The University of Tehran Press

Pollution

Print ISSN: 2383-451X
Online ISSN: 2383-4501

https://jpoll.ut.ac.ir/

Present Status of Surface Water Quality Impacted by Artisanal Crude Oil Contamination in a Coastal Community in Rivers State, Nigeria

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Article Info

Article type:
Research Article

Article history:
Received: 30 October 2024
Revised: 18 February 2025
Accepted: 28 July 2025

Keywords:
Crude Oil, Contamination, Environmental Degradation, Hydrocarbon, Metal Pollution, Water Quality

ABSTRACT

This study evaluates the surface water quality of Bundu-Ama creek in Rivers State, Nigeria, which is impacted by artisanal crude oil refining activities. The area is characterized by mangrove swamps and mudflats and is subject to pollution from industrial waste and illegal oil bunkering. Water samples were collected monthly over six months from three stations, spaced 1,000 meters apart, representing upstream, midstream, and downstream sections. Physicochemical parameters analyzed included pH, temperature, electrical conductivity (EC), total dissolved solids (TDS), salinity, turbidity, and dissolved oxygen (DO). Heavy metals (Cr, Cd, Co, Ni, Fe, Pb, Zn, As) were quantified using atomic absorption spectroscopy, and hydrocarbons (Total Hydrocarbons [THC], Oil and Grease, Polycyclic Aromatic Hydrocarbons [PAH]) were analyzed using gas chromatography. Results showed pH values between 7.22 and 7.28 and temperatures from 30.15°C to 30.32°C, with EC and TDS exceeding WHO guidelines, indicating ionic contamination. Heavy metals like Cd (0.23–0.28 mg/L) and Pb (0.29–0.31 mg/L) exceeded safety limits, suggesting ongoing pollution. PAH concentrations (0.28–0.37 mg/L) were above WHO and NSDWQ limits, highlighting significant health risks. Correlation analysis revealed strong relationships, such as between EC and TDS (r=1.000), indicating shared pollution sources. These findings underscore the need for regulatory interventions and remediation strategies to mitigate environmental and health impacts in the region.

Cite this article: Chris, D. I., Kallem, K., Goh K. W., Lananan, F., Abdul Kari, Z., Azra, M. N. & Wokeh, O. K. (2025). Present Status of Surface Water Quality Impacted by Artisanal Crude Oil Contamination in a Coastal Community in Rivers State, Nigeria. *Pollution*, 11(3), 738-757.
https://doi.org/10.22059/poll.2025.383178.2583

DOI: https://doi.org/10.22059/poll.2025.383178.2583

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INTRODUCTION

The Niger Delta, a region of immense ecological and economic significance due to its abundant oil and gas reserves, is marred by the persistent challenge of illegal crude oil bunkering (Raji & Raheem, 2020). Accounting for approximately 15% of the nation's total crude oil production, this clandestine operation has far-reaching consequences, with the Niger Delta being particularly susceptible to its spatiotemporal effects (Babatunde, 2017; George et al., 2024). One of the focal areas deeply impacted by these illicit activities is the Bundu-Ama Creek in Southern Nigeria.

In Nigeria and other parts of the world, pollution of aquatic systems poses a significant environmental challenge, primarily due to the misconception that these systems have limitless capacity for waste absorption (Adeola, 2012; Bello, 2021). This belief overlooks the severe and enduring consequences of heavy metal pollution and other contaminants on ecosystems and the species reliant on them. Pollution from oil spills, gas flaring, and industrial activity, which spew dangerous compounds like hydrocarbons and hazardous chemicals into the land and water, particularly affects the Niger Delta area (Nwozor et al., 2018; Numbere et al., 2023). These pollutants endanger wildlife, degrade ecosystems, and pose serious health risks to local communities. Despite various efforts to tackle these issues, the persistence of oil spills, gas flaring, and industrial discharges highlights ongoing environmental and health concerns (Johnston et al., 2019).

The coastal environment of the Niger Delta, including the Bundu-Ama Creek, grapples with the pervasive impact of chemical contaminants stemming from anthropogenic sources (Onyena et al., 2024). Sewage, petroleum spills, industrial discharges, and vehicular emissions contribute to the degradation of water quality (Akhtar et al., 2021; Singh et al., 2022). Petroleum hydrocarbons, major pollutants in coastal waters, pose a substantial threat to marine environments (Kuppusamy et al., 2020). Illegal crude oil bunkering, as a method of theft, involves the surreptitious tapping of pipelines and redirection of crude oil into hidden barges nestled within the intricate network of small creeks, often concealed beneath the dense cover of mangrove forests (Orogun, 2010). The prevalence of such activities in Bundu-Ama Creek has not only led to environmental degradation but has also significantly altered the spatiotemporal dynamics of water quality in this crucial waterway (Odekina et al., 2021; Chris & Amaewhule, 2022a, b).

The gravity of this issue is underscored by its manifold consequences. Instances of oil spillages and explosions, intrinsic to the illegal bunkering operations, have become commonplace, rendering the Bundu-Ama Creek highly vulnerable to ecological and environmental disturbances (Chris & Anyanwu, 2022). The spillages and leaks from these activities compromise the water quality, affecting the physicochemical parameters of the creek and exerting spatiotemporal variations on its overall environmental health (Odekina et al., 2021). The United Nations Environment Program's (UNEP) assessment of Ogoniland within the Niger Delta has highlighted the severe repercussions of oil contamination, emphasizing the destruction of mangroves, pollution of sediment and groundwater, and the tangible threats posed to public health (Agbonifo, 2016; Yakubu, 2017). These findings serve as a stark reminder of the urgent need to address the spatiotemporal effects of illegal crude oil bunkering, particularly in sensitive ecosystems such as the Bundu-Ama Creek (Chris & Anyanwu, 2022).

These pollutants, primarily from the petroleum industry, have dire consequences for aquatic life, causing reproductive failures, mortality, and food chain disruption (Okereafor et al., 2020; AbuQamar et al., 2024). The contamination poses health risks to humans, potentially leading to neurological damage, reproductive issues, and cancer, thus increasing healthcare costs and

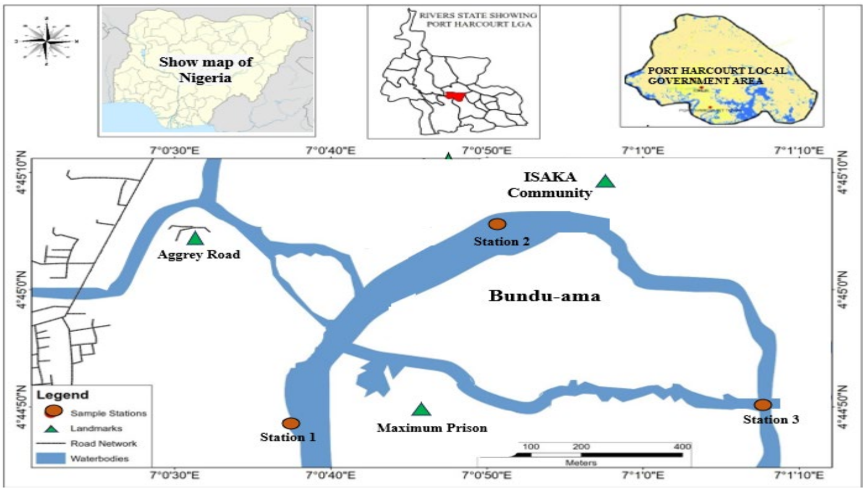

Fig. 1. Map showing Bundu-Ama sampling stations.

diminishing quality of life. Heavy metals persist in sediments and water, maintaining long-term exposure risks (Davies et al., 2023; Chris et al., 2024; Uchenna et al., 2024). This ongoing pollution cycle reduces the abundance and diversity of aquatic species and weakens ecosystem health (Chris & Anyanwu, 2022).

