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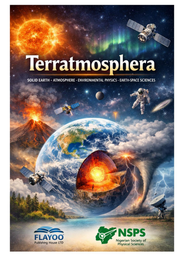

Soil quality assessment of crude oil-exposed environments in Tebidaba, Bayelsa State, Nigeria

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ABSTRACT

Oil exploration and production activities can pose significant risks to soil quality through hydrocarbon contamination and alteration of physicochemical properties. This study assessed the impact of oil operations on soil characteristics around the Tebidaba oil flow station, Bayelsa State, Nigeria, during the 2022 wet and dry seasons. Soil samples were collected from surface (0–15 cm) and subsurface (15–30 cm) layers and analyzed alongside control samples from non-impacted areas. The soils were predominantly clay and clay loam. Mean permeability ranged from 3.49 to 3.58 m/day in surface soils and from 3.88 to 3.97 m/day in subsurface soils across seasons, while porosity ranged from 34.68 to 36.66% in surface soils and from 38.54 to 40.77% in subsurface soils. Soil pH was strongly to moderately acidic (4.11–4.49), and soil temperature averaged 26.31–27.17°C. Total petroleum hydrocarbons (TPH), total hydrocarbon content (THC), and total organic carbon (TOC) were consistently higher in surface soils than in subsurface soils, while benzene, toluene, ethylbenzene, and xylene (BTEX) remained below 0.001 mg/kg in all samples. Cation exchange capacity was low, and carbonate concentrations. Overall, hydrocarbon concentrations were generally low, but periodic environmental monitoring is recommended to prevent pollutant buildup associated with oil production activities.

1. INTRODUCTION

Soil quality is commonly viewed as the capacity of soil to function within natural or managed ecosystem boundaries to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation [1, 2]. It affects not only agricultural productivity but also the quality of agricultural produce and the economic sustainability of land use. Soil quality assessment therefore integrates biological, chemical, and physical attributes that collectively describe the capacity of soil

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to function [3, 4].

Soils possess both inherent properties, such as texture, depth, clay type, cation exchange capacity (CEC), and drainage class, and dynamic properties, such as pH, bulk density, organic matter content, and available nutrients. These properties support plant growth, provide structural support, and buffer the environment against pollutants [5]. Soil quality assessment based on inherent factors and dynamic indicators is an effective method for evaluating the environmental sustainability of land-use and management activities [6].

Nigeria has experienced many crude oil spillages that have contaminated soils and groundwater resources over the years [7]. Crude oil spills affect several environmental compartments, including air, surface water, plants, soils, and groundwater systems. In oil-producing states such as Bayelsa, many land and water systems remain degraded, and remediation efforts have often been inadequate [8]. Oil exploration in Nigeria illustrates both the benefits and the environmental hazards associated with resource extraction, including land degradation, river pollution, air pollution, and biodiversity loss [9]. These impacts can weaken the resilience of nearby communities that depend on fishing, farming, and other natural resources for their livelihoods.

This study was conducted to assess selected soil quality parameters in crude oil-exposed soils around selected oil flow stations in Tebidaba, Bayelsa State, Nigeria.

2. MATERIALS AND METHODS

2.1. STUDY AREA

Laboratory and field studies were carried out at the Tebidaba flow station, Bayelsa State, Nigeria. The facilities are operated by Nigeria Agip Oil Company (NAOC). The sampling points are shown in Figure 1.

2.2. SOIL SAMPLE COLLECTION

Soil samples were collected at two depths: surface soil (0–15 cm) and subsurface soil (15–30 cm). In each season, 13 soil samples were collected at each depth around the flow station during the wet season, and the same procedure was repeated during the dry season. For the control, one sample was collected at each depth from a location away from the flow station. In total, 28 soil samples were collected from the location in each season, giving 56 soil samples for the study.

2.3. DETERMINATION OF PHYSICAL AND CHEMICAL PROPERTIES

The soil samples were air-dried and sieved through a 2 mm sieve, after which subsamples were taken for laboratory analysis. Soil pH was determined using a glass electrode in a 1:2 soil–water suspension. Particle-size analysis was determined by the hydrometer method following Gee and Or [10], and the United States Department of Agriculture textural triangle was used to determine textural class. Total organic carbon and organic matter were determined by the dichromate wet oxidation method [11], while total nitrogen was analyzed using the micro-Kjeldahl digestion technique [12]. Available phosphorus was extracted using the Bray-1 method, and phosphorus concentration was determined using the Murphy and Riley procedure [13].

