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(RESEARCH ARTICLE)

Environmental Analysis of Crude Oil-Contaminated Soils in Niger

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Abstract

This study examines the physicochemical properties of soils contaminated by crude oil in Niger, particularly at the Agadem site and along the pipeline corridor exposed to acts of sabotage. Grain size analyses show a predominance of sand (67–78%), accompanied by moderate proportions of silt (13–25%) and clay (8–10%), classifying these soils as silty sand to sandy silt. This texture, which is highly permeable and weakly adsorbent, promotes the infiltration and vertical migration of hydrocarbons. Chemically, the soils have variable organic matter (1.92–5.76%) and total nitrogen (0.12–0.32%) contents, while the high C/N ratio (9.10–10.57) indicates slow mineralisation. The levels of available phosphorus (2.50–17.20 mg/kg) and exchangeable potassium (0.01–0.04 ppm) reveal limited fertility, accentuated by a slightly acidic pH (5.11–5.25) and low conductivity (4–14 µS/cm). Total hydrocarbon (THC) levels, ranging from 3 to 10%, confirm significant pollution. The positive correlations between TPH and OM, N (r = 0.85–0.87) reflect an accumulation of poorly biodegradable carbon, while the association between C/N and TPH (r = 0.74) suggests a nutritional imbalance linked to microbial inhibition. Negative correlations with phosphorus and potassium (r = −0.30 and −0.19) indicate a decline in nutrient availability. Overall, the combination of sandy texture, acidity and low fertility makes these soils vulnerable, justifying remediation through phytoremediation and organic amendments.

Keywords: Environmental analysis; Contaminated soils; Total petroleum hydrocarbons (TPH); Soil texture; Bioremediation; Niger

1. Introduction

Soil pollution from crude oil is now a major environmental challenge in areas where hydrocarbons are explored, transported and processed. This contamination comes from leaks, accidental spills or acts of sabotage on pipelines, causing lasting damage to terrestrial ecosystems [1, 2, 3]. Once infiltrated, hydrocarbons profoundly alter the structure, pH, nutrient availability and biological capacity of the soil to regenerate [4]. These disturbances affect the fertility, agricultural productivity and self-restoration capacity of contaminated ecosystems [5].

In Niger, particularly in the Agadem region and along the export pipeline, sandy-loam Sahelian soils are highly vulnerable to oil contamination. Semi-arid climatic conditions, low organic matter content and high soil permeability promote the vertical dispersion of hydrocarbons, compromising soil fertility and ecological sustainability [6, 7]. Studying these impacted areas makes it possible to assess the effects of pollution on soil structure and composition and to guide rehabilitation actions appropriate to the Sahelian context.

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Environmental analysis of soil contaminated by crude oil not only allows the extent of pollution to be diagnosed, but also provides an understanding of its interactions with the physical and chemical properties of the soil. These interactions often result in the accumulation of non-biodegradable carbon, an imbalance in the C/N ratio, acidification and a reduction in nutrient availability [8, 9, 10]. Soil texture plays a decisive role in the retention or mobility of hydrocarbons: fine fractions (silt and clay) promote the adsorption and fixation of hydrocarbons due to their large specific surface area, while sandy soils promote their vertical migration and leaching [11]. Thus, textural properties appear to be a key factor in the trapping or dispersion of petroleum contaminants.

Chemically, the presence of hydrocarbons is often accompanied by an apparent increase in total carbon (C) and organic matter (OM), although this matter is largely non-biodegradable. This phenomenon leads to an imbalance in the C/N ratio, a decrease in assimilable phosphorus and disruptions in biogeochemical cycles, reducing soil fertility and regeneration capacity [9]. The quantification of total petroleum hydrocarbons (TPH) still relies heavily on conventional methods such as gravimetry, which is recognised for its robustness on heavy fractions, although it underestimates volatile compounds. Other chromatographic or infrared techniques can complement the analysis for more detailed speciation.

Recent research recommends integrated remediation approaches, combining bioremediation and phytoremediation with the addition of organic amendments (biochar, compost) and, if necessary, bioaugmentation [12, 13, 14]. These strategies are particularly effective in sandy soils with low cation exchange capacity, which are typical of the Agadem context [9]. However, studies detailing soil texture, chemical parameters (C, OM, N, P, K, pH, EC) and statistical correlations with TPH remain rare for Sahelian environments.

