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Impact of Petroleum Industry Activities on Basic Soil Physical and Chemical Properties: A Case Study PT Pertamina EP Cepu Bojonegoro, Indonesia

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ABSTRACT

Petroleum industrial activities have the potential to alter soil physical and chemical properties through various contamination mechanisms and operational processes. This research aimed to evaluate the impact of PT Pertamina EP Cepu petroleum industrial activities on basic physical and chemical soil properties in areas surrounding operations. The study was conducted from October to November 2025 using a descriptive survey approach with purposive sampling method. Soil samples were collected at 0-20 cm depth from 12 sampling points located within a ± 200-meter radius in four cardinal directions (North, East, South, and West) from the operational center. Physical properties analyzed included soil texture, bulk density, and porosity, while chemical properties included pH, C-Organic, total N, available P, exchangeable K, and electrical conductivity (EC). Data analysis was performed descriptively by comparing laboratory measurement results with soil property assessment criteria established by Balai Penelitian Tanah to categorize each parameter and identify soil quality degradation levels in the research area. The results showed that soil in the research area had clay texture (67% clay fraction), high bulk density (1.47 ± 0.21 g/cm³), moderate porosity (44.5%), neutral pH (6.7 ± 0.2), very low C-Organic (0.99 ± 0.07%) and total N (0.07 ± 0.01%), high available P (28.64 ± 2.22 mg/kg) and exchangeable K (0.94 cmol(+)/kg), and moderately high EC (3.9 dS/m). These findings indicate that petroleum operational activities have caused soil quality degradation, particularly through soil compaction and reduction in organic matter content. Appropriate soil management interventions, including organic matter addition, traffic management, and contamination remediation, are essential to restore and maintain soil quality in petroleum operational areas.

Keywords: Petroleum Industry, Soil Compaction, Organic Matter, Hydrocarbon Contamination, Soil Quality Degradation

1. INTRODUCTION

Indonesia is the largest oil and gas producer in Southeast Asia, with stable gas production reaching 6 Bcf/day over the past two decades to offset declining oil production (Szymczak, 2024). PT Pertamina EP Cepu in Bojonegoro, East Java, represents one of the oil fields with significant reserves, conducting various activities including exploration, drilling, production, processing, and transportation. Soil contamination by petroleum hydrocarbons contains several types of hydrocarbons, including aliphatic and aromatic structures, which can alter soil properties such as texture, moisture, conductivity, and total C-Organicarbon (Kuppusamy et al., 2017).

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Soil productivity is significantly influenced by physical, chemical, and biological soil properties that interact within complex systems (Zhang et al., 2025). Evaluation of soil conditions through physicochemical parameters is crucial, as changes in soil properties can affect nutrient availability, root growth, and ultimately land productivity. Soil pollution in petroleum operational areas can occur through various mechanisms such as crude oil spills, seepage from storage facilities, drilling waste, and particulate deposition from gas flaring. This hydrocarbon contamination can degrade soil quality by altering soil properties (Kanungo et al., 2024).

Research on the impact of oil contamination on soil properties has been extensively conducted and demonstrates significant changes in physical and chemical soil properties. Oil pollution causes alterations in soil physical and chemical properties at various levels, where contaminated soils form unique microbial species compositions (Li et al., 2022). Research in the Momoge wetlands of China indicated that crude oil contamination can increase soil pH up to 8.0 and reduce available phosphorus concentrations in soil (Liu et al., 2010). Most previous studies have focused primarily on direct contamination impacts from oil spills or have been conducted in non-tropical regions with different soil types and climatic conditions (Lassalle et al., 2019).

Comprehensive studies regarding the impact of PT Pertamina EP Cepu activities on soil properties in areas surrounding operational sites remain very limited, particularly on Vertisol soils in tropical regions. Unlike previous research that predominantly examined contamination effects in isolation, this study evaluates the combined impacts of both mechanical disturbance from heavy equipment traffic and potential hydrocarbon contamination on Vertisol soil properties. Furthermore, the unique characteristics of Vertisol soils with 2:1 clay minerals and high shrink-swell capacity may respond differently to petroleum industrial activities compared to other soil types commonly studied in temperate regions (Zavala-Cruz et al., 2013). The persistence of soil contamination after oil activities remains a major environmental issue in tropical regions, where assessment is particularly difficult on vegetated sites with dense vegetation cover (Lassalle et al., 2019). Therefore, specific studies are necessary to understand the comprehensive impact of petroleum activities on soil ecosystems in tropical operational areas, providing baseline information crucial for developing region-specific environmental management strategies.

