# **COMPARATIVE EVALUATION OF THE PHYSICO-CHEMICAL PROPERTIES OF FRESH AND SPENT DRILLING MUDS FROM A SELECTED OILFIELD ENVIRONMENT**

**ABSTRACT**

This work evaluated the concentrations of heavy metals, total petroleum hydrocarbons (TPH) using GC-MS and UV-Vis spectrophotometer as well as physico-chemical parameters of freshly formulated, and the effluent samples of drilling muds from Eastern Obolo Oilfield in the Niger Delta of Nigeria, using appropriate standard methods. The samples consisted fresh Base mud, Base mud formulated with chemicals / additives but not used for drilling operation, Spent Oil-base mud (OBM) and Spent Water-base mud (WBM). GC-MS analysis for TPH indicated a range of *n-*alkanes with a higher concentration (46118.28 ug/l) in the OBM compared to WBM concentration (17185.95 ug/l). The analysis of TPH using GC-MS revealed a more comprehensive range of *n*-alkanes present in the OBM and WBM compared to the UV-Vis spectrophotometer. The TPH for OBM (67.0 mg/kg) was substantially higher compared with WBM (1.30 mg/kg), using UV-Vis spectrophotometer. In comparison, the results indicated a lower TPH of 1.00mg/kg for fresh mud not mixed with formulation chemicals. The TPH concentrations were found to be significantly higher in the OBM compared to fresh base mud and WBM. In general, the results indicated a TPH trend thus: OBM > WBM > Base mud. The TPH obtained for OBM (67.0 mg/kg) was higher than 50mg/kg allowable for drilling mud in the environment. Heavy metals analyses indicated variable concentrations and abundance in the drilling mud samples investigated, especially in manganese (Mn) ranging between (42.17mg/l – 76.65mg/l) in all the mud samples investigated. The physical properties (Density, Total Dissolved Solid (TDS), Viscosity and PH) evaluated showed variations in the different drilling muds, specifically between fresh base mud compared to mud already formulated with additives/chemicals. The results from this study are critical for stakeholders when considering drilling mud properties for optimal and efficient performance and also when choosing disposal of drilling mud effluents, especially in the study area where extensive oil/gas operation is currently ongoing.

*Keywords: Drilling mud effluents, physico-chemical analysis, total petroleum hydrocarbon, heavy metals; environment*

**INTRODUCTION**

Amongst other available energy sources, and with growing demands due to increasing global population, the oil Exploration & Production (E&P) industry driven by its wide applications, provides an important and dependable energy source for the world. Besides other drilling wastes such as Produced Water, drilling fluids and drill cuttings together form the second-largest volume of residues generated by the E&P industry operations (Ismail *et al*., 2017). The Niger Delta region of Nigeria with a vast array of E&P industry operations, is not spared the challenges of these operational wastes. Daae *et al.* (2019) reported that in 2016 Norwegian oil and gas industry generated 260,000 tons of drilling wastes, mainly cuttings contaminated with Oil Base Fluids.  A study of the volume of drilling waste generated by a Middle East oil company indicated a quantity of about 3,000 cm3 per year, part of which consisted Oil-based fluids, with a potential to pose more hazardous effects on the environment compared to other types of fluid (Ardjmand & Daneshfar, 2020). According to report by Laine *et al*,. 2022) a volume of 118,000 tons of hazardous solid waste was generated in 2019, with about 5,000 tons corresponding to contaminated cuttings and spent drilling fluids, which are classified as oily waste. This highlights a global concern about the environmental impacts of large volumes of drilling wastes, particularly when they are improperly released into the environment. Drilling fluids are a set of complex chemical mixtures generally used in the upstream oil and gas industry and perform critical multi-functions in drilling operations. Typical drilling fluids generally are a combination of liquids and various chemicals (water, petroleum oils, and other organic liquids, synthetic brine fluids), dissolved inorganic and organic additives, and suspended, finely divided solids of various types (clay, weighting materials) with a function to adjust the properties of the fluid to meet the requirements of each well in both onshore and offshore drilling processes (Ukeles and Grinbaum, 2004). Some of the essential functions performed by the drilling fluid system include carrying cuttings out of the hole (hole cleaning), cooling and lubricating the drill string, providing wellbore stability, conveying a variety of chemicals down the borehole, collecting of information about subsurface formations, killing bacteria and adjusting pH, inhibiting equipment corrosion while protecting formation damage as well as helping to transfer the hydraulic power from the surface to downhole motors (Araka *et al.,* 2019; Mody and Hale, 1993). The physicochemical conditions of geological formations, which invariably change with depth, guide the adjustment of additives in drilling fluids.