In this context, the present study aims to characterise hydrocarbon-contaminated soils in Niger in order to assess their textural and chemical alterations, identify correlations between total petroleum hydrocarbons (TPH) and soil parameters, and propose guidelines for ecological remediation adapted to Sahelian environments. This environmental analysis thus provides essential local data for understanding the dynamics of oil pollution and the sustainable management of impacted soils.

2. Materials and Methods

2.1. Study area

The study was conducted at the Agadem oil field (Figure 1) and along the pipeline corridor, located in the eastern Niger basin. This oil-producing region is one of the country's main production basins. It is crossed by the export pipeline linking Agadem to Zinder, a strategic infrastructure that is vulnerable to technical incidents and acts of sabotage. These events can cause hydrocarbon leaks, which are responsible for chronic contamination of the surrounding soil [6, 7].

The climate in the area is Sahelian with a semi-arid tendency, characterised by a prolonged dry season and a short rainy season. Temperatures are high throughout the year, and the vegetation consists mainly of sparse grasses. The soils, which are mainly sandy to sandy-loamy and poor in organic matter, are highly permeable, which promotes the mobility of hydrocarbons in the event of a spill. Figure 1 shows the area under study.

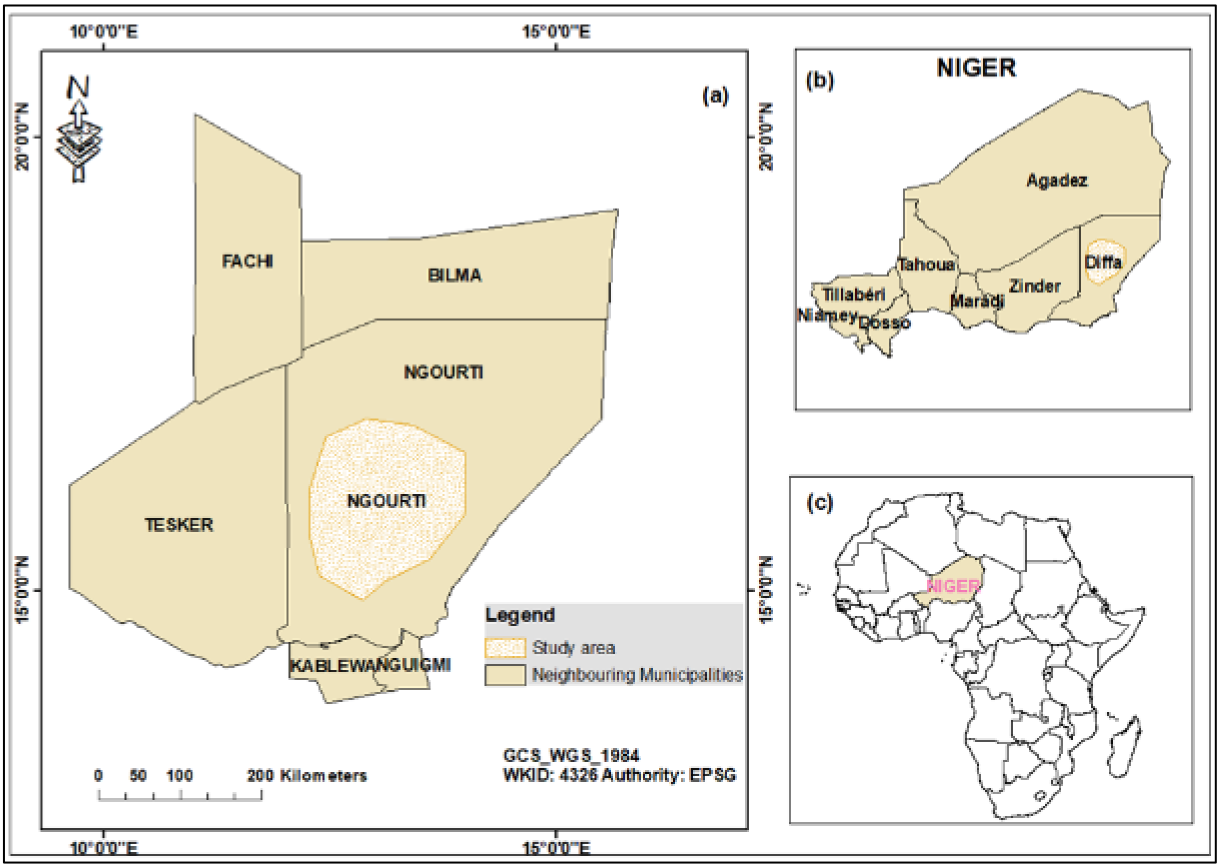


Figure 1 (a) Location of the study area, (b) in Niger and (c) in West Africa

2.2. Soil sampling

To ensure soil representativeness, samples were taken according to standardised protocols described in scientific and technical literature. Sub-samples (several homogeneous points) were combined to form composite samples, in accordance with the recommendations of the Soils4Africa protocol (0–20 cm) [15]. After homogenisation, the samples were dried, ground and sieved to 2 mm according to the practices described in the Gissol manuals [16]. In addition, the methodology follows FAO principles for labelling, sampling depth and sample storage [17]. These multiple approaches reduce sampling error and ensure good representativeness of the soil's physico-chemical parameters. These samples were analysed at the Soil and Surface Dynamics Laboratory (LSDS) of the Faculty of Agronomy at Abdou Moumouni University in Niamey and at the Research Laboratory in Geosciences and Environment at EMIG.

2.3. Particle size analyses

Soil texture was determined using the Robinson pipette method after dispersing the aggregates using a dispersant (sodium hexametaphosphate). This method is considered a benchmark for analysing soil particle size distribution, particularly for clay and silt fractions [18]. The percentages of clay, silt and sand were used to classify the soils according to the USDA textural triangle [19], which made it possible to distinguish dominant textures ranging from sandy loam to silty sand, indicating high permeability and low pollutant adsorption capacity.