Exchangeable acidity was assessed by titration following Page *et al.* [14]. Exchangeable cations (Ca, Mg, Na, and K) were extracted with 1 M ammonium acetate solution buffered at pH 7. Sodium and potassium were quantified using a flame photometer, whereas calcium and magnesium were determined using an atomic absorption spectrophotometer (AAS; UNICAM 936 model). Energy-dispersive X-ray fluorescence spectrophotometry (EDXRF) was also used for elemental analysis following AOAC procedures [15].

2.4. SOIL PERMEABILITY, POROSITY, BULK DENSITY, AND OXIDATION–REDUCTION POTENTIAL

Soil permeability was determined using the constant-head permeameter method following standard soil physics procedures. Air-dried soil samples were packed into permeameter columns, and water flow through the soil column was measured under steady hydraulic conditions. Permeability values were expressed as meters per day.

Soil porosity was estimated from bulk density and particle density measurements using the standard relationship:

$$\text{Total Porosity } (\%) = \left(\frac{1 - \text{Bulk density}}{\text{Particle density}}\right) \times 100. \quad (1)$$

Bulk density was determined using the core sampling method, while particle density was assumed to be 2.65 g/cm^3 for mineral soils. Soil oxidation–reduction potential (ORP) was measured using a digital ORP meter equipped with a platinum electrode and a reference electrode. Measurements were taken directly from soil suspensions prepared with distilled water, and values were expressed in millivolts (mV).

2.5. TOTAL HYDROCARBON CONTENT, TOTAL PETROLEUM HYDROCARBONS, AND BTEX

Total hydrocarbon content (THC) in soil samples was determined using infrared spectrophotometry following the standard procedure from Ref. [16]. The extraction method was the Dutch Standard Method VPRC88-19. THC contents were calculated as follows:

$$\text{THC} = \frac{\text{Instrument Reading} \times \text{Volume of Extract}}{\text{Weight of Sample}}. \quad (2)$$

THC estimates the total concentration of extractable hydrocarbons present in the sample and may exceed total petroleum hydrocarbon (TPH) values because infrared spectrophotometry measures a broader range of hydrocarbon compounds than gas chromatography.

Total petroleum hydrocarbons (TPH) were determined with an Agilent 6890N gas chromatograph in accordance with ASTM and USEPA methods [17–19]. Before analysis, the equipment was calibrated using five-level multistate *n*-alkane mixtures to obtain calibration graphs for individual analytes. Samples were extracted with methylene chloride, fractionated through a silica gel column to obtain the aliphatic fraction, concentrated to 1 mL, and analyzed by injecting 3 μL of sample extract into the gas chromatograph.

Benzene, toluene, ethylbenzene, and xylene (BTEX) were determined using gas chromatography. Stock solutions were prepared in LC–MS-grade analytical methanol from a 2000 mg/L