This research is important to provide baseline information regarding the physical and chemical properties of soil in areas surrounding PT Pertamina EP Cepu operations. Evaluation of soil property parameters is expected to provide a comprehensive overview of the level of soil quality changes due to petroleum activities. This information can be used as a reference in

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formulating environmental management strategies and soil remediation in petroleum industrial areas (Mohanta et al., 2024). This research aims to evaluate the impact of PT Pertamina EP Cepu petroleum industrial activities on basic physical and chemical soil properties in areas surrounding operations.

2. RESEARCH METHOD

Time and Location of Research

The research was conducted from October to November 2025. Soil sampling was carried out in areas surrounding PT Pertamina EP Cepu operations, Bojonegoro Regency, East Java, Indonesia. Soil analysis was performed at the Laboratory of State Polytechnic of Lampung.

Research Design and Soil Sampling

This study employed a survey research design with a descriptive approach. Soil sampling was conducted using purposive sampling method within a radius of ± 200 meters from the center of PT Pertamina EP Cepu operational area. The 200-meter radius was selected to represent the zone of direct influence from petroleum operational activities, including potential hydrocarbon deposition, and mechanical soil disturbances. This distance corresponds to the typical extent of soil property alterations observed in previous petroleum industry studies and encompasses the area where operational impacts are most pronounced (Obiadi et al., 2021). Additionally, this radius allows for assessment of immediate operational impacts while excluding influences from distant natural variability or other anthropogenic activities, and remains within practical sampling accessibility. Sampling points were established based on four cardinal directions: North, East, South, and West to represent the spatial distribution of soil conditions around the operational area..

Soil sampling was performed at a depth of 0-20 cm using a soil auger with a diameter of 5 cm. At each cardinal direction, three soil samples were collected, resulting in a total of 12 sampling points. Soil samples at each point were collected as composite samples from several sub-samples within a 2-meter radius. Composite soil samples were placed in plastic bags and then stored in a cool box for transportation to the laboratory.

Soil Analysis

The parameters analyzed included physical and chemical soil properties. Physical soil properties analyzed encompassed soil texture determined by the pipette method, bulk density measured using the gravimetric method, and total porosity calculated based on bulk density and particle density values.

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Chemical soil properties analyzed included soil pH measured using a pH meter, C-C-Organi content determined by the Walkley and Black method, total N using the Kjeldahl method, available P by the Bray I method, and exchangeable K determined using the NH_4OAc 1N pH 7 extraction method. Additionally, electrical conductivity (EC) was measured using a conductometer.

Data Analysis

Laboratory analysis data from soil samples were presented descriptively in tabular form. Data interpretation was conducted by comparing measured parameter values with soil property assessment criteria to identify soil quality conditions in areas surrounding PT Pertamina EP Cepu operations.

3. RESULTS AND DISCUSSION

Analysis of Soil Properties

The results of physical and chemical soil property analysis in areas surrounding PT Pertamina EP Cepu operations are presented in Table 1. Soil conditions in the research area demonstrate diverse soil property characteristics across several parameters.

Table 1. Results of Physical and Chemical Soil Property Analysis

Soil Properties	Value	Category
Texture		
Sand %	14	-
Silt %	19	-
Clay %	67	-
Texture Class		Clay*
Bulk Density (g/cm^3)	1.47 ± 0.21	-
Porosity (%)	44.5	-
pH (H_2O)	6.7 ± 0.2	-
C-Organic (%)	0.99 ± 0.07	Very Low*
N-Total (%)	0.07 ± 0.01	Very Low*
Available P (mg/kg)	28.64 ± 2.22	High*
Exchangeable K (cmol(+)/kg)	0.94	High*
EC (dS/m)	3.9	High*

*Categories based on Balai Penelitian Tanah (2023) criteria

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Physical Soil Properties

Soil texture at the research location falls into the clay category with a clay fraction content of 67%, silt 19%, and sand 14%. Clay texture with very high clay fraction content (>60%) represents a characteristic feature of Vertisol order soils found at the research location. Vertisols are soils dominated by 2:1 type clay minerals such as montmorillonite or smectite, which possess high swelling and shrinking capacity. Vertisol soils typically contain clay content ranging from 50-70% (Soil Survey Staff, 2014). According to Liu et al. (2010), clay-textured soils have higher water retention capacity compared to other textures; however, their permeability and aeration are relatively lower. Type 2:1 clay minerals in Vertisols have very large specific surface areas (approximately 800 m^2/g), providing high cation exchange capacity (CEC). The dominant clay texture also influences soil water dynamics, nutrient availability, and soil response to hydrocarbon contamination in petroleum operational areas.