2.4. Chemical analyses

Chemical analyses of the soil were carried out to determine the main parameters related to the quality and fertility of the contaminated soil. All measurements were carried out in accordance with the standard protocols described by [20] and AFNOR, in order to ensure the comparability and reliability of the results.

2.4.1. Organic carbon (C%)

Organic carbon was determined using the classic method described in [21], based on the oxidation of organic carbon by potassium dichromate ($K_2Cr_2O_7$) in a concentrated sulphuric acid medium, followed by titration with ferrous sulphate

($FeSO_4$). Although this method slightly underestimates refractory carbon-rich soils, it remains the benchmark for tropical and semi-arid soils.

2.4.2. Organic matter (OM%)

Organic matter was estimated from organic carbon by applying the conversion factor OM = C × 1.72, in accordance with the recommendation of the Soil Survey Staff [20]. This factor assumes that organic matter contains approximately 58% carbon.

2.4.3. Total nitrogen (N%)

Total nitrogen was measured using the Kjeldahl method, which involves acid digestion of the soil with concentrated sulphuric acid (H_2SO_4) in the presence of a catalyst ($CuSO_4$ + Se), followed by distillation with soda (NaOH) and titration with boric acid. This method quantifies total organic and ammoniacal nitrogen.

2.4.4. C/N ratio

The C/N ratio was calculated as the quotient between organic carbon and total nitrogen. This ratio is a key indicator of the degree of decomposition and availability of nitrogen in the soil, directly influencing the mineralisation of organic matter.

2.4.5. Assimilable phosphorus (P)

Assimilable phosphorus was extracted using the Bray I method, adapted for acidic soils. The extract was then analysed colorimetrically using the method described in [22], which is based on the formation of a blue molybdenum-phosphorus complex measured at 882 nm using a UV-Visible spectrophotometer.

2.4.6. Exchangeable potassium (K)

Exchangeable potassium was extracted using a 1 N ammonium acetate solution (pH 7) and then quantified by flame photometry. This method allows direct measurement of the potassium available to plants.

2.4.7. pH (H_2O)

The pH of the soil was measured in a soil/water suspension (1:2.5) after stirring for 30 minutes and decanting, using a digital pH meter calibrated at pH 4.00 and 7.00. This measurement reflects the overall reaction of the soil and its influence on nutrient availability.

2.4.8. Electrical conductivity (EC)

Electrical conductivity was determined on a soil/water suspension (1:5) using a conductivity meter. It expresses the total concentration of dissolved salts (mS/cm), which is an indicator of soil salinity and leaching.