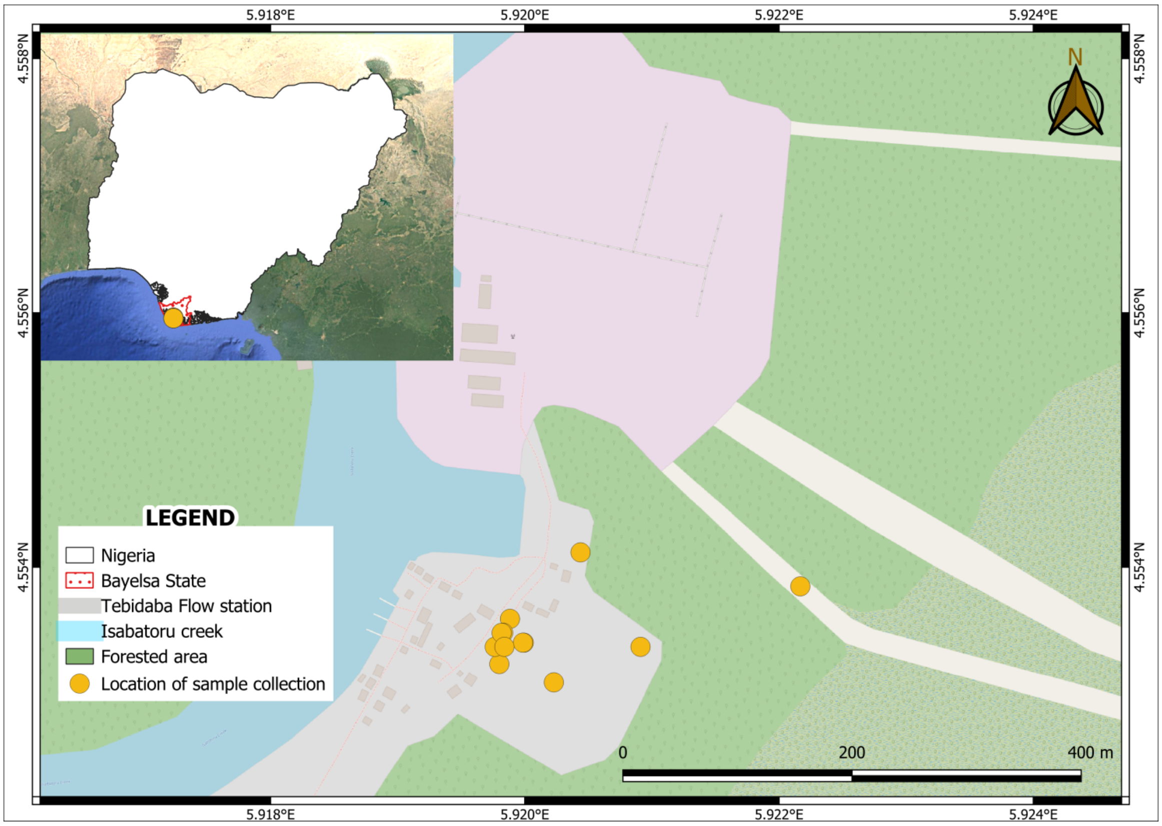

Figure 1. Sampling points for the Tebidaba flow station in Bayelsa State, Nigeria. The map was generated using QGIS version 3.44.0-Solothurn.

calibration standard, and fluorobenzene was used as an internal standard. The solutions were stored in sealed vials without headspace to reduce evaporative losses.

2.6. DATA ANALYSIS

Descriptive statistical analysis was used to summarize the physicochemical characteristics of the soil samples. Mean values and standard deviations were calculated for all measured parameters to describe variations across sampling points, depths, and seasons. The analysis focused on identifying observable trends and patterns in soil properties and hydrocarbon concentrations rather than testing statistical hypotheses. All computations were performed using SPSS version 27.0.

3. RESULTS

3.1. SELECTED PHYSICAL PROPERTIES DURING THE WET SEASON

The selected physical properties of soils from the Tebidaba flow station during the 2022 wet season are presented in Table 1. Soil colour varied from light brown to dark brown in both surface and subsurface soils. Mean pH was lower in the surface layer (4.11) than in the subsurface layer (4.21), while mean soil temperature was slightly higher in the surface layer (26.50°C) than in the subsurface layer (26.31°C). Soil texture ranged from clay to clay loam at both depths. Permeability was lower in surface soils (3.49 m/day) than in subsurface soils (3.88 m/day), and porosity was also lower in surface soils (34.68%) than in subsurface soils (38.54%).

3.2. SELECTED PHYSICAL PROPERTIES DURING THE DRY SEASON

The selected physical properties measured during the 2022 dry season are presented in Table 2. Soil colour varied from light brown to dark brown at both sampled depths. Mean pH was lower in surface soil (4.30) than in subsurface soil (4.49). Soil temperatures were similar at both depths, with mean values of 27.17°C and 27.11°C in the surface and subsurface layers, respectively. The soils were predominantly clay to clay loam. Permeability was lower in surface soils (3.58 m/day) than in subsurface soils (3.97 m/day), and porosity was lower in surface soils (36.66%) than in subsurface soils (40.77%).

3.3. SELECTED CHEMICAL PROPERTIES DURING THE WET SEASON

The selected chemical properties of soil samples from the flow station during the 2022 wet season are shown in Table 3. Mean ORP was lower in surface soil (164.46 mV) than in subsurface soil (176.22 mV). THC was higher in the surface layer (39.99 mg/kg) than in the subsurface layer (18.48 mg/kg). TPH also followed the same pattern, with a mean of 3.45 mg/kg in surface soil and 1.56 mg/kg in subsurface soil. BTEX concentrations were below 0.001 mg/kg at both depths. TOC was higher in surface soil (7.15%) than in subsurface soil (3.64%), while total nitrogen was similar across depths. CEC was low, with values of 0.18 and 0.16 $cmol_c\ kg^{-1}$ in surface and subsurface soils, respectively.

Table 1. Selected physical properties of soil samples from the Tebidaba flow station during the wet season of 2022.