The drilling fluids can be classified according to their base, such as water-based, oil-based, gas-based, or synthetic-based, and these various types are used in variable situations and with different additives (Das *et al.,* 2020). Among these types, the water-based mud is the most used drilling fluid (Fink, 2015; Qin *et al.,* 2021). Drilling fluid contains a variety of special chemicals (‘additives’) each having a different purpose and is formulated based on several factors, and it should primarily be designed to control the formation pressure and to be environmentally friendly (Agbaji, 2010; Abu Khamsin, 2017). Presently, in the oil and gas industry, an increasing operational concern is excessive fluid depletion; hence, some chemical additives are used to regulate fluid loss, such as bentonite, carboxymethyl cellulose (CMC), and starch, to prevent high levels of fluid loss (Moore, 1986; Gamal *et al*., 2019).

Drilling fluids are normally formulated *in situ* by mixing the different additives in a dedicated storage tank, or less preferably, a sump that has been excavated within the drill site. After drilling activities are complete, the waste fluid becomes contaminated with formation material and the final result is a large volume of liquid and solid waste that must be properly managed. The exact amount of waste drilling fluid produced is dependent upon numerous factors, including the depth of the well being drilled (Ismail *et* *al*., 2017).

In general, drilling fluids are to be biologically and chemically nontoxic and non-hazardous to the environment and personnel who come in contact with it due to operational exposures. However, many additives used in the composition of drilling fluids are not toxic-free and are therefore regulated. The use of drilling fluids have widely been connected to some environmental problems due to a variety of wastes including drill cuttings and used drilling fluid (mud) generated during the drilling process (Arpornpong *et al,* 2020; Adewole *et al,* 2010; Awaka-ama, 2012), and have been associated with changing concentrations of hydrocarbons and heavy metal pollution from barium, mercury, cadmium, diesel (from lubricants, spotting fluids and oil-based mud cuttings), arsenic and formaldehyde (biocides) in areas of operations (Neff, 2008; Udosen *et al*, 2010; Udo *et al*, 2021). Hence, discharge of untreated drilling effluents into seas, rivers and land constitutes a serious hazard and is an important concern due to the detrimental effects and degradation of the environment around the oilfield drill sites. The highest impact results from waste discharges into the environment in concentrations that were not naturally found in such locations. The disruption of ecological balance through drilling operations occurs through surface discharge of pollutants from various activities affecting the environment (AlBajalan and Haias, (2021), posing a potential risk to the ecosystem and human health.

Therefore, on this basis, this research was designed to comparatively evaluate the physico-chemical properties of both water-based and oil-based fresh and spent drilling muds from a selected oilfield environment in the Niger Delta of Nigeria. This work also assesses the various properties of fresh base mud compared to mud already formulated with additives/chemicals. It is imperative to investigate properties and concentrations of these potential contaminants in the drilling mud compositions in order to evaluate its properties for optimal and efficient performance and also when choosing options for disposal of drilling mud effluents and its environmental impact. The results from this research provide valuable information on the chemical compositions and physico-chemical properties of drilling mud systems used in oilfield operations and moreover, will contribute to the development of effective management and mitigation strategies to minimise the release of contaminants into the fragile oilfield environment.

**3.1 MATERIALS AND METHODS**

*Location of the Study Area*: The oilfield wells are located in Eastern Obolo, in the Niger Delta fringe between Imo and Qua Iboe Rivers estuaries in Nigeria, and lies between latitudes 4° 28' and 4° 53' and longitudes 7° 50' and 7° 55' East. It is a coastal Local Government under great tidal influence from the Bight of Bonny and is bounded in the south by the Atlantic Ocean.

**3.2 METHODOLOGY**

**3.2.1 Sample Collection**

 Drilling mud samples were collected from the mud tank at the samples site using a cup and were transported to the laboratory and stored in the refrigerator for 2 days prior to the analyses in the laboratory. A total of ten (10) Base mud (BM), fresh base mud (FBM), water based mud (WBM) and oil-based mud (OBM) from the production wells storage tanks were collected for this study and the composite samples collected were analyzed for the total petroleum hydrocarbon (TPH) using Gas chromatography- Mass Spectrophotometer method. The samples were also analyzed for heavy metal concentration using Atomic Absorption Spectrophotometer (AAS) method. The samples were also analyzed for physical properties using standard methods.

  **3.2.1 Digestion of Mud samples for heavy metal analysis:**

 5 ml of each of Base Mud, Fresh base Mud, Water-base Mud and Oil-base Mud samples were digested by the addition of 10 ml of concentrated HNO3 and 10 ml of hydrogen peroxide, (H2O2), to break down the matrix and release the metals into solution. There were heated on a hot plate to about half the original volume (Digestate). The flask was allowed to cool, and its content were then filtered into a 25 ml standard volumetric flask and made up to the mark with distilled water. Triplicate digestion of each sample was carried out in order to rule out experimental bias or random error. A portion of the solution was used for heavy metal analysis using AAS.

**3.2.2 Total Petroleum Hydrocarbon (TPH) Analysis using GC-MS**: 10 g each of the WBM and OBM samples were collected into solvent (dichloromethane) rinsed beakers. 50ml of 50:50 mixture of acetone and dichloromethane was added. The samples were shaken gently but vigorously for 20-minutes while being heated at 20°C. 10g of anhydrous sodium sulphate was added to the samples and allowed to stand until a clear extract were developed. The extract were decanted, the solvent was then concentrated and exchanged with HPLC grade hexane, using column chromatography method, and then re-concentrated to 3ml. The extracted samples were transferred into Teflon-lined screw-cap vials. These were well labeled, corked and taken to the GC MS (GC-MS model HP5890 PLUS II with AGILENT CHEMSTATION quantification software) for TPH analysis.

