Geo-Environmental Risk Assessment of Abandoned Petrol Stations in Essien Udim Local Government Area, Akwa Ibom State

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ABSTRACT

This study examines the contamination of soils and groundwater around abandoned petrol stations in Akwa Ibom State, Nigeria, the study further evaluate associated environmental and health risks. Six sites were purposively selected, and samples were analyzed for pH, Total Petroleum Hydrocarbons (TPH), lead (Pb), nickel (Ni), and benzene using standard APHA and ASTM procedures. Descriptive statistics and Pearson correlation were applied to quantify pollutant relationships. Results shows that, mean soil TPH (1575 ± 510 mg/kg) exceeded the DPR limit (100 mg/kg), indicating severe hydrocarbon pollution. Mean Pb (40.22 ± 11.7 mg/kg) and Ni (29.18 ± 9.3 mg/kg) were below regulatory limits but reflected anthropogenic influence. Groundwater TPH (0.048 ± 0.02 mg/L) and benzene (0.017 ± 0.009 mg/L) exceeded WHO limits (0.05 mg/L;0.01 mg/L). Significant correlations existed between TPH and Pb (r = 0.87) and between benzene and Ni (r = 0.76). Findings highlight hydrocarbon metal co-contamination and potential groundwater migration, necessitating remediation and continuous monitoring.

Keywords: Abandoned petrol stations, Benzene, Groundwater pollution, Heavy metals, Soil contamination

INTRODUCTION

The petroleum hydrocarbons and their byproducts still continue to be one of the most widespread types of environmental contaminants in the world, as they occur due to accidental spills, leaking storage facilities, and normal losses at fuel retail and distribution stations(WHO, 2003; WHO, 2017). The high geo-mobility of most hydrocarbon substances (especially benzene and other BTEX components) under favorable hydro-geological conditions, combined with their toxicity, makes past contamination of fuel deposits a significant remedial and health concern in both developed and developing countries (Fei-Baffoe, 2024; WHO, 2003). Guidelines on drinking water and soil highlight the minimum permissible levels of volatile aromatics like benzene (guideline value 0.01 mg/L) due to their carcinogenic risks and plume-forming properties in groundwater (WHO, 2003; WHO, 2017).

The situation is especially severe in the oil producing and oil consuming nations with high concentrations of petrol stations many of which are located near residential locations and shallow aquifers that make soil and groundwater pollution more likely in case of corroding of tanks or as a result of poorly decommissioned operation (Okop, 2012; IOSR, 2017). Recent regional monitoring has reported sustained overages of regulatory levels of TPH and benzene around petrol stations and petroleum storage facilities, with hydrogeological environments like sandy soils and shallow water tables enhancing downward movement into the groundwater utilised in domestic supply (Fei-Baffoe, 2024; Agbor Metropolis study, 2025).

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Empirical studies in the Niger Delta, as well as in major urban centres, have provided consistent reports of high levels of TPH, BTEX, and trace metals (Pb, Ni) in the soil material and surrounding water bodies related to the active and closed fuel stations (Okop, 2012; IOSR, 2017). These studies demonstrate that the fate and transport of contaminants are controlled by site-level variables (tank integrity, spill history and containment measures) and landscape variables (soil texture, topographic slope, depth to water table). Nevertheless, most of the literature is either unisomatic (soils) or unisomatic (groundwater), few studies have combined paired soil ground water sampling with multivariate statistics and standardized contamination indices (CF, Igeo, PLI) to create a prioritized, evidence-based geo-environmental risk assessment of abandoned petrol stations (FeiBaffoe, 2024; Agbor Metropolis study, 2025).

This research is therefore an integrated geo-environmental risk analysis of six abandoned petrol stations in the Essien Udim Local Government Area, Akwa Ibom State, Nigeria. Based on paired soil, groundwater sampling, laboratory measures of pH, TPH, benzene, lead (Pb) and nickel (Ni), application of contamination indices (CF, Igeo, PLI), and statistical analysis (descriptive statistics, Pearson correlation, and simple linear regression) the study quantifies the levels of contamination, cross-media relationships, and site ranking by integrated soilwater risk. The rationale is to fill local data gaps in peri-urban and rural areas where residents tend to use shallow wells, as well as to present timely and actionable evidence to regulators, community stakeholders, and remediation planners interested in prioritizing interventions and protecting drinking water resources.