Point	pH (H_2O) 0–15 cm	pH (H_2O) 15–30 cm	Temperature (°C) 0–15 cm	Temperature (°C) 15–30 cm	Colour 0–15 cm	Colour 15–30 cm	Texture 0–15 cm	Texture 15–30 cm	Permeability (m/day) 0–15 cm	Permeability (m/day) 15–30 cm	Porosity (%) 0–15 cm	Porosity (%) 15–30 cm
SS1	4.40	5.61	26.71	26.45	Light brown	Light brown	Clay loam	Clay loam	4.4	4.3	43.22	42.49
SS2	4.33	4.14	26.36	26.11	Dark brown	Grayish brown	Clay	Clay	2.9	4.0	29.15	40.11
SS3	4.42	3.66	26.81	26.41	Light brown	Grayish brown	Clay	Clay	2.4	3.1	24.10	31.16
SS4	4.08	5.11	26.37	26.33	Grayish brown	Light brown	Clay	Clay	2.9	3.9	29.55	39.15
SS5	4.06	3.59	26.33	26.34	Brownish	Brownish	Clay	Clay	4.1	3.9	41.05	38.33
SS6	4.16	4.36	26.48	26.32	Brownish	Brownish	Clay	Clay	4.1	4.4	40.43	43.94
SS7	4.58	4.92	26.34	26.16	Brownish	Brownish	Clay loam	Clay loam	5.0	5.2	49.15	51.16
SS8	4.91	5.01	26.41	26.38	Brownish	Brownish	Clay	Clay loam	3.9	4.8	38.33	47.67
SS9	3.09	3.14	26.71	26.11	Brownish	Brownish	Clay	Clay	2.8	4.0	27.55	39.68
SS10	3.81	3.47	26.38	26.19	Brownish	Brownish	Clay	Clay	2.9	3.1	29.15	31.19
SS11	3.88	4.02	26.35	26.21	Brownish	Brownish	Clay	Clay	2.3	2.7	23.21	26.41
SS12	3.61	3.63	26.72	26.51	Brownish	Brownish	Clay	Clay	3.4	3.8	33.73	37.52
SS13	4.11	4.05	26.57	26.47	Brownish	Brownish	Clay	Clay	4.3	3.2	42.22	32.18
SSCTL 1	3.41	3.01	26.91	26.84	Grayish brown	Grayish brown	Clay loam	Clay loam	4.5	4.8	44.27	47.88
Mean	4.11	4.21	26.50	26.31					3.49	3.88	34.68	38.54
Std. Values	0.46	0.75	0.18	0.14					0.86	0.72	8.21	7.00

Table 2. Selected physical properties of soil samples from the Tebidaba flow station during the dry season of 2022.

Point	pH (H_2O) 0–15 cm	pH (H_2O) 15–30 cm	Temperature (°C) 0–15 cm	Temperature (°C) 15–30 cm	Colour 0–15 cm	Colour 15–30 cm	Texture 0–15 cm	Texture 15–30 cm	Permeability (m/day) 0–15 cm	Permeability (m/day) 15–30 cm	Porosity (%) 0–15 cm	Porosity (%) 15–30 cm
SS1	5.37	3.68	27.66	27.14	Light brown	Light brown	Clay loam	Clay loam	4.5	4.4	45.73	44.95
SS2	5.01	5.32	27.08	27.14	Dark brown	Greyish brown	Clay	Clay	3.0	4.1	30.84	42.44
SS3	4.14	3.99	27.28	27.22	Light brown	Light brown	Clay	Clay	2.5	3.2	25.50	32.97
SS4	4.00	4.32	27.14	27.08	Greyish brown	Greyish brown	Clay	Clay	3.0	4.0	30.84	41.42
SS5	4.07	5.06	26.55	26.45	Brownish	Light brown	Clay	Clay	4.2	4.0	43.43	40.55
SS6	3.23	4.14	27.14	27.19	Brownish	Brownish	Clay	Clay	4.2	4.5	42.78	46.49
SS7	4.06	5.11	27.19	27.10	Brownish	Brownish	Clay loam	Clay loam	5.1	5.3	52.00	54.12
SS8	5.03	4.08	27.52	26.41	Brownish	Brownish	Clay	Clay	4.0	4.9	40.55	50.43
SS9	3.66	4.07	27.23	27.44	Brownish	Brownish	Clay	Clay	2.8	4.1	29.14	41.98
SS10	3.38	4.49	27.18	27.61	Brownish	Brownish	Clay	Clay	3.0	3.2	30.84	33.00
SS11	4.36	5.66	27.54	27.63	Brownish	Brownish	Clay	Clay	2.4	2.7	24.56	27.94
SS12	5.31	5.32	27.40	27.32	Brownish	Brownish	Clay	Clay	3.5	3.9	35.69	39.70
SS13	4.33	3.07	26.32	26.66	Brownish	Brownish	Clay	Clay	4.4	3.3	44.67	34.05
SSCTL 1	4.11	5.31	27.11	27.06	Greyish brown	Greyish brown	Clay loam	Clay loam	4.6	5.0	46.84	50.66
Mean	4.30	4.49	27.17	27.11					3.58	3.97	36.66	40.77
Std. Values	0.70	0.76	0.37	0.39					0.86	0.73	8.71	7.41

Table 3. Selected chemical properties of surface (0–15 cm) and subsurface (15–30 cm) soils from the Tebidaba flow station during the wet season of 2022.