This study, therefore, aims to delve into the intricate spatiotemporal effects of illegal crude oil bunkering on water quality in the Bundu-Ama Creek. Recognizing the river's critical significance in local life despite pollution risks, the research on water quality, hydrocarbons, and toxic metal contamination will provide baseline progress statistics essential for controlling water and fishery resources. By meticulously examining the variations over space and time, the research endeavors to provide a nuanced understanding of the ecological, environmental, and public health implications. By means of this research, the study aims to provide insightful analysis that may guide focused interventions, policies, and remedial actions meant to restore and maintain the water quality in Bundu-Ama Creek, thus maintaining this important ecosystem for future generations.

MATERIALS AND METHODS

Study Area

The study area in Rivers State, Nigeria, is a coastal creek known for artisanal crude oil refining activities. The area is prone to high levels of crude oil contamination, which can affect water quality. The research region spans Longitudes 70°02′00″E and Latitudes 40°49′00″ N of the Equator (Figure 1). The region is dominated by red mangrove, black mangrove, and Nympa palm. Industrial wastes, bunkering effluence, and human and animal wastes significantly affect the environment. The bottom of the area is characterized by an extensive mudflat, a fringing mangrove swamp, and a populated coastal settlement with a landing site for illegally refined products. These characteristics add complexity to the overall dynamics of the area, presenting unique environmental challenges that require thorough investigation.

Sample Collection

Along the creek, three sample sites were established. These stations were selected based on proximity to crude oil refining sites and varying exposure to potential contaminants. Samples were collected monthly over a period of six months to assess both spatio-temporal variations in water quality. The three sample stations were selected at approximately 1000 m apart along the river. The prevalence of active illegal crude oil bunkering activities constituted the key criteria for selecting the sampling stations. The sample sites were also chosen in line with river flow. Cutting across the dry and rainy seasons of the area, monthly samples were conducted for six (6) months between October 2023 and March 2024 the monthly sample was place just during the last week of the month.

Water Samples and Sampling Procedure

One-liter polythene bottles were pre-cleaned before collecting surface water samples. To minimize contamination, the bottles were rinsed three times with stream water prior to sampling. Samples were taken approximately thirty centimeters below the sea surface to avoid surface debris. Bottles were immediately sealed and filled to the brim to minimize air space. The samples were then placed in ice-packed coolers and transported to the lab within six hours for immediate analysis. To preserve metal ions for heavy metal analysis, samples were acidified with strong nitric acid to a pH of 2 (Wilson et al., 2024).

Physicochemical parameters *Analysis*

The physicochemical parameters of the water samples were analyzed using standard procedures. pH was measured with a portable pH meter, calibrated using buffer solutions (pH 4, 7, and 10). Temperature was recorded in situ using a digital thermometer after stabilization. Conductivity was determined with a conductivity meter, calibrated with a 1413 μS/cm reference solution, while TDS was measured using a TDS meter, calibrated with a 1000 mg/L standard solution.

Salinity was assessed using a refractometer, calibrated with distilled water, where a few drops of the sample were placed on the prism for reading. Turbidity was quantified using a turbidity meter, with the sample placed in a sterile cuvette until a stable reading was obtained. Dissolved Oxygen (DO) was measured with a DO meter, calibrated with air-saturated water, following APHA (2005) guidelines. All analyses followed APHA 2340C (1998) standards, and tests were conducted in triplicates to ensure accuracy.

Heavy Metal Analysis

Sample Preparation

The water samples were treated with strong nitric acid using a hotplate digestion process to acidify them. A volume of about 100 mL of the sample was transferred into a beaker, followed by the addition of 10 mL of pure HNO_3. The combination was subjected to heat until its volume was decreased to around 20 mL. It was then cooled, filtered, and then diluted with distilled water to a predetermined volume. Using an API-RP 45 model, Atomic Absorption Spectroscopy (AAS) assessed the heavy metals Cr, Cd, Co, Ni, Fe, Pb, Zn, and As. For every metal, the equipment was calibrated with reference to standard solutions.

Samples were aspirated into the flame, and absorbance readings were recorded. Calibration curves with correlation coefficients ($R^2 > 0.995$) were prepared for each metal. Blanks and standard reference materials were analyzed alongside samples to ensure accuracy. Parameters were determined using APHA 2340C (1995) guidelines. The tests were performed in triplicates and recorded.

Hydrocarbon Analysis

Sample Preparation

The water samples were collected by extracting them with dichloromethane using a separatory funnel. A volume of 500 mL of the sample was introduced into the funnel, followed by the addition of 50 mL of dichloromethane. The solution was aggressively agitated and thereafter allowed to undergo phase separation into two distinct layers. The organic layer was gathered and condensed using a rotary evaporator.

Gas Chromatography Analysis

Gas chromatography with a flame ionisation detector (model of the GC-FID) was used to examine the concentrated extract. Standard hydrocarbon mixtures were used in calibrating the gas chromatograph (GC). The GC was injected one μL of the extract for examination. Among the criteria tracked are Total Hydrocarbons (THC), Oil and Grease and Polycyclic Aromatic Hydrocarbons (PAH), APHA, 2005.

Quality Assurance and Quality Control (QA/QC)

All equipment was calibrated with reference to standard solutions before study. Triplicate analysis of every sample guaranteed accuracy and precision. Every set of samples contained verified reference items and procedural blanks to support findings.

Statistical Analysis

Descriptive statistics, such as the mean and standard deviation, were computed for all the measured parameters across stations and months to summarize the data. Pearson correlation coefficients were employed to identify relationships between parameters. Additionally, statistical significance testing was conducted using ANOVA to determine differences between stations and months, with a 95% confidence level and a significance threshold of $p<0.05$.

