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The Impact of oil contamination on soil hydrophobicity and physico-chemical properties around Bandar Abbas oil refinery, Hormozgan Province, Iran

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Abstract

Background: The leakage of oil, in addition to negative environmental effects such as groundwater contamination, causes changes in the geotechnical characteristics of the soil.

Methods: The soil hydrophobicity test was carried out using the Water Drop Penetration Time (WDPT) method in the contaminated places, and soil samples with minimum corrosion were collected, and some physical and chemical properties of the soils were measured. To evaluate the stability of the soil structure, wet sieving and mechanically dispersible clay (MDC) methods were used, and the mean weighted diameter (MWD) and geometric mean diameter (GMD) indicators of soil grains and MDC were calculated.

Results: The results showed that the amount of TOC and TPHs in the soils around the refinery was found to be 68.16 ± 3.18 and 37.27 ± 2.22 percent, respectively. The results indicated that the increasing impact of oil contamination on MWD and GMD and its decreasing impact on MDC were statistically significant. A significant positive correlation was obtained between hydrophobicity and GMD in soils. But the densities of TPHs more than 6.4% in the soil led to a decrease in MWD and GMD, which can be due to the increase of anionic repulsion between clay particles and functional groups of hydrocarbons.

Conclusion: Although hydrophobicity increased the stability of the soil structure in oil-contaminated places compared to the control places, the severe decrease in soil water retention caused by oil contamination creates unfavorable conditions for the green spaces of the soils around Bandar Abbas oil refinery.

Keywords: Soil hydrophobicity, Stability, Hydrocarbons, Oil pollution, Environmental pollution prevention

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Introduction

In the middle of the 1980s, the presence of oil contaminants in the soil was recognized as a critical environmental issue in the world (1,2).

The release of petroleum products into the soil during extraction, transportation, and treatment properties alters soil quality from biological (3,4), chemical, and also, physical (5) aspects, including permeability, hydraulic conductivity, and water retention in the soil (6). Furthermore, oil contamination in the soil causes a decrease in plant growth and a change in electrical conductivity, pH, organic carbon, apparent density, and porosity (7).

Hydrophobicity is considered a key phenomenon in the physical stability of the soil (8). Despite the negative consequences of the hydrophobicity phenomenon (9), this phenomenon also has positive consequences, such as due to the presence of hydrophobic coatings (surfaces with low to medium hydrophobicity) on the soil grains (10). The decomposition of the soil grains caused by the force of the trapped weather is also reduced (11), and the erosion of the soil is to some extent decreased as well (12). Arcenegui et al (13) also found that with the presence of hydrophobic coatings on soil grains, the stability of soil grains increases and soil erosion decreases. Furthermore, investigations demonstrate that the positive consequences of hydrophobicity on the stability of soil grains with a size of 0.5 to 5 mm are higher and have no effect on the stability of larger soil grains (14). Hydrophobic compounds in the long run also cause the formation of clay-humic complexes and thus increase the stability of soil grains, especially the large molecules of the humic part, such as aliphatic and aromatic compounds, which significantly increase the stability of soil grains (15). The presence of hydrophobic organic compounds in the soil increases the water-soil contact angle (16), so water absorption is done slowly, and it prevents the disintegration of soil grains as a result of the rapid entry of water (17,18). Keller and Håkansson (19) found that Hydrocarbon oil sludge increased the porosity of the soil. These researchers attributed the increase in porosity of the soil to the increase in the frequency of 500-50 μm pores. Roy and McGill (20) reported that the presence of crude oil in soils caused severe hydrophobicity and also reduced the stability of soil structure compared to contaminated soils with hydrophilic oil. Oil hydrocarbons in high concentrations, in addition to intensifying hydrophobicity, reduced the stability of soil grains (21).

More recent attention has focused on the provision of effects of refineries in making the soil water-repellent (22,23). However, despite severe oil contamination and contamination caused by refineries and related industries, little research has been conducted on the impact of oil contamination on the hydrophobicity and stability of soil structure in Iran (24).

This study was conducted to investigate the effect of oil contamination on soil hydrophobicity and physico-chemical properties around Bandar Abbas oil refinery, Hormozgan province, Iran. The presence of oil stains on the surface of the refinery's soil has been reported recently (25), and the field evidence also shows that the soils around the oil refinery have been contaminated with oil compounds for many years (26). Over time, the plant cover of the soil around the oil refinery has also been affected (25). It is probable that due to the impact of contamination on the soil structure and the subsequent change in the hydraulic condition of the soil, the plants in the region have been exposed to moisture stress, and the plant cover has been destroyed over time.

Materials and Methods

Study area

This study was conducted in the area around Bandar Abbas Oil Refinery Co., which is located at the coordinates of 27.174184°N 56.078298°E, in the west 30 km away of Bandar Abbas city, Hormozgan province, Iran.

This company is one of the 9 Iranian petroleum refining companies that started with a capacity of 232,000 BPD (barrels per day) in July 2008. As of 2020, it is the third-largest refinery in Iran after Abadan and Isfahan refineries. Currently, its stated capacity exceeds 320,000 BPD (27). The soil of the refinery has an aridic moisture regime and a hyperthermic thermal regime, and the climate of the dry region. The refinery aquifer is contaminated with hydrocarbons due to leaks from tanks and facilities (28).

