

ASSESSMENT OF THE IMPACT OF LOCAL CRUDE OIL REFINERIES ON SOIL QUALITY IN SELECTED ISLAND COMMUNITIES IN DELTA STATE, NIGERIA

***YABRADE, M., IDOMEH, J.E. AND EKPERUSI, A.O.**

Department of Environmental Management and Pollution, Nigeria Maritime University,
Okerenkoko, Warri, Delta State

*Correspondence: yabrosglobal@gmail.com

Abstract

In the last few years, there has been an ongoing effort to combat illegal oil bunkering, including the dismantling of artisanal refining activities in the Niger Delta. This study assessed the level of heavy metals and hydrocarbons concentration in former artisanal sites. Surface soil sample were collected in triplicates from nine island communities along the Escravos Estuary and analysed for nutrients, heavy metals and hydrocarbons using standard laboratory procedures. The mean values of heavy metals and hydrocarbons were above the regulatory limits in soil. A one-way analysis of variance (ANOVA) showed significant differences ($P < 0.05$) in Mn, Fe, Zn, Cu, Pb, Ni, Mb, Cr, Ag, B, V and Au. Significant differences ($P < 0.05$) were also reported for TPH, PAH and THC. The mean concentration of metals in soil in decreasing order includes $Fe > Zn > Mn > Cu > B > Ag > Mo > Au > V > Ni > Cr > Be > Hg > Co > Pb > Se > Cd > Al > As$, while for hydrocarbons it was $TPH > PAH > THC$. For communities, Okerenkoko-gbene (52.74 ± 6.3) and Ikpokpo (52.36 ± 3.9) had the highest metal distribution. The same trend was observed for PAH (Okerenkoko-gbene 149.61 ± 37.1 and Ikpokpo 143.32 ± 18), while the reverse was the case for TPH (Ikpokpo 310.71 ± 79 and Okerenkoko-gbene 291.56 ± 87.1) and THC (Ikpokpo 19.13 ± 0.4 and Okerenkoko-gbene 18.34 ± 0.9). The elevated concentration of metals and hydrocarbons in soil requires remediation to prevent leaching into the estuary thereby affecting fisheries and seafood for human consumption.

Key Words: Artisanal refining, Soil pollution, Niger Delta, Hydrocarbons, Heavy metals

Introduction

The Niger Delta region of Nigeria has an estimated population of over 31 million people and is described as Nigeria's economic heartbeat due to its rich oil and gas deposits (Atubi, 2015; Boris, 2015). The region is surrounded by diverse ecosystems of mangrove swamps, constituting the major oil producing areas

of Nigeria (Idomeh *et al.*, 2019; Ibiene *et al.*, 2011). The Niger Delta region is surrounded by networks of crude oil pipelines, cutting across various towns and villages, well heads and export terminals for oil trade (UNEP, 2011; Ekperusi *et al.*, 2020). The operations of these facilities under poorly monitored regulatory standards could bring about oil

spillage and the location of these facilities has further brought about a serious problem of vandalization by local illegal refinery operators, thereby making the Niger Delta one of the most impacted regions of the world (Sam and Zabbey, 2018).

In recent years, local crude oil refining activities has grown tremendously in the Niger Delta and it is gradually becoming a major source of pollution in the region. The activities of these local refineries, pollutes the air, water and soil in places where they are carried out. Nigeria petroleum industry is plagued with the phenomenon of crude oil theft and associated local refining of consumer fuels. Government agencies and data from private studies estimates that as much as 200,000 - 400,000 barrels of crude oil maybe stolen daily in Nigeria, more than the entire production of some individual countries such as Equatorial Guinea, Gabon, Ghana and Cameron. Crude oil and refined products worth 41.9 billion dollars have been stolen from Nigeria in the past ten years from 2009 - 2018 (NEITI, 2019). The national economic council of Nigeria also reported in August, 2019, that about 22 million barrels of oil was stolen within the first six months of 2019 and if the trend continues, by the end of the year, the figure may likely double and further increase in subsequent years (NNPC, 2019). A significant proportion of the stolen oil goes into local refining; which involves processing of stolen crude in make-shift individual facilities, into low quality petroleum products. It is in the process of procuring the crude oil from pipelines and refining that great harm is done to the environment. The resulting oil spills from broken pipelines and wastes from tenths and series of make-shift

refineries combine to produce enormous environmental pollution on land and in the creeks across the region (Naanen, 2012).