Point	ORP (mV) 0–15 cm	ORP (mV) 15–30 cm	THC (mg kg^{-1}) 0–15 cm	THC (mg kg^{-1}) 15–30 cm	TPH (mg kg^{-1}) 0–15 cm	TPH (mg kg^{-1}) 15–30 cm	BTEX (mg kg^{-1}) 0–15 cm	BTEX (mg kg^{-1}) 15–30 cm	TOC (%) 0–15 cm	TOC (%) 15–30 cm	Total N (%) 0–15 cm	Total N (%) 15–30 cm	CEC ($cmol_c$ kg^{-1}) 0–15 cm	CEC ($cmol_c$ kg^{-1}) 15–30 cm
SS1	186.4	159.2	28.42	31.24	2.39521	2.63292	< 0.001	< 0.001	5.8	5.9	0.981	1.060	0.13	0.19
SS2	173.5	181.2	41.81	27.71	3.52325	2.33531	< 0.001	< 0.001	8.6	5.2	0.973	1.067	0.31	0.18
SS3	166.9	192.3	55.29	4.67	4.70135	0.39352	< 0.001	< 0.001	10.4	4.9	1.074	1.038	0.16	0.13
SS4	181.3	154.8	48.13	29.51	4.05564	2.4868	< 0.001	< 0.001	8.6	5.1	1.120	1.038	0.17	0.13
SS5	141.6	188.3	27.70	17.99	2.33455	1.51623	< 0.001	< 0.001	4.9	3.2	1.1311	1.125	0.28	0.19
SS6	184.5	167.9	35.25	12.55	2.97069	1.05714	< 0.001	< 0.001	6.2	2.2	1.138	1.141	0.24	0.19
SS7	163.7	189.4	50.31	28.64	4.23972	2.41343	< 0.001	< 0.001	8.6	4.9	1.171	1.170	0.14	0.13
SS8	165.7	187.5	18.16	2.34	1.53066	0.19739	< 0.001	< 0.001	3.2	0.4	1.136	1.172	0.15	0.13
SS9	131.2	186.1	52.12	24.72	4.3921	2.08272	< 0.001	< 0.001	9.1	4.2	1.146	1.178	0.14	0.12
SS10	204.2	181.7	49.56	24.19	4.1766	2.03835	< 0.001	< 0.001	8.6	4.1	1.153	1.181	0.16	0.13
SS11	163.3	191.4	63.72	15.07	5.36932	1.2701	< 0.001	< 0.001	10.8	2.6	1.181	1.160	0.19	0.14
SS12	166.3	133.9	20.18	5.25	1.70083	0.44244	< 0.001	< 0.001	3.4	0.9	1.188	1.168	0.13	0.14
SS13	109.4	177.2	29.19	16.38	2.4597	1.3802	< 0.001	< 0.001	4.8	2.7	1.217	1.214	0.13	0.23
SSCTL 1	619.3	172.4	24.13	6.75	2.03327	0.56907	< 0.001	< 0.001	3.9	1.7	1.238	1.229	0.24	0.19
Mean	164.46	176.22	39.99	18.48	3.45	1.56	–	–	7.15	3.64	1.12	1.13	0.18	0.16
Std. Values	25.00	17.55	14.45	10.09	1.24	0.85	–	–	2.57	1.77	0.07	0.06	0.06	0.04

3.4. SELECTED CHEMICAL PROPERTIES DURING THE DRY SEASON

The selected chemical properties measured during the 2022 dry season are presented in Table 4. Mean ORP was slightly higher in subsurface soil (203.10 mV) than in surface soil (200.69 mV). THC and TPH were higher in surface soils (38.34 and 3.14 mg/kg, respectively) than in subsurface soils (19.13 and 1.43 mg/kg, re-

Table 4. Selected chemical properties of surface (0–15 cm) and subsurface (15–30 cm) soils from the Tebidaba flow station during the dry season of 2022.