**3.2.3 Determination of TPH using UV-Vis Spectrophotometer:**

 5 g of sample was weighed. It was mixed with xylene (50ml) then stirred using a magnetic stirrer for 2 minutes. A chromatographic column was parked with anhydrous sodium sulphate and then separation using xylene, DCM and chloroform was performed. The Absorbance (Abs) was read using the UV-Vis spectrophotometer (SpectroLab 752Pro). The spectrophotometer was set at 425 nm wavelength.

 **3.2.4 Viscosity measurements**

The mud was vigorously agitated before conducting the test. Subsequently, the agitated mud was carefully transferred into the rheometer cup and immersed within the rotor sleeve precisely up to the specified mark. It was then secured in place by tightening the locking screw on the left side of the apparatus, the knob was adjusted in other to obtain readings for 600rpm, for 30mins. The viscosity measurements were determined.

**3.2.5 Drilling mud density**

The density was measured using a density meter, DS7000. By comparing the measured parameters with calibration data, density meters accurately determine the density of liquids and sometimes solids.

**3.2.6**  **Total Dissolved Solids (TDS)** referring to the total amount of dissolved minerals and salts (solid materials) present in the drilling fluid, and it is typically measured by taking a sample of the mud and analyzing it in a laboratory using a conductivity meter to determine the electrical conductivity, which is then converted to a TDS concentration using a conversion factor; this method is considered the most accurate way to measure TDS in drilling mud. A representative sample of the drilling mud is taken from the mud system. The sample is analyzed using a conductivity meter, which measures the electrical conductivity of the fluid. The measured conductivity is then converted to TDS concentration using a conversion factor specific to the drilling mud composition.

**3.2.7 pH Measurement**

The drilling mud pH was measured using the pH meter with an accuracy of ±0.05 and the values were recorded.

**3.2.8 Metal Analysis**

One gramme (g) of each of the sample type was digested (to break down the matrix and release the metals into solution) using mixture of perchloric acid HClO4, nitric acid HNO3 and sulphuric acid H2SO4 in the ratio 1:2:2. (Adewole *et al*., 2010; Neff *et al*., 1988b). The prepared solution was analyzed for heavy metals / elements of interest using atomic absorption spectrophotometer (AAS). The method provides critical data on the metal content of the drilling mud samples. The results obtained were compared with both Nigeria Upstream Production and Regulatory Commission (NUPRC, 2022) guidelines and United State Environmental Protection Agency (USEPA, 2011) standards for drilling waste disposal.

**RESULTS AND DISCUSSION**

**Table 1: Heavy metals concentration (mg/l) in the samples**

| **Sample/Parameters** | **Cr**  | **Fe** | **Ni** | **Mn** | **Pb** | **Cd** | **Cu** | **Zn** |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Base Mud (BM) [without additives] | 1.089 | 77.65 | 0.662 | 42.17 | 0.234 | 0.02 | 0.94 | 0.48 |
| Fresh Base Mud (FBM) [with additives] | 1.544 | 76.97 | 0.693 | 44.15 | 0.274 | 0.04 | 0.03 | 0.50 |
| Spent OBM | 0.13 | 24.40 | 0.05 | 75.65 | 0.08 | 0.02 | 0.06 | 0.53 |
| Spent WBM | 0.11 | 12.40 | 0.10 | 43.21 | 0.01 | 0.00 | 0.02 | 0.06 |
| NUPRC | 0.05 | 0.005 | 0.10 | 1.00 | 0.006 | 0.05 | 1.00 | 1.00 |

N**ote:**

**Sample BM** - Base mud without additive (‘formulation chemicals’)

 **FBM** - Fresh base mud mixed with additives (‘formulation chemicals’)

  **Spent** Oil-based mud (OBM)

  **Spent** Water-base mud (WBM)

 **NUPRC** - Nigeria Upstream Production and Regulatory Commission

**Figure.1** Concentration (mg/l) of heavy metals in the samples compared to NUPRC standard.

**Figure.2** Concentration (mg/l) of Fe and Mn in the samples compared to NUPRC standard.

Heavy metal, physicochemical properties and Total Petroleum Hydrocarbon (TPH) concentrations were determined in both influent and effluent drilling mud samples. The results of the heavy metals analyzed in Base mud (sample A), Base mud formulated with chemicals (sample B) but not used for drilling operation, Spent OBM (sample C) and Spent WBM (sample D) respectively are shown in Table 1 and Figure 1 and Figure 2 respectively. In this study, samples A and B are drilling muds that have not yet been used for any drilling operation, whereas, sample C and D are drilling muds that have been used for drilling operations.