Local crude oil refining, also known as artisanal refining involves the processing of stolen crude oil with the help of local cheap labour in concealed areas of forest, creeks and swamps (Obenade and Amangabara, 2014). Artisanal refining is carried out with constructed metal plates (or drums) and pipes welded together into shapes where stolen crude oil is heated and the resultant distillates are collected and sold across the Niger Delta as substitute for imported refine products. Artisanal refineries constructed by local crude oil thieves comes in various shapes and sizes and the finished products are adulterated kerosine, diesel, petrol fuel and large volume of waste products/condensates constituting about 80 percent that could not be refined, but rather released directly into the environment, due to lack of capacity of the artisanal refining setup to refine such products. The refined products are used locally for lighting, energy and transport with major quantity sold to a ready market of syndicates to generate income (UNEP, 2011; Attah, 2012; Yabrade and Tanee, 2015). The process of collecting the crude oil and the refining products releases huge amount of petroleum and oily wastes into the environment, posing a threat to the ecosystem (Yabrade and Tanee, 2016).

In the last few years, there has been an ongoing effort to combat illegal oil bunkering, including the dismantling of artisanal refining activities in the Niger Delta by the federal government with the employment of community members in oil surveillance contract. This contractual agreement has seen the significant decline in artisanal operations in the Niger Delta

region. This study is a follow up to the previous study (Yabrade and Tanee, 2016) when artisanal operations are still very much in place in the region.

The aim of this study is to assess the level of heavy metals and hydrocarbons concentration in abandoned artisanal sites in Warri South West to compare the values between impacted and control sites in the region.

Materials and Methods

Study Area

The study was carried out in abandoned artisanal crude oil refining sites at nine island communities in Warri South-West Local Government Area of Delta State. Delta State is one of the oil producing states in the Niger Delta region of Nigeria. The climate of the area is basically that of equatorial tropical climate that is characterized by two distinct climatic seasons. The dry and wet seasons with a brief harmattan in December. Rainfall occurs throughout most part of the year with 12-hour photoperiod and tidal

alternation that is flooded during high tides and receding at low tide tides. The soil type is mainly clay soil (chikoko soil) that dark and brown in colour. The vegetation of this area is predominantly saltwater wetlands and a vast array of mangrove swamp forest with luxuriant evergreen cover all throughout the year. The vegetation is dominated mangrove (*Rhizophora mangle* and *Rhizophora racemosa*) forest. Other plants species include *Paspalum virginatum*, *Achrostichum aureum* and *Nypa fruiticans*. The main economic activities of the region are fishing and subsistence agriculture. The region is host to several multinational oil companies engaged in petroleum exploration and production activities in the shallow waters of the region. Speed boats are the major means of transport within the area. Other major activities include the main campuses of the Nigeria Maritime University, which is established in the Gbaramatu Kingdom axis in the area.