Point	ORP (mV) 0–15 cm	ORP (mV) 15–30 cm	THC (mg kg^{-1}) 0–15 cm	THC (mg kg^{-1}) 15–30 cm	TPH (mg kg^{-1}) 0–15 cm	TPH (mg kg^{-1}) 15–30 cm	BTEX (mg kg^{-1}) 0–15 cm	BTEX (mg kg^{-1}) 15–30 cm	TOC (%) 0–15 cm	TOC (%) 15–30 cm	Total N (%) 0–15 cm	Total N (%) 15–30 cm	CEC ($cmol_c$ kg^{-1}) 0–15 cm	CEC ($cmol_c$ kg^{-1}) 15–30 cm
SS1	234.4	220.4	26.63	29.27	2.183	2.400	< 0.001	< 0.001	5.2	5.0	0.981	1.060	0.027	0.031
SS2	210.3	178.1	39.17	25.96	3.211	2.129	< 0.001	< 0.001	7.9	5.3	0.973	1.067	0.038	0.032
SS3	234	253.2	52.26	4.37	4.285	0.359	< 0.001	< 0.001	9.4	4.9	1.074	1.038	0.032	0.028
SS4	166.8	167.8	45.09	27.65	3.697	2.267	< 0.001	< 0.001	8.6	5.1	1.120	1.158	0.022	0.018
SS5	216.4	199.7	25.95	16.86	2.128	1.382	< 0.001	< 0.001	4.2	8.6	1.178	1.153	0.014	0.017
SS6	169	194.9	33.02	11.75	2.708	0.964	< 0.001	< 0.001	4.1	10.8	1.181	1.181	0.027	0.031
SS7	156.3	189.5	47.13	26.83	3.865	2.200	< 0.001	< 0.001	8.6	4.9	1.171	1.038	0.008	0.007
SS8	203.7	187.6	17.02	22.00	1.395	0.180	< 0.001	< 0.001	8.6	5.1	1.120	1.158	0.031	0.028
SS9	211	173.6	48.83	23.15	4.005	1.898	< 0.001	< 0.001	9.1	4.2	1.146	1.676	0.031	0.030
SS10	198.5	157.3	46.43	22.66	3.807	1.858	< 0.001	< 0.001	8.6	4.1	1.171	1.181	0.034	0.031
SS11	199.8	211.5	59.69	14.12	4.894	1.158	< 0.001	< 0.001	10.1	4.2	1.082	1.200	0.028	0.036
SS12	208.1	303.6	18.91	4.92	1.550	0.403	< 0.001	< 0.001	5.3	2.1	1.186	1.174	0.019	0.016
SS13	211.6	216.8	27.34	15.34	2.242	1.258	< 0.001	< 0.001	4.2	2	1.217	1.140	0.006	0.010
SSCTL 1	200.1	202.7	22.60	6.33	1.853	0.519	< 0.001	< 0.001	3.6	1	1.216	1.461	0.020	0.016
Mean	200.69	203.10	38.34	19.13	3.14	1.43	–	–	7.48	5.36	1.12	1.17	0.03	0.03
Std. Values	25.02	40.81	13.82	8.65	1.13	0.81	–	–	2.14	2.25	0.07	0.17	0.01	0.01

Table 5. Exchangeable cations of surface (0–15 cm) and subsurface (15–30 cm) soils at the Tebidaba flow station during the wet season of 2022.

Point	Na^+ 0–15 cm	Na^+ 15–30 cm	K^+ 0–15 cm	K^+ 15–30 cm	Ca^{2+} 0–15 cm	Ca^{2+} 15–30 cm	Mg^{2+} 0–15 cm	Mg^{2+} 15–30 cm	Total bases 0–15 cm	Total bases 15–30 cm
SS1	0.031	0.104	0.988	1.386	0.075	0.119	1.507	2.114	2.601	3.723
SS2	0.062	0.132	2.372	1.322	0.215	0.104	3.617	2.016	6.266	3.574
SS3	0.057	0.024	0.967	1.024	0.782	0.000	1.475	1.562	3.281	2.610
SS4	0.095	0.048	1.202	0.988	0.231	0.059	1.834	1.506	3.362	2.601
SS5	0.138	0.055	1.473	1.051	1.736	1.115	2.246	1.602	5.593	3.823
SS6	0.146	0.121	1.561	1.295	0.672	0.458	2.381	1.975	4.760	3.849
SS7	0.031	0.030	1.022	0.990	0.132	0.047	1.559	1.510	2.775	2.577
SS8	0.164	0.117	1.042	0.867	0.232	0.203	1.589	1.322	3.027	2.509
SS9	0.044	0.173	0.973	0.815	0.298	0.265	1.484	1.243	2.799	2.496
SS10	0.124	0.138	0.926	0.726	0.808	0.653	1.412	1.108	3.270	2.625
SS11	0.101	0.037	1.323	1.007	0.425	0.205	2.018	1.535	3.867	2.784
SS12	0.038	0.028	0.999	1.008	0.065	0.241	1.523	1.537	2.625	2.814
SS13	0.048	0.086	0.990	1.585	0.138	0.427	1.510	2.417	2.686	4.515
SSCTL 1	0.073	0.061	1.651	1.326	0.551	0.368	2.518	2.022	4.793	3.777
Mean	0.08	0.08	1.22	1.08	0.45	0.30	1.86	1.61	3.61	3.12
Std. value	0.05	0.05	0.40	0.25	0.47	0.31	0.62	0.36	1.20	0.68