The heavy metals analyses indicated variable concentrations in the drilling mud samples investigated. The result as shown in Figure.2 indicated exceptionally very high concentrations of manganese (Mn) ranging between (42.17mg/l – 76.65mg/l) in all the mud samples investigated. There was a significant elevation and enrichment in the concentration (76.65mg/l) of Mn in the OBM (sample C) compared with samples A, B and D respectively. Similarly, the result also showed a marked difference between the concentration of Mn in OBM (76.65mg/l) and WBM (43.21mg\l). Typical concentrations of manganese in drilling muds can range between 10-500mg/l for oil-base mud and 1-100mg/l for water-based muds (Bakhtiari *et al*., 2024). In comparison, the concentrations of Mn in all the four drilling mud samples (A, B, C and D) indicated values significantly higher than the NUPRC (2022) recommended threshold value (1.00 mg/l). This showed a significantly high enrichment of Mn in the drilling mud samples. It has been reported that Mn is often introduced into oil-based drilling muds through the use of manganese-based additives (Amenyah Kove *et al*., 2021). Manganese plays a key role in influencing the rheological properties of drilling mud by contributing to the overall mineralogical structure. The concentration of manganese in drilling mud can vary widely depending on several factors such as the type of drilling mud (i.e either oil-based or water-based), additives and chemicals used in the formulation such as manganese oxide or manganese carbonate, geological formations whereby drilling through manganese-rich formations or drilling locations can easily contaminate the mud with elevated manganese levels.

The result also indicated extremely high concentration of Fe in sample A (77.65mg/l) and sample B (76.97mg\l), compared to the Fe concentrations in sample C (24.40mg/l) representing OBM, and sample D (12.40mg\l) representing WBM. This is shown in Figure.2. These high concentrations are of environmental concern when compared to NUPRC concentration value of 0.005mg/l for drilling mud. These elevated concentrations will contribute to increased Fe accumulation in the aquatic environment where the drill wastes are disposed. Onwuka *et al*., 2018 reported an elevated level of Fe in a study of drilling wastes in a Niger Delta oil/gas field and attributed this to the dissolution of iron or manganese oxides or from weathering of pyrite (iron sulfide) suspected to have contributed to the elevated Fe concentrations.

Similarly, in terms of abundance, as shown in the Table.1 and Figure 1, the concentrations in Cr, Ni and Pb were found to be substantially higher in samples A and B, compared to samples A and B respectively, particularly in Cr which were above the 0.05mg/l threshold value recommended by NUPRC (2022; WHO (1993). Chromium pollution resulting from ferrochrome lignosulphate (a constituent of waterbased mud) has been identified as a source of environmental pollution (Shadizadeh and Zoveidavianpoor, 2010; Offiong *et al*, 2023; Awaka-ama *et al.,* 2024). Generally, the results indicated heavy metals of higher concentration in the unused drilling muds A and B, compared to OBM and WBM. However, the exceptionally high values of Iron (Fe) in both the OBM and WBM are of great concern when compared with the WHO (1993) and drinking water standard and Water Quality Criteria (1972) for irrigation and fishery. Though these elements are likely to be of nutritional importance to the aquatic animals, the associated metals will constitute a problem to aquatic lives through food chain biomagnifications even in very small concentrations. It is essential for drilling operators to monitor and control the concentrations of heavy metals found in drilling wastes discharges/mud to mitigate environmental impacts and ensure compliance with regulations.

**Table 2 Total Petroleum Hydrocarbon (TPH) for water-based mud (WBM) and oil-based mud (OBM)**

| **TPH** | **WBM(µg/L)** | **OBM(µg/L)** |
| --- | --- | --- |
| *n*-octane | 3392.652 | 723.413200 |
| *n*-nonane | 9063.970 | 4730.77200 |
| *n*-decane | 352.0269 | 143.632300 |
| *n*-undecane  | 1981.834 | 658.161400 |
| *n*-dodecane | 71.11008 | 10170.6500 |
| *n*-tridecane | 37.29415 | 1190.78400 |
| *n*-tetradecane | 69.39721 | 1418.04000 |
| *n*-pentadecane | 403.6161 | 435.518100 |
| *n*-hexadecane | 67.09979 | 10530.1700 |
| *n*-heptadecane | 491.2397 | 1209.47200 |
| Pristane | 140.3726 | 1666.23100 |
| *n*-octadecane | 249.1221 | 1584.50700 |
| Phytane | 847.3272 | 859.757500 |
| *n*-nonadecane | 3.028081 | 5320.17900 |
| *n*-eicosane | 6.197512 | 160.588100 |
| *n*-heneicosane | 2.693108 | 114.099100 |
| *n*-docasane | 2.617612 | 15.5074400 |
| *n*-tricosane | <0.01 | 8.70715100 |
| *n*-tetracosane | 0.182448 | 3.50437800 |
| *n*-pentacosane | <0.01 | 1.23685400 |
| *n*-hexacosane | <0.01 | <0.01 |
| *n*-heptacosane  | <0.01 | 0.50350500 |
| *n*-octacosane | 0.211653 | <0.01 |
| *n*-nonacosane | <0.01 | <0.01 |
| *n*-tricontane | <0.01 | <0.01 |
| *n*-hentriacontane | <0.01 | <0.01 |
| *n*-dotriacontane | <0.01 | 5170.20400 |
| *n*-tritriacontane | 3.962289 | 2.58869500 |
| **⅀TPH** | **17185.95** | **46118.2300** |

