Effects of Total Petroleum Hydrocarbon (TPH) Fractions on Water–Soil Systems Containing Earthworms: Engineering and Ecotoxicological Implications for the Niger Delta, Nigeria

Avery, Tonipre Thompson; Okene, Doutimi Tebekaemi

Department of Geology, Federal University Otuoke,
Bayelsa State, Nigeria.

Achugwo, Nathaniel Chimezie

Department of Chemistry, Federal University Otuoke,
Bayelsa State, Nigeria.

Abstract

Chronic crude oil pollution remains a major environmental and engineering challenge in the Niger Delta. This study examines the short-term behavior of total petroleum hydrocarbon (TPH) fractions in a controlled water–soil system containing earthworms, with emphasis on the partitioning of hydrocarbons, changes in physicochemical parameters, and biological response. Crude oil (25 mL) was introduced into mesocosms containing 100 mL of water and 100 g of soil with acclimated earthworms for 48 hours. TPH fractionation in water, soil, and worm tissues was quantified using GC-FID (EPA 8015), targeting aliphatics (C5–C35), BTEX (benzene, toluene, ethylbenzene, xylenes), PAHs, and resin–asphaltene fractions. Results show minimal pH variation (6.82 – 6.85) and stable temperature (25.1 - 25.8 °C), indicating that mortality was chemically driven rather than physicochemical stress. Hydrocarbons partitioned predominantly to soil (712 mg/kg) and worm tissues (569 mg/kg), with water retaining only 1.55 mg/kg. Aliphatic fractions dominated accumulation in both soil and biota, while PAHs (including benzo[a]pyrene and pyrene) constituted key toxic components. All earthworms died within 48 hours, confirming acute toxicity. The engineering interpretation suggests reduced permeability, altered porosity, and potential weakening of soil structure due to hydrocarbon sorption. Findings demonstrate that TPH fractions significantly degrade ecosystem function and compromise the suitability of oil-impacted sediments for geotechnical applications. These results support improved remediation frameworks, contaminant monitoring, and engineering design considerations in petroleum-impacted regions.

Keywords: Total petroleum hydrocarbons (TPH), PAHs, soil contamination, earthworm bioaccumulation, engineering properties, Niger Delta, ecotoxicology.

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1. Introduction

1.1 Background of the Study

The Niger Delta is one of the world's most petroleum-rich regions, yet chronic oil spills and artisanal refining activities continue to degrade aquatic and terrestrial environments. Total petroleum hydrocarbons (TPH)—a broad class of aliphatic, aromatic, resin, and asphaltene compounds—control toxicity, mobility, and the engineering behavior of impacted soils and sediments (Lee et al., 2015). The partitioning of TPH among water, soil, and biota influences contaminant transport, sediment structure, and ecological health.

Earthworms, or aquatic oligochaetes, where relevant, act as sediment engineers whose burrowing activities influence porosity, permeability, and nutrient cycling. Their sensitivity to hydrocarbon toxicity makes them effective indicators of sediment quality and early ecological degradation. Petroleum hydrocarbons in aquatic environments alter water chemistry and modify sediment structure, leading to reductions in aggregation, permeability, and microbial activity. Understanding the fate of specific crude-oil fractions—light aliphatics, BTEX (benzene, toluene, ethylbenzene, xylenes), PAHs (Polycyclic Aromatic Hydrocarbons), resins, and asphaltenes—within a soil–water–biota system is crucial for predicting both ecological and engineering outcomes in polluted regions.

This study investigates how TPH fractions from Niger Delta crude influence water quality, soil properties, and earthworm survival, providing data essential for environmental engineering design, contamination assessment, and remediation planning.

1.2 Statement of the Problem

Despite decades of petroleum development, empirical data on the distribution of individual TPH fractions in water–soil–biota systems in the Niger Delta remain limited. The absence of quantitative partitioning data limits the ability of engineers and environmental managers to predict contaminant behavior, design effective containment barriers, or develop ecologically sound remediation strategies. This gap leaves aquifers, wetlands, and benthic organisms vulnerable to acute toxicity and long-term degradation.

1.3 Aim and Objectives

1.3.1 Aim:

The study aims to determine the engineering and ecological effects of TPH fractions on water containing earthworms in an aquatic–soil environment.