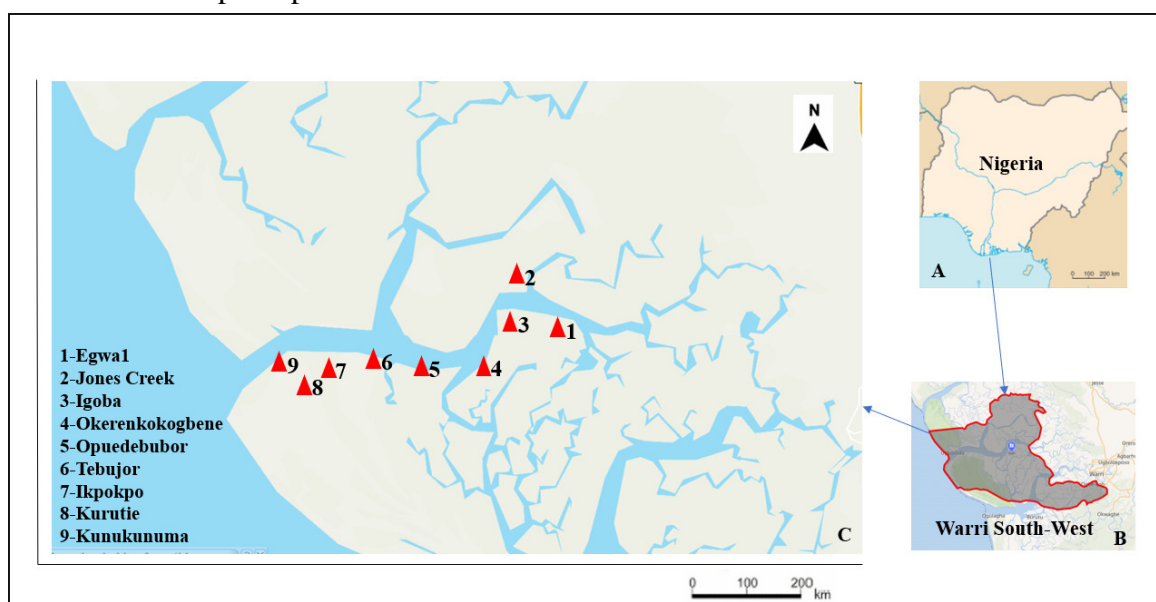


Fig. 1: Map of study area showing a) Nigeria, b) Warri South-West and c) sample sites along the Escravos Estuary in Delta State

Sample Collection

Soil sample for the study were collected from nine coastal island communities along the Escravos Estuary in Warri South-West. Seven of the sites selected for sample collection were abandoned sites used previously for artisanal crude oil refining operations. They include Egwal (5°35'10"N, 5°25'59"E), Jones Creek (5°41'60"N, 5°23'30"E), Igoba (5°32'25"N, 5°17'38"E), Okerenkoko-gbene (5°35'24"N, 5°14'45"E), Opuedebubor (5°35'35"N, 5°14'45"E), Tebujor (5°35'35"N, 5°13'41"E), Ikpoko (5°35'30"N, 5°13'44"E) and two control sites such as Kurutie (5°34'52.24"N, 5°20'52.35"E) and Kunukunuma (5°34'52.32"N, 5°20'59.80"E) with no history of artisanal refining operations.

At each sampling sites, soil was collected from three randomly selected points to form a composite sample. The soil auger was used to collect surface soil of 0-15 cm depth. All soil samples were collected in triplicates, wrapped in aluminium foil, labelled accurately using a permanent marker, stored in ice packs before transported to the laboratory for nutrient, heavy metals, hydrocarbons and microbial analysis.

Elemental Analysis

Nutrients such as calcium, magnesium, sodium, potassium, phosphorous were determined using EDTA method. For heavy metals analysis, about 5 g of the soil sample was air-dried and sieved using a 2 mm mesh size sieved to remove debris and large stones. The sample was then digested using 2 ml of nitric acid and 10 ml of hydrochloric acid (aqua-regia mixture). The extract was filtered through

Whitman filter paper, into a 50 ml volumetric flask. The filtrate was diluted and made up to mark using distilled water. In the same manner, a method blank was prepared by digesting 5 ml of distilled water with aqua-regia mixture, thereby serving as a standard solution for quality control purposes (Uzoekwe and Aighenia, 2019). The filtrate and the standard solutions for each sample were aspirated into the air-acetylene flame of the Atomic Absorption Spectrophotometer (Buck Scientific Model-210) for heavy metal analysis following APHA (1998) method.

Determination of TPH, THC and PAH

Soil samples were extracted following standard procedures and analysed for hydrocarbons using pyrolysis GC-MS. The pyrolyner (Simadau, Pyr-4A) was directly interfaced with a gas chromatograph / mass spectrometer (Shimadzu, GCMS-QP5050A). A 30m x 0.25mm ID, 0.25µm film thick dimethylpolysiloxane capillary column was used. The data was analysed using the National Institute of Standards and Technology (NIST, 2005) mass spectral library compound identification, while automated mass spectral deconvolution and identification system (AMDIS) package for deconvolution and Mass lynx suite used for data acquisition.

Data Analysis

Data obtained were subjected to statistical analysis using SPSS v18. Descriptive statistics such as mean, standard deviation and range values were obtained while one-way analysis of variance (ANOVA) was used to test for the level of significance at 0.05 probability level. Tables and figures were prepared using Microsoft Excel v. 2020.

Results and Discussion

Nutrients in Soil

The variation in the mean concentration of nutrients in soil from abandoned artisanal crude oil refining sites in selected islands (Egwa1, Jones Creek, Igoba, Okerenkoko-gbene, Opuedebubor, Tebujor and Ikpokpo) and the control sites (Kurutie and Kunukunuma) are shown in Figure 2. Significant differences ($P < 0.05$) were reported in the mean concentration of nutrients between the control soil and the impacted sites across the nine island communities. The mean values were above the national recommended limit in soil as described in the Environmental Guidelines and Standard for the Petroleum Industry in Nigeria (EGASPIN, 2010). No specific trend was observed in the mean concentration of nutrients in the impacted soil across the sampled sites. Spatially, the highest mean concentration of nutrients was reported in Ikpokpo (633.45 ± 70.6), followed by Okerenkoko-gbene (621.55 ± 93.2) and the least was in Jones Creek (386.33 ± 21.9) and Igoba (362.82 ± 3.4) respectively, rather than the two control sites (Kurutie, 409.44 ± 12.1

and Kunukunuma, 479.97 ± 2.5). The mean concentration of nutrients in soil in decreasing order includes $\text{Ca} > \text{K} > \text{P} > \text{Mg} > \text{Na}$.