Sampling

To study the impact of oil contamination on the water and soil of this region, experiments were conducted in both field and laboratory units. According to accessibility in the study area and its entire cover, a total of 18 points were randomly selected within four parallel transects, where 15 points were selected with different degrees of visible oil pollution, around Bandar Abbas refinery, Kaveh Steel Co., Al-Mahdi Aluminum and Special Economic Zone and three points were selected as controls (Figure 1 and Table 1). Control points were selected far from the source of oil pollution and based on their similarity to contaminated sites in terms of basic soil characteristics such as texture, organic matter, structure, lime content, etc.

Combined sampling was performed so that the central point and four surrounding points were sampled at 5-meter intervals. These five samples were then mixed together, and a composite sample was taken. Sampling was done from surface soil at a depth of 0 to 10 cm. After transfer to the laboratory, the soil samples were dried and passed through a 4 mm sieve without tapping to measure hydraulic and structural properties.

As, sampling refers to the process of selecting a representative subset of a larger population or material for analysis or testing. Following quality control and quality assurance (QC/QA) standards during both sampling and transportation ensures the reliability and accuracy of the data obtained from those samples. This involves implementing specific procedures and checks throughout the entire process, from sample collection to delivery at the testing facility.

To ensure the reliability and accuracy of the data obtained from the collected samples, both the sampling process and subsequent transportation were conducted in accordance with established Quality Control and Quality Assurance (QC/QA) standards. This involved implementing specific protocols and systematic checks throughout all stages of the workflow—from the initial sample collection in the field to their secure delivery to the analytical laboratory. These measures were designed to minimize contamination, preserve sample integrity, and maintain traceability, thereby enhancing the credibility of the analytical results.

Measurement of physical and chemical properties of soil

To measure the soil texture, the oil compounds were first eliminated in the oven. Regarding the high amounts of lime in the soil and the adverse effects that high temperatures (more than 360°C) have on the amount of lime in the soil and the relative frequency of soil particles, the elimination of soil organic substances was performed at 360°C for 2 hours, and oxygenated water was used to completely eliminate the remaining organic compounds in the soil. Then, the soil texture was determined by the

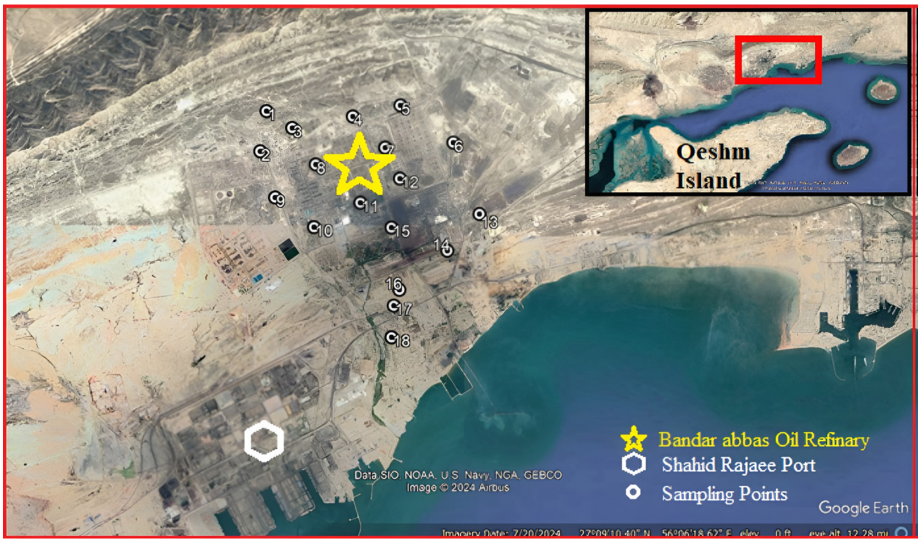

Figure 1. Location of sampling points in the study area.

Table 1. UTM coordinates of the soil sampling points

Sampling Point	X	Y	Sampling Point	X	Y
1	3007735.34	406713.40	10	3004865.00	407703.00
2	3006690.45	406409.67	11	3005668.35	409092.35
3	3007319.00	408131.00	12	3006060.61	409843.72
4	3007719.89	408838.67	13	3005310.27	411835.66
5	3007838.00	409927.00	14	3004486.40	411121.18
6	3007050.82	411366.96	15	3004882.32	410069.15
7	3006696.96	409442.61	16 (Control)	3004222.16	409734.95
8	3006504.91	407764.17	17 (Control)	3003993.44	408611.00
9	3005522.65	407016.18	18 (Control)	3003526.39	407604.51

pipette method (24,29).

The residual acid titration method with half-normal sodium hydroxide (reversible titration) was used to measure the soil calcium carbonate equivalent. Soil organic matter was measured by wet oxidation or Walkley–Black method as reported by Nelson and Sommer (30).

The TOC-Analyzer (Primacs model, Skular Co.) was used to measure the total organic carbon (TOC) in contaminated and non-contaminated water (31).