RESULTS AND DISCUSSION

Physicochemical parameters Across Stations

Table 1 presents the average physicochemical parameters at three sites in Bundu-Ama Creek, Niger Delta. The mean pH ranged from 7.22 to 7.28, the water temperature was between 30.15 to 30.32oC, EC was between 10301 to 12000μS/cm, and TDS was between 5150-6000mg/L. Station 1 had the highest salinity (8.27±0.51), while station 3 had the least. Significant differences were observed across the three stations, with station 1 having the highest turbidity (2.17±0.17) and station 3 having the lowest (1.00±0.00). The mean values for DO range between 5.9 to 6.8, with no significant differences observed across the three stations.

The pH levels across the stations ranged from 7.22 to 7.28, which falls within the WHO and NSDWQ acceptable range (6.5–8.5), indicating that the water remains neutral and does not pose immediate acidity or alkalinity risks to aquatic life or human use. However, mean temperature values (30.15°C–30.32°C) slightly exceeded the WHO guideline (27.8°C–30°C), potentially causing thermal stress for aquatic organisms, especially during hotter months. According to Pankhurst & Munday (2011), aquatic organisms are highly sensitive to temperature changes, with even slight increases affecting metabolism, reproduction, and survival rates (Okey-Wokeh et al., 2021; Fubara et al., 2022). Prolonged exposure to higher temperatures can lead to decreased dissolved oxygen levels, which are essential for fish and aquatic life (Mariu et al., 2023). However, the elevated temperatures may favor heat-tolerant species, potentially leading to biodiversity shifts and altered species composition (Edori & Edori, 2021).

Total Dissolved Solids (TDS) ranged from 5,150 to 6,000 mg/L, while Electrical Conductivity (EC) values were between 10,301 and 12,000 μS/cm, both significantly exceeding WHO and NSDWQ limits, suggesting high ionic contamination from crude oil pollution (Origbe et al., 2021). Salinity levels ranged from 5.82 to 8.27, surpassing the NSDWQ limit of 250, indicating saltwater intrusion or crude oil residue contamination (Badmus et al., 2021). Turbidity was highest at Station 1, likely due to elevated particulate matter, which reduces light penetration and affects photosynthesis in aquatic plants (Chris et al., 2023). Dissolved Oxygen (DO) levels ranged from 5.9 to 6.8 mg/L, close to WHO and NSDWQ standards, but lower levels at some stations could stress aquatic organisms, particularly when combined with high temperatures and pollution (Olasupo et al., 2021).

Similar studies in the Niger Delta consistently report elevated EC, TDS, and salinity levels due to crude oil pollution (Origbe et al., 2021). For instance, research by Ali et al. (2022) found comparable hydrocarbon and heavy metal contamination, leading to ecological and health risks. The results align with studies linking oil pollution to public health concerns, including increased cases of waterborne diseases and negative effects on fisheries and agriculture (Babatunde, 2020; Andrews et al., 2021). Similar physicochemical disturbances are reported in Venezuela and Ecuador, where oil extraction contributes to high EC and TDS levels, resulting in ecosystem degradation and health challenges (Morin-Crini et al., 2022; Raimi et al., 2021).

Physicochemical parameters Results Across Months

The average values of the physicochemical parameters obtained from October 2021 to March 2022 for the section of Bundu-Ama creek that was examined during the research are shown in Table 2. In February, the average pH value was the greatest at 7.70±0.00, while in November, it was the lowest at 6.87±0.03. There were notable variations seen across months, with a statistically insignificant p-value of more than 0.05. The maximum temperature was recorded in February with a value of 32.47±0.03, while the minimum temperature of 27.30±0.15 was noted in March.

There were notable variations seen throughout the months, with a p-value more than 0.05. The electrical conductivity (EC) reached its peak in December with a value of 14206.67±931.26, while it was at its lowest in November with a value of 6196.67±314.98. Statistically significant differences were identified across the months (P>0.05). The TDS value reached its peak in December (7103.33±465.63) and to its lowest point in November (3098.33±157.49). There were noticeable variations in TDS levels across the months (P>0.05).

The maximum salinity measurement was seen in November (8.64±0.34), and the minimum was recorded in October (6.17±0.68). There were notable variations in the salinity measurements obtained across the months, with a p-value more than 0.05. The turbidity reached its peak in January with a value of 2.00±0.30, while it was at its lowest in November and March with a value of 1.33±0.30. No significant variations in salinity measurements across the months were noted (P<0.05). The greatest recorded turbidity levels were seen in November and March, with a value of 6.90±0.07. The lowest turbidity levels were observed in December, with a value of 4.70±0.44. There was not a significant difference noticed in the turbidity findings collected throughout the investigation between the months (P<0.05).

Table 1. Mean Physicochemical Parameters Across Stations

Station	pH	Temp	EC	TDS	Salinity	Turbidity	DO
ST 1	7.28±0.13[a]	30.27±0.72[a]	12000.00±1822.55[a]	6000.00±911.27[a]	8.27±0.51[a]	2.17±0.17[a]	6.02±0.33[a]
ST 2	7.27±0.14[a]	30.15±0.80[a]	10781.67±1616.08[a]	5390.83±808.04[a]	6.79±0.46[b]	1.67±0.21[a]	6.89±0.46[a]
ST 3	7.22±0.14[a]	30.32±0.96[a]	10301.67±1174.06[a]	5150.83±587.03[a]	5.82±0.49b[a]	1.00±0.00[b]	5.98±0.46[a]
WHO	6.5-8.5	27.8-30	500-1000	<1500	600	1-3	6.5-8
NSDWQ	6.5-8.5	25-30	1000	500	250	5.0	5.0

The physicochemical parameters observed in the Bundu-Ama Creek from October 2021 to March 2022 indicate significant variability in water quality due to artisanal crude oil contamination (Chris & Oghenetekevwe, 2023). pH values ranged from 6.87 in November to 7.70 in February, suggesting periodic fluctuations in water chemistry due to contamination or seasonal effects (Dey et al., 2021). Since aquatic organisms are sensitive to pH changes, variability can impact species survival and ecosystem stability (Brezonik et al., 2020). A consistently neutral pH is ideal for aquatic ecosystems (Agarin et al., 2019). Temperatures ranged from 27.30°C to 32.47°C, exceeding WHO guidelines (27.8°C–30°C) in certain months. Higher temperatures reduce dissolved oxygen levels, increasing toxicity and stressing aquatic life (Olasupo et al., 2021).

Electrical Conductivity (EC) and Total Dissolved Solids (TDS) values peaked in December and February, exceeding WHO and NSDWQ limits, indicating substantial ionic contamination likely due to crude oil residues (Origbe et al., 2021). Salinity peaked at 8.64 in November, well above NSDWQ standards, suggesting saltwater intrusion or high pollution levels (Ghalambor et al., 2021). Elevated salinity harms freshwater species, disrupts osmoregulation, and reduces biodiversity (Hintz & Relyea, 2019). Turbidity values showed variability but remained mostly within acceptable ranges, with the highest levels recorded in January, which can affect light penetration and photosynthesis in aquatic plants (Chris et al., 2023). Dissolved Oxygen (DO) levels remained relatively stable, though notable declines in December may stress aquatic organisms, particularly when combined with high temperatures and pollutants (Onyena et al., 2024).

