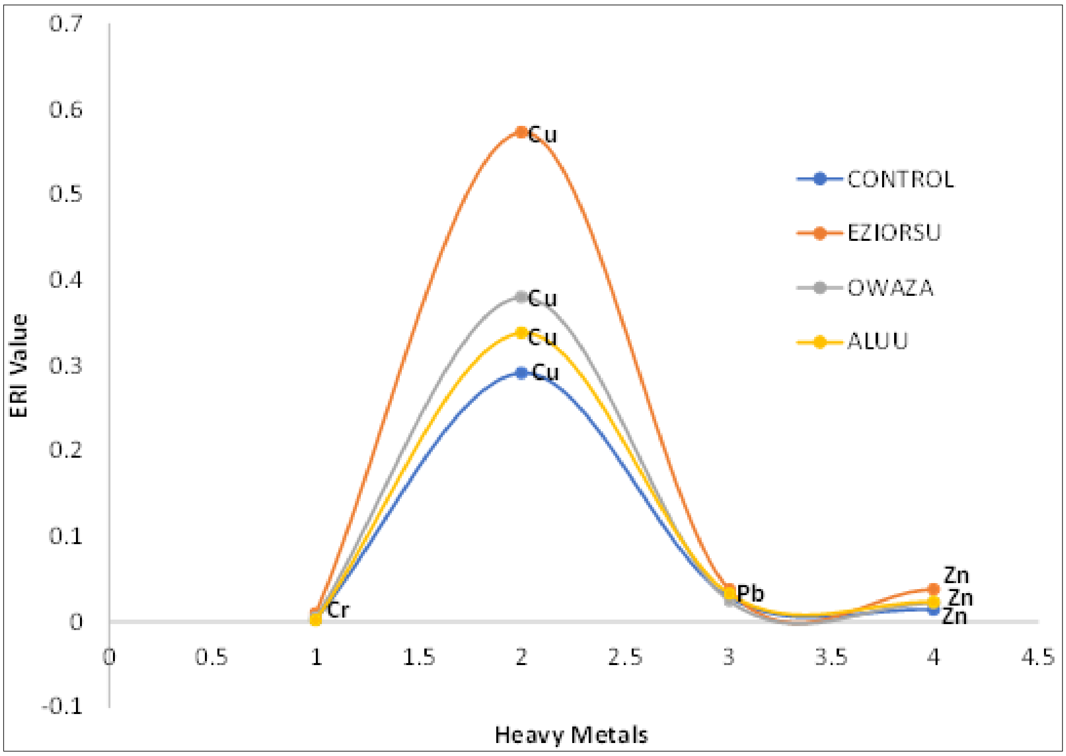

Fig 8: Index of ecological risk factor (Eri) of sub-surface soils in the wet season.

Eri is adequate for evaluating the toxicity of trace elements in sediments.

However, this index has been used extensively in the toxicity assessment of heavy metals in soil samples Liang *et al*. (2015) [23]. The ecological and health impact of heavy metals contamination of soil has been widely reported because of various forms of interaction (soil-plant transfer) of soil concentration of metals with agricultural plants where these stressors (sometimes highly toxic metals) get into the food chain and subsequently in humans causing severe health implications. When there is a high accumulation of toxic metals in agricultural soils, the quality and security of food are compromised, leading to severe diseases due to chronic exposure to these toxic metals. This development also affects the ecosystem (Liang *et al*., 2015; Suresh *et al*., 2012) [23, 34].

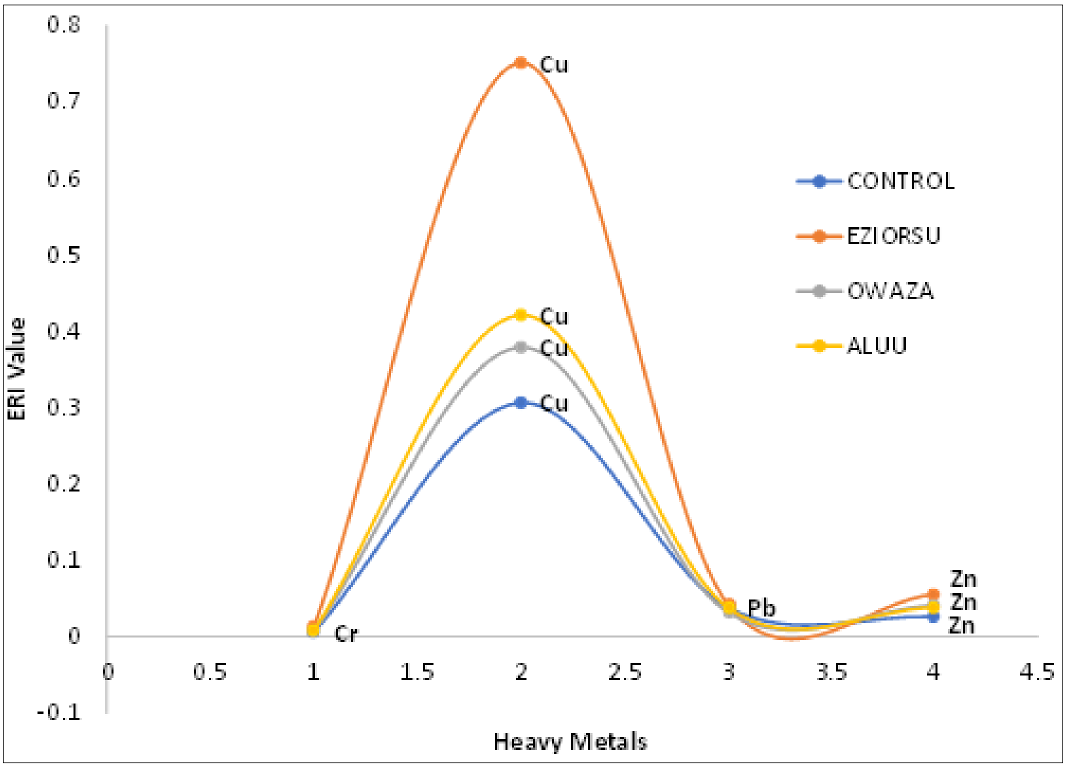

Fig 9: Index of surface soil ecological risk factor (Eri) during the dry season.