To measure total poly-hydrocarbons (TPHs) in contaminated soils, Soxhlet and two normal-hexane and dichloromethane extractors, at a ratio of 1:1, were used as reported by Briedis et al (31).

High-performance liquid chromatography (HPLC) was used to measure water's TPHs after liquid extraction.

Measurement of soil structure stability

The stability test of the soil structure was conducted by the wet sieving method. For this purpose, sieve series of 0.05, 0.1, 0.25, 0.5, 1, and 2 mm were used. 50 grams of soil (without crushing) passed through a 4 mm sieve was placed on the largest sieve. The sieves were moved up and down in water for 10 minutes with a transfer of 1 cm and 45 rpm. Then, the residual soil grains were washed on each sieve and weighed after oven-drying. Also, the rectification related to the amount of sand was conducted using equation 1. After that, the mean weight diameter (MWD) of stable soil grains in water was calculated from Equation (2) (31).

$$W_i = \frac{W_{i(g+s)} - W_{i(s)}}{W_T - \Sigma_{i=0}^{n} W_{i(s)}} \quad (1)$$

$$MWD = \sum_{i=1}^{n} W_i \overline{X_t} \quad (2)$$

In Equation (1), $W_{i(g+s)}$ is the mass of soil grains together with sand and gravel in the desired range, $W_{i(s)}$ is the mass of sand and gravel in the desired size range, W_T is the mass of the total dry soil, and W_i is the weight ratio of soil grains in the desired range. In Equation 2, $\overline{X_i}$ is the arithmetic mean of the diameter of soil grains in each range. Also, the geometric mean diameter (GMD) of soil grains, which is stable in water, was calculated using Equation (3) (32). In this equation, W_i and $\overline{X_i}$ are the same factors in Equation (2).

$$MD = \exp\left(\sum_{i=1}^{n} W_i \log \overline{X_i}\right) \quad (3)$$

Where W_i is the weight ratio of soil grains in the desired range and $\bar{X}_i$ is the arithmetic mean of the diameter of soil grains in each range.

Mechanical dispersible clay (MDC) was also measured as an indicator of the microstructure instability of the soil using Rengasamy et al (33) method. By so doing, a 1:10 suspension of water and soil was prepared with 50 grams of soil passed through a 2 mm sieve and 500 ml of distilled water, and was stirred back and forth for 1 hour at 65 rpm, and then, was transferred to 1-liter jars. After 24 hours, the samples were stirred by a hand stirrer, and the temperature of the suspensions was recorded by a thermometer. After 3 hours and 50 minutes (according to Stokes' law), sampling was done with a 25 ml pipette from a suspension depth of 5 cm, weighed after oven-drying, and MDC was calculated based on the amount of total clay of the soil.

Saturated hydraulic conductivity (Ks)

Saturated hydraulic conductivity (Ks) of soil samples was measured using the constant load method and Equation 4 based on the Darcy's law (34).

$$K_s = \frac{QL}{At\Delta\varphi h} \quad (4)$$

Where Q is the volume of water (cm^3), L is the length of the soil sample (cm), A is the cross-sectional area of the soil (cm^2), t is the time (hours), and $\Delta\varphi h$ is the difference in hydraulic potential between the two ends of the soil sample.

Statistical analysis

Data normality was checked separately for each metal at each point using a one-sample Kolmogorov-Smirnov test, which revealed normal distribution of the data in all cases and the need to use parametric statistics.

For the statistical analysis of the effect of oil pollution on soil structural parameters (MWD, GMD, MDC), hydraulic parameters such as saturated hydraulic conductivity (Ks) were used from an unbalanced two-way grouping scheme.

Statistical analyses of the unbalanced two-way grouping scheme with four groups of soil texture (loam, clay loam, sandy loam, and loamy sand) and four levels of soil contamination (control, TPHs < 3%, 6% > TPHs > 3%, and TPHs > 6%) were used. Minitab 16 and SAS 9 software were used for statistical analysis.

Results

In Table 2, the statistical description of some chemical and physical characteristics of the soils of the region is presented. These data confirm that the soil texture of the study area is mostly medium to light, so that the loam attribute is seen in all names. Due to the proximity to the coast, the percentage of sand in these soils is high, and the amount of gravel in all the soil samples was found to be high and almost equal (Table 2).

The comparison of contaminated soil treatment with control soil sample for EC, pH, BD, TOC, and OM parameters using t-test showed that the mean of soil organic matter (t_{value} = 4.47) and TOC (t_{value} = 9.32) in contaminated treatments are significantly different from the control treatment (P < 0.001).

The impact of oil contamination on soil hydrophobicity (WDPT)

Table 3 demonstrates the total amount of polyhydrocarbons and WDPT in contaminated soils. Contaminated soils were highly and extremely hydrophobic. TPH values of soils vary from 2.41 to 9.44%.

The relationship between WDPT with TPHs/Clay and TOC was calculated as follows.

