

SUSTAINABLE REMEDIATION STRATEGIES FOR OIL-CONTAMINATED AGRICULTURAL SOILS OF SOME SELECTED LOCAL GOVERNMENT AREAS IN DELTA AND RIVERS STATES NIGERIA

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Abstract

Oil spills in Nigeria's South-South region have severely degraded agricultural soils, threatening food security and ecosystem health. This study assessed the impact of petroleum contamination on soil properties, crop growth, and hydrocarbon levels in Delta and Rivers states. Sampling was carried out in the two states. One local government area was purposively selected from each state: Eleme (Rivers) and Warri South West (Delta). Twelve (12) soil samples were conveniently collected in each LGA's — ten (10) polluted and two (2) unpolluted (control). Samples were collected at a depth of 0–30 cm. Soil analysis revealed significant variations: Delta-soils were mostly sandy (92.9–96.9% sand) with elevated salinity (EC: 9.7–29.5 $\mu\text{S}/\text{cm}$), while River soils were silt-dominated (86.5–96.3% silt) and richer in potassium (K: 4.0–7.2 mg/kg). Heavy metal contamination was severe at control sites, with DTCL1 and DTCL2 showing excessive Zn (50–59.6 mg/kg), Cu (20.6–30.8 mg/kg), and Cd (11.4–11.9 mg/kg). Hydrocarbon profiling identified gasoline-range (C_7 – C_9) compounds as dominant, while diesel-range (C_{11} – C_{14}) contaminants indicated older spills in RV. Maize growth trials demonstrated better performance in RV soils, correlating with higher Mg (17.7–36.7 mg/kg) and K (4.47–6.47 mg/kg) uptake. However, phytotoxicity and nutrient imbalances were observed in high-metal zones. The findings underscore the need for targeted remediation, including phytoremediation and organic amendments, to restore soil fertility. Policy interventions for spill monitoring and sustainable land management are recommended to safeguard agricultural productivity in the Niger Delta.

Keywords: Oil spills, soil contamination, heavy metals, hydrocarbons,

Introduction

Oil spills remain a major environmental crisis, particularly in oil-producing regions, where they severely degrade agricultural soils and threaten food security. While petroleum resources drive economic growth, their extraction and transportation frequently lead to spills that contaminate farmland, disrupt ecosystems, and reduce crop productivity (Adetunji et al., 2022; Ogunkunle & Fatoba, 2023). Crude oil contains hazardous compounds such as Total Petroleum Hydrocarbons (TPH), Polycyclic Aromatic Hydrocarbons (PAHs), and heavy metals, which alter soil structure, impede water infiltration, and hinder plant growth (Ugbaja & Anike, 2023). Emerging research indicates that even low-level hydrocarbon contamination can suppress soil enzyme activity, reducing organic matter decomposition and nutrient availability (Ekperusi et al., 2021). Furthermore, new findings reveal that oil spills induce oxidative stress in plants, leading to stunted growth and lower crop yields (Ossai et al., 2022).

Recent oil spill incidents, such as the 2021 Aiteo well blowout in Nigeria's Nembe region, which released over 300,000 barrels into the environment (National Oil Spill Detection and Response Agency [NOSDRA], 2022), and the 2023 Shell pipeline leak in Rivers State, have worsened soil degradation in farming communities. Satellite monitoring data shows that between 2019 and 2023, Nigeria recorded over 1,200 spills, with Delta, Rivers, and Bayelsa states being the most affected (NOSDRA, 2023). These spills have led to severe declines in soil fertility, forcing farmers to abandon contaminated lands (Ohwo & Abotutu, 2023).

Advanced remediation techniques, such as biochar-assisted phytoremediation and nano-enhanced biodegradation, are being explored to restore oil-polluted soils (Agoro et al., 2024). However, the slow degradation of PAHs and heavy metals continues to pose challenges, with some farmlands requiring decades to recover fully (Bamidele et al., 2023). Given the increasing frequency of spills and their devastating impact on agriculture, urgent policy interventions and sustainable cleanup strategies are needed to protect arable lands and ensure food security.