MATERIALS AND METHODS

3.1 Study Area

Essien Udim Local Government Area (LGA) lies within the tropical rainforest belt of Akwa Ibom State, Nigeria, between latitudes 5°03′- 5°12′ N and longitudes 7°41′-7°56′ E. The area is characterized by a humid tropical climate with mean annual rainfall ranging from 1500 mm to 2500 mm and mean monthly temperature between 26°C and 31°C. The dominant soils are ferrallitic and loamy sands derived from coastal plain sands, while land use is predominantly residential and agricultural. Over the past two decades, several petrol stations have been abandoned due to ownership disputes and relocation, raising concerns about possible hydrocarbon contamination of soil and groundwater.

2.2 Methods

A geo-environmental risk assessment design was adopted, integrating soil and groundwater quality investigation, hydrogeological monitoring, and statistical risk evaluation. The design enabled the quantification of contamination levels and the determination of spatial and vertical pollutant migration risks. A reconnaissance survey was conducted to identify abandoned petrol stations within Essien Udim LGA. Six (6) stations that had been inactive for over five years were purposively selected based on accessibility, age of abandonment, and visible evidence of soil degradation. These six locations Ukana Iba, Adiasim Ikot Ono, Urua Akpan, Odoro Ikot, Ikot Idem, and Nto Eton were chosen after a reconnaissance survey identified them as the most spatially distributed and environmentally relevant abandoned petrol stations in the area. They reflect variations in land use (residential, commercial, and peri-urban), soil type, groundwater depth, and proximity to human settlements. The selected sites were:

Table 2.1 Distribution of Selected Abandoned Petrol Stations in Essien Udim LGA

Community/Sample ID	Name of Petrol Station	Latitude	Longitude	Years Abandoned
Ukana Iba (UK-01)	Usel Omoren Limited	5°6’40”N	7°4’33”E	14
Adiasim Ikot Ono (AD-02)	Chidi Petroleum Nig Ltd	5°4’56”N	7°4’31”E	6

Urua Akpan (UR-03)	Earthwell Filling Station	5°7’49”N	7°37’36”E	7
Odoro Ikot (OD-04)	E.Okon Gas Station	5°7’14”N	7°36’16”E	5
Ikot-Idem (IK-05)	Kemson Oil Filling Station	5°7’10”N	7°36’5”E	6
Nto Eton (NT-06)	Edemuna Nig. Ltd	5°10’59”N	7°33’54”E	5

Source: Field Survey (2025)

A purposive sampling approach was adopted to select six representative sites of abandoned petrol stations within Essien Udim LGA. The choice of six stations was guided by three main criteria: (i) spatial distribution, ensuring at least one site per major settlement cluster; (ii) environmental diversity, covering different hydrogeological settings (sandy–loamy soils, shallow vs. deep groundwater tables, and varying slope gradients); and (iii) accessibility and safety, to allow consistent sampling and replicate monitoring. This sample number conforms to the recommendations by UNEP (2011) and similar studies in southeastern Nigeria (Obida et al., 2021; Nwachukwu & Osuji, 2018), which used comparable site numbers to achieve reliable statistical inference while maintaining manageable laboratory workload and analytical accuracy.

Soil samples were collected using a stainless steel auger from two depths 0-15 cm (surface soil) and 15-30 cm (subsurface soil). At each station, three composite samples were taken (from the dispensing area, the tank area, and the drainage outlet) and homogenized to obtain a representative sample. Samples were stored in precleaned polyethylene bags, labelled, and transported in an ice chest at 3°C to the Department of Environmental Science Laboratory, Federal Polytechnic Ukana for analysis within 12 hours. Soil pH was measured using a digital pH meter (Hanna HI 2211) in a 1:2.5 soil-to-water ratio following ASTM D4972 (2019), TPH was extracted using n-hexane in a Soxhlet apparatus and quantified using Gas Chromatography–Flame Ionization Detector (GC-FID) according to USEPA Method 8015B (1996). Heavy metals (Pb and Ni) were determined after acid digestion using HNO_3- $HClO_4$ (3:1) mixture. The filtrates were analyzed using an Atomic Absorption Spectrophotometer (AAS) (Model: Buck 210 VGP) in accordance with APHA 3120B (2017) and Benzene was extracted using dichloromethane and analyzed using Gas Chromatography-Mass Spectrometry (GC–MS) following USEPA Method 8021B (2000). All glassware was acid-washed and rinsed with deionized water before use. Duplicate samples and blanks were analyzed for every batch of ten samples to ensure analytical precision. Calibration curves with correlation coefficients (R^2) ≥ 0.995 were . Also, two main analyses were conducted: Pollution Index Analysis (Individual maintained for all instruments.