Table 2. Statistical description of the physical and chemical characteristics of the investigated soils in and around the Bandar Abbas oil refinery

Soil characteristics	Unit	Min.	Max.	Average	SE	CV	Skewness	Kurtosis
Dry soil density	Mg m^{-3}	1.59	-0.14	11.86	0.18	1.46	1.65	1.15
Reference soil density	Mg m^{-3}	0.48	-0.88	7.75	0.15	1.37	1.46	1.05
Relative soil density	-	-1.59	-0.23	13.83	0.16	1.26	1.47	1.06
Clay	%	1.21	1.31	26.68	6.76	16.11	31.64	8.50
Silt	%	0.58	0.47	38.88	13.54	26.26	49.35	4.43
Sand	%	-1.29	0.29	26.26	15.39	51.43	66.43	35.42
Organic matter	%	-0.37	0.83	97.15	5.24	6.17	14.26	0.27
Calcium carbonate	%	1.46	-1.11	2.35	1.57	39.76	35.43	39.20
MWD	mm	-1.18	0.45	56.15	0.58	0.88	2.06	0.11
GMD	mm	-1.32	0.38	18.08	0.32	0.91	1.13	0.58
MDCI	%	-0.67	0.74	68.77	0.38	0.63	1.45	0.24
MDC_2	%	-0.17	1.12	59.83	2.49	4.16	9.06	1.26
TOC	%	-1.39	0.29	68.16	3.18	4.76	8.35	0.27
TPHs	%	-0.56	0.26	37.27	2.22	5.48	8.27	2.42

Table 3. General specifications, TPHs values, and hydrophobicity severity in contaminated soils of the study area

Sample No.	Sand (%)	Clay (%)	Silt (%)	TOC (%)	$CaCO_3$ (%)	Oc (%)	TPHS (%)	WDPT (S)	Hydrophobicity Severity
1	61.0	12.7	26.3	5.12	41.7	5.23	3.48	871	Severe
2	40.0	19.2	40.8	9.17	42.8	14.11	7.98	3241	Severe
3	68.8	14.6	16.6	6.01	45.1	9.18	4.21	1625	Severe
4	73.0	8.4	18.6	8.27	41.0	16.28	6.02	4681	Infinite
5	55.4	17.2	27.4	5.13	46.7	4.37	2.25	798	Severe
6	42.7	17.8	39.5	5.28	44.4	5.34	2.13	982	Severe
7	41.1	21.5	37.4	6.16	45.3	8.78	5.37	1306	Severe
8	32.8	21.7	45.5	8.98	46.2	15.13	9.84	3114	Severe
9	70.2	16.9	12.9	5.23	45.2	5.13	6.52	3186	Severe

Log WDPT = 1.5607 (TPHs/Clay) + 2.5121 and Log WDPT = 1.127 (TOC) + 2.4611

This equation confirms that there is a logarithmic increase with the increase of TPHs or TOC. Moreover, the relationship between WDPT with the ratio of the total polyhydrocarbons to clay (TPHs/Clay) and total organic carbon TOC is shown in Figure 2.

The impact of oil contamination on soil pore size distribution

The results showed that the effect of oil pollution on increasing coarse porosity of soil was significant ($P < 0.001$). Furthermore, the effect on reducing fine porosity was significant ($P < 0.01$). However, the effect of oil pollution on average porosity was not significant ($P > 0.01$) (Figure 3). All three levels of oil pollution increased soil coarse porosity compared to the control treatment. Also, contamination was significantly reduced in the small pores of the soil by more than 6% compared to the control treatment. Our analysis also revealed significant correlations between soil porosity characteristics and organic carbon indices ($P < 0.01$).

The effect of oil pollution on soil saturation hydraulic conductivity

Oil pollution caused an increase in the saturated hydraulic conductivity (K_s (lab)) of the studied soils, but it was not significant at the 5% statistical level. However, there is a positive correlation between organic indices, including OM, TOC, and K_s(Lab) (Figure 4).

The impact of oil contamination on soil structure stability (MWD, GMD, and MDC)

The two groups of soils with lower contamination levels (TPHs < 6%) did not significantly differ from the control treatment, and only high contamination had a significant impact on reducing the MDC of soils. However, the impact of soil texture was not significant on any of the indicators of soil structure stability. Figure 5-a shows that the highest MDC was in soils with no contamination (control), and the lowest MDC was in soils with TPHs > 6%. Moreover, the oil contamination at levels of 6% > TPHs > 3% and TPHs > 6% caused a significant increase in soil grain stability (MWD) (Figure 5-b). The impact of oil contamination on GMD was also significant, so oil contamination in all three levels caused a significant increase in the geometric mean diameter (GMD) of soil grains stable in water (Figure 5-c).

Correlation of soil structure stability and organic indicators

The correlation matrix reveals significant relationships between soil organic components and structural stability indicators ($P < 0.001$). The analysis demonstrates a particularly strong positive correlation between organic matter (OM) and total organic carbon (TOC) ($r = 0.89$, $P < 0.001$), indicating these organic parameters are closely interdependent in the studied soil system.