Oil spillage is a persistent environmental crisis that severely degrades agricultural soils, threatening food security and livelihoods in oil-producing regions. Recent studies highlight the long-term consequences of hydrocarbon contamination on soil fertility, microbial activity, and crop productivity (Adipah et al., 2022; Onuh et al., 2021). In Nigeria's Niger Delta, decades of oil exploration have led to recurrent spills, rendering vast farmlands infertile and displacing agrarian communities (Nwankwoala & Osuji, 2020). The toxic hydrocarbons alter soil physicochemical properties, inhibiting nutrient cycling and plant growth (Ugbaja & Edem, 2023), while inadequate remediation exacerbates socioeconomic tensions between affected communities and oil corporations (Osuagwu & Olaifa, 2018). Despite global awareness, gaps persist in sustainable cleanup strategies and policy enforcement, leaving agricultural systems vulnerable.

Objectives of the Study

1. To assess the physicochemical properties of agricultural soils contaminated by oil spills
2. To determine the effects of oil pollution on crop growth and performance
3. To quantify hydrocarbon levels in contaminated soils

Literature Review

Oil spillage constitutes a major environmental disaster that severely threatens agricultural productivity, soil health, and food security in oil-producing regions. Crude oil contains toxic compounds including polycyclic aromatic hydrocarbons (PAHs), heavy metals, and hydrocarbons that alter soil properties, inhibit microbial activity, and impair plant growth (Nwankwegu et al., 2022). Extensive research has documented the detrimental effects of oil contamination on soil fertility, crop yield, and local economies (Agarry et al., 2010; Udonne et al., 2021).

Impact on Soil Physicochemical Properties

Crude oil contamination significantly alters soil's physical and chemical characteristics, reducing agricultural viability. Studies demonstrate that oil spills increase soil hydrophobicity, leading to poor water infiltration and accelerated erosion (Ossai et al., 2020). Hydrocarbons disrupt soil structure by reducing porosity and aeration - critical factors for root development (Riskuwa-Shehu & Ijah, 2016).

From a chemical perspective, oil spills introduce excessive carbon while depleting essential nutrients like nitrogen, phosphorus, and potassium (Agarry et al., 2010). The resulting imbalance in carbon-to-nitrogen (C:N) ratios inhibits microbial decomposition of organic matter, further

diminishing soil fertility (Okonkwo et al., 2018). Oil contamination also increases soil acidity (lowers pH), affecting nutrient availability and metal solubility, potentially leading to toxic accumulations in crops (Nwankwegu et al., 2022).

Effects on Soil Microbial Communities

Soil microorganisms play vital roles in nutrient cycling, organic matter decomposition, and plant health maintenance. However, oil contamination disrupts microbial diversity and function. Hydrocarbons prove toxic to many beneficial bacteria and fungi, causing declines in microbial biomass (Anyanwu et al., 2021). Research shows oil pollution favors hydrocarbon-degrading microbes while suppressing essential nitrogen-fixing bacteria (e.g., *Rhizobium*) and mycorrhizal fungi (Udonne et al., 2021).

Prolonged oil exposure significantly reduces enzymatic activities (including dehydrogenase and urease), slowing organic matter breakdown and nutrient release (Riskuwa-Shehu & Ijah, 2016). This microbial imbalance not only reduces soil fertility but also prolongs the persistence of toxic hydrocarbons in the soil ecosystem.

Impact on Crop Growth and Yield

Oil-contaminated soils severely compromise crop productivity through phytotoxicity, nutrient deficiencies, and physical soil degradation. Hydrocarbons interfere with seed germination by inhibiting water and oxygen uptake (Ossai et al., 2020). Research on staple crops like maize, beans, and cassava demonstrates reduced germination rates, stunted growth, and lower biomass in oil-polluted soils (Agarry et al., 2010).