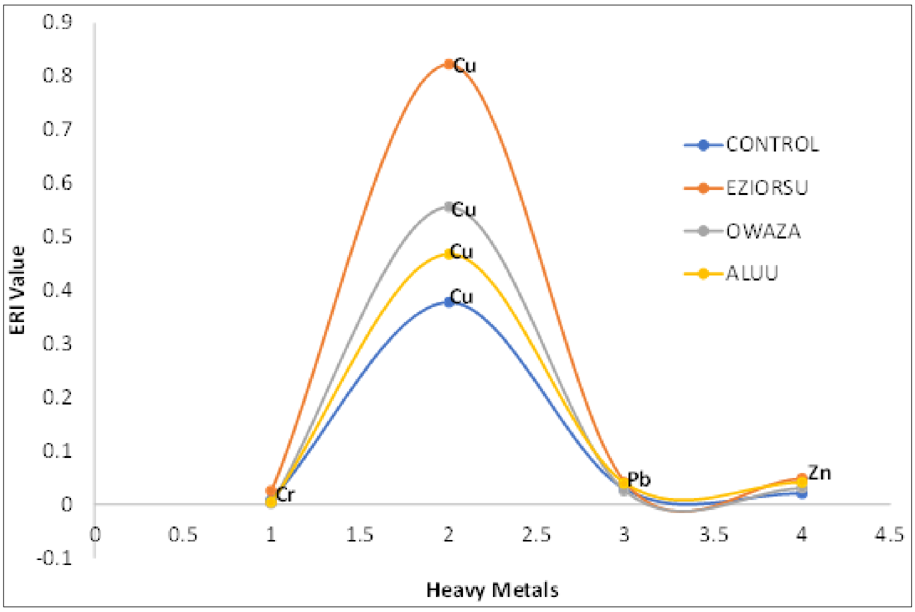

Fig 10: Index of ecological risk factor (Eri) of sub-surface soils during the dry season

The results from the study are below the results of Santos-Francés, Martínez-Graña, Alonso Rojo, and García Sánchez (2017) [30], and Kolawole *et al*. (2018) [22], who reported high values of Eri, but the result conforms with the report of (Zhang & Liu, 2014) [40]. From this study, the Eziorsu post-remediated site recorded the highest ER value. This represents the state of remediation work carried out in the previously spilt site. However, the standard table chart for an index of ecological risk factors and potential ecological risk signifies that all results from this study were within safe levels of less than one, indicating that the study area's soil pollution levels are within safe limits. Between the two seasons, there was no marked difference between the Eri of wet and dry seasons; chromium had the least ER from the study area and was the least heavy metal, whereas copper, with an Eri value of 0.823 at Eziorsu, was the highest.

Potential ecological risk index (RI)

As depicted in Figure 11, the RI elucidates distinctive variations across different scenarios. During the wet season, the RI values within the surface soil exhibited a range spanning from 0.278 (Control) to 0.623 (Eziorsu). This pattern is juxtaposed by the wet season sub-surface soil, where the RI values presented a range extending from 0.338 (Control) to 0.660 (Eziorsu). Transitioning to the dry season, the potential ecological risk index RI in surface soil displayed a spectrum ranging from 0.376 (control) to 0.861 (Eziorsu). In a parallel vein, the RI values within the sub-surface soil during the dry season ranged from 0.441 (Control) to 0.937 (Eziorsu).

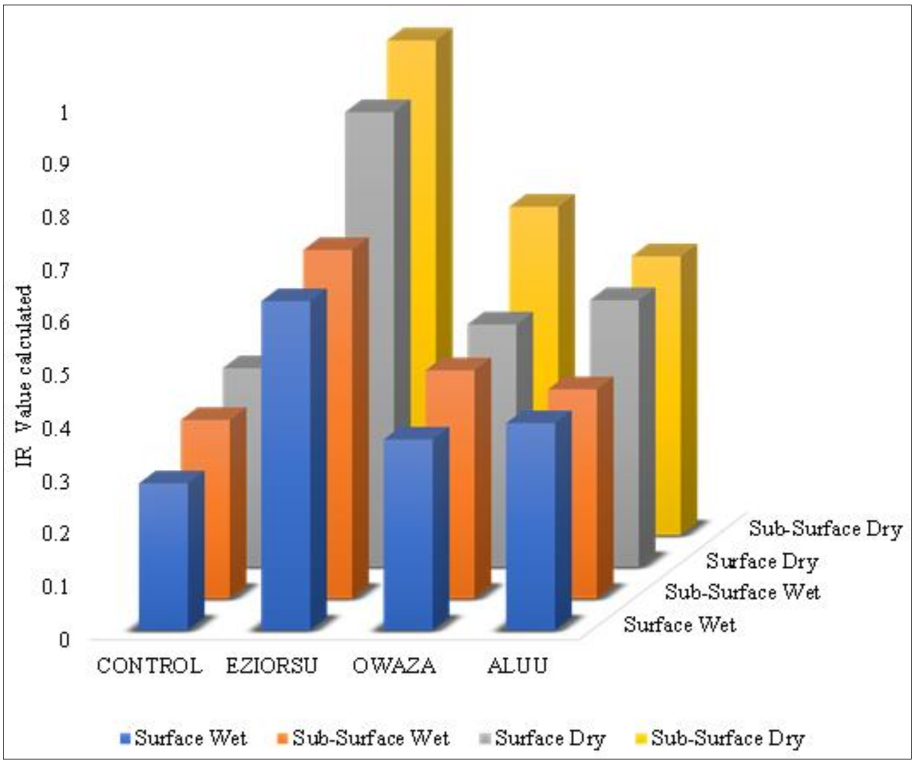

Fig 11: Potential ecological risk index (RI) from the study area.

The potential ecological risk index (RI) index reflects the general situation of pollution caused by the simultaneous presence of the four heavy metals associated with petroleum hydrocarbon of the previously oil-spilt remediated sites. RI (Potential Ecological risk index) presented in Figure 11 indicate that, in wet season sub-surface soil, RI ranges from Control (0.278) to Eziorsu (0.623), while in wet season sub-surface soil, RI value range from Control (0.338), Eziorsu (0.660) In the dry season, the potential ecological risk index RI in surface soil ranged from Control (0.376) to Eziorsu (0.861). In contrast, in sub-surface dry season soil, RI values ranged from Control (0.441) to Eziorsu (0.937); these results are below the reports of Zhang and Liu (2014) [40] and Santos-Francés *et al*. (2017) [30], who reported high levels of potential ecological risk.

Human health risk assessment

Average daily intake (ADI) of metals in surface soil during the wet season (Mg/Kg-Day).

The ensuing results delineate the Average Daily Intake (ADI) of chromium, copper, lead, and zinc within surface soil during the wet season within the study area. Chromium's ADI values in surface soil ranged from 0.123 (Aluu) to 0.587 (Owaza). In parallel, lead manifested an ADI spectrum extending from 0.350 (Aluu) to 0.587 (Owaza). Copper's ADI spanned from 1.370 (Owaza) to 5.280 (Eziorsu). The ADI values for zinc oscillated between 1.370 (Owaza) and 8.465 (Eziorsu), as portrayed in Figure 12.