Soil structural stability, as represented by MWD and GMD of aggregates, showed significant positive correlations with both TOC (MWD-TOC: $r = 0.75$; GMD-TOC: $r = 0.64$) and OM (MWD-OM: $r = 0.63$; GMD-OM: $r = 0.89$). These strong relationships suggest that organic components play a crucial role in maintaining and enhancing soil aggregate stability, likely through the binding action of organic compounds and microbial activity. Interestingly, mechanical dispersible clay (MDC) exhibited contrasting relationships with other parameters. While showing a moderate positive correlation with MWD ($r = 0.64$) and GMD ($r = 0.48$), MDC displayed a significant negative correlation with TOC ($r = -0.61$). This inverse relationship suggests that increased clay dispersibility may be associated with reduced organic carbon content, possibly due to preferential erosion of carbon-rich clay particles or reduced carbon stabilization in more dispersible clay systems.

The particularly strong correlation between GMD and OM ($r = 0.89$) highlights the importance of organic matter in maintaining aggregate structure across different size classes. These results collectively emphasize the critical role of organic components in soil structural stability while revealing complex interactions with clay mineralogy

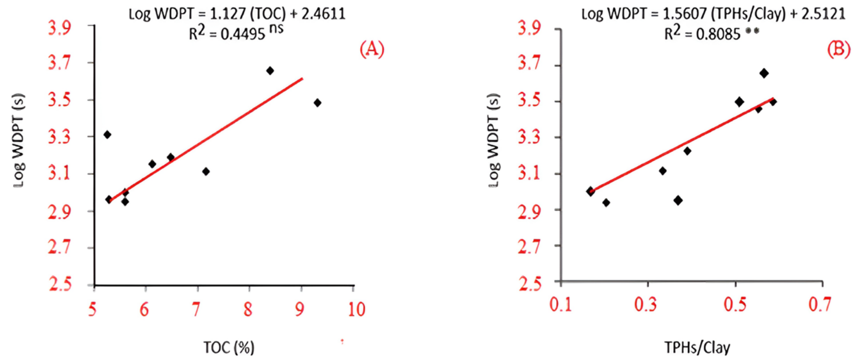

Figure 2. Impact of TOC oil contamination on (A) TPHs/Clay and (B) on water repellency or water droplet penetration time (WDPT) in the contaminated soils under study

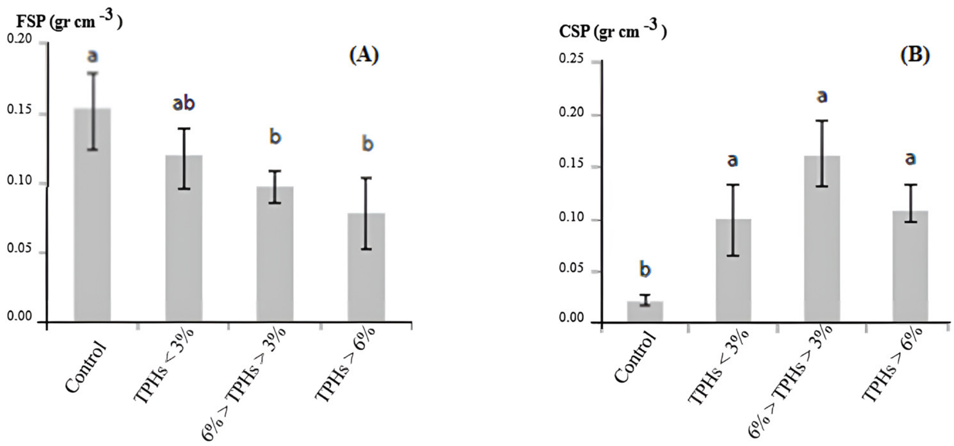

Figure 3. The effect of different levels of oil contamination on (A) fine and (B) coarse (b) porosity in the soils

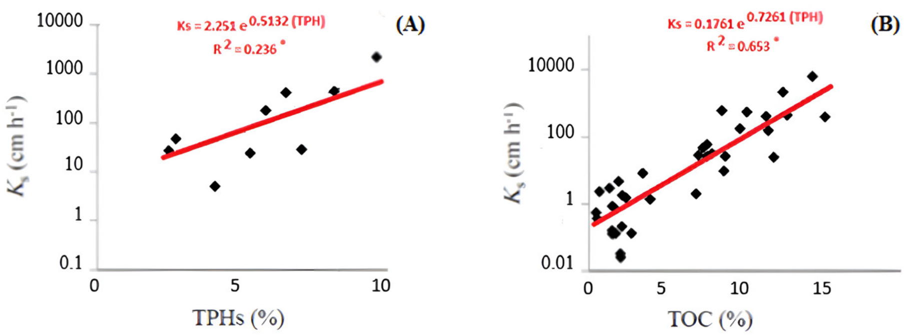

Figure 4. The effect of total pollution indices of soil organic polyhydrocarbons (A) and total soil organic carbon (B) on saturated soil hydraulic conductivity in laboratory conditions