It is expected that the control sites should be the least among the nine sites, but this is not the case. The factor responsible for this trend may be unclear, but it is important to indicate that many of the island communities within the region rely on refined petroleum products for the running of power generating plants which provides regular electricity to the people. In most cases, the refined petroleum products used for the powering of the plants are procured from artisanal refined products. The logistics for the purchase, transport and use of artisanal refined products results in the contamination of soil in these islands where artisanal refining operations are not available.

In an earlier study in the same region, Yabrade and Tanee (2016) reported higher levels of calcium, magnesium and potassium compared to our study. The trend in the decline of nutrients in the impacted soil is expected given the natural attenuation process by microbes to restore the mineral balance in the soil after the artisanal operation has ended.

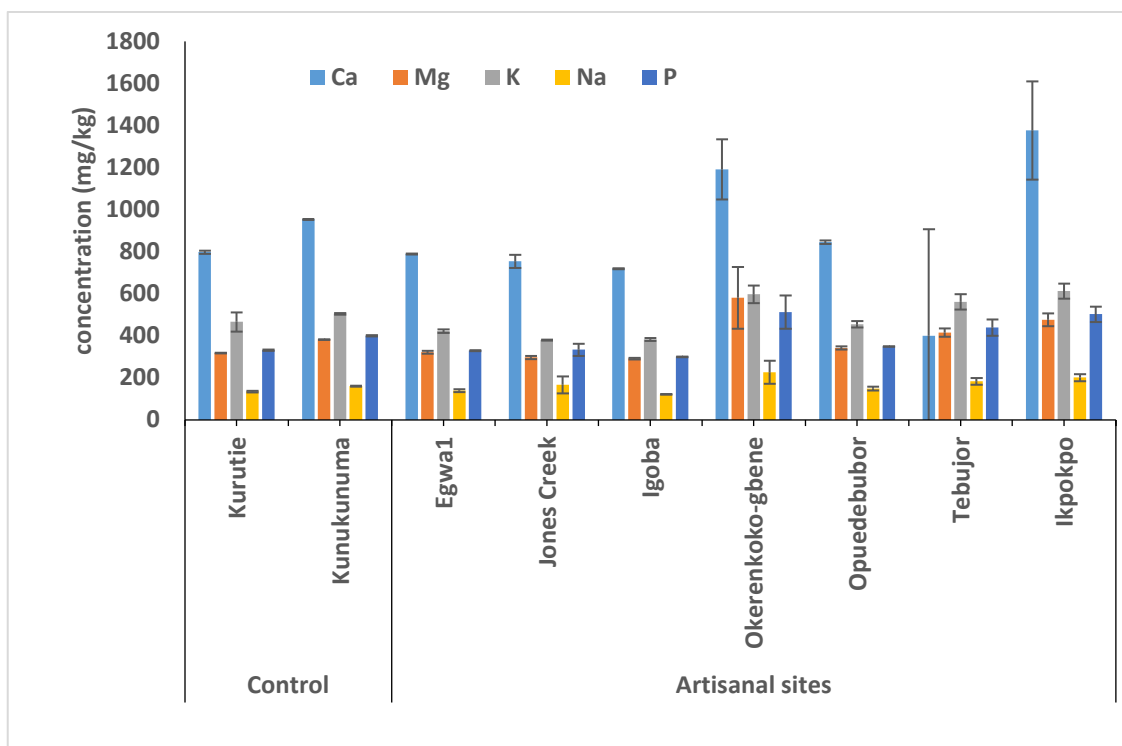


Fig. 2. Nutrients concentration (mean $\pm$ SD) in former artisanal refining sites and control soil from island communities collected in December, 2022, Warri South West, Nigeria