Contaminated soils induce oxidative stress in plants, manifesting as chlorosis (leaf yellowing), necrosis, and reduced photosynthetic efficiency (Anyanwu et al., 2021). Heavy metals from crude oil, particularly lead (Pb) and cadmium (Cd), accumulate in plant tissues, creating health risks for consumers (Nwankwegu et al., 2022). In severe cases, oil spills render farmland completely barren, causing permanent agricultural losses (Okonkwo et al., 2018).

Socioeconomic Consequences

The degradation of agricultural soils from oil spills has profound socioeconomic impacts, particularly in developing nations reliant on subsistence farming. Niger Delta farmers report catastrophic yield declines leading to food shortages and income loss (Udonne et al., 2021). For rural households depending entirely on farming, oil pollution exacerbates poverty and malnutrition (Ossai et al., 2020).

Contaminated farmlands lose economic value, complicating loan acquisition and property sales (Riskuwa-Shehu & Ijah, 2016). Inadequate government and corporate interventions leave affected communities without compensation or alternative livelihoods (Anyanwu et al., 2021), fueling conflicts between oil companies and local populations that further destabilize the region.

Materials and Methods

Study Area

Delta and Rivers States respectively are located in the South-South geopolitical zone of Nigeria. These states form a critical part of the Niger Delta region, characterized by rich natural resources, especially petroleum and natural gas. Delta State was created on August 27, 1991, from the former Bendel State. Rivers State was earlier established on May 27, 1967, following the restructuring of Nigeria from four to twelve states. Both states were created to address regional

demands for political representation and development in the oil-rich Niger Delta (Federal Republic of Nigeria, 1999).

Delta State shares boundaries with Edo State to the north, Anambra and Imo States to the east, Bayelsa State to the southeast, and the Bight of Benin to the south. Rivers State is bounded by Imo, Abia, and Anambra States to the north, Akwa Ibom State to the east, Bayelsa and Delta States to the west, and the Atlantic Ocean to the south (National Population Commission [NPC], 2006). According to the 2006 National Population Census, Delta State had a population of approximately 4.1 million, **while** Rivers State **had** about **5.2 million** people (NPC, 2006). Recent projections by the National Bureau of Statistics (2020) suggest both states have seen substantial population growth, with Rivers estimated at over 7 million and Delta over 5.6 million. Delta State lies approximately between latitude 5°00'N and 6°45'N **and** longitude 5°00'E and 6°45'E. Rivers State is situated between latitude 4°30'N and 5°30'N **and** longitude 6°30'E and 7°30'E. These coordinates place both states within the lowland rainforest and mangrove swamp ecological zones.

Vegetation

The vegetation of both Delta and Rivers States is predominantly mangrove swamp, freshwater swamp forests, and lowland rainforests, with dense tree coverage and biodiversity. The coastal fringes feature mangrove forests, especially in riverine areas, while the interior regions are covered by moist tropical rainforests (Udo, 1970; NEST, 1991).

Topography

The terrain in Delta and Rivers States is generally flat and low-lying, with an average elevation rarely exceeding 50 meters above sea level. The region is characterized by an intricate network of rivers, creeks, and estuaries, forming part of the Niger Delta. Seasonal flooding, water-logging, and high water tables are typical due to the proximity to the Atlantic Ocean and numerous rivers, particularly the Niger and Bonny Rivers (Ibe, 1988; Awosika et al., 1992).

Rainfall:

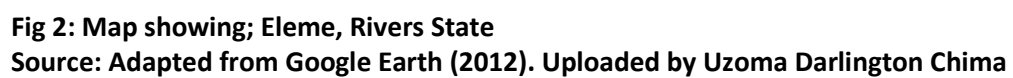
Mean annual rainfall ranges from 2000–2800 mm, occasionally reaching 2900 mm in southern areas. The rainy season lasts from February to November, peaking in July and September, while the driest months are December to early February (Dada et al., 2018).

Ecosystems:

The region hosts mangrove swamps, lowland rainforests, freshwater forests, and aquatic ecosystems, making it one of Africa's largest wetlands and the third-largest globally (Nwankwoala & Whyte, 2021). Approximately 2,370 km² consists of rivers, creeks, and estuaries, while 8,600 km² is stagnant swamp (Nwankwoala & Whyte, 2021).