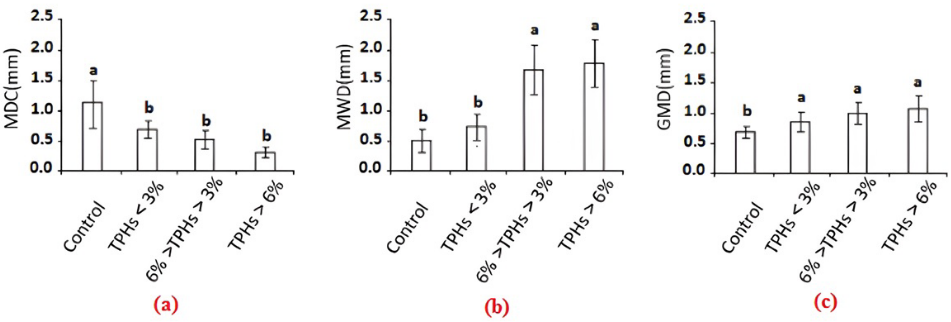

Figure 5. The impact of oil contamination levels on soil structure stability indicators, including: a) mechanical dispersible clay, b) weighted mean of diameter of soil grains, and c) geometric mean of diameter of soil grains

that warrant further investigation. The findings support management practices that enhance soil organic matter as a means to improve overall soil structural quality.

By increasing the total soil polyhydrocarbons (TPHs) up to about 6.4%, GMD and MWD increased, which is due to the increase in the stability (size) of soil grains caused by oil contamination, but for TPHs more than 6.4%, oil contamination has caused a decrease in the weighted mean and size of stable soil grains in water (Figure 6).

In addition to the relationships presented in this study, regarding the influence that clay particles have on stability indicators of soil structure, dividing TPHs by clay percentage removes the impact of texture on soil structure stability. It can be observed that with the increase in TPHs/Clay in contaminated soils, the MWD and GMD indicators have also increased. Therefore, the indicators of soil structure stability increase with the increase in the hydrocarbon compounds.

To determine the effect of oil pollution on the infiltration of unsaturated water into the soil, the percentage of reduction in final infiltration volume resulting from increased oil pollution in two types of loamy and olefin soils with the same percentage of gravel on the surface was investigated. The results showed that for the first contaminated soil TPHs (maximum equal to 8.27%) and the second contaminated soil TPHs (minimum equal to 2.42%) decreased the volume of infiltrated water by 72.75% and 64.93%, respectively, compared to the control treatment.

Correlation of stability indicators of structure with soil hydrophobicity

The relationship between the GMD difference in contaminated and control samples and hydrophobic stability (WDPT) was significant at the 5% statistical level (Figure 7).

Discussion

Oil compounds are among the most important organic contaminants of the environment, especially soil (9), which due to their toxicity, the entry of these compounds into the food chain, their carcinogenic attributes for living organisms, and the contamination of underground and surface water resources have become one of the most significant concerns of environmental advocates (35,36). On the other hand, this cluster of organic contaminants is so stable in the soil that their gradual accumulation in the soil over time causes disturbances in the natural function of the soil, such as a decrease in the performance of agricultural products and changes in the characteristics of contaminated soils (1). In granular soils, these changes occur primarily in physical properties, while in fine-grained soils (37). Therefore, to examine the impact of oil contamination on soil hydrophobicity and its relationship with soil structural stability, this study was conducted in the soils around Bandar Abbas oil refinery.

In terms of dry apparent soil density, a significant difference was observed between the polluted soil and the control treatment at a statistical level of 5%. Furthermore, in terms of soil electrical conductivity in polluted soils, there is no statistically significant difference with the control treatment at the 5% significance level. This means that oil pollution did not have a significant effect on increasing or decreasing the soil's electrical conductivity. Also, as total soil polyhydrocarbons increased, WDPT increased logarithmically.

Clay particles, with a high specific surface area, affect the physical and chemical properties of the soil (38). Even small amounts of clay particles in soil decrease the impact of organic compounds on hydrophobicity (39). For this reason, by dividing TPHs by the amount of clay, the impact of soil texture on soil hydrophobicity is eliminated and controlled to some extent. Also, as the total organic carbon (TOC) increased, soil hydrophobicity increased logarithmically. Since uncontaminated soil generally has little organic matter, the increase in total organic carbon in contaminated soils is due to the presence of oil compounds (36). Oil contains aliphatic compounds, which are non-polar molecules with partial positive or negative charges only at the end of their hydrocarbon chain (40). Thus, these compounds do not dissolve in water and cover the surfaces of soil grains in the form of water-repellent coatings (10), and by increasing the water-soil contact angle, they prevent the penetration of water drops into the soil (41). Furthermore, the fluid part of the oil leads to the hydrophobicity severity by flowing on the soil surfaces (36). Over time, tiny molecules evaporate, and the resulting steam creates an organic layer on the surface of the particles and the walls of the pores, and the soil's cracks. Also, the steam resulting from the volatile compounds forms a crust on the surface of the soil, which reduces the moisture content of the soil (42).