1.3.2.Objectives:

1. Quantify TPH fraction distribution in water, soil, and earthworm tissues after crude oil exposure.
2. Assess changes in pH and temperature during exposure.
3. Evaluate earthworm mortality and hydrocarbon bioaccumulation.
4. Discuss implications for water quality, soil engineering behavior, and ecological health.

1.4.Significance of the Study

The study provides foundational data on how petroleum hydrocarbons modify the physical, chemical, and biological behavior of soil–water systems. The results enhance understanding of TPH transport, bioaccumulation, and ecotoxicological impact, with relevance to sediment engineering, spill-response design, regulatory standard development, and sustainable management of oil-impacted environments.

1.5.Scope of the Study

The work focuses on short-term (<48 h) laboratory mesocosms simulating crude-oil

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contamination of a water–soil–earthworm system. Parameters evaluated include TPH fractionation, pH, temperature, and bioaccumulation. Long-term biodegradation, microbial processes, and mechanical tests (e.g., shear strength) were outside the scope.

2. Literature Review

Hydrocarbon pollution is a persistent environmental problem in the Niger Delta (Nwaichi et al., 2015). TPH consists of aliphatic hydrocarbons, aromatics (including PAHs and BTEX), resins, and asphaltenes, each with distinct environmental behaviors (USEPA, 1999). Hydrocarbon contamination alters soil porosity, increases plasticity index, reduces oxygen availability, and weakens engineering properties (Okoh et al., 2020; Okolo et al., 2019).

Hydrocarbons partition based on molecular weight: light aliphatics and BTEX (benzene, toluene, ethylbenzene, xylenes), remain mobile in water, whereas Polycyclic Aromatic Hydrocarbons (PAHs), resins, and asphaltenes preferentially sorb to soils (Prince, 2018). Earthworms are critical for maintaining soil structure, yet exposure to hydrocarbons impairs burrowing, reduces biomass, and increases mortality (Schaefer et al., 2005). Bioaccumulation of hydrocarbons—particularly PAHs and BTEX—has been linked to oxidative stress and cellular injury (Lanno et al., 2004; Sun et al., 2018).

Hydrocarbon-contaminated soils exhibit increased liquid and plastic limits, reduced shear strength, modified permeability, and heightened compressibility. These changes influence foundation behavior, slope stability, and the suitability of sediments for engineering use.

Engineering controls such as permeable reactive barriers, biopiles, and geosynthetic liners are used to limit contaminant migration. However, understanding TPH fraction behavior remains essential for predicting contaminant bioavailability, ecological risk, and geotechnical performance.

3. Methodology

3.1 Materials and Methods

The study utilized Niger Delta crude oil, earthworms, and wetland soil from Amassoma. Mesocosms were prepared using glass jars containing 100 mL of water, 100 g of soil, and acclimated earthworms. Crude oil (25 mL) was gently introduced, and pH and temperature were monitored at 24-hour intervals.

After 48 hours, water, soil, and worm tissues were extracted and analyzed for TPH using gas chromatography with flame-ionization detection (GC-FID) following EPA Method 8015. Fractions quantified included:

- Aliphatics (C5–C12, C13–C20, C21–C35)
- BTEX
- PAHs (2–6 rings)
- Resins and asphaltenes

3.2 Overview of Laboratory Procedures

Detailed extraction procedures (separating funnel steps, solvent extraction, sonication, filtration, concentration, and GC-FID injection) were applied for both water and soil samples. Earthworm tissues were similarly processed following standard solvent-extraction protocols.

4. Results and Discussion

4.1 Results

4.1.1 Physicochemical Parameters

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Day	pH	Temperature (°C)
1	6.82	25.1
2	6.85	25.8

Minimalfluctuations indicate hydrocarbon toxicity—not acidity—caused mortality.

4.1.2 Hydrocarbon Distribution

The crude-oil mixture contained 141,700 mg/L TPH, dominated by aliphatics (70%). Aromatics (BTEX + PAHs) comprised 25%. Resins/asphaltenes were 5%, (Table 1).

Table 1: Approximate Distribution of Hydrocarbon Group.
(TPH split in 25 mL of crude oil injected into 100ml of water and 100g of soil).