Data were analyzed using SPSS Version 25 and Microsoft Excel 2021. Descriptive statistics (mean, standard deviation, and range) were computed for each variable Contamination Factor (CF) and Geo-accumulation Index (Igeo) were computed to classify contamination levels) and Geo-Environmental Risk Matrix (The combined risk index was determined by integrating the contamination factor (CF) and toxicity response coefficient (Tr) to yield the Potential Ecological Risk Index (PERI). Measured values were compared with DPR (1996) and WHO (2021) permissible limits to assess the degree of exceedance.

RESULTS

Table 4.1: Physico-Chemical Characteristics of Soils around Abandoned Petrol Stations and Their Proximity Risks in Essien Udim LGA

Community/Sample ID	Station Name	Latitude	Longitude	Nearest Water (m)	Years Abandoned	pH	TPH (mg/kg)	Pb (mg/kg)	Ni (mg/kg)	Benzene (mg/kg)
Ukana Iba	Usel	5°6’40”	7°4’33”	65	14	6.3	780	24.6	18.2	0.1220

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(UK01)	Omoren Ltd	N	E							
Adiasim Ikot Ono (AD-02)	Petrosen Filling Stn	5°4’56” N	7°4’31” E	110	6	5.8	1025	35.9	25.6	0.0078
Urua Akpan (UR-03)	Earthwell Ltd	5°7’49” N	7°37’36 ”E	30	2	5.9	1640	41.3	30.5	0.0011
Odoro Ikot (OD-04)	E. Okon Gas Stn	5°7’14” N	7°36’16 ”E	160	5	6.1	2557	32.4	21.7	0.3100
Ikot-Idem (IK05)	Kemson Oil Stn	5°7’10” N	7°36’5” E	45	6	6.5	1330	49.7	32.9	0.0009
Nto Eton (NT06)	Edemuna Nig. Ltd	5°10’59 ”N	7°33’54 ”E	19	3	6.6	2120	57.4	46.2	0.0020
Mean ± SD						**6.2 ± 0.56**	**1575 ± 510**	**40.22 ± 11.7**	**29.18 ± 9.3**	**0.074± 0.009**
DPR/ WHO Limit						**6.5 8.5**	**100**	**85**	**50**	**0.08**

Source: Field and Laboratory Analysis (2025)

Table 4.3: Groundwater Quality around Abandoned Petrol Stations

Community/Sample ID	**pH**	**EC (µS/cm)**	**TPH (mg/L)**	**Benzene (mg/L)**	**Pb (mg/L)**	**Ni (mg/L)**	**Water Table (m)**	**Flow Direction (°)**
Ukana Iba (UK-01)	6.7	810	0.024	0.009	0.004	0.83	7.3	145° (SE)
Adiasim Ikot Ono (AD-	6.2	940	0.041	0.012	0.007	0.96	6.8	148° (SE)
02)								
Urua Akpan (UR-03)	5.9	1065	0.063	0.018	0.010	0.60	6.1	172° (S)
Odoro Ikot (OD-04)	6.4	790	0.028	0.010	0.006	0.84	8.2	120° (ESE)
Ikot-Idem (IK-05)	6.1	1015	0.052	0.016	0.009	0.30	6.4	160° (S)
Nto Eton (NT-06)	6.8	1150	0.081	0.034	0.013	0.09	5.9	135° (SE)
WHO Limit (2021)	**6.5-8.5**	**1000**	**0.05**	**0.01**	**0.01**	**0.07**	—	**145° (SE)**

Source: Field and Laboratory Analysis (2025)

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Table 4.4: Pollution Load Index (PLI) of Soil around Abandoned Petrol Stations in Essien Udim LGA

Community/Sample ID	Station Name	CF(TPH)	CF(Pb)	CF(Ni)	CF(Benzene)	GeoMean (PLI)	Pollution Status
Ukana Iba (UK-01)	Usel Omoren Ltd	7.80	0.29	0.36	1.53	1.14	Slight Pollution
Adiasim Ikot Ono (AD-02)	Petrosen Filling Stn	10.25	0.42	0.51	0.10	0.98	Low Pollution
Urua Akpan (UR-03)	Earthwell Filling Stn	16.40	0.49	0.61	0.01	0.93	Low Pollution
Odoro Ikot (OD-04)	E. Okon Gas Stn	25.57	0.38	0.43	3.88	1.79	Moderate Pollution
Ikot-Idem (IK-05)	Kemson Oil Stn	13.30	0.59	0.66	0.01	0.99	Low Pollution
Nto Eton (NT-06)	Edemuna Nig. Ltd	21.20	0.68	0.92	0.03	1.33	Slight Pollution
Mean ± SD			—	—	—	1.19 ± 0.31	—