**Total Petroleum Hydrocarbon (TPH) of OBM and WBM Using GC-MS analysis:**

The results as given in Table 2 showed that the concentration of TPH in WBM to the OBM was in the ratio of 1:4. The TPH analysis indicated a range of *n*-alkanes with a higher concentration (46118.23µg/l) in the OBM compared with the WBM concentration (17185.95 µg/l). The limit for TPH disposal into the marine environment is regulated by Nigeria Upstream Production and Regulatory Commission (NUPRC) guidelines. The TPH value was higher in the OBM. Investigations in other studies reported by TPHCWG ,1998b; Udo *et al,* 2020; Udo *et al*, 2023b; Awaka-ama *et al,* 2024 stated that most petroleum hydrocarbon mixtures contain relatively high concentration of TPH. Similarly, Gbadebo *et al.* (2010) in another study reported results which indicated comparatively high levels of TPH reaching 7156.57 mg/kg−1 for water-based drilling fluid waste and 6449.55 mg/kg−1 for oil-based drilling fluid waste. These samples also presented PAHs levels higher than the permissible limits by regulatory authority. One of the major concerns regarding TPH is their mutagenic and potential carcinogenicity of some molecules (0ffiong *et al*., 2023; IPCS, 1998a), that can lead to various human health problems. Oil-field drilling fluids, especially oil-based mud, contain hazardous constituents (Martin, 1991; UKOOA, 2000) which can adversely affect the flora and fauna leading to health problems due to the volatilization of hazardous oil components such as benzene, toluene, [ethylbenzene](https://www.sciencedirect.com/topics/chemical-engineering/ethylbenzene) and xylene in the environment. Due to these reasons, TPH deserves special attention therefore it is imperative to identify the origin and potential sources of these hydrocarbons in the environment to assess the environmental risk (Offiong *et al*, 2023).

**Table 3 Physicochemical Analyses**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Sample / Parameters** | **Density (g/mL)** | **PH** | **TDS (mg/L)** | **Viscosity/Rheology (mPa.s)** |
| **A** | 0.98 | 5.02 – 4.95 | 0.31 | 341.0 |
| **B** | 1.02 | 5.01 – 4.88 | 3.71 | 274.0 |
| **C** | 0.98 | 4.03 – 2.93 | 3.47 | 343.0 |
| **D** | 0.89 | 4.05 - 2.84 | 3.42 | 339.0 |

**4.3 Total Petroleum Hydrocarbon (TPH) of drilling muds using UV-Vis Spectrophotometer.**

**Table 4 Showing Total Petroleum Hydrocarbon (TPH) Contents in Base mud (without formulation ‘chemicals’, OBM and WBM effluents) Using UV-Vis Spectrophotometric analysis:**

|  |  |  |  |
| --- | --- | --- | --- |
| **Sample** | **Base mud (without ‘chemicals’) (A) (mg/kg)** | **OBM (mg/kg) (C)** | **WBM (mg/kg) (D)** |
| **TPH** | 1.0 | 67.0 | 1.30 |

**Figure.3** Showing the Total Petroleum Hydrocarbon (TPH) in the Base Mud, OBM and WBM

The total petroleum hydrocarbon (TPH) of the base mud without chemicals (Sample A), spent oil based mud (Sample B) and Spent water based mud (Sample C) respectively, were analyzed using Ultraviolet – Visible Spectrophotometer. This is shown in Table 4 and Figure 3 respectively. The TPH for sample B representing OBM was 67.0 mg/kg. For sample C, representing WBM, the TPH obtained was 1.30 mg/kg. In comparison, the results indicated a lower TPH of 1.00mg/kg for fresh mud which has not been mixed with formulation chemicals. The TPH concentrations were found to be significantly higher in the OBM compared to base mud (sample A) and WBM (sample C). In general, the results indicated a TPH trend thus: OBM > WBM > Base mud. The results indicated that the TPH for OBM (67.0 mg/kg) was higher than 50mg/kg allowable for drilling mud in the environment recommended by the NUPRC (1991). The high TPH level in the OBM is of environmental concern and can indicate a higher risk of environmental contamination particularly in sensitive ecosystems. Monitoring and regulatory compliance is critical to protect the environment. However, similar investigations of TPH using UV-Vis spectroscopy (Khorshid *et al*., 2021; Dumka and Kingdom, 2018; Adewole *et al*., 2010) have shown a comparably lower concentrations for drilling mud used in some environment. The results from this investigation also indicated that the analyses of TPH using UV-Vis Spectrophotometer, although being qualitative, can be fast and reliable approach to complement a more comprehensive outline of the range of *n*-alkanes present in the drilling mud samples that may be revealed by GC-MS analysis.