Heavy Metals in Soil

The variation in the mean values of heavy metals concentration in the soil from the 9 sites is represented in Table 1. Significant differences ($P < 0.05$) were reported for manganese, iron, zinc, copper, lead, nickel, molybdenum, chromium, silver, boron, vanadium, gold, but no differences ($P > 0.05$) were observed with selenium, cadmium, cobalt, arsenic, aluminium, beryllium and mercury in the impacted and the control soil. The mean concentration of heavy metals was above the national recommended limit (EGASPIN, 2010) and the WHO limits in soil. In a similar trend observed with nutrients, the highest concentration of heavy metals was reported in Okerenkoko-gbene (52.74 ± 6.3) followed by Ikpokpo (52.36 ± 3.9) and the least was in Igoba

(31.95 ± 0.3) and not the controlled sites (Kurutie, 35.44 ± 0.5 and Kunukunuma 42.58 ± 0.5). The highest mean metal concentration in the study sites was observed in iron (389.18 ± 40.2) at Ikpokpo (site 9) and the least was in aluminium (0.17 ± 0) in Kurutie (control site). Similar mean values were reported for Kurutie, Jones Creek and Egwa1.

Jones Creek, Egwa1 and Igoba had low and similar concentrations of metals to one of the control sites (Kurutie). This is associated with the low level of artisanal refining operations carried out in those three islands. The three islands are close to major routes of transportation in the coastal region hence activities of artisanal refiners were limited to avoid detection by security agencies compared to other islands where artisanal operations were more pronounced. The mean values of

metals in relations to the sample sites shows a decreasing trend from Okerenkoko-gbene > Ikpokpo > Tebujor > Kunukunuma > Opuedebubor > Jones Creek > Egwal > Kurutie > Igoba. For the metals, the decreasing trend include Fe > Zn > Mn > Cu > B > Ag > Mo > Au > V > Ni Cr > Be > Hg > Co > Pb > Se > Cd > Al > As. The uneven distribution of heavy metals in the various impacted soil is expected given the various capacity of refining operations in the various sites. Artisanal refining operations in Ikpokpo and Okerenkoko-gbene are well sophisticated and higher refining capacity than the other impacted sites before the closure of the refinery operations. Increased refining operations results in increased refine products, land contamination and also elevated levels of heavy metals in impacted soil.

The elevated level of heavy metals reported in the control sites, particularly in Kunukunuma calls for concern. As observed in the results with nutrients, the mean concentration in the control sites for heavy metals were quite higher than the concentrations reported in the least of the impacted sites (Igoba). The underlining factor responsible for this trend in metal contamination is unclear. It is important to highlight that islands like Kurutie and Kunukunuma are well populated than the two islands with the least metal

distribution and rely on generator plants for regular electricity to its inhabitants. The increased level of contaminants may be associated with the use of refine petroleum products which could contaminate soil since the refine products are provided in drums at the waterfront before getting to the point of discharged into the plants. Runoff and erosion could leach the contaminants into the soil. Another possible explanation could come from atmospheric deposition from artisanal sites which are less than five kilometres from the control sites. Also, no significant differences exist between the least impacted sites and the control sites reflecting almost similar contaminant concentration in the four sites.

Onwuna *et al.* (2022) investigated the impact of artisanal crude oil refinery on the environment in Igia-Ama, Rivers State. They reported higher concentrations of arsenic, cadmium, chromium, iron nickel, lead and selenium than our study. In another artisanal sites in the same state, Sibe and Onwugbuta (2023) reported higher concentration of iron, zinc and cadmium compared to our studies. The increased levels of heavy metals reported in both studies is related to the active operations of the artisanal sites when the studies were carried out compared to our study where the artisanal sites are no longer in operations.

Table 1. Heavy metals concentration (mean±SD) in artisanal and control sites from island communities collected in December 2022, Warri South, Nigeria