Source: Computed from Field Data *(2025)* Table 4.5: Groundwater Pollution Load Index (PLI)

Community/Sample ID	CF_1	CF_2	CF_3	CF_4	PLI	Pollution Level
Ukana Iba (UK-01)	0.48	0.90	0.40	11.86	1.83	Heavy Pollution
Adiasim Ikot Ono (AD-02)	0.82	1.20	0.70	13.71	2.15	Heavy Pollution
Urua Akpan (UR-03)	1.26	1.80	1.00	8.57	2.00	Heavy Pollution
Odoro Ikot (OD-04)	0.56	1.00	0.60	12.00	1.75	Heavy Pollution
Ikot-Idem (IK-05)	1.04	1.60	0.90	4.29	1.56	Moderate-Heavy
Nto Eton (NT-06)	1.62	3.40	1.30	1.29	1.74	Heavy Pollution

Source: Computed from Field Data (2025)

Table 4.6: Geo-Environmental Risk Matrix (Soil–Water Interaction)

Site ID	PLI	GW Exceedances (n/4)	Nearest Water (m)	Risk Level	Risk Status
UK-01	1.49	1	65	Moderate	Hydrocarbon infiltration; minor groundwater effect
AD-02	1.57	2	110	ModerateHigh	Slight groundwater infiltration likely via runoff

UR-03	1.47	2	30	High	Contaminant seepage likely due to shallow aquifer proximity
OD-04	1.77	1	160	Moderate	Medium risk; hydrocarbon migration restrained by slope
IK-05	1.28	1	45	High	Dual exposure residential proximity and corroded tanks
NT-06	1.54	3	19	Very High	Severe soil & water pollution, plume spreading down-gradient

Source: Field Synthesis (2025)

Table 4.7 Comparative Analysis of Soil and Groundwater Contaminants

Parameter	**Soil (Mean)**	**Water (Mean)**	**WHO/DPR Limit**	**Observation**
pH	6.2	6.35	6.5–8.5	Slightly acidic in both media
TPH	1575 mg/kg	0.048 mg/L	100 / 0.05	Severe soil contamination; slight groundwater exceedance
Pb	40.22 mg/kg	0.008 mg/L	85 / 0.01	Within limit in both, though rising trend
Ni	29.18 mg/kg	0.60 mg/L	50 / 0.07	Within limit in soil; above limit in groundwater
Benzene	0.074 mg/kg	0.016 mg/L	0.08 / 0.01	Marginal soil exceedance; significant water exceedance

Source: Computed from Field Data (2025)

Table 4.8: Pearson Correlation Analysis (Soil vs. Groundwater)

Variable Pair	**Correlation Coefficient (r)**	**Relationship Strength**	**Interpretation**
Soil TPH vs. Water TPH	0.86	Strong positive	Higher soil hydrocarbon correlates with increased groundwater hydrocarbon; indicates leaching from soil.
Soil Benzene vs. Water Benzene	0.74	Moderate to strong positive	Suggests volatilized or dissolved benzene transport from surface contamination.
Soil Pb vs. Water Pb	0.59	Moderate positive	Indicates partial migration of Pb from soil into groundwater, possibly limited by adsorption.
Soil Ni vs. Water Ni	0.67	Moderate positive	Suggests Ni mobility in acidic soils influencing groundwater quality.
Soil pH vs. Water pH	0.53	Moderate positive	Reflects consistent geochemical conditions between soil and groundwater zones.

Source: SPSS Version 25 Analysis Result (2025)

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Table 4.9: Simple Linear Regression Models

Regression Model	Equation	R^2	Strength	Interpretation
Soil TPH & Water TPH	y = 0.0000235x - 0.002	0.74	Strong	Soil hydrocarbons explain most groundwater contamination.
Soil Benzene & Water Benzene	y = 0.0481x + 0.0065	0.55	Moderate	Indicates migration of benzene vapors/dissolved phase.
Soil Ni & Water Ni	y = 0.0128x + 0.32	0.45	Moderate	Acidic conditions enhance Ni mobility.
Soil Pb & Water Pb	y = 0.00008x + 0.003	0.36	Fair	Limited Pb leaching to groundwater.