Studies in the Niger Delta consistently report elevated EC, TDS, and salinity due to oil pollution (Raimi & Sawyerr, 2022). Hintz & Relyea (2019) observed similar seasonal fluctuations, emphasizing oil pollution's widespread impact on water quality. Research by Ghalambor et al. (2021) highlights chronic health risks associated with fluctuating physicochemical parameters, supporting findings of potential health hazards to local communities (Chris et al., 2024). Global studies in the Amazon Basin (Ecuador) and Orinoco Delta (Venezuela), regions also impacted by oil pollution, reveal similar physicochemical disturbances, underscoring a global trend in oil-related water contamination (Valdivia & Lyall, 2018; Adeola et al., 2022).

The correlation analysis of water quality parameters measured at the three stations reveals significant relationships among the parameters (Table 3). Positive correlations, such as those between pH and Salinity (0.884) is evident that when one parameter grows, the other parameter also tends to increase. This suggests that pH and Salinity are likely to rise together in the sampled environments. On the other hand, there is a strong negative association (-0.969) between Temperature (Temp) and Dissolved Oxygen (DO) indicate that an increase in one parameter corresponds to a decrease in the other, implying that higher temperatures are associated with lower DO levels.

Table 2. Mean Physicochemical Parameters Across Months

Station	pH	Temp	EC	TDS	Salinity	Turbidity	DO
October	$7.33{\pm}0.22^{ae}$	$31.87{\pm}0.57^{a}$	$6390.00{\pm}340.05^{a}$	$3195.00{\pm}170.02^{a}$	$6.17{\pm}0.68^{a}$	$1.67{\pm}0.30^{a}$	$6.40{\pm}0.43^{a}$
November	$6.87{\pm}0.03^{bc}$	$31.50{\pm}0.00^{a}$	$6196.67{\pm}314.98^{a}$	$3098.33{\pm}157.49^{b}$	$8.64{\pm}0.34^{a}$	$1.33{\pm}0.30^{a}$	$6.90{\pm}0.07^{a}$
December	$7.17{\pm}0.07^{acd}$	$29.30{\pm}0.10^{b}$	$14206.67{\pm}931.26^{b}$	$7103.33{\pm}465.63^{b}$	$7.11{\pm}1.14^{a}$	$1.67{\pm}0.30^{a}$	$4.70{\pm}0.44^{a}$
January	$7.00{\pm}0.00^{ac}$	$29.04{\pm}0.00^{b}$	$12353.33{\pm}885.71^{b}$	$6176.67{\pm}442.85^{b}$	$6.87{\pm}1.35^{a}$	$2.00{\pm}0.30^{a}$	$6.48{\pm}0.99^{a}$
February	$7.70{\pm}0.00^{e}$	$32.47{\pm}0.03^{a}$	$14106.67{\pm}1061.98^{b}$	$7053.33{\pm}530.99^{b}$	$6.50{\pm}0.97^{a}$	$1.67{\pm}0.30^{a}$	$6.40{\pm}0.43^{a}$
March	$7.47{\pm}0.03^{ad}$	$27.30{\pm}0.15^{b}$	$12913.33{\pm}474.14^{b}$	$6456.67{\pm}237.07^{b}$	$6.48{\pm}0.14^{a}$	$1.33{\pm}0.30^{a}$	$6.90{\pm}0.07^{a}$
WHO	6.5-8.5	27.8-30	400	500	600	1-3	6.5-8
NSDWQ	6.5-8.5	25-30	1000	500	250	5.0	5.0

Furthermore, there is a significant and direct relationship between EC and TDS with a correlation coefficient of 1.0, signifying that these parameters increase in tandem. The relationships between these parameters provide insights into the dynamics of water quality and the interactions among different environmental factors at the study sites.

The correlation analysis of water quality parameters in Bundu-Ama Creek reveals key physicochemical interactions. A strong positive correlation between salinity and pH suggests that ions affecting salinity also influence water alkalinity (Kaushal et al., 2018). The perfect correlation between EC and TDS confirms their direct proportionality, as higher TDS leads to increased EC due to greater ion concentration. Additionally, turbidity strongly correlates with pH (0.960), EC (0.946), TDS (0.946), and salinity (0.979), indicating that elevated particulate matter is linked to higher dissolved substances and increased pH and salinity levels.

A strong negative correlation shows that temperature rise decreases dissolved oxygen (DO), as warmer water holds less oxygen, stressing aquatic organisms (Nelson et al., 2017). A moderate negative correlation suggests higher temperatures slightly lower pH, possibly due to increased metabolic activities and decomposition by-products (Mengqi et al., 2021; Nie et al., 2021). The negative correlation between temperature and DO indicates oxygen depletion during warmer months, endangering aquatic life and biodiversity (Mahaffey et al., 2020). The correlation between EC, TDS, turbidity, pH, and salinity suggests that crude oil pollution affects multiple water quality parameters simultaneously (El Nahhal et al., 2021).

Similar patterns occur in other Niger Delta studies, linking high EC and TDS to oil pollution, altering water chemistry and posing health risks (Wokoma & Njoku, 2017; Igbemi et al., 2020; Onyena et al., 2021). Globally, rising temperatures correlate with lower DO, stressing ecosystems (Chakraborty & Chakraborty, 2021; Imran et al., 2023). This trend appears in oil-contaminated regions like the Amazon Basin and Gulf of Mexico (Ozigis et al., 2020; Thakur & Koul, 2022).

Heavy metal Results Across stations

Table 4 shows the mean levels of toxic metals at various sites in the Bundu-Ama stream. The mean Cr values ranged from 0.74 to 0.79, with no significant differences across stations ($P<0.05$). The mean values for Cd and Co were also similar, but no significant differences were found. The mean values for Ni and Fe were also similar, with no significant differences found across locations. The mean values for Pb and Zn were also similar, with no significant differences found. The mean value for As was below 0.002 across the three sites. These results suggest that the levels of toxic metals in the Bundu-Ama stream are not significantly different across stations.