Sites	Kurutie	Kunukunuma	Egwal	Jones Creek	Igoba	Okerenkoko-gbene	Opuedebubor	Tebujor	Ikpokpo	F
Mn	120.74±1.1 (119.58-121.76)	145.94±1.9 (144.09-147.89)	120.71±1.4 (119.15-121.89)	126.42±15.1 (109.38-138.03)	108.86±0.3 (108.53-109.08)	166.1±7 (158.09-171.26)	128.45±1.7 (126.7-130.01)	175.74±23.4 (149.33-193.9)	182.77±14.1 (167.98-196.07)	19.036
Fe	268.26±4.9 (263.07-272.89)	318.51±1.4 (316.99-319.67)	270.7±7.7 (262.13-276.89)	257.23±16.2 (240.64-272.99)	239.18±0.4 (238.78-239.65)	389.18±40.2 (347.8-428.09)	286.56±7.3 (278.74-293.07)	364.14±31.6 (328.53-388.67)	388.5±18.7 (369.55-406.91)	27.173
Zn	147.46±1.1 (146.15-148.24)	177.26±1.2 (176.11-178.45)	146.52±0.8 (145.63-147.03)	147.31±12.4 (133.69-157.89)	133.07±0.5 (132.65-133.67)	220.72±30.2 (193.22-253.07)	156.61±2.1 (154.86-159)	195.37±11.6 (182.52-204.92)	217.35±11.3 (205.31-227.84)	21.745
Cu	94.62±0.9 (93.95-95.64)	114.69±1.4 (113.21-115.89)	93.96±0.3 (93.62-94.27)	109.71±22.2 (85.94-129.88)	85.13±0.1 (85.0-85.28)	168.85±38.8 (124.21-194.09)	100.46±0.8 (99.55-101.2)	155.08±34.5 (117.33-185.07)	144.37±25.1 (127.89-173.24)	6.402
Pb	0.79±0 (0.78-0.8)	0.98±0 (0.94-1.01)	0.92±0.1 (0.77-1.01)	0.93±0.2 (0.71-1.09)	0.78±0.1 (0.7-0.83)	1.23±0.2 (1.03-1.38)	0.94±0.1 (0.82-1.01)	1.15±0.2 (0.97-1.28)	1.45±0.3 (1.09-1.68)	5.538
Ni	1.93±0 (1.9-1.98)	2.55±0.3 (2.28-2.83)	2.11±0.2 (1.89-2.28)	1.91±0.2 (1.73-2.09)	1.86±0.1 (1.72-1.98)	2.8±0.3 (2.51-2.98)	2.41±0.5 (2.01-2.97)	2.67±0.3 (2.37-2.88)	2.9±0.2 (2.66-3.11)	7.326
Mo	5.99±0.1 (5.91-6.1)	7.55±0.3 (7.17-7.8)	6.27±0.3 (5.93-6.49)	5.78±0.3 (5.44-6.01)	6.08±0.7 (5.4-6.82)	8.08±0.2 (7.87-8.25)	6.74±0.4 (6.31-7.03)	7.73±0.3 (7.43-7.92)	8.69±0.3 (8.36-8.91)	26.065
Se	0.73±0.1 (0.7-0.8)	0.89±0.1 (0.84-0.95)	0.78±0.1 (0.7-0.9)	0.88±0.2 (0.64-1.09)	0.76±0.1 (0.630.89)	1.04±0.1 (0.92-1.11)	0.92±0.2 (0.74-1.1)	1.13±0.2 (0.87-1.34)	1.37±0.4 (0.98-1.79)	3.328
Cd	0.64±0.1 (0.58-0.74)	0.73±0.1 (0.69-0.79)	0.78±0.2 (0.57-0.92)	0.73±0.2 (0.53-0.93)	0.64±0.1 (0.52-0.74)	0.85±0.1 (0.76-0.94)	0.85±0.2 (0.61-1.09)	0.9±0.2 (0.72-1.09)	1.14±0.3 (0.81-1.41)	2.227
Co	1.11±0.1 (1.02-1.21)	1.52±0.3 (1.23-1.86)	1.41±0.4 (1.02-1.74)	1.16±0.2 (0.94-1.28)	0.98±0 (0.93-1.01)	1.64±0.3 (1.35-1.83)	1.43±0.4 (1.09-1.85)	1.44±0.1 (1.28-1.55)	1.7±0.2 (1.44-1.87)	2.81
Cr	1.72±0.2 (1.58-1.89)	2.26±0.4 (2.02-2.69)	1.87±0.2 (1.67-2.01)	1.74±0.2 (1.53-1.89)	1.67±0.2 (1.52-1.85)	2.51±0.3 (2.22-2.73)	1.94±0.1 (1.78-2.05)	2.32±0.2 (2.1-2.45)	2.67±0.4 (2.36-2.96)	7.76
Ag	7.67±0.1 (7.56-7.83)	9.35±0.2 (9.11-9.57)	7.71±0.2 (7.53-7.97)	7.16±0.3 (6.91-7.48)	6.97±0.1 (6.86-7.08)	10.13±0.2 (9.99-10.37)	8.53±0.5 (8.01-8.93)	9.7±0.2 (9.44-9.85)	10.84±0.2 (10.62-11.07)	88.889
As	0.31±0.2 (0.13-0.5)	0.34±0.2 (0.16-0.49)	0.33±0.2 (0.13-0.45)	0.43±0.3 (0.12-0.63)	0.45±0.3 (0.12-0.74)	0.28±0.1 (0.17-0.39)	0.44±0.3 (0.14-0.65)	0.26±0.1 (0.16-0.33)	0.5±0.3 (0.19-0.72)	0.449
B	7.67±0.1 (7.56-7.78)	9.48±0.3 (9.11-9.74)	7.74±0.2 (7.53-7.9)	7.12±0.2 (6.91-7.37)	6.99±0.1 (6.86-7.1)	10.17±0.2 (9.99-10.28)	8.45±0.4 (8.01-8.81)	9.69±0.2 (9.44-9.86)	10.87±0.2 (10.62-11.06)	105.295
Al	0.17±0 (0.14-0.2)	0.39±0.2 (0.17-0.58)	0.44±0.2 (0.14-0.57)	0.4±0.2 (0.13-0.59)	0.37±0.2 (0.13-0.59)	0.59±0.4 (0.19-0.88)	0.33±0.2 (0.15-0.45)	0.29±0.1 (0.18-0.39)	0.54±0.3 (0.2-0.72)	0.919
V	5.54±0.3 (5.24-5.9)	6.57±0.2 (6.31-6.81)	5.38±0.2 (5.22-5.53)	4.98±0.2 (4.79-5.24)	4.94±0.2 (4.76-5.07)	7.29±0.3 (6.93-7.54)	5.83±0.2 (5.55-6.03)	6.74±0.2 (6.54-6.98)	7.62±0.2 (7.36-7.86)	48.313
Be	1.29±0.1 (1.21-1.39)	1.71±0.2 (1.46-1.91)	1.42±0.2 (1.21-1.57)	1.43±0.3 (1.11-1.63)	1.57±0.4 (1.1-1.91)	1.78±0.2 (1.6-1.99)	1.62±0.3 (1.29-1.87)	1.73±0.2 (1.52-1.88)	1.91±0.2 (1.71-2.1)	1.931
Au	5.49±0.2 (5.26-5.74)	6.61±0.3 (6.34-6.9)	5.56±0.3 (5.24-5.81)	5.05±0.2 (4.81-5.24)	5.14±0.4 (4.77-5.62)	7.18±0.2 (6.95-7.36)	5.86±0.3 (5.57-6.09)	6.73±0.1 (6.57-6.82)	7.72±0.3 (7.39-7.92)	36.036
Hg	1.26±0 (1.21-1.3)	1.7±0.2 (1.46-1.9)	1.53±0.3 (1.21-1.74)	1.56±0.4 (1.11-1.89)	1.58±0.4 (1.1-1.9)	1.63±0.3 (1.34-1.94)	1.57±0.3 (1.29-1.95)	1.75±0.2 (1.52-1.94)	1.87±0.2 (1.71-2.01)	1.006