Based on the relationships between soil porosity and organic carbon dynamics, a positive correlation was observed between total porosity and TOC ($P<0.05$), suggesting that well-aerated soils with greater pore connectivity facilitate organic matter accumulation. This aligns with established theories linking macropore

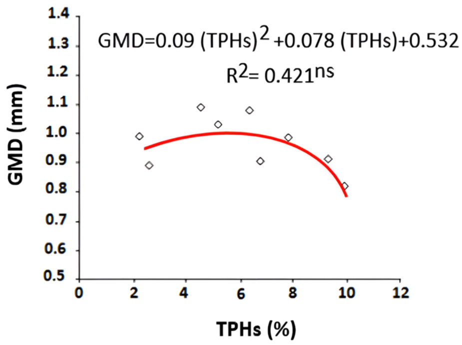

Figure 6. The total effect of TPHs on the GMD of water-stable soil grains.

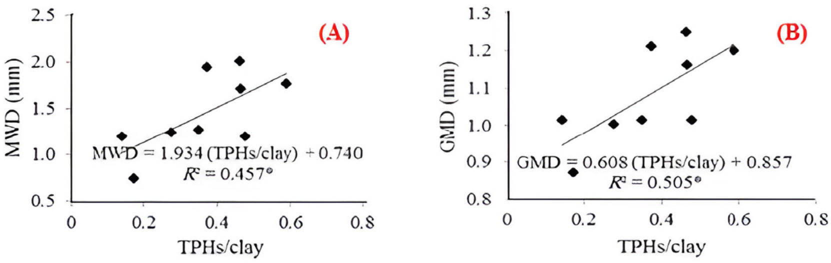

Figure 7. Impact of hydrophobicity severity (WDPT/Clay) on: a) ∆MWD and b) ∆GMD between contaminated and control soil samples

dominance (e.g., SCP) to enhanced root growth and microbial activity, which collectively promote carbon input and stabilization (43).

Conversely, fine soil porosity (SFP) exhibited negative correlations with TOC (r = −0.21, *ns*) and total organic matter (TOM) (r = −0.51, $P < 0.01$). These results imply that fine-textured soils may limit organic carbon sequestration due to restricted oxygen diffusion and reduced microbial decomposition rates (44). Notably, SFP also correlated negatively with coarse porosity (SCP; r = −0.36, $P < 0.01$), highlighting a trade-off between pore size classes that could influence carbon cycling pathways. The strong positive association between TOM and TOC (r = 0.82, $P < 0.01$) underscores organic matter as the primary carbon reservoir. Medium porosity (SMP) showed no significant relationships, possibly reflecting its transitional role in water retention and aeration. These findings suggest that soil management strategies targeting pore-size distribution (e.g., reduced tillage to preserve macropores) could optimize carbon sequestration. Future work should quantify pore-size thresholds and microbial community dynamics to refine these relationships.

The results of the study on the impact of oil contamination on soil pore size distribution showed that oil pollution increases the abundance of large pores in the soil, which is due to the effect of hydrocarbons on the stability of coarse porosity, change of the pores shape and size of the soil grains in the long term. This finding was also reported by Aghajani et al (45). However, contrary to the general idea, some organic compounds play a role in the stability of the soil structure (46). The presence of some organic ions from folic acid and citric acid compounds greatly increases dispersible clay (DC) and strongly decreases the stability of soil grains (47). Some organic anions, such as fulvate, citrate, oxalate, lactate, and acetate, increase dispersible clay and decrease the stability of soil structure (48). There is also a significant positive correlation between organic compounds, such as aromatic humic substances, and the stability of soil grains (49,50). The presence of humic acid in the soil causes the physical retention of particles in the size range of clay and silt (51). However, studies show that the total soil organic carbon and the total carbohydrates in the soil do not directly cause the stability of the soil structure. Nevertheless, with the increase in the soil organic carbon, the dispersible clay content decreases (52).

According to the field data results, oil pollution has caused a decrease in Ks, which differs from the laboratory results. In the field tests, the soil is dry, intact (compacted), and contains gravel. The saturated hydraulic conductivity of the soil is calculated using extrapolation and modeling rather than being measured directly. However, in the laboratory, the soil samples are saturated, and then the saturated hydraulic conductivity is estimated. This is why the results obtained from the field data using laboratory methods provide different estimates of the saturated hydraulic conductivity (53).

The increase in the concentration of polyhydrocarbon compounds had a positive effect on the stability of the soil structure. The results of the statistical analysis indicate that the impact of oil contamination on mechanical dispersible clay (MDC) has become significant at the 1% statistical level, which is consistent with the findings of Kermanpour et al (24).

Based on the results, by increasing the concentration of oil hydrocarbons, the stability of the soil structure increased. Hydrocarbon compounds in the soil include alkanes with long chains and some cyclic compounds with high molecular weight. In addition to creating hydrophobicity, these compounds do not dissolve easily in water and form complexes with soil mineral particles; therefore, they help mix soil particles, and the dispersion of clay is reduced in wet conditions. Therefore, the stability of the soil structure is maintained in moist conditions. On the other hand, in addition to organic substances, lime also plays a crucial role in maintaining the stability of the soil structure. The presence of oil contamination appears to enhance the impact of lime on the soil structure stability, possibly due to the formation of strong complexes with calcium ions in the soil. Hydrocarbon compounds also help the stability of the soil structure by creating water repellency. These substances, by creating hydrophobic hydrocarbon coatings on the surfaces of the soil grains, inhibit water from entering them, and the impact of trapped air in breaking the soil grains is decreased. One of the positive consequences of hydrophobicity due to oil contamination is the stability of soil structure units (soil particles). Kermanpour, Mosaddeghi (24) found that the presence of water-repellent coatings on soil grains increases their stability, thereby reducing soil erosion.