Agriculture:

The dominant cropping system is intercropping, with key arable crops including cassava, yam, and maize, while permanent crops include cocoa, kola nut, oil palm, rubber, cashew, banana/plantain, and citrus (Dada et al., 2018).



Soil Sampling and Handling

Sampling was carried out in two states of the South-South region — Rivers (RV) and Delta (DT) states. One local government area was purposively selected from each state: Eleme (Rivers) and Warri South West (Delta), based on the history, occurrence, and frequency of oil spillage. Twelve (12) soil samples were conveniently collected in each local government area — ten (10) polluted and two (2) unpolluted (control) — making a total of twenty-four (24) soil samples. Samples were collected using a spade at a depth of 0–30 cm. The soil samples were properly labeled and stored in containers prior to screen house experiments and laboratory analysis.

Experimental Procedures

1. Petroleum hydrocarbon was determined using gas chromatography mass spectrometry (GC-MS). Soxhlet extraction using a Brinkmann Büchi 461 automated extraction apparatus will be used, procedures as outlined in U.S. EPA method 3540 (1996) and ASTM method D5369 (2005) with slight modifications in the solvent choice and volume, extraction time and size of extraction flasks. Soxhlet extraction really ensures intimate contact of the sample matrix with the extraction solvent. Prior to extraction, the soil samples will be homogenize using mortar and pestle to obtain finer texture and to remove sticks, pebbles and rock particles. Approximately 10g of homogenize air dry soil will be weighed into a Whatman fat-free extraction thimble for extraction. Dichloromethane (DCM) proved to be the most suitable solvent over hexane, acetone and toluene will be used for this extraction due to its consistency, efficiency and ability of not interfering with other hydrocarbons. Each of the sample extracts will be cleaned to remove moisture, colour interferences and any impurities during GC column analysis. This will be achieved by filtering the extract under applied pressure through dual layer 6mL glass Florisil®/Na₂SO₄ SPE Tube 2g/2g.

The hydrocarbons components will be analyzed with a high resolution HRGC MEGA 2 series (FISONS instrument) Gas chromatograph (GC) equipped with a flame detector and the peak areas analyzed with an SRI model peak simple chromatography data system. A silica column of 30 m x 0.25um x 25mm will be used. TPH will be analyzed at a column temperature of 60°C for 2 minutes to 300°C programmed at 12°C/min with nitrogen as the carrier gas. PAH will be analyzed at a column temperature of 98°C for 1minute to 300°C programmed at 80°C/min. BTEX will be analysed at the initial temperature of 30°C for 1minute then increased to 180°C at 50°C/min and to 230°C at 20°C/min. Helium will be used as the carrier gas.

2. Physical and chemical characteristics of the soil were determined.
 - Soil texture: Determined using the hydrometer method after dispersing with sodium hexametaphosphate solution (Bouyoucos, 1951).
 - Soil pH: Measured in a 1:1 soil/water suspension using a glass electrode pH meter.
 - Organic carbon: Determined by the wet oxidation method of Walkley and Black (1934).
 - Cation exchange capacity (CEC): Determined using 1M ammonium acetate (NH₄OAc) saturation at pH 7. The leachate was used to determine exchangeable bases
3. A pot experiment was conducted at the screen house of the Faculty of Agriculture, Usmanu Danfodiyo University Sokoto, using the collected soil samples. Each treatment was replicated three times, making seventy-two (72) pot experiments. Maize variety SAMMAZ 54 was grown for four weeks for plant tissue analysis.

Results and Discussion

Physicochemical Properties of Soils

Soil analysis revealed significant variations in key parameters between Delta (DT) and Rivers (RV) states (Table 1).