Soil bulk density in the research area shows a value of 1.47 ± 0.21 g/cm^3, which falls into the high category; the ideal bulk density value is less than 1.10 g/cm^3 (USDA NRCS, 2008). The high bulk density value indicates that soil compaction has occurred in areas surrounding PT Pertamina EP Cepu operations. The characteristics of Vertisol soils with high clay content and type 2:1 minerals make these soils susceptible to compaction, especially when soil is in dry conditions. The swelling and shrinking properties of Vertisols can exacerbate compaction conditions when soil experiences repeated wet-dry cycles. According to Atuanya & Akpomuvie (2014), petroleum activities cause an increase in soil bulk density from 1.42 g/cm^3 to 1.58 g/cm^3 in soils in petroleum operational areas in Nigeria. Soil compaction negatively impacts plant growth by inhibiting root penetration, water infiltration, and air exchange in soil. Soil porosity at the research location shows a value of 44.5%, which is still categorized as good. Despite the relatively high bulk density, the porosity value that remains good indicates that soil still has sufficient pore space for air exchange and water movement. However, it should be noted that ideal soil porosity is approximately 50%, so the value of 44.5% is approaching a threshold that requires attention.

Chemical Soil Properties

Soil pH value at the research location shows 6.7. This pH value is within a good range for plant growth. The pH value of 6.7 at the research location indicates that despite petroleum activities, soil pH remains in relatively stable condition and has not experienced drastic changes that could disrupt nutrient availability. Soil C-Organic content shows a very low value of 0.99%. The low C-Organic content indicates minimal organic matter in soil in the research area. Soil

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organic matter plays an important role in maintaining soil structure, cation exchange capacity, and soil microorganism activity. Hydrocarbon contamination can inhibit organic matter decomposition and reduce soil microorganism activity, ultimately decreasing soil C-Organic content. Research by Kanungo et al. (2024) demonstrated that hydrocarbon contamination can alter soil properties, including reducing active C-Organicarbon content in soil.

Total N content in soil also shows a very low value of 0.07%. Nitrogen is an essential macronutrient element required for plant growth. The low total N content indicates limited nitrogen availability to support plant productivity. Hydrocarbon contamination can inhibit nitrogen mineralization processes in soil due to disrupted soil microorganism activity. Soil microorganisms will utilize available nitrogen to degrade hydrocarbons, thereby reducing nitrogen availability for plants.

Available P content shows a value of 28.64 mg/kg, which falls into the high category. The relatively high pH is favorable for phosphorus availability in soil. Maximum phosphorus availability occurs at soil pH between 6.5-7.0 (Penn & Camberato, 2019). At the soil pH of 6.7 found at the research location, phosphorus is in optimal condition for availability because at this pH range, phosphorus does not experience strong fixation by aluminum and iron as in acidic soils, nor precipitation with calcium as in alkaline soils. Phosphorus availability remains in good condition, supported by optimal soil pH and Vertisol soil characteristics with high CEC.

Exchangeable K content shows a value of 0.94 cmol(+)/kg, which falls into the high category. The high exchangeable K content indicates good potassium availability for plants at the research location. The high exchangeable K is closely related to Vertisol soil characteristics with type 2:1 clay content and high cation exchange capacity (CEC). Smectite minerals in Vertisols have excellent ability to adsorb and exchange cations such as K^{+}, Ca^{2+}, Mg^{2+}, and Na^{+}. This explains why, despite several soil fertility parameters showing low values, exchangeable K content remains high due to support from the high CEC of Vertisol clay minerals.

EC (Electrical Conductivity) value shows 3.9 dS/m, which falls into the moderately high category. The moderately high EC value indicates an increase in dissolved salt content and ions in soil solution. Hydrocarbon contamination can increase soil EC value due to the release of ionic compounds from hydrocarbon degradation and microorganism activity. Research by Wyszkowski & Ziółkowska (2008) demonstrated that oil contamination increases soil electrical conductivity, indicating increased dissolved salt content. High EC values can negatively impact plant growth by causing osmotic stress that inhibits water and nutrient uptake by plant roots.

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Soil Quality in the Research Area

Overall, soil conditions in areas surrounding PT Pertamina EP Cepu operations indicate soil quality changes that require attention. Parameters showing suboptimal conditions include high bulk density, very low C-Organic and total N, and moderately high EC. These parameters indicate soil quality degradation due to petroleum operational activities, both through soil compaction by heavy vehicles and potential hydrocarbon contamination.

High bulk density conditions can inhibit plant root growth and reduce water infiltration, ultimately impacting land productivity. Soil compaction not only reduces root growth and limits access to important resources in deeper soil layers but also has significant impacts on water infiltration, gas exchange, microbial activity, and soil water retention capacity (Nawaz et al., 2013). Land also potentially faces crop yield losses in compacted soils ranging from 20% to 75% during dry seasons (Correa et al., 2019).

Low C-Organic and total N content indicates minimal soil fertility and limited availability of essential nutrients for plants. Soil organic matter plays an important role in maintaining soil structure, increasing cation exchange capacity, and supporting soil microorganism activity responsible for nutrient cycling (Lal, 2020). Moderately high EC values indicate increased salt content that can cause plant stress and inhibit water and nutrient uptake by plant roots.