Another important finding is that the decrease in MDC and the increase in MWD and GMD with increasing OM and TOC indicate an increase in the stability of oil-contaminated soil structure. Goebel, Bachmann (54) reported that the increase in the organic substance in soil increases the stability of soil grains. The values of the correlation coefficient indicate that the impact of TOC on the stability of soil structure is greater than that of OM. Within a particular context, Dexter, Richard (55) reported that the impact of carbonaceous organic compounds on the stability of soil structure depends on their presence in the soil. When carbonaceous organic compounds become complex with soil particles, they have a greater impact on soil structure stability than uncomplex organic compounds (56). Regarding the aging of oil waste (approximately 10 to 15 years) in the soils surrounding the oil refinery, the stability of the soil structure may increase over time due to the complexation of clay particles with hydrocarbon compounds. Investigations have shown that one of the effects of hydrophobicity is the positive impact of hydrophobic compounds on soil structure stability (57).

Another finding that stands out from the results reported earlier is that with the increase of oil contamination, the anionic repulsion between the functional groups of oil compounds and soil clay particles, which prevents the aggregation of soil grains, is probable. Roy and McGill (21) reported that the MWD indicator decreased severely in soils that were contaminated with crude oil for a long period, indicating the destructive effect of severe oil contamination on the soil structure. This finding is the result of the interaction of the long-term effects of oil contamination and soil micro-organisms and mineral particles, as described by Bungau et al (58) and Biswas et al (59).

Based on the correlation of stability indicators of structure with soil hydrophobicity, the positive correlation of GMD with organic factors OM and TOC suggests that as hydrophobic stability increases, GMD also increases in contaminated soils compared to control soils. Therefore, hydrocarbon compounds, in addition to increasing the stability of the structure and the size of stable soil grains in water, have also contributed to an increase in stable soil grains in water through hydrophobicity. Despite the increasing effect of TPHs on GMD up to the contamination level of 6.4% and its decreasing effect on TPH values greater than 6.4%, the influence of oil contamination on the stability of soil structure through hydrophobicity in severely hydrophobic soils (characterized by severe oil contamination) exhibited an increasing trend.

Conclusion

Hydrocarbon contamination leads to an increase in soil hydrophobicity and a decrease in moisture retention in sandy soils. Even the presence of a layer of organic compounds on the soil's surface can significantly reduce its water absorption feature. The type of plant cover, soil usage, humidity, features, and type of soil are also factors that influence the occurrence and intensity of water repellency. A comprehensive understanding of the distribution of oil-contaminant compounds in contaminated areas and the relationship between oil contamination of the soil and physical, geochemical, and biological properties is crucial for the rehabilitation and reconstruction of contaminated areas.

The present research aimed to examine the impact of oil contamination on the physicochemical properties of soils around the Bandar Abbas oil refinery, in Hormozgan Province, Iran. Taken together, these results suggest that:

1) As a result of oil contamination in the soils surrounding the Bandar Abbas oil refinery, soil hydrophobicity has been created, and with the increase in the total concentration of hydrocarbons, independent of soil texture, soil hydrophobicity (WDPT) has intensified. The presence of hydrocarbons in the soils surrounding the oil refinery over many years, combined with the aging of these compounds, led to the stability of the soil structure in water by increasing the frequency of stable soil grains in water and by creating the phenomenon of hydrophobicity in the soil. Examining the impact of contamination on the indicators of soil structure stability (MWD, GMD, and MDC) revealed that as the concentration of hydrocarbons in the soil increased, MWD and GMD indicators also increased, while the MDC indicator decreased.

2) Concentrations higher than 6.4% of total polyhydrocarbons in the soil caused a decrease in MWD and GMD, which can be due to the increase in the anionic repulsion between clay particles and the functional groups of hydrocarbons. In other words, a high amount of hydrocarbons prevents the aggregation of soil grains. Although the severity of hydrophobicity caused an increase in the stability of the soil structure of the soils around the oil refinery (increase in MWD and GMD and decrease in MDC) in oil-contaminated places compared to control places, hydrocarbons (organic substances) have caused an increase in the size of soil grains and as a result, an increase in large pores in the soil and a severe decrease in water retention. Therefore, unfavorable conditions for the green space of the soil around the oil refinery have been created. Over time, this has led to the destruction of the plant cover of the soil surrounding the Bandar Abbas oil refinery.

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Competing interests

The authors declare that they have no conflict of interest.

Ethical issues

The authors hereby certify that all data collected during the study are as stated in the manuscript. This manuscript is the original work of the authors, and no data from the study has been or will be published separately elsewhere. This article was extracted from a PhD thesis approved by the Soil Science Department, Faculty of Agriculture, Islamic Azad University, Isfahan branch (Approval thesis code: 17548128799729513991). It has no ethical issues.

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