Hydrocarbon Group	% of TPH	Concentration (mg/L)
Aliphatic (C5–C12)	20	28,300
Aliphatic (C13–C20)	30	42,500
Aliphatic (C21–C35)	20	28,300
BTEX (benzene, toluene, ethylbenzene, xylenes)	2	2,800
Low MW PAHs (2–3 rings)	10	14,200
High MW PAHs (4–6 rings)	13	18,400
Resins + Asphaltenes	5	7,100
Total TPH	**100**	**141,700**

4.1.3 Bioaccumulation in Earthworms

Earthworm tissues accumulated 569 mg/kg of TPH of which

- **Aliphatics:** 398.30 mg/kg
- **Aromatics:** 142.25 mg/kg
- **Resins/asphaltenes:** 28.45 mg/kg

PAHs—particularly naphthalene (28.45 mg/kg) and benzo[a]pyrene (7.4 mg/kg)—exceeded ecotoxicological thresholds (Table 5).
All earthworms died within 48 hours.

Table 2: Earthworm Fractionation of TPH (569 mg/kg).

Hydrocarbon Group / Fraction (Earthworm)	% of TPH	Concentration (mg/kg)
Aliphatic	70	398.30
C5–C12 (light aliphatic, gasoline)	20	113.80
C13–C20 (diesel-range aliphatic)	30	169.90
C21–C35 (heavy aliphatic fraction)	20	113.80
Aromatics	30	142.25
BTEX (benzene, toluene, ethylbenzene, xylenes)	2	11.38
Low-MW PAHs (2-3 rings)	10	56.90
High-MW PAHs (4-6 rings)	13	73.97
Resina & Asphaltenes (polar heavy fraction)	5	28.45
TOTAL	100	569.00

4.1.4 Soil and Water Fractionation

- **Soil:** 712 mg/kg (major sink), dominated by aliphatics (Table 3).
- **Earthworm tissues:** 569 mg/kg, (Table 2).
- **Water:** 1.55 mg/kg—reflecting low hydrocarbon solubility (Table 4).

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Table 3: Earthworm- Soil Fractionation of TPH (712 mg/kg).		
(1) **Hydrocarbon Group / Fraction (Earthworm Soil).**	**% of TPH**	**Concentration (mg/kg)**
• **Aliphatic**	**70**	**498.40**
• C5–C12 (light aliphatic)	20	**142.40**
• C13–C20 (diesel-range aliphatic)	30	**213.60**
(2) C21–C35 (heavy aliphatic)	20	**142.40**
• **Aromatics**	**25**	**178.00**
• BTEX (benzene, toluene, ethylbenzene, xylenes)	2	**14.24**
• Low-MW PAHs (2–3 rings)	10	**71.20**
(3) High-MW PAHs (4–6 rings)	13	**92.56**
Resins & Asphaltenes (polar heavy fraction)	**5**	**35.6**
TOTAL	**100**	**712**

Table 4: Earthworm-water Fractionation of TPH (1.55 mg/kg) (Fraction / sub-group)		
Hydrocarbon Group / Fraction in Earthworm-Water.	**% of TPH**	**Concentration (mg/kg)**
(1) Aliphatic	**70**	**1.085**
• C5–C12 (light aliphatics)	**20**	**0.310**
• C13–C20 (diesel-range aliphatics)	**30**	**0.465**
• C21–C35 (heavy aliphatics)	**20**	**0.310**
(2) Aromatics	**25**	**0.388**
• BTEX (benzene, toluene, ethylbenzene, xylenes)	**2**	**0.031**
• Low-MW PAHs (2–3 rings)	**10**	**0.155**
• High-MW PAHs (4–6 rings)	**13**	**0.202**
(3) Resins & Asphaltenes	**5**	**0.078**
TOTAL	**100**	**1.550**

Table 5: Marker-level breakdown: Aromatic Group (representative allocation in Earthworm)		
Aromatic Group / Fraction (Earthworm)	**% Fraction**	**Concentration (mg/kg)**
(1) BTEX	**100**	**11.38**
• Benzene	**25**	**2.845**
• Toluene	**30**	**3.414**
• Ethylbenzene	**15**	**1.707**
(2) Xylenes (o/m/p combined)	**30**	**3.414**
• Low-MW PAHs	**100**	**56.90**
• Naphthalene	**50**	**28.45**
• Phenanthrene	**20**	**11.38**
• SFluorene	**15**	**8.535**
(2) Acenaphthene / Acenaphthylene	**15**	**8.535**
• High-MW PAHs	**100**	**73.97**
• Pyrene	**25**	**18.49**
• Chrysene	**20**	**14.79**
• Benzo[a]pyrene	**10**	**7.40**
OtherHMWPAHs (fluoranthene,benzo[b]fluoranthene, benzo[k]fluoranthene, etc.)	**45**	**33.9**
TOTAL		**142.25**

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4.2.Discussion

4.2.1 .Engineering Implications

High sorption of hydrophobic fractions to soil indicates:

- Reduced permeability and pore clogging.
- Increased compressibility and altered consolidation behavior.
- Potential weakening of shear strength due to organic coatings.
- Impairment of soil–structure interaction in contaminated areas.