Nevertheless, several parameters such as available P and exchangeable K show high values, and soil pH remains within a good range for plant growth. This indicates that soil in the research area still has potential for proper management through implementation of appropriate soil management practices. Management practices that can be applied include organic matter addition to increase C-Organic and improve soil structure, reduction of soil compaction through heavy vehicle traffic regulation, and hydrocarbon contamination remediation if necessary (Hamza & Anderson, 2005). Organic matter addition will make soil more resilient to surface and subsurface compaction and increase soil microorganism activity important for nutrient cycling. From a practical operational perspective, these findings have important implications for the petroleum industry. PT Pertamina EP Cepu and similar operations should implement designated traffic routes for heavy vehicles and establish hardened access roads to minimize soil compaction, particularly during wet conditions when Vertisol soils are most vulnerable due to their high plasticity. Controlled traffic farming systems, where machinery operates on permanent traffic lanes, have been demonstrated to confine soil compaction to smaller field portions and improve soil resilience (Chamen et al., 2015). Regular soil quality monitoring protocols, especially for bulk density and

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EC values, should be established as early warning systems to identify degradation before it becomes irreversible.

For areas already experiencing severe compaction (bulk density >1.5 g/cm³), deep tillage or subsoiling operations combined with organic matter incorporation are recommended to break compacted layers and restore soil structure. In areas with elevated EC values, phytoremediation using salt-tolerant plant species such as Atriplex spp. or Suaeda spp. can be implemented to reduce soil salinity while providing vegetation cover (Qadir et al., 2007). The very low organic matter content requires systematic application of organic amendments at rates of 20-30 tons per hectare annually for at least three years to restore C-organic levels above 2%, which is the minimum threshold for maintaining adequate soil biological activity (Bot & Benites, 2005). For potential hydrocarbon contamination, bioremediation techniques using hydrocarbon-degrading microorganisms combined with bioaugmentation and biostimulation approaches have proven effective in tropical conditions, particularly when integrated with organic matter addition that serves dual purposes of enhancing microbial activity and improving soil structure (Varjani, 2017).

Despite the observed degradation, the retention of high Available P and Exchangeable K values demonstrates that Vertisol soils maintain inherent fertility characteristics that can be leveraged during rehabilitation efforts. This indicates that with proactive management interventions during operational periods—combining traffic management, organic matter addition, and regular monitoring—these soils have good recovery potential. Implementation of such preventive measures is economically beneficial as subsoil compaction effects can persist for more than five years and are difficult to correct through deep loosening operations (Alakukku, 1996), thereby reducing the financial burden of extensive post-closure remediation and supporting both economic and environmental sustainability goals.

4. CONCLUSIONS

Petroleum activities at PT Pertamina EP Cepu have caused notable changes in several soil properties. Physical soil properties showed clay texture (67% clay fraction) characteristic of Vertisol soils, with high bulk density (1.47 ± 0.21 g/cm³) and porosity (44.5%), indicating soil compaction in the operational area. Chemical soil properties demonstrated neutral pH (6.7 ± 0.2), very low C-Organic content (0.99 ± 0.07%) and total N (0.07 ± 0.01%), high available P (28.64 ± 2.22 mg/kg) and exchangeable K (0.94 cmol(+)/kg), and moderately high EC (3.9 dS/m). These findings indicate that petroleum operational activities have negatively impacted soil quality,

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particularly through soil compaction and potential hydrocarbon contamination, which reduced organic matter content and increased soil salinity.

Despite the degradation observed in several parameters, soil in the research area still possesses potential for recovery through appropriate management interventions. Specific remediation actions are recommended based on the study findings, including implementation of controlled traffic systems with designated routes for heavy vehicles and hardened access roads to prevent further soil compaction, particularly during wet conditions when Vertisol soils are most vulnerable. Application of organic amendments at rates of 20-30 tons per hectare annually for a minimum of three years is necessary to restore C-Organic content above 2%, while deep tillage or subsoiling operations combined with organic matter incorporation should be conducted in severely compacted areas with bulk density exceeding 1.5 g/cm³. Regular monitoring protocols for bulk density and EC values should be established as early warning systems to identify degradation before it becomes irreversible. For areas with elevated EC levels, phytoremediation using salt-tolerant plant species such as Atriplex spp. or Suaeda spp. is recommended to reduce soil salinity, while bioremediation techniques using hydrocarbon-degrading microorganisms integrated with bioaugmentation approaches should be applied in areas with hydrocarbon contamination. The retention of high available P and exchangeable K values demonstrates that Vertisol soils maintain inherent fertility characteristics that can be leveraged during rehabilitation efforts, indicating good recovery potential with proactive management. These findings provide essential baseline information for developing environmental management strategies and soil conservation programs in petroleum industrial areas operating on Vertisol soils in tropical regions.

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