**4.4 Physical Properties of mud samples.**

 The results for analyses of the physicochemical properties of the drilling mud samples are given in Table 3. These physical properties play a key role in determining the performance and effectiveness of drilling fluids when used in drilling operations.

**Density:** The densities varied between 0.89g/mL and 1.82g/mL. The lowest density (0.89g/mL was obtained for WBM (sample D) compared to the highest value obtained in sample B (base mud formulated with chemicals). Generally, the results showed that there was no significant variation in the densities. Typical density for drilling mud system range between 1.02-2.6 g/mL .

 **PH:** The pH indicates the degree of acidity or alkalinity of the drilling mud and was measured using the pH meter with an accuracy of ±0.05. The results obtained indicated a PH range of 2.84 – 5.04, as shown in Table 3. There was close similarities between the range obtained for samples A and B (5.02- 5.01) as well as samples B and C (4.03-4.05) respectively. The values obtained were much lower than the ideal PH range between 8.0 and 10.5 required toprovide the optimum mud rheological and filtration properties for efficient high-performance drilling operations and to mitigate corrosion (Gamal *et al*., 2019)..

**Total Dissolved Solids (TDS)**

The results obtained indicated TDS values ranging between 0.31mg/L and 3.71mg/L. It showed a considerable difference between the TDS value for sample A (0.31mg/L and sample B (3.71m/L) as shown in Table 3. The difference in values obtained for sample A and B may be due to introduction of various additives into sample B during formulation process.High TDS can lead to the deposition of salts in the formation, impairing its ability to produce hydrocarbons. Excessive TDS can affect the quality and properties of the mud cake, potentially causing sticking problems. It is essential to monitor TDS to ensure that the drilling fluid maintains proper fluid loss characteristics

**Viscosity:** The results for the viscosities of the samples are shown in Table 3. The viscosities ranged between 274.0 mPa.s – 343.0 mPa.s, indicating minimal difference between samples A, C and D. However, the viscosity obtained for sample B (274.0 mPa.s) was much lower comparable to other drilling mud samples. Typical viscosities for drilling mud often range between 10- 1000 mPa.s. High-viscosity drilling mud is typically described as “thick,” while low-viscosity mud is characterized as “thin”. This property is essential because it directly impacts the ability to effectively carry drill cuttings to the surface, maintain wellbore stability, lubricate the drill bit, and control formation pressure. Therefore, proper viscosity ensures efficient drilling by balancing the need to lift cuttings without causing excessive pressure on the wellbore walls or hindering drilling progress due to excessive resistance to flow (Agwu *et al*., 2021)

**CONCLUSION AND RECOMMENDATIONS**

# **5.1 Conclusion**

The investigation in this work revealed considerable variations in the concentrations of parameters evaluated such as heavy metals and Total Hydrocarbon content profiles, showing that drilling mud effluents (OBM and WBM) are usually laden with varying concentrations of heavy metals especially in OBM. The discharge of contaminated drilling mud into the environment without pre –treatment may result in pollution with adverse environmental impacts on aquatic, edaphic, and ground water systems, if it permeates through aquifer. This study have also revealed that comparatively, drilling mud samples exhibit varying physicochemical properties as indicated in drilling mud without formulation chemicals, freshly formulated drilling mud, spent OBM and WBM respectively. The evaluation of the concentrations of heavy metals and other parameters in the different drilling mud samples are of environmental significance from pollution viewpoint especially manganese, ferrochrome lignosulphate (chromium pollution) and lead compounds (lead pollution). Hence, the findings from this study are critical when considering drilling mud properties for optimal and efficient performance and also when making the choice for subsequent disposal of drilling mud effluents, especially in the study area where extensive oil/gas operations is currently ongoing.

It is therefore recommended that drilling mud resulting from drilling operations should be properly treated and managed before discharge to the environment. Chemical companies should be encouraged to adopt alternative ‘green’ additives for formulation of drilling muds for sustainable development. The oil/gas exploration companies should adhere to procedures and legislations recommended for hydrocarbon waste management by NUPRC, and other regulatory bodies, with strict monitoring for compliance and enforcement of penalties for non-compliance.

Moreover, circular economy principles and sustainable development of resources should be adopted including the modern trend in the industry which emphasizes re-use and recycling of wastes. Appropriate applications of technology can convert drilling wastes to feedstock for industrial uses, helping to protect and sustain the environment.

**References**

Abu Khamsin, A. (2017). Environmental regulations for drilling operations in Saudi Arabia. *Proceedings of the Middle East Drilling Technology Conference.* 2(3): 052-056.

 Adewole, G. M., Adewale, T. M., & Ufuoma, E. (2010). Environmental aspect of oil and water-based drilling muds and cuttings from Dibi and Ewan off-shore wells in the Niger Delta, Nigeria Gbadebo M. Adewole, Taiwo M. Adewale and Eughele U.  *African Journal of Environmental Science and Technology*, *4*(5).