spectively). BTEX concentrations remained below 0.001 mg/kg at both depths. TOC was higher in the surface layer (7.48%) than in the subsurface layer (5.36%), while total nitrogen and CEC showed only minor differences between depths.

3.5. EXCHANGEABLE CATIONS

Exchangeable cation concentrations during the wet and dry seasons are presented in Tables 5 and 6. During the wet season, mean sodium concentration was similar at both depths (0.08 $cmol_c$ kg^{-1}), while potassium was slightly higher in surface soil (1.22 $cmol_c$ kg^{-1}) than in subsurface soil (1.08 $cmol_c$ kg^{-1}). Calcium was 0.45 $cmol_c$ kg^{-1} in surface soil and 0.30 $cmol_c$ kg^{-1} in subsurface soil. Magnesium ranged from 1.86 $cmol_c$ kg^{-1} at the surface to 1.61 $cmol_c$ kg^{-1} in the subsurface layer, while total bases ranged from 3.61 to 3.12 $cmol_c$ kg^{-1}.

During the dry season, sodium was 0.73 $cmol_c$ kg^{-1} in surface soil and 0.71 $cmol_c$ kg^{-1} in subsurface soil. Potassium was slightly higher in surface soil (1.13 $cmol_c$ kg^{-1}) than in subsurface soil (1.03 $cmol_c$ kg^{-1}). Calcium was 0.13 and 0.18 $cmol_c$ kg^{-1} in surface and subsurface soils, respectively. Magnesium was higher in surface soil (2.27 $cmol_c$ kg^{-1}) than in subsurface soil (2.12 $cmol_c$ kg^{-1}), and total bases were 4.25 and 4.01 $cmol_c$ kg^{-1} in surface and subsurface soils, respectively.

4. DISCUSSION

This study assessed the extent of soil contamination and associated changes in selected physical and chemical properties around the Tebidaba flow station, Bayelsa State, Nigeria, during the wet and dry seasons of 2022. Mean pH values were strongly acidic across both depths and seasons. This acidic status indicates deviation from optimal soil conditions for microbial activity and plant growth. In oil-impacted soils, acidity may be enhanced by the oxidation of sulphides, release of organic acids from hydrocarbon breakdown, or mobilization of acidic metabolites [20]. The acidity may also hinder microbial degradation of hydrocarbons and nutrient cycling in the soil [21].

Mean soil temperature varied only slightly with depth and season, with values of about 26.31–27.17°C. These values are within typical tropical soil temperature ranges and are broadly compatible with microbial and plant function [22]. Although temperature differences were small, the slightly warmer surface horizon could support faster biochemical activity; however, the strong acidity of the soils may suppress these processes.

Soil colour ranged from light brown to dark brown, and textures ranged from clay to clay loam across both depths and seasons. Fine-textured soils typically contain a high clay fraction, which can reduce permeability and enhance retention of hydrocarbons and organic residues. In the present study, permeability and porosity were slightly lower in surface soils than in subsurface soils. This suggests that the surface horizon may be more compacted or more affected by contamination and surface processes than the subsurface horizon. The combination of fine texture, lower permeability, and lower porosity may limit vertical leaching and promote contaminant retention near the surface.

The chemical data show that TPH and THC were higher in surface soils than in subsurface soils in both seasons. In the wet sea-

Table 6. Exchangeable cations of surface (0–15 cm) and subsurface (15–30 cm) soils at the Tebidaba flow station during the dry season of 2022.