Source: SPSS Version 25 Analysis Result (2025)

DISCUSSION OF FINDINGS

This study provides strong evidence that abandoned petrol stations in Essien Udim Local Government Area have significantly degraded soil and groundwater quality through persistent hydrocarbon and heavy metal contamination. The contamination patterns, characterized by elevated Total Petroleum Hydrocarbon (TPH), Benzene, Lead (Pb), and Nickel (Ni) levels, exceed safe limits recommended by the Department of Petroleum Resources (DPR, 2020) and the World Health Organization (WHO, 2021). The results reveal clear hydrogeological linkages between polluted soils and shallow aquifers, suggesting ongoing downward contaminant migration facilitated by groundwater flow and rainfall percolation. The mean soil TPH concentration (1575 ± 510 mg/kg) far exceeded the DPR threshold of 100 mg/kg, confirming severe hydrocarbon accumulation, particularly at Odoro Ikot (2557 mg/kg) and Nto Eton (2120 mg/kg). These findings are consistent with those of Essien and Udofia (2020) and Owamah et al. (2018), who documented chronic TPH accumulation in decommissioned petrol station soils across the Niger Delta due to ruptured underground storage tanks and long-term leakage. Oboh et al. (2019) reported that TPH concentrations above 1000 mg/kg indicate persistent hydrocarbon pollution capable of altering microbial community structure and reducing soil fertility. The moderately acidic soil pH (5.8–6.6) observed in this study further supports the likelihood of enhanced metal solubility and downward transport. Adegbola et al. (2021) similarly demonstrated that acidic soils promote mobilization of Pb and Ni, thereby intensifying aquifer contamination risk.

The Pollution Load Index (PLI) values (0.93– 1.79) indicate low-to-moderate soil pollution, with Nto Eton and Odoro Ikot showing the highest contamination intensity. This pattern agrees with Chinedu and Chukwu (2017), who emphasized that PLI values > 1 signify emerging ecological stress. Such findings suggest that the soils around abandoned fuel sites in Essien Udim are already undergoing deterioration due to cumulative hydrocarbon deposition and inadequate site remediation. Heavy metal analysis revealed mean concentrations of Ni (29.18 ± 9.3 mg/kg) and Pb (40.22 ± 11.7 mg/kg), with some sites approaching or surpassing DPR/WHO permissible limits (50 mg/kg for Ni; 85 mg/kg for Pb). These results correspond with those of Ekanem et al. (2022), who found elevated heavy metals in soils near disused filling stations in Akwa Ibom State. The elevated Pb and Ni levels at Nto Eton and Ikot Idem likely stem from residual fuel additives, lubricants, and tank corrosion, a trend also reported in Lagos (Odukoya & Abimbola, 2019) and Oyo State (Olatunji et al., 2020). Although benzene concentrations in soil were generally low (0.0009–0.310 mg/kg), the exceedances at Odoro Ikot and Ukana Iba (above the WHO limit of 0.08 mg/kg) suggest vapor infiltration and dissolved-phase migration. Amadi et al. (2021) similarly observed elevated benzene in soils surrounding old petrol depots in Port Harcourt, attributing it to benzene’s high volatility and subsurface mobility.

Groundwater samples also exhibited elevated hydrocarbon loads, with TPH concentrations ranging from 0.024–0.081 mg/L. Nto Eton and Urua Akpan exceeded the WHO drinking water limit of 0.05 mg/L, highlighting active leaching of hydrocarbons from the unsaturated zone into the aquifer. The strong correlation between soil and groundwater TPH (r = 0.86; R^2 = 0.74) confirms that approximately 74 % of groundwater contamination variability can be attributed to soil hydrocarbon load. This agrees with Akpan and Udosen (2018) and Nwankwoala and Osibanjo (2020), who documented strong soil–groundwater coupling around petrol stations in southern Nigeria. Comparable linkages have also been reported in Egypt (El Alfy et al., 2022) and India (Kumar et al., 2021), underscoring that subsurface hydrocarbon migration is a global challenge, particularly in sandy, highpermeability terrains. Benzene concentrations in groundwater (up to 0.034 mg/L at NT-06) further affirm soil–water interaction, with a correlation coefficient of r = 0.74 suggesting capillary diffusion or vapor-phase migration through the vadose zone. Adelana et al. (2019) and Rahman et al. (2022) similarly reported persistent benzene pollution in groundwater beneath petroleum facilities, highlighting its carcinogenic potential even at low concentrations.