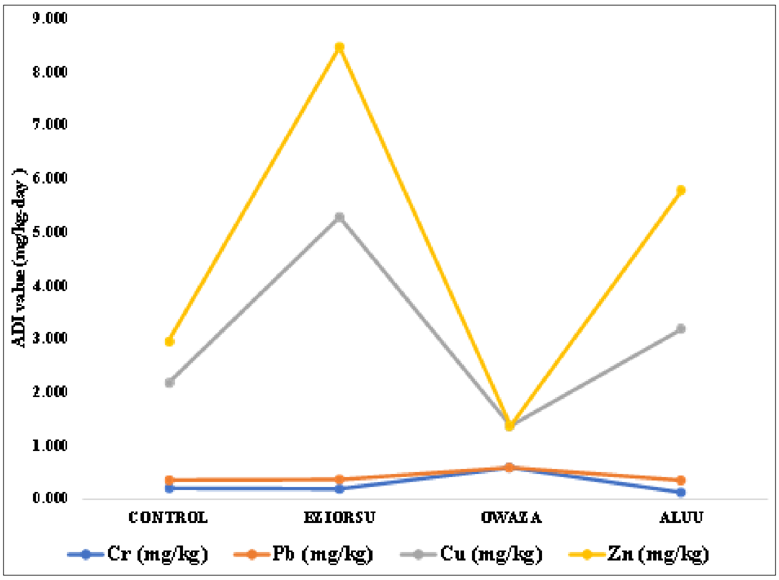

Fig 12: Average daily intake of metals for surface soil from the study area during the wet season.

Average daily intake (ADI) of metals in sub-surface soil during the wet season (Mg/Kg-Day)

The subsequent outcomes elucidate the Average Daily Intake (ADI) of chromium, copper, lead, and zinc within sub-surface soil during the wet season in the study area. Chromium's ADI values within sub-surface soil during this season ranged from 0.050 (Aluu) to 0.590 (Owaza). Likewise, lead exhibited values spanning from 0.280 (Control) to 0.590 (Owaza). Copper's ADI spanned from 1.370 (Owaza) to 5.660 (Eziorsu). Correspondingly, zinc's ADI values oscillated between 1.370 (Owaza) and 7.330 (Eziorsu), as depicted in Figure 13.

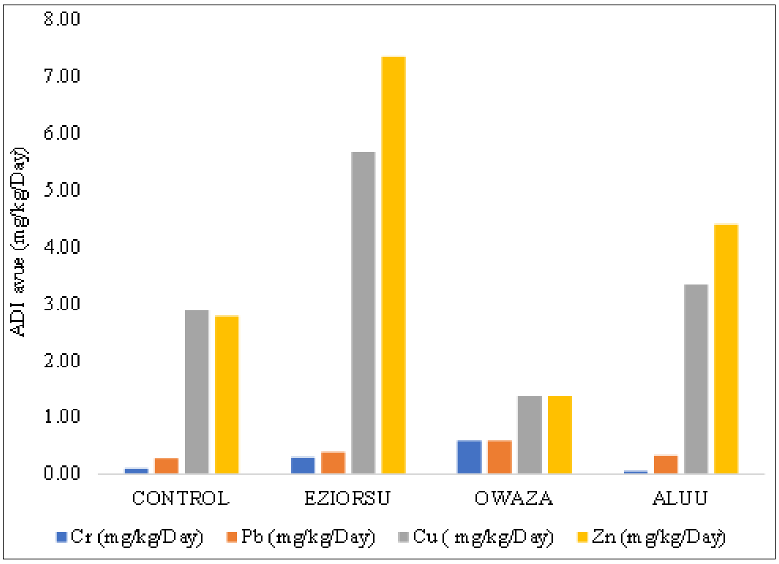

Fig 13: Average daily intakes of metals for sub-surface soil from the study area during the wet season

Average daily intake (ADI) of metals in surface soil during the dry season (Mg/Kg-Day)

The ADI values for chromium, copper, lead, and zinc within surface soil during the dry season in the study area are aptly illustrated in Figure 13. Chromium's ADI spanned from 0.171 (Control) to 0.587 (Owaza). Conversely, lead's ADI Values ranged from 0.327 (Aluu) to 0.587 (Owaza).

Copper's ADI values spanned from 1.370 (Owaza) to 7.408 (Eziorsu). Similarly, zinc's ADI values oscillated between 1.370 (Owaza) and 10.539 (Eziorsu).

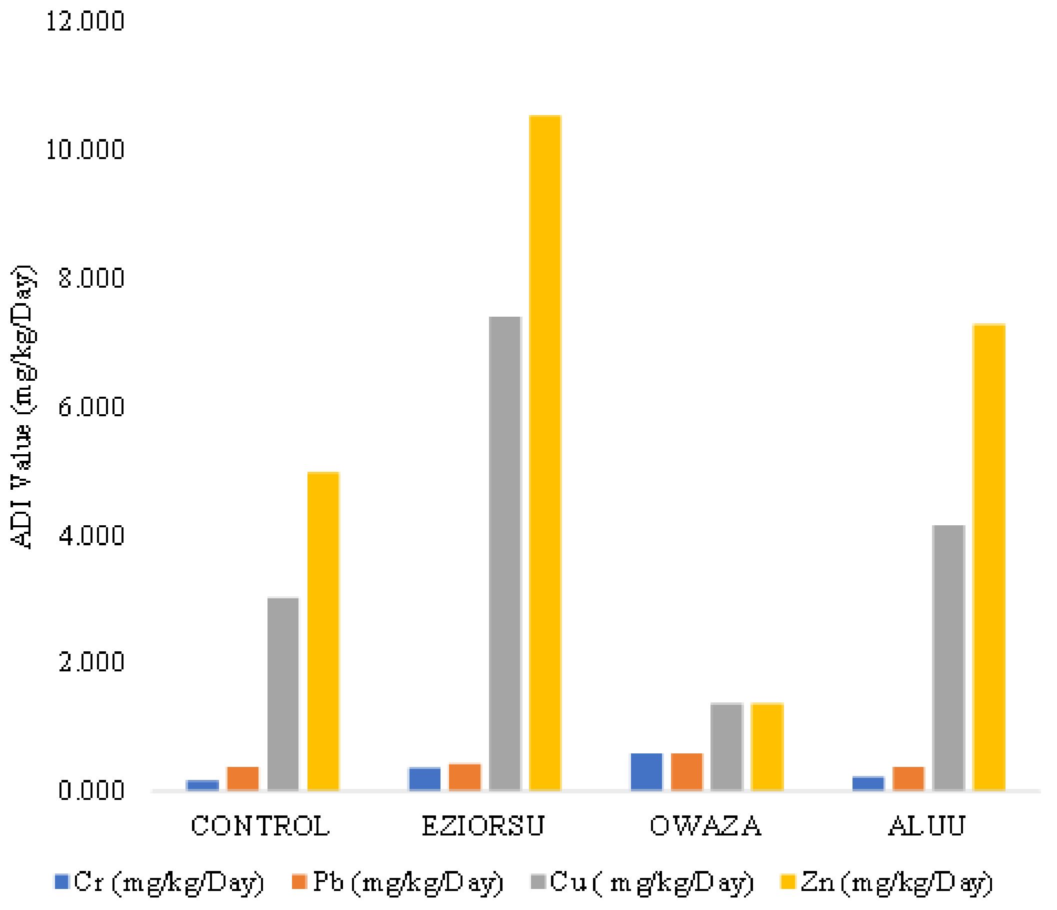

Fig 14: Average daily intakes of metals for surface soil from the study area during the dry season.