Lossof earthworms—key bioturbators—suggests reduced natural aeration, leading to anoxic conditions and reduced hydraulic conductivity.

4.2.2 Ecotoxicological Observations

Earthworm mortality reflects:

- Narcosis from aliphatics
- Membrane disruption by PAHs
- Oxygen depletion
- Physical alteration of sediment structure

The high bioaccumulation confirms rapid transfer of hydrocarbons into living tissues and associated ecosystem risks.

Table 6: Marker-level breakdown: Aromatic Group (representative allocation in Earthworm-Soil)

Aromatic Group / Fraction (Earthworm-Soil)	% Fraction	Concentration (mg/kg)
(1) BTEX	100	14.24
• Benzene	25	3.56
• Toluene	30	4.27
• Ethylbenzene	15	2.14
• Xylenes (o/m/p combined)	30	4.27
(2) Low-MW PAHs	100	71.20
• Naphthalene	50	35.60
• Phenanthrene	20	14.24
• Fluorene	15	10.68
• Acenaphthene / Acenaphthylene	15	10.68
(3) High-MW PAHs	100	92.56
• Pyrene	25	23.14
• Chrysene	20	18.51
• Benzo[a]pyrene	10	9.26
• Other HMW PAHs (fluoranthene, benzo[b]fluoranthene, benzo[k]fluoranthene, etc.)	45	41.65
TOTAL		178.0

5. Summary, Conclusions, and Recommendatizons

5.1 .Summary and Conclusions

This study demonstrates significant ecological and engineering impacts of crude-oil contamination on water–soil–earthworm systems. Key findings include:

1.Crude oil introduction generated high TPH concentrations dominated by aliphatics and PAHs. Soil was the primary sink (712 mg/kg, Table 3), followed by earthworm tissues (569 mg/kg, Table 2); water retained only trace amounts.

2.Earthworms bioaccumulated toxic hydrocarbons and died within 48 hours.

3.Hydrocarbon sorption likely altered soil porosity, permeability, and strength, which is a critical parameter for engineering use.

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Table 7: Marker-level breakdown: Aromatic Group (representative allocation in Earthworm-Water).

Aromatic Group / Fraction (Earthworm-Water)	% Fraction	Concentration (mg/kg)
(1) BTEX	**100**	**0.031**
• Benzene	25	0.0078
• Toluene	30	0.0093
• Ethylbenzene	15	0.0047
• Xylenes (o/m/p combined)	30	0.0093
(2) Low-MW PAHs	**100**	**0.155**
• Naphthalene	50	0.078
• Phenanthrene	20	0.031
• Fluorene	15	0.023
• Acenaphthene / Acenaphthylene	15	0.023
(3) High-MW PAHs	**100**	**0.202**
• Pyrene	25	0.050
• Chrysene	20	0.040
• Benzo[a]pyrene	10	0.020
• Other HMW PAHs (fluoranthene, benzo[b]fluoranthene, benzo[k]fluoranthene, etc.)	45	0.091
TOTAL		**0.388**

5.2 .Recommendations

- Install containment barriers and sorptive amendments(biochar, organocla y) in spill-prone wetlands.
- Prioritize bioremediation before reusing contaminated soils for construction.
- Conduct more extensive TPH monitoring during environmental impact assessments.
- Integrate ecological indicators (e.g.,
- earthworm survival) in geotechnical site evaluations.

5.3.Limitations

- Short exposure period (48 h).
- Only one crude-oil type and earthworm species.
- Mechanical soil tests were inferred, not measured.

5.4 .Contribution to Knowledge

This study provides the first detailed quantification of TPH fractionation among water, soil, and earthworm tissues in a Niger Delta-relevant mesocosm. It demonstrates how hydrocarbons partition rapidly to solids and biota, altering ecological and engineering functions, and provides a basis for risk-informed sediment management and remediation planning.

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