The analysis of heavy metal concentrations in Bundu-Ama Creek highlights severe contamination across stations. Chromium (Cr) levels ranged from 0.74 to 0.79 mg/L, significantly exceeding NSDWQ (0.2 mg/L) and WHO (0.05 mg/L) limits, posing risks of skin rashes, respiratory issues, and cancer (Younis et al., 2017; Budi et al., 2024). Cadmium (Cd) levels (0.23–0.28 mg/L) also far surpassed WHO and NSDWQ limits (0.003 mg/L), raising concerns

Table 3. The correlation coefficient table for the parameters measured

Stations	Cr	Cd	Co	Ni	Fe	Pb	Zn	As
Station 1	0.78±0.02[a]	0.24±0.02[a]	0.73±0.04[a]	0.17±0.00[a]	6.21±0.27[a]	0.29±0.01[a]	0.72±0.14[a]	<0.002
Station 2	0.79±0.03[a]	0.23±0.02[a]	0.71±0.05[a]	0.16±0.01[a]	5.75±0.38[a]	0.31±0.02[a]	0.80±0.15[a]	<0.002
Station 3	0.74±0.04[a]	0.28±0.0[a]	0.73±0.04[a]	0.18±0.00[a]	6.00±0.24[a]	0.29±0.02[a]	0.83±0.15[a]	<0.002
WHO	0.5	0.003	0.01	0.1	0.3	0.01	3.0	0.01
NSDWQ	0.02	0.003	-	0.02	0.3	0.01	3	0.05

due to kidney damage, bone demineralization, and carcinogenic effects (Reyes-Hinojosa et al., 2019; Ma et al., 2021). Cobalt (Co) concentrations (0.71–0.73 mg/L) exceeded the WHO limit (0.01 mg/L), and while Co is essential in trace amounts, excessive exposure can cause respiratory issues (Leyssens et al., 2017; Mozrzymas, 2018). The presence of Cr, Cd, and Co suggests pollution from industrial activities, artisanal mining, and crude oil processing (Chris & Oghenetekevwe, 2023).

Nickel (Ni) values (0.16–0.18 mg/L) exceeded WHO (0.1 mg/L) and NSDWQ (0.02 mg/L) limits, with high levels linked to allergic reactions, lung and nasal cancers (Zhang et al., 2019; Genchi et al., 2020). Iron (Fe) concentrations (5.75–6.21 mg/L) were far above WHO and NSDWQ limits (0.3 mg/L), affecting water taste, staining, and clogging pipes (McFarland & Dozier, 2024). Although Fe is less toxic, its high levels indicate industrial discharge and corrosion from iron-containing materials (Gong et al., 2022). Lead (Pb) levels (0.29–0.31 mg/L) were substantially higher than WHO and NSDWQ limits (0.01 mg/L), with Pb known for its neurological toxicity, especially in children (Olufemi et al., 2022). Its presence points to contamination from oil exploration and waste disposal (Davies et al., 2023).

Zinc (Zn) values (0.72–0.83 mg/L) remained below WHO and NSDWQ limits (3 mg/L), indicating lower contamination risks (Onakpa et al., 2018). Arsenic (As) levels (<0.002 mg/L) were also within safe limits, posing minimal risk (Radfard et al., 2019). Research in the Niger Delta frequently reports elevated levels of Cr, Cd, and Pb due to oil pollution (Aigberua et al., 2017; Chinedu & Chukwuemeka, 2018; Radfard et al., 2019). Onyena et al. (2024) documented similar contamination trends, reinforcing concerns over severe environmental and health risks in the region.

Heavy Metals Results Across Months

Table 5 shows that while the largest value was noted in December (0.84±0.02a), March (0.66±0.03b) showed the lowest Cr level. Month-wide statistically significant changes were found (P>0.05). The average values for Cd ranged from 0.21±0.02a to 0.29±0.01a; no statistically significant changes were noted (P<0.05). October (0.81±0.00a) had the highest value for Co; March (0.58±0.01b) had the highest value. There were no statistically significant variations throughout the months (P>0.05). There were no statistically significant variations seen during the months (P<0.05; the average values for Ni ranged from 0.15±0.02a to 0.18±0.00a). There were no notable variations in the mean values for Fe; they ranged from 5.61±0.91a to 6.70±0.25a. P<0.05. The average Pb readings ranged from 0.26±0.01a to 0.36±0.02a; there were no appreciable changes between the months (P<0.05). The maximum concentration of Zn was seen in October (1.13±0.03a), whilst the lowest concentration was reported in March (0.23±0.03b). There were significant variations in Zn levels across the different months (P>0.05). The reported values for all the months covered in the sample were consistently below 0.002.

The analysis of heavy metal concentrations in Bundu-Ama Creek across different months highlights temporal variations in contamination levels. Chromium (Cr) values ranged from 0.66 mg/L in March to 0.84 mg/L in December, consistently exceeding WHO and NSDWQ limits,

Table 4. Mean Heavy Metals Results Across Stations

Stations	Cr	Cd	Co	Ni	Fe	Pb	Zn	As
Station 1	0.78±0.02[a]	0.24±0.02[a]	0.73±0.04[a]	0.17±0.00[a]	6.21±0.27[a]	0.29±0.01[a]	0.72±0.14[a]	<0.002
Station 2	0.79±0.03[a]	0.23±0.02[a]	0.71±0.05[a]	0.16±0.01[a]	5.75±0.38[a]	0.31±0.02[a]	0.80±0.15[a]	<0.002
Station 3	0.74±0.04[a]	0.28±0.0[a]	0.73±0.04[a]	0.18±0.00[a]	6.00±0.24[a]	0.29±0.02[a]	0.83±0.15[a]	<0.002
WHO	0.5	0.003	0.01	0.1	0.3	0.01	3.0	0.01
NSDWQ	0.02	0.003	-	0.02	0.3	0.01	3	0.05

posing skin irritation and potential carcinogenic risks (Younis et al., 2017; Chris et al., 2024). Cadmium (Cd) levels (0.21–0.29 mg/L) showed no significant differences across months but remained alarmingly high compared to the WHO limit (0.003 mg/L), indicating chronic kidney damage and bone demineralization risks from oil extraction pollution (Budi et al., 2024). Cobalt (Co) concentrations (0.58–0.81 mg/L) also exhibited no major seasonal differences but exceeded WHO limits, leading to respiratory concerns, with fluctuations likely influenced by industrial discharge and water flow variations (Mozrzymas, 2018).

Nickel (Ni) values (0.15–0.18 mg/L) remained consistently above WHO guidelines (0.1 mg/L), posing risks of allergic reactions and cancers, suggesting steady pollution from oil-related activities (Adeola, 2012; Bello, 2021). Iron (Fe) concentrations (5.61–6.70 mg/L), though less toxic, exceeded safe limits, affecting water taste and staining, pointing to persistent industrial pollution (Chris & Anyanwu, 2022). Lead (Pb) levels (0.26–0.36 mg/L), significantly above acceptable limits, pose neurological and developmental risks, particularly in children (Davies et al., 2023). Zinc (Zn) values (0.23–1.13 mg/L) varied significantly ($P>0.05$), with lower concentrations in March, possibly due to dilution effects or reduced industrial activity (Uchenna et al., 2024). Arsenic (As) levels remained consistently <0.002 mg/L, posing minimal risk in the study area (Chris et al., 2024).

Similar research in the Niger Delta confirms chronic heavy metal pollution from oil activities, emphasizing health and ecological risks (Chris & Anyanwu, 2022). Persistent contamination necessitates stricter regulations and remediation efforts. Studies in oil-contaminated regions like Delta State reveal similar heavy metal pollution trends, highlighting a global issue linked to oil extraction and processing (Fatoba et al., 2016). Internationally, advanced treatment technologies and policy frameworks have proven effective and could guide pollution mitigation strategies in the Niger Delta.