Average daily intake (ADI) of metals in sub-surface soil during the dry season (Mg/Kg-Day)

The ADI values of chromium, copper, lead, and zinc within sub-surface soil during the dry season within the study area are vividly portrayed in Figure 15. The ADI values for chromium ranged from 0.128 (Aluu) to 0.742 (Eziorsu). Lead's ADI values spanned from 0.327 (Aluu) to 0.587 (Eziorsu). Copper's ADI exhibited values oscillating between 1.370 (Owaza) and 8.115 (Eziorsu). Similarly, zinc's ADI values showcased a spectrum extending from 1.370 (Owaza) to 9.201 (Eziorsu).

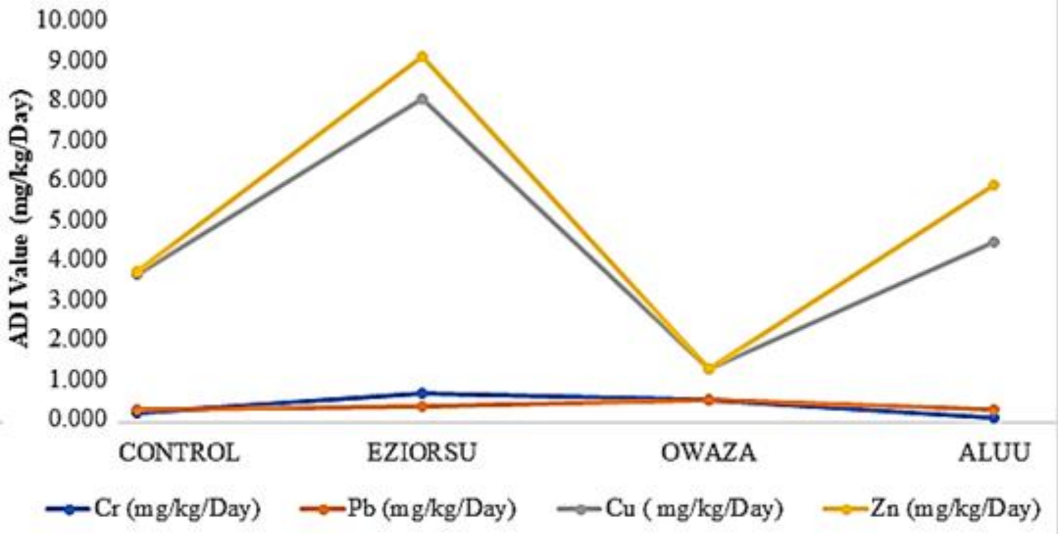

Fig 15: Average daily intakes of metals for the sub-surface soil from the study area during the dry season.

ADI (Average daily intake) of metals in plant samples

ADI of human exposure to plant parts contaminated by heavy metals during the wet season.

The Average daily intake for human exposure to heavy metals in plant parts from the study area and the control site is presented in Table 8. ADI for chromium was highest in Owaza with a value of 0.002, while the rest of the stems from the rest of the sampling sites was 0.000, chromium in leaves was 0.001 in Control, Eziorsu, and Aluu, while Owaza 0.002 was the highest. The range of Pb ADI was from 0.002 for Owaza and Aluu, Control and Eziorsu 0.003 in both stem and leaves. Control, Eziorsu, and Owaza had values of 0.004, while Aluu recorded 0.005. in leaves, copper Eziorsu and Owaza values were 0.004, while Control and Aluu recorded 0.005. The Average daily intake for zinc exposure through contaminated stem was 0.002 for Aluu and 0.010 in the control site; ADI of leaves in the wet season ranged from 0.004 Owaza and Control while Eziorsu and Aluu had values of 0.005 (Table 8).

Table 8: The average daily intake from human exposure to plants during the wet season in the study area.

Wet season stem ADI Mg/kg/Day				
Parameter	Control	Eziorsu	Owaza	Aluu
Cr (mg/kg/Day)	0.001	0.001	0.002	0.000
Pb (mg/kg/Day)	0.003	0.003	0.002	0.002
Cu (mg/kg/Day)	0.004	0.004	0.004	0.005
Zn (mg/kg/Day)	0.010	0.004	0.004	0.002
Wet Season Leaf ADI Mg/kg/Day				
Cr (mg/kg/Day)	0.001	0.001	0.002	0.001
Pb (mg/kg/Day)	0.003	0.003	0.002	0.002
Cu (mg/kg/Day)	0.005	0.004	0.004	0.005
Zn (mg/kg/Day)	0.004	0.005	0.004	0.005

ADI of human exposure to plants contaminated by heavy metals during the dry season.

The average daily intake of human exposure to chromium from the stem of the contaminated plants during the dry season ranged from 0.001 in Aluu, Eziorsu, and Control to Owaza 0.002. In the leaves, 0.001 was the lowest value in Aluu, while the Control, Eziorsu, and Owaza recorded 0.002. lead in stem ranged from 0.002 in Aluu to 0.004 in Control, in leaf lead ranged from 0.002 in Owaza to 0.004 in Eziorsu, ADI of copper in storm ranged from 0.004 in Owaza to 0.008 in Aluu, while in leaves, the rang 0.004 in control site to 0.007 in Aluu. The average daily intake for zinc in the stem in the dry season ranged from 0.004 in Owaza to 0.011 in the control site. In comparison, the lowest ADI values of Zn in leaves ranged from 0.004 in owaza to 0.007 (Eziorsu and Owaza) (Table 9).

Table 9: The average daily intake from the study area from human exposure to plants during the dry season.

Wet season stem ADI Mg/kg/Day				
Parameter	Control	Eziorsu	Owaza	Aluu
Cr (mg/kg/Day)	0.001	0.001	0.002	0.000
Pb (mg/kg/Day)	0.004	0.003	0.002	0.002
Cu (mg/kg/Day)	0.007	0.005	0.004	0.008
Zn (mg/kg/Day)	0.011	0.007	0.004	0.005
Wet season leaf ADI Mg/kg/Day				
Cr (mg/kg/Day)	0.002	0.002	0.002	0.001
Pb (mg/kg/Day)	0.003	0.004	0.002	0.003
Cu (mg/kg/Day)	0.007	0.005	0.004	0.007
Zn (mg/kg/Day)	0.005	0.007	0.004	0.007

Assessing human exposure to heavy metal levels is indispensable in determining human health risks (Singh *et al*., 2010) [32]. The Average daily intake (ADI) of metals by humans due to exposure to contaminated soil from the post-remediated sites understudy is presented in figures 12-15. These results show that copper at the Eziorsu post-remediated site recorded the highest ADI value and Eziorsu recorded the highest ADI of metals according to site rating. The study shows that lead exposure through soil ingestion is below the permitted maximum tolerable daily intake (PMTDI) endorsed by WHO (2008) [39] of 0.21mg/person per day.

The average daily intake (ADI) of human exposure to the plant stem samples from the study area during the wet and dry seasons, represented in tables 8 and 9, revealed the maximum level of ADI in each heavy metal in the sampling sites. In plant samples, zinc from the Control site had calculated ADI values of 0.011 as the highest. All calculated ADI values in plant fall below the value of 1; this indicates that the human health associated with exposure to plants from the study area via ingestion is deficient. Zinc is an essential metal in the human body as it plays a vital role in average growth and development. Higher Zn intake can suppress Cu and Fe absorption, gastrointestinal irritation, and interference with physiological processes (Singh *et al*., 2010) [32]; deficiency of Zn results from insufficient dietary intake, reduced absorption, excessive excretion, or inherited defects in zinc metabolism.