2.5. Total petroleum hydrocarbon (TPH) analysis

The total petroleum hydrocarbon (TPH) content was determined by gravimetric extraction, a method still widely used in recent studies on contaminated soils. Several studies confirm the effectiveness of extraction with organic solvents, particularly n-hexane, followed by evaporation and weighing of the residue to quantify TPH. For example, procedures based on extraction with a DCM/hexane mixture, combining mechanical agitation, filtration and evaporation under gentle heat, have been described in the literature [23]. Similar protocols, based on the extraction of 10 g of dry soil with hexane followed by filtration and evaporation of the solvent before weighing the residue, have also been reported [24]. More recently, work based on the recommendations of the EPA 9071B method has confirmed the relevance of hexane extraction followed by evaporation concentration for the gravimetric determination of TPH [25]. Furthermore, a recent methodological review emphasises that gravimetry remains a reference technique for quantifying heavy hydrocarbons in soils due to its robustness and adaptability to heavily contaminated matrices [26].

2.6. Statistical analysis and correlation

The data were processed using Microsoft Excel, IBM SPSS Statistics 25 and ArcGIS software to produce maps. A Pearson correlation analysis was performed to assess the relationships between physicochemical parameters (C, OM, N, P, K, pH, EC) and TPH concentrations in order to identify possible interactions between contamination and soil quality [7]. The significance thresholds adopted were: $p < 0.10$ (significant trend), $p < 0.05$ (significant), $p < 0.001$ (highly significant). The results were presented in the form of a correlation matrix with coefficients and significance levels.

3. Results and discussions

3.1. Soil particle size distribution

The particle size distribution of the soils sampled in six (6) sections is presented in Table 1. It highlights the predominance of sandy fractions, characteristic of Sahelian soils, with varying proportions of silt and clay depending on the sampling points.

Table 1 Soil particle size distribution (%)

Sites	Clay	Fine lemon	Coarse limon	Fine sand	Medium sand	Coarse sand
S1	8.55	2.01	11.06	30.53	36.99	10.86
S2	8.05	11.57	7.54	25.90	36.81	10.13
S3	8.50	3.00	21.50	25.35	30.56	11.09
S4	10.11	4.05	14.16	22.24	36.34	13.10
S5	10.15	7.10	12.18	12.68	36.54	21.35

Site S1 has the highest proportion of fine sand (30.53%) and medium sand (36.99%), while site S5 has the highest proportion of coarse sand (21.35%). Site S2 shows a notable concentration of fine silt (11.57%), contrasting with site S3, which has the highest proportion of coarse silt (21.50%). Sites S4 and S5 have the highest clay content (10.11% and 10.15% respectively). These variations in the distribution of grain size fractions directly influence the retention and mobility properties of pollutants within each site.

Table 1 illustrates the textural classification of the samples according to the USDA triangle, which distinguishes between the dominant textures of silty sand to sandy silt. These classes reflect high permeability and low adsorption capacity, conditions that favour the vertical mobility of hydrocarbons in the soil profile. Table 2 presents the particle size distribution in three (3) ranges.

Table 2 Particle size distribution

Sites	CLAY (%)	LIMON (%)	SABLE (%)
S1	8.55	13.07	78.38
S2	8.05	19.11	72.84
S3	8.5	24.5	67
S4	10.11	18.21	71.68
S5	10.15	19.28	70.57

The grain size analyses carried out on five composite samples (S1–S5) reveal a clear dominance of the sand fraction, with proportions ranging from 67.00% (S3) to 78.38% (S1). Total silt (fine silt + coarse silt) varies from 13.07% (S1) to 24.50% (S3), while the clay fraction remains low, ranging from 8.05% (S2) to 10.15% (S5). Projection of the data onto the USDA texture triangle indicates that the five samples are mainly in the silt loam to sandy loam classes. More specifically, S1 is close to the silt loam limit, reflecting a very sandy texture characterised by a low proportion of fine particles, while S2, S3, S4 and S5 belong to the silty sand class, indicating a predominance of sand but with a sufficient proportion of silt (approximately 18 to 25%) to slightly increase the adsorption capacity compared to S1. These results confirm that texture, dominated by sand, plays a decisive role in the dynamics of hydrocarbon retention and transfer in Agadem soils, in line with the observations of [11].