The correlation coefficient table for the heavy metal parameters measured

The correlation analysis of heavy metal concentrations across the stations revealed distinct relationships among the measured parameters as seen in Table 6. Negative correlations, such as those between Chromium (Cr) and Cadmium (Cd), indicate an inverse relationship, where an increase in one metal's concentration is associated with a decrease in another's. For example, Cr and Nickel (Ni) have a strong negative correlation of -0.945, suggesting that as Cr concentrations increase, Ni levels tend to decrease. Conversely, positive correlations, such as the one between Cobalt (Co) and Iron (Fe) at 0.890, suggest that these metals increase or decrease together. Notably, lead (Pb) shows a strong positive correlation with Cd, implying that these two metals are likely to vary together in the sampled stations. The correlation with Arsenic (As) is not calculated due to the constant values being below detection limits. These correlations provide insights into the potential interactions and shared sources of heavy metals within the studied environment.

Table 5. Mean Heavy Metal Results Across Months

Months	Cr	Cd	Co	Ni	Fe	Pb	Zn	As
October	0.74±0.03^{a}	0.21±0.02^{a}	0.81±0.00^{a}	0.17±0.00^{a}	5.76±0.28^{a}	0.29±0.01^{a}	1.13±0.03^{a}	<0.002
November	0.81±0.01^{a}	0.24±0.03^{a}	0.80±0.01^{a}	0.18±0.00^{a}	6.70±0.25^{a}	0.29±0.01^{a}	1.09±0.08^{a}	<0.002
December	0.84±0.02^{a}	0.29±0.01^{a}	0.77±0.01^{a}	0.17±0.01^{a}	5.98±0.07^{a}	0.27±0.01^{a}	0.89±0.01^{a}	<0.002
January	0.84±0.0^{a}	0.29±0.01^{a}	0.75±0.03^{a}	0.18±0.01^{a}	6.13±0.02^{a}	0.26±0.01^{a}	0.89±0.01^{a}	<0.002
February	0.75±0.04^{ab}	0.24±0.04^{a}	0.62±0.07^{ab}	0.15±0.02^{a}	5.61±0.91^{a}	0.36±0.02^{a}	0.47±0.11^{b}	<0.002
March	0.66±0.03^{b}	0.22±0.03^{a}	0.58±0.01^{b}	0.17±0.01^{a}	5.74±0.37^{a}	0.29±0.04^{a}	0.23±0.03^{b}	<0.002
WHO	0.5	0.003	0.01	0.1	0.3	0.01	3.0	0.01
NSDWQ	0.02	0.003	-	0.02	0.3	0.01	3	0.05

The correlation analysis of heavy metal concentrations in Bundu-Ama Creek reveals complex interactions among pollutants, helping to identify shared sources and environmental pathways. A perfect negative correlation between Chromium (Cr) and Cadmium (Cd) suggests distinct sources or competitive binding in the environment (Chakraborty & Chakraborty, 2021). Similarly, a strong negative correlation between Cr and Nickel (Ni) implies separate origins or inhibitory interactions (Mengqi et al., 2021). A perfect negative correlation between Lead (Pb) and Cobalt (Co) indicates they are likely influenced by different industrial or artisanal activities (Kaushal et al., 2018).

A strong positive correlation between Cobalt (Co) and Iron (Fe) suggests common sources such as industrial runoff or mineral deposits (Imran et al., 2023). Likewise, Cadmium (Cd) and Nickel (Ni) show a strong positive correlation, indicating they may originate from similar pollution sources or are transported together within the aquatic system (Nie et al., 2021). A moderate positive correlation between Lead (Pb) and Cadmium (Cd) suggests they are linked to oil extraction and refining activities (Kaushal et al., 2018). No correlation was observed for Arsenic (As), as its levels remained below detection limits, indicating minimal presence in the environment. These positive correlations highlight common pollution sources, while negative correlations suggest distinct origins or interactions, informing pollution control efforts (Younis et al., 2017; Nie et al., 2021).

Similar correlation patterns have been observed in Niger Delta studies, where heavy metal interactions result from diverse pollution sources. Ghalambor et al. (2021) reported strong associations between heavy metals, emphasizing shared industrial origins. These interactions contribute to cumulative exposure, exacerbating health risks to local communities (Payne-Sturges et al., 2018). Comparable trends are seen in oil-producing regions like Venezuela and Angola, where heavy metal correlations indicate the global environmental impact of oil-related activities (Andrews et al., 2021).

The Total Hydrocarbons (THC), Oil and Grease, and Polycyclic Aromatic Hydrocarbons (PAH) measured Results Across the stations

The study examined Total Hydrocarbons (THC), Oil and Grease, and Polycyclic Aromatic Hydrocarbons (PAH) at three sites. Station 3 exhibited the highest THC concentration, while Station 1 had the lowest. Overall, THC levels showed no significant variations (Figures 2-4) and remained well below the World Health Organization (WHO) standard of 10 mg/L, indicating no immediate concern for THC pollution. Oil and grease levels were measured at 1.71±0.04 mg/L at Station 1, 1.53±0.04 mg/L at Station 2, and 1.44±0.05 mg/L at Station 3. Neither the Nigerian Standard for Drinking Water Quality (NSDWQ) nor the WHO provides specific guidelines for oil and grease. However, all PAH levels exceeded the WHO recommendation of 0.2 mg/L and the NSDWQ limit of 0.007 mg/L, suggesting potential health risks and the need for corrective measures.

Table 6. The correlation coefficient table for the heavy metal parameters measured

	Cr	Cd	Co	Ni	Fe	Pb	Zn	As
Cr	1.0							
Cd	-1.0	1.0						
Co	-0.655	0.655	1.0					
Ni	-0.945	0.945	0.866	1.0				
Fe	-0.238	0.238	0.890	0.543	1.0			
Pb	0.655	-0.655	-1.000	-0.866	-0.890	1.0		
Zn	-0.565	0.565	-0.254	0.264	-0.667	0.254	1.0	
As	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0