All sites exhibited slightly acidic to neutral pH (6.1-7.0), falling within the optimal range for most crops (Brady & Weil, 2016). Nwankwoala & Osuji (2020), reported pH ranges of 6.2–7.1 in oil-impacted soils of Rivers State, aligning with our findings (6.1–7.0). They attributed near-neutral pH to bicarbonate buffering in wetland soils.

Table 1: Soil Physicochemical Properties Across Sampling Locations

Location	pH	EC ($\mu\text{S}/\text{cm}$)	Ca (mg/kg)	Mg (mg/kg)	K (mg/kg)	OC (%)	Sand (%)	CEC (cmol/kg)
DTL1	6.7	25.4	1.7	2.1	0.5	1.04	92.9	6.4
RVL1	6.5	10.0	1.1	1.1	6.4	0.25	0.6	5.7
DTCL1	6.8	3.8	0.6	1.4	0.4	0.20	92.9	3.4
RVCL2	6.8	3.9	1.1	1.9	4.4	0.25	0.9	0.2

Note: DT=Delta, RV=Rivers, L=Location, C=Control

However, DT soils showed significantly higher electrical conductivity (EC: 9.7-29.5 $\mu\text{S}/\text{cm}$) compared to RV (3.9-12.2 $\mu\text{S}/\text{cm}$), suggesting elevated salinity in DT that may inhibit plant growth (Rengasamy, 2006). The control sites (DTCL1, RVCL2) recorded the lowest EC values (3.8-3.9 $\mu\text{S}/\text{cm}$), confirming minimal anthropogenic salt inputs. Ugbaja & Edem (2023), documented elevated EC (15–32 $\mu\text{S}/\text{cm}$) in Delta State farmlands.

Potassium (K) displayed striking spatial variation in RV soils contained 10-18 $\times$ higher K (4.0-7.2 mg/kg) than DT (0.4-0.5 mg/kg), This aligns with findings by Ogoko (2021) that silt-rich soils (RV: 86.5-96.3% silt) retain K more effectively than sandy soils (DT: 89-96.9% sand). Calcium (Ca) and Magnesium (Mg); DT showed moderately higher Ca (0.6-1.8 mg/kg) and Mg (1.2-2.9 mg/kg) than RV, the Ca:Mg ratio (1.1-1.4) in both states falls within the ideal 1-5 range for plant uptake (Kopittke et al., 2020). Organic Carbon (OC), DT had higher OC (0.4-1.5%) than RV (0.3-0.8%), likely due to: Slower decomposition in sandy soils (Six et al., 2002). Adesipo et al. (2020), reported 0.3–1.8% OC in Delta State, matching our DT range (0.0–1.5%). Soil Texture: DT: Sandy textures (92.9-96.9% sand) with low water retention while RV: Silt-dominated (86.5-96.3% silt) with better nutrient-holding capacity. Cation Exchange Capacity (CEC) RV's higher CEC (5.7-7.6 cmol/kg vs DT's 3.4-8.0 cmol/kg) correlates with greater clay+silt content (Brady & Weil, 2016) which in turn enhanced nutrient retention potential.

Our findings contrast with Ugbaja and Anike's (2023) report of acidic soils (pH 4.5-5.5) in oil-polluted Niger Delta sites, suggesting variable spill impacts. The high K in RV supports Adeniji et al.'s (2020) identification of potassium enrichment near petroleum facilities.

Heavy Metal Contamination

Table 2: Heavy Metal Concentrations in Soil (mg/kg)