The predominance of sand indicates the presence of relatively large pores and high permeability. These characteristics promote rapid water infiltration and facilitate the vertical migration of poorly adsorbed contaminants, thereby increasing the risk of transfer to the groundwater when it is shallow [27]. The low proportion of clay, combined with a moderate silt content, limits the specific adsorption surface area and therefore the ability of fine particles to retain hydrophobic contaminants. However, the more balanced texture of site S3, which has the highest silt content (approximately 24.5%), gives this soil a better relative ability to trap hydrocarbons and other organic compounds [28].

Sandy-loam soils are generally well aerated, which promotes aerobic microbial activity, but their low water retention capacity limits the persistence of a moist and nutritious environment essential for sustained biodegradation. To improve the performance of bioremediation processes in such contexts, the addition of organic amendments or appropriate water management is often necessary to maintain conditions favourable to microbial activity [29]. Finally, the low variation in clay, combined with moderate differences in silt and sandy grain size between sites, suggests the influence of local processes such as wind deposits, the nature of the parent material and microtopography. To better assess the vertical migration of hydrocarbons, it is recommended that this study be supplemented with stratified core sampling (0–20, 20–50, >50 cm) to examine the distribution of contaminants in the soil profile [30].

3.2. Chemical analysis

Table 3 presents the main chemical characteristics of the soils studied, including organic carbon (C), organic matter (OM), total nitrogen (N), C/N ratio, available phosphorus (P), exchangeable potassium (K), pH and electrical conductivity (EC).

Table 3 Chemical characteristics

Sites		Carbon %	MO %	Azote %	C/N	P (ass)	K (PPM)	pH(eau)	CE (µS/cm)	TPH %
S1		1.84	3.16	0.19	9.91	6.18	0.02	5.11	7	3
S2		3.35	5.76	0.32	10.57	2.50	0.02	5.25	6	10
S3		1.28	2.20	0.14	9.35	17.20	0.01	5.19	4	4
S4		1.12	1.92	0.12	9.10	2.50	0.04	5.14	14	5
S5		1.12	1.92	0.12	9.10	2.50	0.04	5.14	14	3

Chemical analyses of the soil show that the five composite samples have organic carbon contents ranging from 1.12% to 3.35%, while organic matter varies from 1.92% to 5.76%. Total nitrogen ranges from 0.12% to 0.32%, with a C/N ratio ranging from 9.10 to 10.57. These values reflect moderate mineralisation activity of organic matter, indicating a balance between carbon decomposition and stabilisation processes [31]. The low nitrogen content, combined with a predominantly sandy texture, suggests that the nitrogen fertility of these soils is naturally limited and probably exacerbated by the presence of hydrocarbons. Indeed, oil contamination often introduces non-biodegradable carbon, which artificially increases the apparent organic matter content without actually improving the nutritional quality of the soil [32].

The levels of available phosphorus vary greatly from one site to another, ranging from 2.50 mg/kg to 17.20 mg/kg, reflecting marked heterogeneity in local conditions. This variability may result from differences in the nature of the parent material, the mobility of phosphorus or its retention on metal oxides. The slightly acidic pH, ranging from 5.11 to 5.25, promotes the fixation of phosphorus on iron and aluminium oxides, thereby reducing its availability to plants. As for exchangeable potassium, it remains extremely low (0.01 to 0.04 ppm), which is characteristic of coarse-textured soils with low cation exchange capacity. Hydrocarbon pollution exacerbates this deficit by limiting ion exchange between the solid phase and the soil solution, a phenomenon already observed in several studies on contaminated sandy-loam environments [33].

The slightly acidic pH confirms a low buffering capacity, typical of soils poor in clay and stable organic matter. This moderate acidity limits the availability of certain essential nutrients and reduces the effective cation exchange capacity, thus affecting overall fertility. The electrical conductivity, between 4 and 14 µS/cm, indicates negligible salinity, suggesting that, despite the presence of hydrocarbons, ionic pollution remains low or that soluble ions are rapidly leached in these highly permeable profiles [31].