Petroleum Hydrocarbons in Soil

The variation in the mean concentration of petroleum hydrocarbons recorded in soil from the nine sample sites are shown in Figure 3. The mean concentration of hydrocarbons was above the recommended limit for soil ecosystem for the petroleum industry (EGASPIN, 2010) and the WHO recommended value in soil. A significant difference ($P < 0.05$, F-value = 6.192) was observed in the mean values of TPH across the study sites. The highest concentration of TPH was reported in Ikpokpo (310.71 ± 79), followed by Okerenkoko-gbene (291.56 ± 87.1) and the least was in Igoba (149.47 ± 0.6). For PAH, there was a significant variation ($P < 0.05$, F-value = 7.791) in the mean concentration across the nine sites. The highest concentration of PAH was reported in Okerenkoko-gbene (149.61 ± 37.1), followed by Ikpokpo (143.32 ± 18) and the least was in Igoba (79.92 ± 0.4). A significant variation ($P < 0.05$, F-value = 23.834) was recorded in the mean concentration of THC across the nine sites. The highest concentration of THC was reported in Ikpokpo (19.13 ± 0.4), then Okerenkoko-gbene (18.34 ± 0.9) and the least was in Igoba (12.35 ± 0.3).

The concentration of hydrocarbons present in soil are in the decreasing order of $\text{TPH} > \text{PAH} > \text{THC}$. The higher concentration of hydrocarbons reported in Ikpokpo (TPH and THC) and Okerenkoko-gbene (PAH) which follow similar trend for heavy metals is a clear indication that elevated levels of heavy metals are associated with crude oil production in the Niger Delta region of Nigeria. The increase levels of hydrocarbons reported in the control sites compared to some of the affected sites could results from atmospheric deposition and flooding episodes in island communities during the rainy season.