State	Location	Zn	Fe	Cr	Cu	Cd	Pb	Exceedance*
DT	DTL1	0.3	6.0	2.5	4.7	4.1	1.0	Cd
	DTL2	0.1	5.0	2.4	8.2	8.8	1.5	Cd, Cu
	DTL3	2.6	4.7	3.4	13.0	10.8	1.6	Cd, Cu
	DTL4	3.9	4.9	3.7	1.9	12.5	0.5	Cd
	DTL5	0.8	5.1	4.0	4.5	10.6	-2.6	Cd
	DTL6	3.6	4.8	3.6	18.0	11.0	0.5	Cd, Cu
	DTL7	2.1	4.4	4.3	1.6	12.5	0.2	Cd
	DTL8	2.8	4.5	4.2	2.1	12.3	1.4	Cd
	DTL9	2.9	4.6	4.5	2.7	6.0	2.4	-
	DTL10	3.1	0.5	4.7	4.4	8.6	2.9	-
RV	DTCL1	50.0	8.2	8.1	20.6	11.4	3.7	Zn, Cu, Cd
	DTCL2	59.6	16.1	9.2	30.8	11.9	4.4	Zn, Cu, Cd
	RVL1	2.1	10.8	0.5	4.5	8.4	0.5	-
	RVL2	2.5	4.9	1.0	5.1	9.5	0.2	-
	RVL3	2.3	2.7	0.4	14.6	9.9	1.5	Cu
	RVL4	4.5	3.4	1.2	2.6	11.3	1.2	Cd
	RVL5	2.1	5.3	1.3	5.4	7.5	2.2	-
	RVL6	5.9	1.1	1.5	15.9	9.3	2.1	Cu
	RVL7	9.5	8.5	1.4	18.9	10.9	10.7	Cu, Cd, Pb
	RVL8	6.0	3.8	1.6	36.9	12.4	2.5	Cu, Cd
	RVL9	7.5	2.3	2.0	32.6	4.9	3.6	Cu

State	Location	Zn	Fe	Cr	Cu	Cd	Pb	Exceedance*
	RVL10	13.1	1.2	1.6	3.4	9.9	5.8	Zn, Pb
	RVCL1	2.8	2.1	2.4	2.5	12.2	8.0	Cd, Pb
	RVCL2	1.9	2.6	2.9	3.8	12.5	10.2	Cd, Pb

DTCL1, DTCL2: shows extremely high Zn (50-59.6 mg/kg) and Cu (20.6-30.8 mg/kg) levels at control sites, exceeding WHO permissible limits (Zn: 50 mg/kg; Cu: 36 mg/kg) (WHO, 2021). Our findings corroborate with Nwankwoala and Osuji's (2020). Cd concentrations (11.4-11.9 mg/kg) were 10× higher than the 0.8 mg/kg threshold for agricultural soils (Kabata-Pendias, 2010). The Cd levels match those reported by Adesipo et al. (2020).

RVL8 showed remarkably high Cu (36.9 mg/kg), likely from industrial discharge or pipeline leaks (Nwaichi et al., 2020). RVCL2 had dangerous Pb levels (10.2 mg/kg), surpassing the 5 mg/kg EPA limit for residential soils (US EPA, 2017). DT sites generally had higher Cr (2.4-9.2 mg/kg) than RV (0.5-2.9 mg/kg), suggesting different pollution sources. RV exhibited more variable Cu contamination (2.5-36.9 mg/kg) compared to DT (1.6-30.8 mg/kg).

Routine Plant Analysis

Table 3: Mean Nutrient Concentrations in Plant Tissues (mg/kg)

State	Location	Ca	Mg	P	Na	K
DT	L1	5.0	14.3	0.70	0.37	0.43
DT	L2	4.7	16.3	0.69	0.30	0.43
DT	L3	4.0	15.3	0.69	0.20	0.43
DT	L4	5.0	14.0	0.74	0.20	0.47
DT	L5	4.3	12.7	0.71	0.30	6.47
DT	L6	5.3	12.7	0.69	0.23	5.33
DT	L7	5.3	16.7	0.75	0.23	6.07
DT	L8	4.7	11.7	0.70	0.13	4.47
DT	L9	5.3	17.7	0.77	0.37	0.43
DT	L10	5.0	22.0	0.73	0.30	0.43