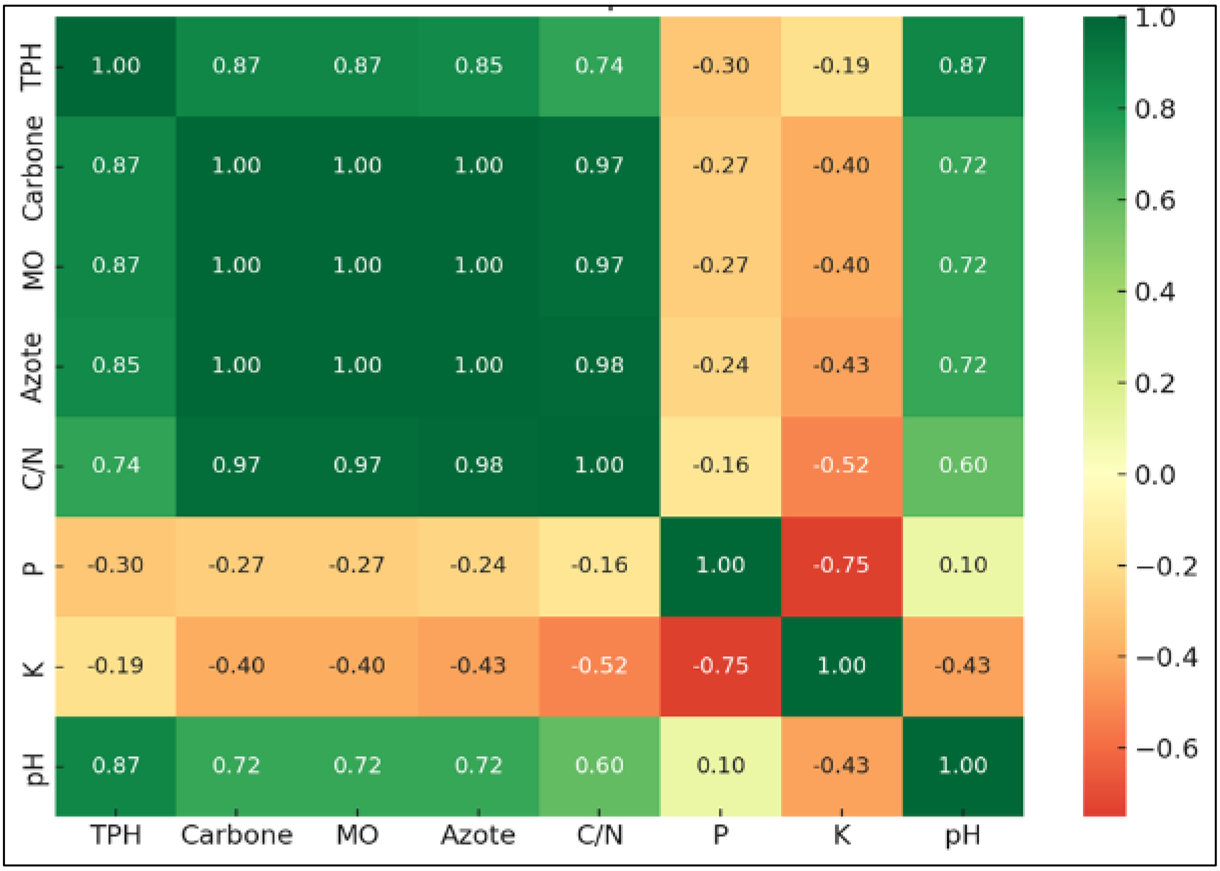
Total hydrocarbon (THC) levels, determined using the gravimetric method, vary from 3% to 10%. These levels indicate significant contamination, particularly at sites with levels close to 10%, where the physical and biological properties of the soil are clearly impaired. It should be noted, however, that the gravimetric method may underestimate light volatile fractions, but it remains a robust approach for assessing heavy hydrocarbon contamination in sandy soils.

Overall, the combination of a very sandy texture, a low proportion of clay and silt, a moderately acidic pH and low nutrient content shows that these soils are particularly vulnerable to oil contamination. The presence of hydrocarbons exacerbates this fragility by altering soil structure, disrupting biogeochemical cycles and reducing water and nutrient retention capacity. These results highlight the need to adopt integrated remediation strategies, including the addition of organic amendments and the implementation of phytoremediation using adapted local species, in order to restore the ecological functions of the soil and limit the migration of pollutants to deeper horizons.

The levels observed reveal marked variability between sampling points. Carbon and organic matter concentrations are generally high in areas with high TPH content, while phosphorus and potassium levels are low, indicating a decline in the chemical fertility of contaminated soils.