Copper is a vital element in the human body as it is responsible for upholding central nervous system health, proper working of the metabolic processes, pigmentation, and prevention of anaemia (Alam *et al*., 2003) [5]. People suffering from Wilson's disease are at significant risk for health effects when overexposed to copper. When Cu exceeds safe limits in the human body, it possesses health hazards like hypertension, sporadic fever, coma, anaemia, liver and kidney damage, and stomach and intestine irritation (Bermudez *et al*., 2011) [7]. The average daily intake of Cu maximum levels was calculated as Eziorsu 5.655 and 8.115 in soils, while in plants, the maximum copper intake was Aluu 0.008 in stem and 007 in leaves.

Hazard quotient (HQ) and hazard index (HI) hazard quotient of heavy metals from exposed remediated sites during the wet season.

The HQ and HI of human exposure to soil contaminated by heavy metals during the wet season (Table 10) revealed that chromium was lowest and highest at Aluu (0.082) and Owaza (0.391). The HQ of human exposure to lead ranged from 88.11 (Control) to 146.77 (Owaza). For copper, the value ranged from 34.247 (Owaza) to 132.01 (Eziorsu). Interestingly, the human quotient of human exposure to surface soil contaminated by zinc ranged from 4.566 for Owaza and the highest in Aluu, with an HQ value of 19.28. In sub-surface soil, the HQ and heavy metals exposure in contaminated sub-surface soil during the wet season in the study area had a chromium value ranging between 0.035in samples from Aluu to 0.391 in samples from Owaza. The hazard quotient for human exposure to contaminated sub-surface soil in the wet season ranged from 71.208 in the control site to 146.771. The hazard quotient ranged from 34.25 in Owaza to 141.38 in Eziorsu. HQ in zinc surface soil was from Owaza 4.566 to Aluu and 24.44 (Table 10).

Table 10: Hazard quotient and index (mg/kg-day) of human exposure to contaminated surface soils in Wet Season

Wet season soil HQ mg/kg-day (Surface)					
Parameter	RfD	Control	Eziorsu	Owaza	Aluu
Cr	1.500	0.14	0.13	0.39	0.08
Pb	0.004	88.11	91.63	146.77	87.43
Cu	0.040	54.33	132.01	34.25	79.62
Zn	0.300	9.83	28.22	4.57	19.28
HI		152.41	251.99	185.98	186.40
Wet Season Soil HQ mg/kg-day (Sub-Surface)					
Parameter	RfD	Control	Eziorsu	Owaza	Aluu
Cr	1.500	0.07	0.20	0.39	0.03
Pb	0.004	71.21	95.72	146.77	81.41
Cu	0.040	71.84	141.38	34.25	83.42
Zn	0.300	9.25	24.44	4.57	14.62
HI		152.36	261.74	185.98	179.49

Hazard quotient and hazard index of human exposure to soil contaminated by heavy metals in the dry season.

This section examines the HQ and HI about human exposure to heavy metal-contaminated soil during the dry season. The HQ associated with exposure to chromium-contaminated soil within the surface soil during this period displayed a range from 0.114 (Control) to 0.39 (Owaza). In parallel, the HQ values for human exposure to lead-contaminated surface soil ranged from 94.89 (Aluu) to 146.771 (Owaza).

Concerning copper, the HQ exhibited a range from 34.25 (Owaza) to 185.20 (Eziorsu). Notably, the HQ for zinc ranged from 4.8 (Owaza) as the lowest to 35.132 (Eziorsu) as the highest, as outlined in Table 4.8. Delving into the sub-surface, the HQ associated with chromium-contaminated sub-surface soil indicated that Aluu registered the lowest HQ value of 0.09. In contrast, Eziorsu exhibited the highest HQ value of 0.49. Similarly, the lowest HQ was recorded for the lead at Aluu (81.723), while the highest was observed at Owaza (146.77). Copper's HQ spanned 34.25 (Owaza) to 202.865 (Eziorsu). In the context of zinc, the HQ values ranged from 4.567 (Owaza) to 30.67 (Eziorsu), as detailed in Table 11.

Table 11: Hazard quotient and index (mg/kg-day) of human exposure to contaminated surface soils in the dry season

Dry season soil HQ mg/kg-day (Surface)					
Parameter	RfD	Control	Eziorsu	Owaza	Aluu
Cr	1.500	0.11	0.24	0.39	0.15
Pb	0.004	95.57	106.02	146.77	94.89
Cu	0.040	75.53	185.20	34.25	103.80
Zn	0.300	16.59	35.13	4.57	24.27
HI		187.80	326.59	185.98	223.11
Dry season soil HQ mg/kg-day (Sub-Surface)					
Parameter	RfD	Control	Eziorsu	Owaza	Aluu
Cr	1.500	0.18	0.49	0.39	0.09
Pb	0.004	85.18	102.81	146.77	81.73
Cu	0.040	93.20	202.87	34.25	113.29
Zn	0.300	12.66	30.67	4.57	19.93
HI		191.22	336.84	185.98	215.04

Hazard quotient of human exposure to plant parts contaminated by heavy metals in the wet season.

The HQ is pertinent to human exposure to heavy metals within plant parts from the study area and the control site during the wet season yields the ensuing findings. HQ values for chromium indicated the highest value in Owaza at 0.001, while stems from other sampling sites recorded HQ values of 0.000. All sampled leaves exhibited HQ values of 0.001 for chromium. The range for lead (Pb) HQ spanned from 0.402 (Aluu) to 0.796 (stem samples from control sites). Within leaves, the HQ for Pb ranged from 0.440 (Awaza) to 0.805 (Eziorsu), representing the highest. The HQ for copper in the stem of contaminated plants showcased Eziorsu as the lowest (0.091), while Aluu registered the highest (0.128). HQ values for copper in leaves during the wet season ranged from 0.096 (Eziorsu) to 0.120 (Aluu). Regarding zinc, the HQ associated with contaminated stems displayed values of 0.007 (Aluu) and 0.032 (control site), while within leaves, HQ values ranged from 0.013 (Control) to 0.017 (Eziorsu), as delineated in Table 12.

Table 12: Hazard quotient and index (mg/kg-day) of human exposure stem and leaf in the wet season

Wet season stem HQ					
Parameter	RfD	Control	Eziorsu	Owaza	Aluu
Cr	1.500	0.000	0.000	0.001	0.000
Pb	0.004	0.796	0.674	0.440	0.402
Cu	0.040	0.106	0.091	0.103	0.128
Zn	0.300	0.032	0.013	0.014	0.007
HI		0.934	0.778	0.558	0.537
Wet season leaf HQ					
Parameter	RfD	Control	Eziorsu	Owaza	Aluu
Cr	1.500	0.001	0.001	0.001	0.001
Pb	0.004	0.678	0.805	0.440	0.496
Cu	0.040	0.113	0.096	0.103	0.120
Zn	0.300	0.013	0.017	0.014	0.016
HI		0.805	0.918	0.558	0.633

Hazard quotient of human exposure to plants contaminated by heavy metals during the dry season.