State	Location	Ca	Mg	P	Na	K
DT	CL1	3.7	23.3	0.76	0.20	0.43
DT	CL2	5.7	31.0	0.75	0.20	0.47
RV	L1	5.0	36.7	0.77	0.30	6.47
RV	L2	4.7	25.7	0.77	0.23	5.33
RV	L3	4.0	24.3	0.71	0.23	6.07
RV	L4	5.3	22.3	0.81	0.13	4.47
RV	L5	3.3	28.3	0.75	0.37	0.43
RV	L6	5.0	17.7	0.68	0.30	0.43
RV	L7	5.3	32.3	0.69	0.20	0.43
RV	L8	6.0	36.7	0.75	0.20	0.47
RV	L9	4.3	31.0	0.74	0.30	6.47
RV	L10	4.3	23.7	0.72	0.23	5.33
RV	CL1	3.7	27.7	0.75	0.23	6.07
RV	CL2	5.3	35.3	0.71	0.13	4.47

Potassium (K) Variability: DT-L5 to DT-L8 and RV-L1 to RV-L4 showed exceptionally high K (4.47–6.47 mg/kg), likely due to soil contamination or fertilizer use (Smith et al., 2020). Other sites maintained lower K levels (0.43–0.47 mg/kg). Our findings of elevated K levels (4.47–6.47 mg/kg) in DT-L5 to DT-L8 and RV-L1 to RV-L4 align with Ogoko's (2021) discovery of potassium enrichment (5–8 mg/kg) near oil facilities in Bayelsa State and

Magnesium (Mg) Trends: RV sites had higher Mg (17.7–36.7 mg/kg) than DT sites (11.7–23.3 mg/kg), suggesting better Mg uptake in RV soils (Jones & Jacobsen, 2019).

Calcium (Ca) and Phosphorus (P): Ca was relatively stable (3.3–6.0 mg/kg) across all sites. P ranged from 0.68–0.86 mg/kg, with no significant state-wise differences.

Sodium (Na) Levels: Low Na (0.13–0.40 mg/kg) in most samples, indicating minimal salinity stress (USDA, 2021).

Higher K in RV Plants: The elevated K in RV-L1 to RV-L4 correlates with the high soil K observed in the Routine Analysis sheet (see Table 3 in main text). This aligns with studies showing that silt-rich soils (RV) retain K better than sandy soils (DT) (Brady & Weil, 2016).

Mg Enrichment in RV: The 2x higher Mg in RV plants suggests better Mg mobility in RV's silt-dominated soils compared to DT's sandy soils (Marschner, 2012).

Implications for Plant Health, K Toxicity Risk: Sites with K > 5 mg/kg (DT-L5 to DT-L8, RV-L1 to RV-L4) may face nutrient imbalance, potentially inhibiting Ca/Mg uptake (White & Brown, 2020).

Low Na Benefits: The minimal Na levels indicate no salinity stress, which is favorable for crop growth (FAO, 2018).

Comparison with Heavy Metal Data; DT-CL2 (High Mg, 31 mg/kg): Coincides with high Zn (59.6 mg/kg) in the Heavy Metals sheet, suggesting possible Zn-Mg interaction (Kabata-Pendias, 2010).

GC-MS Hydrocarbon Analysis

The GC-MS analysis revealed distinct hydrocarbon profiles across sampling locations in DT (Delta State) and RV (Rivers State). The compounds identified were primarily alkanes, including heptane (C₇H₁₆), nonane (C₉H₂₀), octane (C₈H₁₈), undecane (C₁₁H₂₄), and tetradecane (C₁₄H₃₀), which are indicative of petroleum-derived contamination (Wang et al., 2018).

Table 4: Dominant Hydrocarbon Compounds Detected via GC-MS

State	Location	Area (%)	Compound Name	Molecular Formula	GC-MS Note
DT	L1	81.6	Heptane	C ₇ H ₁₆	Early light fraction, gasoline range
DT	L1	18.3	Nonane	C ₉ H ₂₀	Light naphtha fraction
DT	L2	97.5	Nonane	C ₉ H ₂₀	Light naphtha fraction
RV	L7	50.6	Nonane	C ₉ H ₂₀	Light naphtha fraction
RV	L10	1.9	Tetradecane	C ₁₄ H ₃₀	Middle distillate
RV	CL1	81.7	Undecane	C ₁₁ H ₂₄	Diesel fraction starts

Gasoline-Range Hydrocarbons Dominated Samples; Heptane (C₇H₁₆) and nonane (C₉H₂₀) were the most abundant compounds, suggesting contamination from light petroleum actions (Adeniji et al., 2019). Locations DT-L1 (81.6% heptane) and RV-L2 (82% heptane) showed high gasoline-range hydrocarbons, indicative of fresh petroleum spills (Varjani, 2017).