3.3. Pearson correlation between the analysed parameters

Figure 2 illustrates the Pearson correlation matrix between TPH and the physico-chemical parameters of the soil in the form of a heat map. This visual representation allows the identification of linear relationships between variables, where intensity and colour (green for positive correlations, red for negative correlations) reflect the strength and direction of the associations, highlighting the indicators most sensitive to oil contamination.



	TPH	Carbone	MO	Azote	C/N	P	K	pH
TPH	1.00	0.87	0.87	0.85	0.74	-0.30	-0.19	0.87
Carbone	0.87	1.00	1.00	1.00	0.97	-0.27	-0.40	0.72
MO	0.87	1.00	1.00	1.00	0.97	-0.27	-0.40	0.72
Azote	0.85	1.00	1.00	1.00	0.98	-0.24	-0.43	0.72
C/N	0.74	0.97	0.97	0.98	1.00	-0.16	-0.52	0.60
P	-0.30	-0.27	-0.27	-0.24	-0.16	1.00	-0.75	0.10
K	-0.19	-0.40	-0.40	-0.43	-0.52	-0.75	1.00	-0.43
pH	0.87	0.72	0.72	0.72	0.60	0.10	-0.43	1.00

Figure 2 Correlation matrix (heatmap) between soil physicochemical parameters

The correlations observed between soil physicochemical parameters (Figure 2) show clear relationships between hydrocarbon contamination (TPH) and the organic and nutrient properties of soils. The dark green areas of the heatmap indicate strong positive correlations, particularly between TPH, total carbon (r = 0.87), organic matter (r = 0.87) and total nitrogen (r = 0.85), reflecting a strong interdependence between contamination and apparent enrichment in carbon compounds. This behaviour is often attributed to the accumulation of petroleum-derived carbon and the adsorption of hydrocarbons onto existing organic matter, which artificially increase total carbon without improving actual soil fertility [8, 32].

The C/N ratio also shows a notable positive correlation with TPH (r = 0.74; $p < 0.10$), indicating a nutrient imbalance in contaminated areas. This increase in C/N reflects a slowdown in the mineralisation of organic matter, typical of environments where hydrocarbons block microbial activity and reduce the bioavailability of nitrogen [9].

Conversely, assimilable phosphorus (P) shows a negative correlation (r = − 0.30) with TPH, reflecting a reduction in its availability in contaminated soils. This phenomenon is linked to the fixation of phosphorus on metal oxides and the disruption of the biogeochemical cycle of P in the presence of hydrocarbons [8]. Exchangeable potassium (K) also shows a more pronounced but insignificant negative correlation (r = − 0.19), indicating low ion retention in these sandy-loam soils with low cation exchange capacity [34].

The pH shows a significant positive correlation with TPH (r = 0.87; $p < 0.10$), suggesting a slight alkalisation of the most contaminated soils. This behaviour may result from the presence of bases produced by the partial degradation of hydrocarbons or from a reduction in acidogenic microbial activity [8]. However, as electrical conductivity (EC) is not significantly correlated with TPH, it does not appear to be a relevant indicator of oil contamination in these highly permeable soils.

Overall, the significant correlations ($p < 0.10$ and $p < 0.001$) between TPH and organic variables (OM, N) confirm that increased contamination is accompanied by a disruption of nutrient cycles, particularly the C/N ratio and phosphorus. These interactions reflect a functional loss of soil and justify the implementation of integrated decontamination strategies, such as phytoremediation assisted by organic amendments, promoting the restoration of biogeochemical cycles and the stimulation of hydrocarbonoclastic microflora [8].

3.4. Textural ratio and TPH

Figure 3 illustrates the main relationships between TPH and textural parameters, highlighting the most significant trends and their level of significance.