The HQ of human exposure to chromium from the stem of the contaminated plant during the dry season ranged from 0.00 in samples from Aluu to 0.001 in samples from the control site, Eziorsu and Owaza; all leaf samples show HQ values of 0.000 across all stations and control site. The hazard quotient for Human exposure to stem and leaf contaminated by lead ranged from 0.570 in Aluu to 0.964 in the control site in the stem.

For the leaves, 0.44 in Owaza to 0.98 in Eziorsu, HQ of Cu ranged from 0.103 in Owaza to 0.19 in Aluu, while plant leaf ranges from 0.103 to 0.187 in the control site, hazard quotient for copper exposure is 0.58 and 0.60 for stem and leaf. The hazard quotient for zinc in stem from the dry season in the study area revealed a range of 0.014 in Owaza to 0.037 in the control site; in plant leaf, HQ values ranged from 0.014 in Owaza to Eziorsu 0.024 as the highest (Table 13).

Table 13: Hazard quotient and index (mg/kg-day) of human exposure stem and leaf in the dry season

Dry season stem HQ					
Parameter	RfD	Control	Eziorsu	Owaza	Aluu
Cr	1.500	0.001	0.001	0.001	0.000
Pb	0.004	0.964	0.868	0.440	0.570
Cu	0.040	0.168	0.118	0.103	0.190
Zn	0.300	0.037	0.022	0.014	0.017
HI		1.170	1.009	0.558	0.777
Dry season leaf HQ					
Parameter	RfD	Control	Eziorsu	Owaza	Aluu
Cr	1.500	0.001	0.001	0.001	0.001
Pb	0.004	0.839	0.976	0.440	0.652
Cu	0.040	0.187	0.130	0.103	0.182
Zn	0.300	0.018	0.024	0.014	0.023
HI		1.045	1.131	0.558	0.858

When Hazard Quotient (HQ) and Hazard Index (HI) values exceed 1, the population has no apparent risk. However, if these values exceed one, there may be a concern for potential non-carcinogenic effects (US EPA, 2004) [38]. The result of the Hazard quotient for the study population was only calculated for adult populations through the ingestion route of exposure.

The hazard quotient and hazard Index of human exposure to soil contaminated by heavy metals during the wet season

The hazard quotient of human exposure to lead (mg/kg-day) from contaminated surface soil during the wet and dry seasons was maximum at 146.77 (Owaza and Aluu). The hazard quotient for human exposure to copper-contaminated soil was highest in soil samples from Eziorsu (141.381) during the wet season. The hazard quotient of zinc was highest in soil samples from Aluu at 24.44; all the values of the Hazard index of heavy metal in soil exceeded value one, according to US EPA (2004) [38]. If these values exceed one, human exposure to the toxicant has potential non-carcinogenic effects. The high HQ value is over 100% above the recommended level. It is a flection of the state of remediation work carried out on the previously spilt sites from the Niger Delta region. It, therefore, shows that the probability of exposed individuals developing non-carcinogenic disease conditions is very high.

The hazard quotient and hazard index of human exposure to soil contaminated by heavy metals during the dry season

Hazard assessment of soil in the dry season indicated that chromium is the metal that contributes least to the total hazard quotient of the study area, with a maximum hazard quotient of 0.086 in soil samples from Aluu. At the same time, the lead with HQ 146.771 from soil samples from Owaza was the highest across all sampling sites. This result indicates that the potential non-carcinogenic risk associated with heavy metals during the dry season is very high.

The hazard quotient and hazard index of human exposure to plant parts contaminated by heavy metals during the wet season

The hazard quotient of heavy metal exposure to plant parts in wet and dry seasons was all below the standard of one, again, this indicates that exposure to stem and leaves will have a low potential non-carcinogenic risk. Among all heavy metals assessed, lead recorded HQ values of 0.964 as the highest among the metals, chromium with its highest HQ value of 0.001 across all seasons, plant parts and the different post-remediated sites, was the heavy metal with the least potential for non-carcinogenic risk.

The result of the present study for the hazard quotient of heavy metals in soil samples was very high compared to the reports (Kacholi & Sahu, 2018) [20]. However, the HQ values reported by (Kacholi & Sahu, 2018) [20] of 2.46 and 7.12 for vegetables are way higher than the reports of the present study on HQ values in plants. The result of this study is also higher than the reports of Kacholi & Sahu (2018) [20], who reported negative values of HQ in all samples they studied. Overall, the hazard quotient of heavy metals in the post-remediated sites reflects very high potential non-carcinogenic risk; this could be attributed to the processes and type of remediation activities carried out by remediating companies or organizations.

Hazard index of human exposure to soil and plants from the study sites

Hazard index of soil samples from wet and dry seasons from the post-remediated sites and Control revealed values that were more than 100 (Tables 10 and 11). This indicates a very high human health risk associated with exposure to heavy metal-contaminated soil from the post-remediated sites. The hazard index from human exposure to heavy metals in plant stem and leaves during the dry season in the study area indicates that Eziorsu with a maximum HI value of 1.13 after the control site 1.17, Aluu and Owaza recorded values that were all less than one, indicating that the potential hazard involved in human exposure to plants from those previously remediated sites was shallow.

Carcinogenic risk of heavy metal exposure to soil and plants in the post-remediated sites.

The carcinogenic risk of chromium and lead exposure to the surface and sub-surface soil during the wet season is represented in Figure 13. Cr was lowest at Aluu 6.2x10 -2 and 2.6x10 -2 in surface and sub-surface soil, while Awaza (2. 9x10 -1) was the highest value for both surface and sub-surface soil during the wet season. Pb value of 2.97 x10 -3 (Aluu) was the lowest in surface soil, while Awaza 4.9 x10 -3 was the highest in surface soil. 2.4 x10 -3 in Control was the highest value sub-surface, while 3.2 x10 -3 in Owaza was the highest. The carcinogenic risk of chromium and lead exposure to the surface and sub-surface soil during the dry season is represented in Figure 14. Cr was lowest at Control 8.5x10 -2 (surface) and 1.4x10 -4 (sub-surface) soil for the dry season. Awaza (2. 9x10 -1) was the highest value of Cr for surface and sub-surface. Pb value of 3.2 x10 -3

(Aluu) was the lowest in surface soil, while Awaza at 4.9 x10 -3 was the highest in surface soil. 2.8 x10 -3 in the Aluu was the lowest lead value in the sub-surface, while 4.9 x10 -3 in Owaza was the highest Pb value.