Point	Na^+ 0–15 cm	Na^+ 15–30 cm	K^+ 0–15 cm	K^+ 15–30 cm	Ca^{2+} 0–15 cm	Ca^{2+} 15–30 cm	Mg^{2+} 0–15 cm	Mg^{2+} 15–30 cm	Total bases 0–15 cm	Total bases 15–30 cm
SS1	0.716	0.715	0.967	1.024	0.225	0.227	2.556	2.443	4.464	4.407
SS2	0.673	0.658	1.202	0.988	0.23	0.245	3.665	2.897	5.770	4.788
SS3	1.203	0.476	1.473	1.051	0.524	0.701	2.447	2.669	5.647	4.897
SS4	0.31	0.314	1.202	0.988	< 0.001	0.129	2.399	0.8911	3.912	2.322
SS5	0.339	0.772	1.473	1.051	0.16	0.236	0.8724	0.8693	2.844	2.928
SS6	0.776	0.762	1.561	1.295	0.001	0.02	2.444	2.1899	4.782	4.267
SS7	0.773	0.771	1.022	0.990	0.018	0.021	0.9254	2.366	2.738	4.148
SS8	1.3	0.989	1.042	0.867	0.023	0.019	2.477	2.433	4.842	4.298
SS9	0.635	0.635	0.977	0.795	0.019	0.021	2.987	2.5561	4.618	4.007
SS10	0.444	0.451	0.943	1.036	0.02	0.018	3.665	2.8899	5.072	4.395
SS11	0.589	0.474	0.830	0.653	0.02	0.243	2.789	2.699	4.228	4.069
SS12	0.883	1.205	0.999	1.008	0.25	0.237	1.3234	1.3065	3.455	3.751
SS13	0.800	1.007	0.992	1.585	0.023	< 0.001	1.0006	1.2918	2.815	3.891
SSCTL 1	1.234	1.225	1.651	1.326	0.014	0.012	1.2858	0.8837	4.185	3.449
Mean	0.73	0.71	1.13	1.03	0.13	0.18	2.27	2.12	4.25	4.01
Std. value	0.29	0.25	0.23	0.23	0.16	0.20	0.96	0.75	1.03	0.71

son, surface TPH was 3.45 mg/kg compared with 1.56 mg/kg in subsurface soil, while surface THC was 39.99 mg/kg compared with 18.48 mg/kg in subsurface soil. In the dry season, similar patterns were observed, with surface TPH and THC of 3.14 and 38.34 mg/kg, respectively, compared with 1.43 and 19.13 mg/kg in subsurface soil. The higher surface concentrations are consistent with near-surface deposition of hydrocarbon residues and limited downward migration due to fine texture and lower permeability [21]. Similar elevation of hydrocarbon residues in surface soils has been reported in the Niger Delta, although the concentrations measured in this study were much lower than those reported for heavily contaminated sites [23].

BTEX concentrations below 0.001 mg/kg at both depths and in both seasons indicate low volatile aromatic hydrocarbon levels at the time of sampling. However, residual TPH and THC in surface soils remain relevant for long-term soil monitoring. TOC was higher in surface soils than in subsurface soils in both seasons. The elevated TOC near the surface may reflect accumulation of hydrocarbon residues, organic matter retention, or slower decomposition under acidic conditions. Oil-impacted soils can show altered organic matter dynamics and increased organic carbon concentrations [24]. Total nitrogen was similar at both depths, with slightly higher values in subsurface soils during the dry season, suggesting possible nitrogen immobilization or reduced mineralization in surface soils affected by acidity and hydrocarbon residues.

Exchangeable cations showed modest concentrations across the study area. In the wet season, Ca, Mg, K, and total bases were generally higher in surface soils than in subsurface soils, whereas sodium concentrations were similar. In the dry season, exchangeable bases were also slightly higher in surface soils, while calcium differed only slightly between depths. These patterns suggest that some cation reserves remain despite the acidic status of the soils, but the absolute values are low and indicate a nutrient-poor condition [25]. Low calcium and potassium in oil-affected soils may impair crop productivity and soil fertility [26, 27].

5. CONCLUSION

This study evaluated the physicochemical characteristics and hydrocarbon concentrations of soils around the Tebidaba flow station, Bayelsa State, Nigeria, during the 2022 wet and dry seasons. The soils were strongly acidic and predominantly clay to clay loam, with slightly lower permeability and porosity in surface layers than in subsurface layers. TPH and THC were consistently higher in surface soils than in subsurface soils, reflecting the typical deposition pattern of petroleum residues near the soil surface. However, the concentrations recorded were relatively low compared with heavily contaminated oil-producing sites. BTEX concentrations were below detectable limits in all analyzed samples. These findings suggest that soils around the Tebidaba flow station are not presently experiencing substantial hydrocarbon contamination, although localized surface accumulation may occur due to operational activities. Continuous environmental monitoring is recommended to ensure early detection of potential contamination and to maintain soil quality within acceptable ecological limits.

DATA AVAILABILITY

Data will be made available upon reasonable request from the corresponding author.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

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