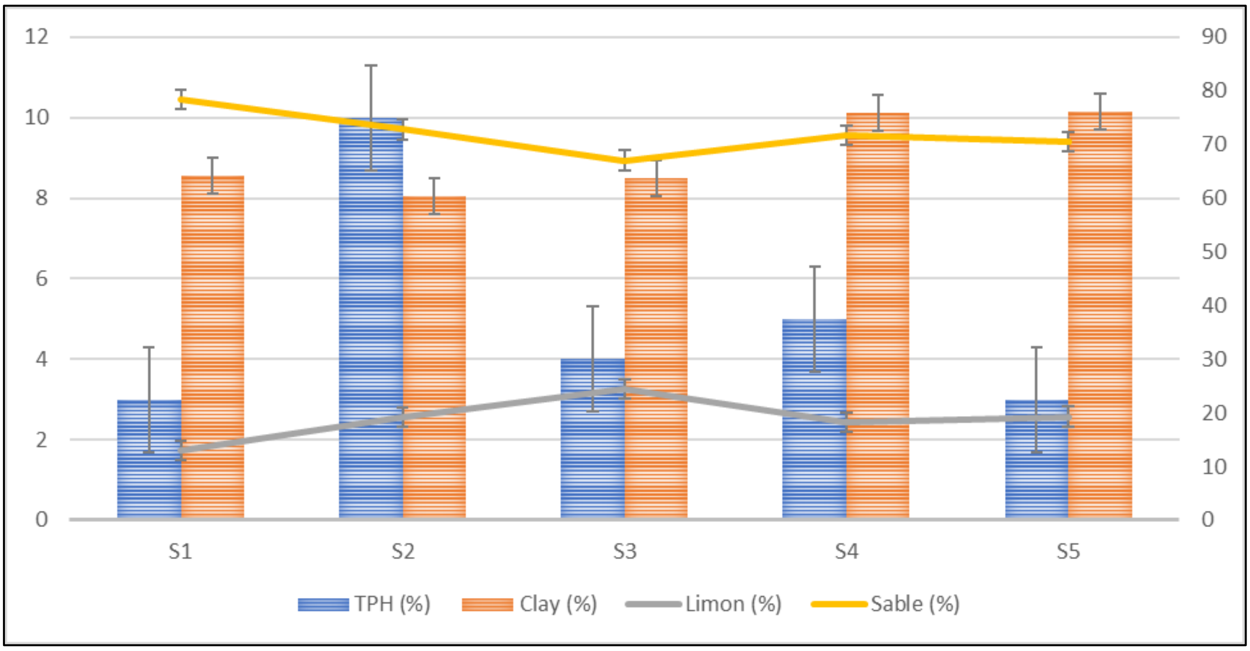


Figure 3 Grain size distribution and TPH concentrations across study sites

Comparative visualisation reveals a significant inverse relationship between sand content and hydrocarbon concentration. Site S2, which has the highest contamination (10% TPH), is characterised by the lowest proportion of sand (73%) and the highest silt content (19%) among all samples.

Fine soil fractions (silt) promote hydrocarbon retention by increasing specific surface area and adsorption capacity; this trend has been documented by [28, 35], unlike predominantly sandy soils where high permeability facilitates the leaching of pollutants.

The homogeneous distribution of clays (8-10%) across all sites suggests that the variability in TPH content is mainly controlled by the silt fraction, confirming the importance of textural properties in trapping petroleum contaminants.

Overall, granulometric, chemical and correlational analysis reveals that the combination of sandy texture, low nutrient content and high hydrocarbon contamination compromises the quality and resilience of Agadem's soils. These results provide an essential scientific basis for choosing remediation strategies adapted to the Sahelian context.

4. Conclusion

This study enabled an in-depth environmental analysis of soil contaminated by crude oil in Niger, through a multidimensional characterisation combining physical and chemical properties and specific contamination by total petroleum hydrocarbons (TPH). The approach adopted, combining analytical measurements and statistical correlations, highlighted the interdependence between texture, chemical composition and hydrocarbon retention dynamics in the soil.

The results show high contamination (3–10% TPH) in predominantly sandy soils, characterised by pronounced acidity (pH 5.1–5.3) and a deficiency in essential nutrients (N, P, K). The positive correlations between TPH, organic matter and total carbon reflect an accumulation of non-biodegradable organic compounds, while the relationships observed with pH and the C/N ratio highlight the importance of physicochemical conditions in the persistence of hydrocarbons.

This integrated environmental assessment justifies the use of bioremediation strategies adapted to Sahelian environments, including pH correction (liming), balanced fertilisation and targeted microbial biostimulation. The results obtained provide a solid scientific and decision-making basis for guiding policies for the sustainable management and ecological restoration of soil polluted by crude oil in Niger.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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