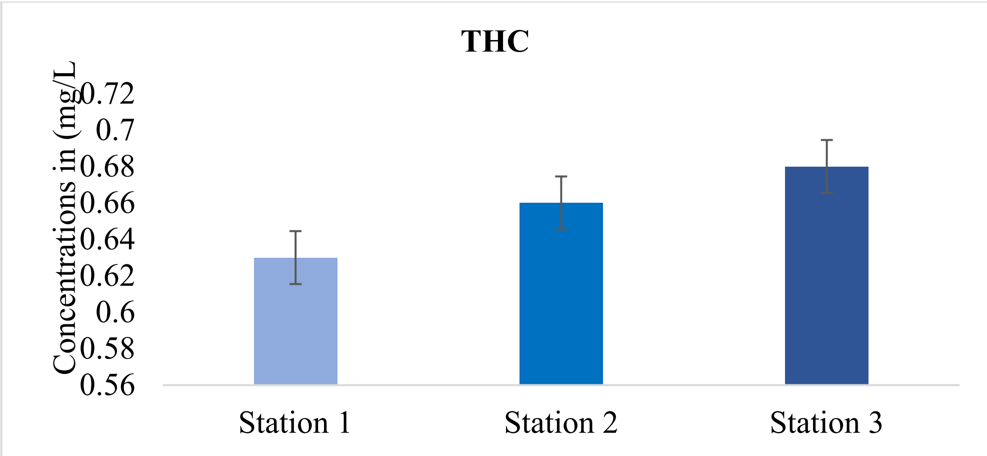

Fig. 2. Total Hydrocarbons (THC) across the stations

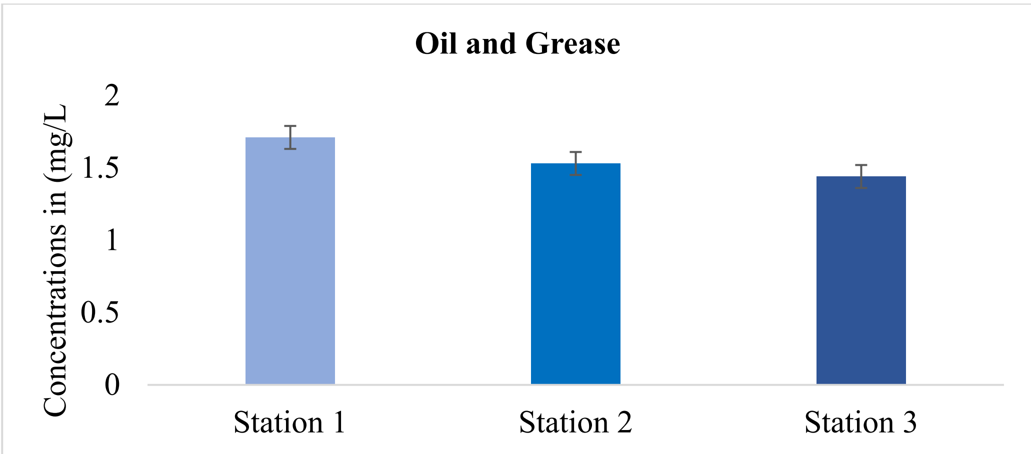

Fig. 3. The concentrations Oil and Grease across the stations

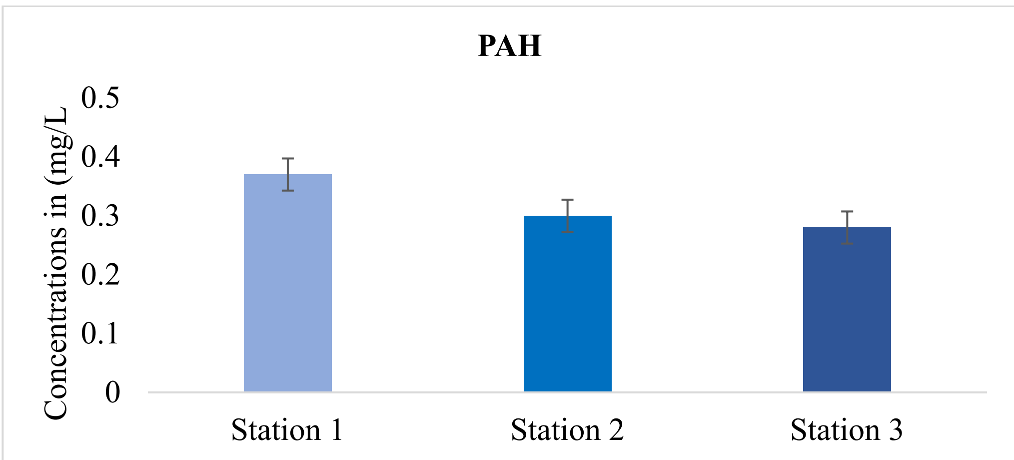

Fig. 4. Polycyclic Aromatic Hydrocarbons (PAH) across the stations

The analysis of hydrocarbon concentrations in Bundu-Ama Creek highlights potential pollution and health risks. Total Hydrocarbons (THC) levels were below the WHO guideline (10 mg/L), suggesting no immediate health concerns (Little & Galperin, 2017). The lack of significant differences across stations indicates uniform THC distribution, likely due to consistent pollution sources or widespread dispersion. Although WHO and NSDWQ do not specify limits for oil and grease, the higher concentration at Station 1 suggests localized pollution from industrial or artisanal activities (Oloruntoba & Ogunbunmi, 2020).

Polycyclic Aromatic Hydrocarbons (PAH) levels exceeded WHO (0.2 mg/L) and NSDWQ (0.007 mg/L) limits, posing serious health risks. PAHs are carcinogenic and linked to respiratory issues and skin irritation (Abdel-Shafy & Mansour, 2016; Mallah et al., 2022). The higher PAH concentration at Station 1 suggests contamination from combustion or oil spillage activities, necessitating targeted remediation efforts.

Similar Niger Delta studies report elevated PAH levels due to oil extraction and processing. Shelton et al. (2018) found comparable contamination, emphasizing the need for continuous monitoring. High PAH levels align with research linking oil pollution to increased cancer risks and ecological harm to aquatic life (Little & Galperin, 2017).

Mean Hydrocarbon Results Across Months

The Results polycyclic aromatic hydrocarbons (PAH), total hydrocarbons (THC), and oil and grease measured Across the months

Table 7 shows the mean concentrations of polycyclic aromatic hydrocarbons (PAH), total hydrocarbons (THC), and oil and grease for each month, along with reference recommendations from the World Health Organisation (WHO) and the Nigerian Standard for Drinking Water Quality (NSDWQ). THC concentrations range from 0.59±0.02 to 0.74±0.05 mg/L, with no significant variation across different months. THC levels consistently stay below the World Health Organization's suggested threshold of 10 mg/L, indicating acceptable levels. Oil and grease concentrations vary slightly from month to month, ranging between 1.46±0.08 and 1.69±0.06 mg/L. There is no specific WHO or NSDWQ guidelines for oil and grease, but the observed levels suggest a relatively consistent presence of these contaminants. PAH concentrations range from 0.23±0.03 to 0.40±0.05 mg/L, with all measured PAH values exceeding the WHO guideline of 0.2 mg/L. However, PAH concentrations are substantially higher than the NSDWQ standard of 0.007 mg/L, indicating a need for regulatory attention and intervention.

The mean concentrations of Polycyclic Aromatic Hydrocarbons (PAH), Total Hydrocarbons (THC), and oil and grease in Bundu-Ama Creek reveal temporal variations in contamination levels. THC concentrations ranged from 0.59±0.02 mg/L (October) to 0.74±0.05 mg/L (November), with no significant differences across months. These values remain below the WHO guideline (10 mg/L), suggesting a stable source of hydrocarbons, likely from ongoing oil-related activities (Abdel-Shafy & Mansour, 2016).