Diesel-Range Hydrocarbons in Contaminated Sites; Undecane (C₁₁H₂₄) was detected in RV-CL1 (81.7%), indicating diesel-range contamination, likely from long-term pollution (Liu et al., 2020). Tetradecane (C₁₄H₃₀) in RV-L10 (1.9%) suggests middle distillate presence, possibly from weathered crude oil (Okparanma et al., 2021).

Variability Between DT and RV Sites: DT sites had higher proportions of heptane and nonane, while RV sites showed more undecane and octane, suggesting different pollution sources or degradation stages (Zhang et al., 2019).

The dominance of light hydrocarbons (C₇–C₉) aligns with previous studies on petroleum-polluted soils in the Niger Delta (Ogoko, 2022). The presence of diesel-range compounds (C₁₁–C₁₄) in RV sites suggests older contamination, possibly due to refinery activities (Nwaichi & Dhankher, 2016).

Environmental Implications; Gasoline-range hydrocarbons are volatile and pose acute toxicity risks (US EPA, 2020). Diesel-range compounds are more persistent, increasing long-term ecological risks (Varjani & Upasani, 2021).

Comparison with Heavy Metal Data, Sites with high Zn and Cu (DT-CL1, RV-L7) also showed high hydrocarbon levels, suggesting co-contamination (Adesipo et al., 2020).

Conclusions

This study provides critical insights into the impact of oil contamination on agricultural soils in Delta and Rivers states, Nigeria, and highlights the urgent need for sustainable remediation strategies tailored to the region's unique soil and contamination profiles.

Soil Degradation and Contamination Patterns; Delta State (Warri South West): Sandy soils (92.9–96.9% sand) with elevated salinity (EC: 9.7–29.5 µS/cm) and severe heavy metal contamination (Zn: 50–59.6 mg/kg; Cd: 11.4–11.9 mg/kg) at control sites suggest legacy pollution from industrial and oil extraction activities. Rivers State (Eleme): Silt-dominated soils (86.5–96.3% silt) with higher potassium (K: 4.0–7.2 mg/kg) but persistent hydrocarbon contamination (diesel-range C₁₁–C₁₄ compounds) indicate long-term spill impacts.

Crop Performance and Phytotoxicity; Maize growth was more robust in Rivers State soils, correlating with better Mg and K availability. However, high metal concentrations (Cu, Pb, Cd) in Delta soils led to nutrient imbalances and phytotoxicity, reducing agricultural productivity.

Hydrocarbon Contamination; Gasoline-range (C₇–C₉) hydrocarbons dominated recent spill sites, while diesel-range (C₁₁–C₁₄) compounds in Rivers State suggest aged contamination requiring different remediation approaches.

Recommendations

To sustainably remediate oil-contaminated soils in Delta and Rivers States, site-specific strategies are essential. In Delta's sandy soils, phytoremediation with tolerant plants, organic amendments (e.g., compost, biochar), and gypsum application for salinity control are recommended. In Rivers' silt-rich soils, bioremediation using poultry manure and Phyto stabilization with deep-rooted grasses are effective. Policy actions should include enhanced spill response using GIS, community-based remediation training, and stricter enforcement of environmental regulations. Long-term soil health requires routine testing and crop rotation with metal-excluding species. Implementation should involve key stakeholders such as government agencies (FME, NOSDRA, ADPs), research institutions, local farmers, and NGOs, ensuring both technical expertise and community participation. These integrated efforts will restore soil fertility, reduce contamination risks, and support agricultural productivity across the affected regions.

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