The carcinogenic risk of human exposure to contaminated plant stems and leaves by lead and chromium in the study area is represented in Figures 15 and 16. In the wet season show, the carcinogenic risk of chromium in the stem was lowest at 1.4 x10 -4 in Aluu; the highest value was recorded at Owaza at 8.8 x10 -4. In the leaves, the lowest value for chromium was revealed in Aluu (3.7 x10 -4). The highest value was also recorded at Owaza 8.8 x10 -4. For lead, the lowest value in the stem was recorded at 1.4 x10 -5 in Owaza, and the highest value was recorded at Control 2.7 x10 -5. In the leaves, the lowest value for lead was 1.4 x10 -5 in Owaza, while the highest value was revealed in Aluu (2.7 x10 -5). The highest value was also recorded at Awaza 8.8 x10 -4. The carcinogenic risk of human exposure to contaminated plant stems and leaves by lead and chromium in the study area during the dry season is represented in Figure 15.

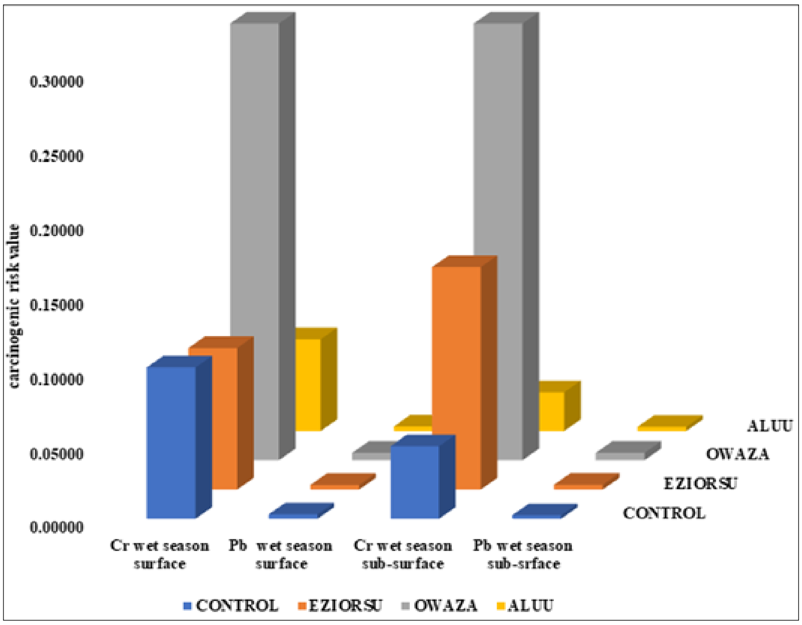

Fig 13: Carcinogenic risk of Pb and Cr in the soil in the wet season from the Niger Delta.

In the dry season, the carcinogenic risk of chromium in the stem was lowest at 2.7 x10 -4 in Aluu; the highest value was recorded at Owaza at 8.8 x10 -4. In the leaves, the lowest value for chromium was revealed in Aluu (6.7 x10 -4). The highest value was also recorded at Owaza 8.8 x10 -4. For lead, the lowest value in the stem was recorded at 1.4 x10 -5 in Owaza, and the highest value was recorded at Control 3.3 x10 -5. In the leaves, the lowest value for lead was 1.4 x10 -5 in Owaza, while the highest value was revealed in Eziorsu (3.3 x10 -5). The highest value was also recorded at Awaza 8.8 x10 -4 in Figure 16.

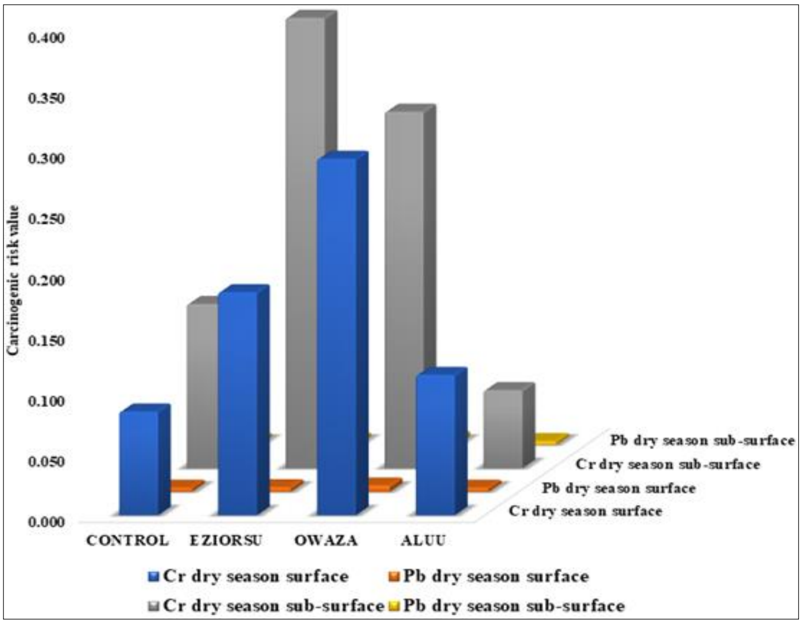

Fig 14: Carcinogenic risk of Pb and Cr in the soil in the dry season from the Niger Delta.

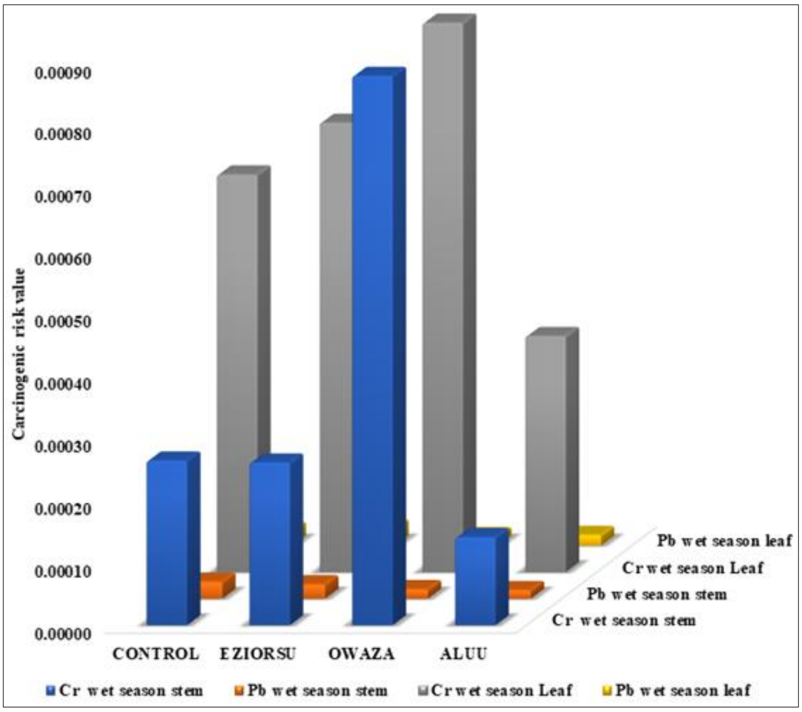

Fig 15: Carcinogenic risk of Pb and Cr in plants in the the wet season of the Niger Delta.

Figures 13 to 16 revealed a carcinogenic risk of Pb and Cr in soil and plants during wet and dry seasons in the Niger Delta. The carcinogenic risk was calculated using data obtained for Pb and Cr. Chromium was the highest contributor to the likely probability that people exposed to the post-remediated site would develop cancer.