In a previous study in the same location, Yabrade and Tanee (2016) reported higher levels of hydrocarbons in soil compared to the values reported in our study. As indicated for nutrients, the increased level of hydrocarbons in 2016 resulted from the active refining operations compared to our study where the sites have been abandoned and artisanal refining activities are no longer operational. In the same vein, higher concentrations of TPH and PAH were reported in artisanal refining sites in Igia-Ama and Ogoni land in Rivers State (Onwuna *et al.*, 2022; Sibe and Onwugbuta, 2023).

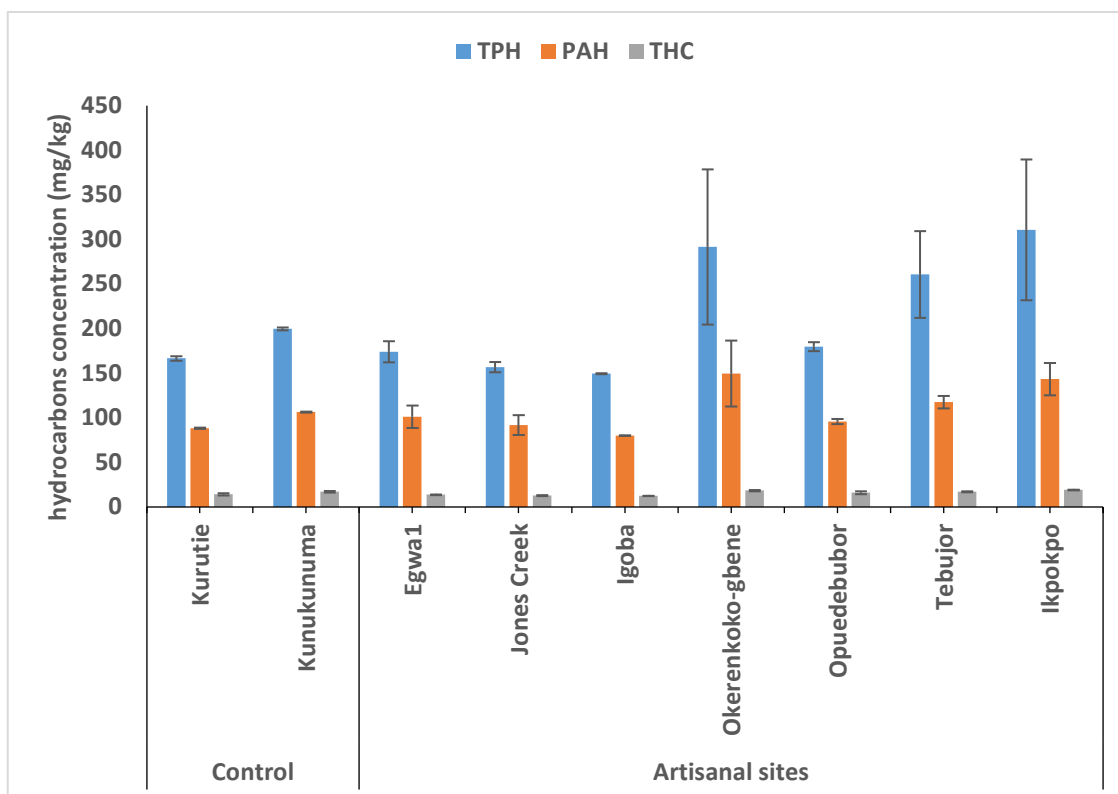


Fig. 3: Petroleum hydrocarbons concentration (mean $\pm$ SD) in soil across 9 artisanal refining sites in Warri, Nigeria, December 2022

Conclusion

Illegal oil bunkering and artisanal refining of crude oil complicates the already devastating effects of decades of petrochemical exploration and production in the Niger Delta region. It contributes to forest degradation, reduces carbon storage and depletes soil fertility for farming in local communities, even years after halting artisanal refining. The concentration of heavy metals associated with crude oil and hydrocarbons in soil in former artisanal refining sites was above the regulatory limits for soil health. The levels of these contaminants in control islands were similar to some of the affected islands, which reflects non-linear contamination of islands where artisanal refining activities are absent. The elevated concentration of metals and hydrocarbons

in soil requires mitigative approach and remediation to restore soil health and fertility and prevent leaching into the estuary thereby affecting fisheries and seafood for human consumption.

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