Agbaji, A.L. (2010) Optimizing the Planning, Design And Drilling Of Extended Reach and Complex Wells (SPE 136901). Abu Dhabi International Petroleum Exhibition and Conference, Abu Dhabi, UAE.

Agwu, O. E; Akpabio, J. U; Ekpenyong, M. E; Inyang, U. G; Asuquo,D. E; Eyoh, I. J; Adeoye, O. S (2021). A critical review of drilling mud rheological models, *Journal of Petroleum Science and Engineering, Volume 203, 108659.*

 AlBajalan, A; Haias, H. (2021). Evaluation of the performance of conventional water-based mud characteristics by applying zinc oxide and silica dioxide nanoparticle materials for a selected well in the kurdistan/iraq oil field. Adv. Mater. Sci. 1- 10. https://doi.org/10.1155/2021/4376366

 Amenyah Kove, E. P., Buah, W. K., Dankwa, O. K. and Mends, E. A. (2021), “Attenuation of Heavy Metals from Waste Oil-Based Drilling Mud using Locally Produced Activated Carbon”, *Ghana Mining Journal, Vol. 21, No. 2, pp. 55-61*

 Araka, P; Okparanma, R; Ayotamuno, J. (2019). Diagnostic screening of organic contaminant level in solidified/stabilized pre-treated oil-based drill cuttings. Heliyon, 5(10), e02644. https://doi.org/10.1016/j.heliyon.2019.e02644

Arpornpong, N., Padungpol, R., Khondee, N., Tongcumpou, C., Soonglerdsongpha, S., Suttiponparnit, K. and Luepromchai, E. (2020). Formulation of bio-based washing agent and its application for removal of petroleum hydrocarbons from drill cuttings before bioremediation. *Frontiers in Bioengineering and Biotechnology*, 8.

 Awaka-ama, J. J (2012). Investigation of the role of chemical composition on the Weathering and Emulsification behaviour of North Sea crude oil [Doctoral Theses, Heriot-Watt University]. Heriot-Watt University Research Repository. ros.hw.ac.uk. http://hdl.handle.net/10399/ -2498

Awaka-ama, J. J; Udo, G. J; Nyong, A. E; Umanah, I; Bassey, M. E (2024). Heavy Metals, Polycyclic Aromatic Hydrocarbons, Total Petroleum Hydrocarbons and Total Hydrocarbon Contents in Drilling Mud Effluents From Eastern Obolo Oilfield In The Niger Delta Region Of Nigeria. J. Appl. Sci. Environ. Manage. 28 (9) 2849-2854

Bakhtiari, H., Amanipoor, H., Sedigheh Battaleb‑Looie, S. (2024). Analysis of heavy metal accumulation and environmental indicators in fuids and drilling cuttings. *Journal of Petroleum Exploration and Production Technology*, 14:41–58 <https://doi.org/10.1007/s13202-023-01690-7>

Daae, H. L., Heldal, K. K., Madsen, A. M., Olsen, R., Skaugset, N. P., & Graff, P. (2019). Occupational exposure during treatment of offshore drilling waste and characterization of microbiological diversity. *Science of the Total Environment*, *681*, 533-540.

 Daneshfar, M. A., & Ardjmand, M. (2020). Selecting a suitable model for collecting, transferring, and recycling drilling wastes produced in the operational areas of the Iranian offshore oil company (IOOC) using analytical hierarchy process (AHP). *Journal of environmental management*, *259*, 109791.

Das, B., Borah, B., and Bhattacharyya, S. (2020). Comparative analysis of carboxymethyl cellulose and partially hydrolyzed polyacrylamide – low-solid nondispersed drilling mud with respect to proper-ty enhancement and shale inhibition. *Resource-Efficient Technologies*, (2), 24-33.

Dumka, NJ; Kingdom, A. (2018). Total Hydrocarbon Concentrations (THC) in surface water, sediments and biota from Otamiri River, Rivers State, Nigeria. Int. J. Chem. Stud. 2018; 6(3): 2743-2748

 Fink, J. (2015). *Water-based chemicals and technology for drilling, completion, and workover fluids*. Gulf Professional Publishing.

Gamal, H., Elkatatny, S., Basfar, S., & Al-Majed, A. (2019). Effect of pH on Rheological and Filtration Properties of Water-Based Drilling Fluid Based on Bentonite. Sustainability, 11(23), 6714. https://doi.org/10.3390/su11236714

 Ismail, A. R., Alias, A. H., Sulaiman, W. R. W., Jaafar, M. Z., & Ismail, I. (2017). Drilling fluid waste management in drilling for oil and gas wells. *Chemical Engineering Transactions*, *56*, 1351-1356.

Khorshid, Z. B; Mahdi, M and Abdollahi , S (2021). UV–Vis. Spectrophotometric method for oil and grease determination in water, soil and different mediates based on emulsion. *Michrochemical Journal. 160(6):105620*

Laine B. Pereira, Cristina M.S. Sad, Eustáquio V.R. Castro, Paulo R. Filgueiras, Valdemar Lacerda (2022). Environmental impacts related to drilling fluid waste and treatment methods: A critical review, *Fuel, Volume 310, Part B, 122301*.