The results of the present study for all plant-based samples were within the recommended Cancer risk range of 1 × 10−6 to 1 × 10−4 is to the US EPA standard (2004) [38]. However, the carcinogenic risk for soil revealed a value of 1×10-1 1×10-3, outside the stipulated range and the recommended limits. This result implies that there is a probability that an individual exposed to soil in the study will experience cancer.

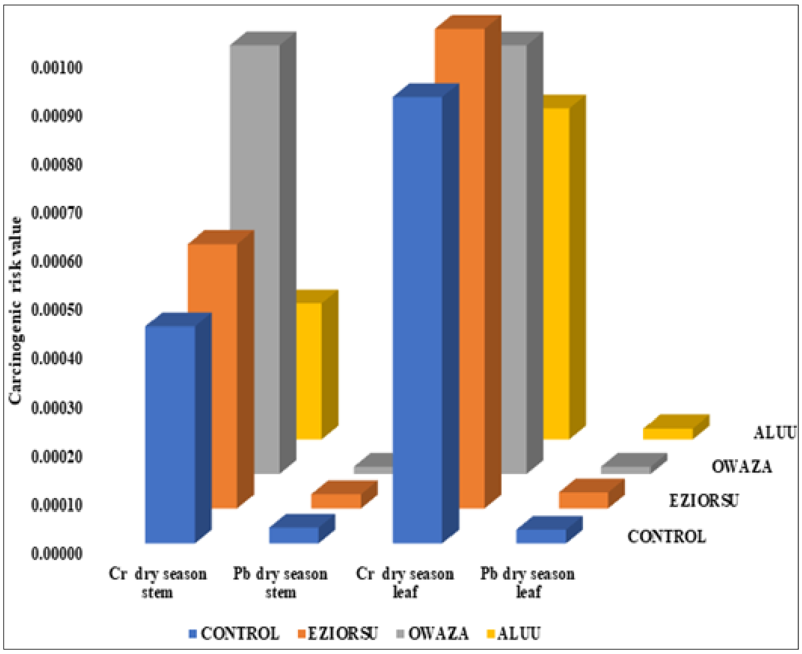

Fig 16: Carcinogenic risk of Pb and Cr in plants during the dry season of the Niger Delta.

Overall, the results presented in this study underscore the complexity of heavy metal contamination in the Niger Delta region. The variation in contamination levels across metals, seasons, and soil types highlights the heterogeneous nature of pollution sources and their impacts.

These findings call for a multifaceted approach to environmental management, encompassing stringent regulatory measures, effective monitoring strategies, and proactive remediation efforts. Furthermore, the insights gained from this research contribute to the broader discourse on sustainable development and environmental preservation in regions grappling with the consequences of industrial activities and pollution.

Summary and conclusion

This study thoroughly investigated the ecological and human health risks arising from heavy metal contamination resulting from oil spills in the Niger Delta region. Employing standardized methodologies, including the Index of Geoaccumulation (Igeo), Index of Ecological Risk Factor (Eri), Average Daily Intake (ADI), and Hazard Quotient (HQ), the research analyzed the extent of heavy metal accumulation and potential impacts on both the environment and human populations.

The Igeo of heavy metals from the study area were within the zero category, showing that the contamination's ecological impact was within safe limits. The Eri provides information on the ecological risk of pollution events. The results of the present study for ecological risk factors and potential ecological risk presented report values below 1, which signifies that all results were within safe levels, with very negligible ecological risk factors. Non-carcinogenic and carcinogenic risks of human exposure to contaminated soil from the study area were evaluated. These results were an indication that the source of pollution was anthropogenic. Results of the average daily intake of heavy metals (ADI) for Cr, Cu, Pb, and Zn analyzed from soil samples from the study area indicate that less than 30% of samples recorded ADI less than 1, the rest 70% recorded values as high as 8.115, which signifies high toxicity risk of human exposure to contaminated soils from the study area. Among all the heavy metals under study, copper recorded the highest ADI values, while Eziorsu was the site with the highest ADI values.

Hazards quotient of human exposure is rated from 1-5; however, values from the present study reveal incredibly high values of up to 146.77 from lead in Aluu and Owaza, just as we noted during the Average daily intake of metals, values of hazard quotient for metal exposure is an indication that there is high risk associated to human exposure to this health stressors. So absolute caution must be employed to ensure that remediation activities are appropriately done for the safety of the environment and the people's health. The hazard quotient of heavy metal exposure to plants indicates all safe levels for all heavy from the study sites. However, lead with HQ values of 0.964 was the highest among all metals under study, which is of concern due to the known toxic effects of lead on human exposure.

The hazard index of soil indicated values that were all more than 100, which reflects the high human health risk associated with human exposure to heavy metal-contaminated soil from the post-remediated sites is very high. The hazard index in plant stem and leaves shows a high health hazard for human exposure to plants from the study sites because HI values in some sites were above the grade value of 1. The carcinogenic risk of Pb and Cr exposure in soil and plant samples from post-remediated sites in the Niger Delta signifies a very low probability of people exposed to plants from the study area developing cancer. However, the carcinogenic risk for exposure to soil is outside the stipulated range of (10-6 to 10-4) by the USEPA (2011) [36].

In conclusion, the results of ecological risk signify non-ecological risk. However, the potential ecological risk (Er) value indicated anthropogenic sources of pollution. HQ and HI signify the health risks of human exposure to non-carcinogenic risks. Carcinogenic risks reveal a high probability of human lifetime cancer occurrence due to exposure to chromium and lead. This study offers valuable insights into the multifaceted challenges of heavy metal contamination resulting from oil spills in the Niger Delta region.

Contribution to knowledge and recommendations

Ecological and human health risk assessment calculated by this research provides vital information about the risk of human exposure to heavy metals from contaminated soil from the post-remediated sites in the Niger Delta region of Nigeria. The study's contributions to knowledge are multifarious. Firstly, using standardized methodologies such as Igeo, Eri, ADI, and HQ provides a systematic framework for assessing heavy metal contamination and its subsequent impacts. Secondly, the research sheds light on the heterogeneity of pollution sources, urging stakeholders to adopt context-specific contamination control and management strategies. Thirdly, the investigation highlights the potential risks to ecological systems and human health, emphasizing the urgent need for informed decision-making and sustainable practices. Ultimately, this study advances the scientific understanding of the intricate relationship between oil spills, heavy metal contamination, ecological risks, and human health concerns. The insights gained contribute to the broader discourse on sustainable development, environmental preservation, and practical policy formulation in regions facing similar challenges. As industrial activities continue to impact delicate ecosystems, this study serves as a crucial reference point for fostering resilience, guiding policy interventions, and promoting harmonious coexistence between human activities and the environment. The findings underscore the need and recommendations for comprehensive and integrated approaches to environmental management, combining stringent regulatory measures, efficient monitoring strategies, and proactive remediation efforts. The research also recommends assessing the radiological risks of human exposure.

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