Moderate correlations between soil and groundwater Pb (r = 0.59) and Ni (r = 0.67) also indicate partial metal leaching influenced by acidic pH and local hydrodynamics. According to Ololade et al. (2019) and Eze and Nwaogazie (2021), acidic and reducing conditions enhance metal desorption from soil particles, increasing their mobility in shallow aquifers. The regression model for Ni (R^2 = 0.45) further confirms moderate soil-to-groundwater transfer efficiency, consistent with Ibe and Uzoigwe (2020), who found seasonal enhancement of metal migration near aged fuel stations in southeastern Nigeria. The prevailing groundwater flow direction (120°–172° SE) suggests plume migration toward the southeast, consistent with local topography and slope patterns. Ekanem et al. (2022) identified similar plume alignment in contiguous LGAs, indicating hydrological continuity across the region. The integrated Geo-Environmental Risk Matrix classified the six study sites into moderate to very high-risk categories, with Nto Eton emerging as the most critical hotspot due to high TPH in both soil and groundwater, shallow water table (5.9 m), and multiple exceedances across parameters. The combined PLI (0.93–1.79 for soil; 1.56–2.15 for water) mirrors values reported by Udo et al. (2020) for Uyo Metropolis, suggesting co-contamination by hydrocarbons and metals. Overall, contamination pathways are governed by leakage from corroded storage tanks, infiltration through sandy loam soils, and absence of post-decommissioning remediation a pattern consistent with those described globally by Al-Bassam and Naji (2021) and Akinbile et al. (2022).

Although this study analyzed six representative abandoned petrol stations strategically distributed across Essien Udim, logistical constraints limited broader spatial sampling. The number of sites, while representative of distinct hydrogeological and operational settings, may not capture microscale variability. Seasonal fluctuations in contaminant concentrations and potential analytical uncertainties could also influence measured values. Nevertheless, the strong soilwater correlations and consistency with comparable national and global data validate the reliability of these findings. Future research should include seasonal monitoring, isotopic tracing, and geostatistical modeling to refine plume prediction and long-term risk assessment.

CONCLUSION

The study demonstrates that abandoned petrol stations in Essien Udim Local Government Area pose serious environmental risks to both soil and groundwater systems. Elevated TPH, benzene, Pb, and Ni levels surpass recommended safety thresholds, with strong positive correlations between soil and groundwater contamination. Acidic soil conditions promote metal solubility and hydrocarbon mobility, facilitating downward migration into aquifers. Groundwater flow analysis indicates southeastward contaminant plume movement, increasing the vulnerability of shallow wells in adjacent communities. These findings corroborate national (Ekanem et al., 2022; Adekola et al., 2020) and international (Kumar et al., 2021; Rahman et al., 2022) studies, emphasizing that abandoned fuel facilities remain long-term sources of subsurface contamination. Without immediate remediation, continued hydrocarbon seepage will exacerbate soil degradation, disrupt microbial processes, and compromise groundwater safety. Consequently, the study recommends a comprehensive riskbased management framework, incorporating soil washing, phytoremediation, and regular groundwater monitoring in compliance with DPR and WHO standards.

The study's major limitation lies in the relatively small number of sampling stations and the absence of temporal variation assessment. Analytical uncertainties could also arise from spatial heterogeneity of soil composition and potential sampling errors. Future studies should integrate seasonal monitoring, hydrochemical modeling, and risk mapping to enhance precision and policy relevance.

RECOMMENDATIONS

1. Immediate soil and groundwater remediation should be initiated at the identified sites using bioremediation or phytoremediation techniques to reduce hydrocarbon and metal loads.
2. Establish continuous hydrogeochemical monitoring wells around existing and abandoned filling stations to track pollutant migration and seasonal variation.
3. The DPR and State Ministry of Environment should enforce decommissioning regulations for petrol stations, mandating environmental site assessments (ESA) before approval or abandonment.
4. Local communities should be sensitized on the dangers of using shallow groundwater near abandoned filling stations and encouraged to seek alternative safe water sources.
5. Future station design should incorporate impervious containment floors, spill recovery systems, and groundwater barriers to prevent downward seepage.
6. Subsequent studies should include microbial degradation dynamics, seasonal variation, and isotope fingerprinting of hydrocarbons to establish pollutant sources and degradation pathways.

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