Martin, WB. (1991). Oil Chemicals and Regulatory Concerns. *J. Pet. Sci. Eng. 35:14-16*

Mody, F. and Hale, A. (1993). Borehole-stability model to couple the mechanics and chemistry of drilling-fluid/shale interactions. *Journal of Petroleum Technology*, 45(11), 1093-1101.

 Moore, P. L. (1986). Drilling Practices Manual, Second Edition. Penn Well Publishing Company, Tulsa, Oklahoma.

 Neff, J. (2008). Estimation of bioavailability of metals from drilling mud barite. *Integrated Environmental Assessment and Management,* 4(2), 184-193.

Neff. J. M., Hillman, R. E, Waugh J. J (1988b). "Bioavailability of Trace Metals from Drilling Mud Barite to Benthic Marine Animals". in Drilling Wastes, Proceedings of the 1988 International Conference on Drilling Wastes. Calgary, Alberta, Canada. *Elsevier Applied Science Publishers Ltd., London, England*. pp. 461-479.

NUPRC (2022). Upstream Petroleum Safety Regulations. Petroleum Industry Act. Nigeria National Petroleum Company Limited (NNPCL), *Nigeria*.

Offiong, NO; Udo, GJ; Inam, EJ; Ekanem, AN; Awaka-ama, JJ; Uwanta, EJ; Dong, J. (2023). Screening of bio-derived surfactants for soil washing of PAHs: effects of substrate sources and trace metals distribution. *Environ. Eng. Res. 2023; 28(2): 210502*

Onwuka, O. S., Igwe, O., Ifediegwu, S. I., & Uwom, C. S. (2018). An assessment of the effectiveness of drilling waste treatment process in X-gas field, Niger Delta, Nigeria. *Geology, Ecology, and Landscapes*, *2*(4), 288-302.

Qin, G., Xu, M., He, M., and Chen, K. (2021). Synergistic effect of polyaspartate and polyethylene glycol on lubrication performance of the water-based drilling mud. *Acs Omega*, 6(21), 13817-13830.

Shadizadeh, S.R., Zoveidavianpoor, M. (2010). Impact of ferrochrome lignosulphate on chromium pollution. *International Journal of Environmental Research,* 4(1): 91-97.

 TPHCWG (1998b). Composition of petroleum mixtures. Amherst, MA, Amherst Scientific Publishers *Total Petroleum Hydrocarbon Criteria Working Group Series* p. 2.

Udo GJ, Awaka-Ama JJ, Uwanta EJ, Ekwere IO and Chibueze IR (2020) Comparative Analyses of Physicochemical Properties of Artisanal Refined Gasoline and Regular Automotive Gasoline. Front. Chem. 8:753. doi: 10.3389/fchem.2020.00753

 Udo, G.J., Offiong, NA.O., Nwadinigwe, A., Obadimu, C.0; Nyong, A.E;  Awaka-ama, J. J. (2021). Efficiency and Kinetics of Total Petroleum Hydrocarbons (TPHs) Removal from Crude Oil Polluted Arable Soil using Palm Bunch Ash and Tween 80. *Chemistry Africa* **4**, 333–337

Udo, GJ; Awaka-Ama, JJ; Nyong, AE; Ekanem, AN; Igwe, RC. (2023b).GC-MS Analysis of artisanal refined and regular automotive gasoline: comparative study of quality. *Inter. J. Novel Res. Develop. 8 (1): 2456-4184*

 Udosen, E. D., Ibia, T. O., & Awaka-Ama, J. J. (2010). Distribution of heavy metals in soil of beach sand origin in Niger Delta area of Nigeria. *World J Appl. Sci. and Tech*, *2*, 124-129.

## Ukeles, S.D and Grinbaum, B. (2004). Drilling Fluids: In Kirk-Othmer Encyclopedia of Chemical Technology. John Wiley & Sons

UKOOA (2000). United Kingdom Offshore Operators Association (UKOOA). Methodology for the evaluation of management and disposal option for drill cuttings on the seabed. In: UKOOA Drill Cutting Initiative, *Research and Development Dames and Morre*. p. 85

 USEPA (2011). "METHOD 218.7: Determination of Hexavalent Chromium in Drinking Water by Ion Chromatography with Post-Column Derivatization and UV–Visible Spectroscopic Detection."Fromhttp://water.epa.gov/scitech/drinkingwater/labcert/upload/EPA\_Method\_218-7.pdf.

Water Quality Criteria. (1972). Water quality criteria, U.S. *Environmental Protection Agency.* 27(4): 72-77.

West, G., Hall, J., & Seaton S. (2006). Drilling Engineering In L Lake (Ed.), Petroleum Engineering Handbook. (pp II-89-II118). Richardson, USA: Society of Petroleum Engineers.