Oil and grease levels varied between 1.46±0.08 mg/L (March) and 1.69±0.06 mg/L (October), with no statistically significant monthly variations. While WHO and NSDWQ do not specify limits, their consistent presence suggests continuous industrial or transportation-related contamination (Adeola, 2012; Bello, 2021). PAH concentrations exceeded WHO (0.2 mg/L) and NSDWQ (0.007 mg/L) limits, posing carcinogenic health risks (Davies et al., 2023). The persistently high PAH levels highlight the urgent need for regulatory intervention and remediation efforts to mitigate contamination.

Similar Niger Delta studies report elevated PAH levels due to oil extraction and processing. Kourmentza et al. (2017) identified similar contamination trends, emphasizing the need for continuous monitoring. PAH pollution is a regional concern, with studies linking it to cancer risks and ecological damage (Mallah et al., 2022). Comparable hydrocarbon pollution challenges are documented in industrial regions (Zainal et al., 2022).

The correlation coefficient table for the hydrocarbons measured

The study found significant relationships between hydrocarbon concentrations across the stations, as shown in Table 8, indicating complex interactions between Total Hydrocarbons (THC), Oil and Grease, and Polycyclic Aromatic Hydrocarbons (PAH) in the aquatic environment.

A strong negative correlation (-0.997) between THC and Oil and Grease suggests an inverse relationship, meaning that as THC concentrations increase, Oil and Grease levels decrease. This may be attributed to differences in the sources, degradation rates, or environmental behavior of these hydrocarbon fractions. THC often consists of a broader range of hydrocarbon compounds that may degrade or disperse differently compared to Oil and Grease, which can persist in localized areas due to their hydrophobic nature.

Similarly, a strong negative correlation (-0.981) between THC and PAH suggests that higher THC levels are associated with lower PAH concentrations. This may indicate that PAHs typically more stable and persistent—are less likely to be present in high concentrations when THC levels are elevated, possibly due to dilution effects or varying degradation pathways in the environment.

On the other hand, Oil and Grease and PAH exhibited a strong positive correlation (0.993), meaning that when Oil and Grease levels increase, PAH concentrations also rise. This relationship suggests that PAHs many of which are byproducts of petroleum-based contaminants may be strongly associated with the Oil and Grease fraction. This could be due to their similar hydrophobic properties, which lead them to co-accumulate in sediments or water bodies with high organic pollution.

These findings highlight the complex interactions between hydrocarbon components, emphasizing the need for detailed hydrocarbon profiling to understand their environmental fate, potential risks, and the effectiveness of remediation efforts in polluted ecosystems.

The correlation analysis of hydrocarbon concentrations in Bundu-Ama Creek reveals key interactions between hydrocarbon components. THC and oil and grease exhibit a strong negative correlation, meaning that as THC levels rise, oil and grease levels decrease, and

Table 7. Mean Hydrocarbon Results Across Months

Months	THC	Oil and grease	PAH
October	0.59 ± 0.02^a	1.69 ± 0.06^a	0.23 ± 0.03^a
November	0.74 ± 0.05^a	1.57 ± 0.10^a	0.32 ± 0.09^a
December	0.67 ± 0.03^a	1.46 ± 0.11^a	0.36 ± 0.10^a
January	0.72 ± 0.05^a	1.59 ± 0.09^a	0.29 ± 0.11^a
February	0.62 ± 0.04^a	1.58 ± 0.09^a	0.30 ± 0.07^a
March	0.60 ± 0.04^a	1.46 ± 0.08^a	0.40 ± 0.05^a
WHO	10	-	0.2
NSDWQ	-	-	0.007

Table 8. The correlation coefficient table for the hydrocarbons measured

	THC	Oil and Grease	PAH
THC	1.000		
Oil and Grease	-0.997	1.000	
PAH	-0.981	0.993	1.000

vice versa (Gertsen et al., 2024). This suggests different sources or degradation processes, or that these hydrocarbons compete for environmental binding sites. Similarly, THC and PAH concentrations show a strong negative correlation, indicating that higher THC levels coincide with lower PAH concentrations, likely due to distinct degradation processes or environmental behaviors (Alegbeleye et al., 2017; Elijah, 2022).

Conversely, PAH and oil and grease demonstrate a strong positive correlation, meaning they increase or decrease together, suggesting they share common sources and are transported or deposited simultaneously (Dalton et al., 2022). Understanding these hydrocarbon relationships is crucial for developing effective pollution management and remediation strategies. The strong positive correlation between oil and grease and PAH supports the theory that they originate from similar sources such as oil spills or industrial discharges (Acharjee et al., 2023).

Similar Niger Delta studies confirm complex hydrocarbon interactions due to diverse pollution sources (Ihunwo et al., 2021). Aa et al. (2022) found strong associations between hydrocarbons, highlighting shared industrial origins and the potential for cumulative exposure and health risks. Globally, oil-producing regions report similar hydrocarbon correlations, underscoring the widespread environmental impact of oil-related activities (Adeola et al., 2022).

CONCLUSIONS

The study of Bundu-Ama Creek in Rivers State, Nigeria, reveals significant hydrocarbon and heavy metal contamination from artisanal crude oil refining. Physicochemical parameters, including pH, electrical conductivity, total dissolved solids, and dissolved oxygen, exceeded WHO and NSDWQ guidelines, indicating persistent ionic pollution. Elevated levels of chromium, cadmium, cobalt, nickel, iron, lead, and zinc pose severe ecological and human health risks, suggesting ongoing contamination from industrial and illegal activities. Hydrocarbon analysis showed high concentrations of Total Hydrocarbons (THC), Oil and Grease, and Polycyclic Aromatic Hydrocarbons (PAH), with PAHs surpassing safety thresholds. Correlation analysis revealed strong interactions between hydrocarbon components, highlighting complex environmental behavior.

To mitigate these impacts, continuous water quality monitoring should be conducted to assess seasonal variations and pollutant trends. Research on bioaccumulation in fish and other aquatic organisms is essential to evaluate health risks. Advanced remediation strategies, such as microbial bioremediation and nanotechnology-based filtration, should be explored. Strengthening environmental regulations, enforcing anti-pollution laws, and engaging local communities in conservation efforts are critical for sustainable management. International collaboration and policy-driven interventions are necessary to restore Bundu-Ama Creek's ecological integrity and protect public health from long-term pollution effects.

Author contribution

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Davies Ibienebo Chris and Okechukwu Kenneth Wokeh. The first draft and editing of the manuscript was written by Parashuram Kallem, Khang Wen Goh, Fathurrahman Lananan, Zulhisyam Abdul Kari, Mohamad Nor Azra and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Competing Interests and Funding

No conflict of interest to declare and no funding for the proposed project except for the Article Processing Charge.

Ethical Approval

No specific ethical approval was not required for this study.

Data Availability Statement

All relevant data supporting the study are in the article, and raw data is also available in request by the readers.

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