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Evaluation of Physical and Chemical Soil Quality to Support Post–Oil Mining Land Rehabilitation in PT. Bumi Siak Pusako

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ABSTRACT

Oil and gas mining activities conducted within conservation areas require careful post-mining land management to ensure the recovery of ecological functions. The Zamrud Oil Field operated by PT Bumi Siak Pusako is located within the buffer and utilization zones of Zamrud National Park, Riau Province, where post-mining land degradation has become a critical environmental concern. This study aimed to evaluate the physical and chemical properties of soils in post–oil mining areas as a basis for formulating sustainable land rehabilitation and environmental management strategies. The evaluation was conducted through field surveys and purposive soil sampling at inactive oil wells, representing two land conditions: initial condition (pre-mining reference) and production condition (post-mining). Soil physical parameters analyzed included soil texture, bulk density, particle density, and total porosity, while chemical parameters comprised soil pH, organic carbon, total nitrogen, C/N ratio, available and potential phosphorus, exchangeable potassium, base cations, and cation exchange capacity. Laboratory results were analyzed descriptively by comparing soil conditions between the two land conditions. The results indicated that post–oil mining areas experienced a decline in soil quality, characterized by increased soil compaction, reduced porosity, low organic matter content, and limited nutrient availability. Although soil pH in production areas tended to increase due to the influence of mineral materials, this change was not accompanied by improvements in soil fertility. These conditions limit soil functionality as a growing medium and constrain natural vegetation recovery. The findings highlight the need for integrated soil rehabilitation measures, including organic matter enrichment and phytoremediation, to support sustainable land management in post–oil mining areas within conservation zones.

1. INTRODUCTION

Soil is a fundamental component of terrestrial ecosystems that plays a crucial role in sustaining ecological processes, supporting plant growth, and maintaining environmental stability. As a dynamic natural system, soil integrates physical, chemical, and biological properties that collectively determine its ability to function as a medium for vegetation, a regulator of water and nutrient cycles, and a support system for biodiversity. According to Brady and Weil (2017), soil quality is closely linked to ecosystem productivity and resilience, making it a key indicator of environmental health. Similarly, Doran and Zeiss (2000) emphasize that soil quality reflects the capacity of soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health. However, despite its essential role, soil is highly vulnerable to degradation, particularly under conditions of intensive land use and extractive activities.

Among various anthropogenic pressures, mining activities—including oil and gas exploitation—are recognized as major contributors to soil degradation. These activities typically involve land clearing, removal of vegetation cover, soil excavation, compaction due to heavy machinery, and the introduction of foreign materials, all of which significantly alter soil structure and composition. Sheoran et al. (2010) explain that mining disrupts natural soil horizons and reduces organic matter content, leading to long-term degradation of soil functionality. In addition, Sharif and Shin (2020) note that post-mining soils often exhibit unfavorable physical characteristics such as high bulk density and low porosity, along with chemical limitations including nutrient deficiency and low cation exchange capacity. These conditions collectively hinder plant growth, reduce soil biological activity, and limit the natural recovery of ecosystems.

The impacts of soil degradation become more critical when mining activities occur within conservation areas, where ecological sensitivity is high and environmental functions must be preserved. Conservation zones are designated to protect biodiversity, maintain ecosystem balance, and support long-term environmental sustainability; therefore, disturbances caused by extractive activities can have far-reaching consequences. Adhikari and Hartemink (2016) highlight that soil is a key component of ecosystem services, and its degradation can lead to a decline in functions such as carbon sequestration, water regulation, and habitat support. Consequently, degraded soils in conservation areas not only affect local ecological conditions but also undermine broader environmental stability.

The Zamrud Oil Field, operated by PT Bumi Siak Pusako and located within the buffer and utilization zones of Zamrud National Park in Riau Province, represents a unique case where oil and gas exploitation intersects with conservation objectives. Zamrud National Park is characterized by peatland and wetland ecosystems that are highly sensitive to environmental disturbance and play an important role in biodiversity conservation and hydrological regulation. While oil and gas operations in the area contribute to regional economic development and energy production, they also generate significant environmental challenges, particularly in the form of post-mining land degradation. Previous studies in Riau have reported that post–oil mining areas are characterized by low soil fertility, compacted soil structure, and limited capacity to support vegetation growth, thereby constraining ecosystem recovery (Abdillah, 2023; Elvania et al., 2023).

Post-mining soil degradation is typically reflected in both physical and chemical changes that collectively reduce soil quality. Physically, soils often experience compaction due to the use of heavy machinery, resulting in increased bulk density and reduced porosity. These changes limit root penetration, restrict water infiltration, and reduce soil aeration, thereby creating unfavorable conditions for plant establishment. Chemically, post-mining soils tend to exhibit low organic matter content, reduced nutrient availability, and low cation exchange capacity, which further limit soil fertility and biological activity. Karlen et al. (2001) emphasize that soil quality assessment based on physical and chemical indicators is essential for understanding degradation processes and determining appropriate rehabilitation strategies. Without such evaluation, rehabilitation efforts may not effectively address the underlying constraints of degraded soils.

Soil quality evaluation therefore plays a critical role in supporting post-mining land rehabilitation and environmental management. By analyzing key parameters such as soil texture, bulk density, porosity, pH, organic carbon, nutrient content, and cation exchange capacity, it is possible to identify the extent of degradation and determine suitable interventions for restoring soil functionality. Costanza et al. (1992) argue that ecosystem health is closely linked to the condition of its components, including soil, and that maintaining soil quality is essential for sustaining ecological balance. In this context, soil quality evaluation not only provides baseline data for rehabilitation planning but also contributes to the development of sustainable land management strategies.

Despite the growing importance of soil quality evaluation in post-mining areas, existing research in Indonesia remains limited, particularly in the context of oil and gas mining within conservation zones. Most previous studies have focused on other types of mining, such as coal and nickel, or have been conducted outside conservation areas. In addition, many studies tend to examine soil properties separately, focusing either on physical or chemical aspects without integrating both dimensions into a comprehensive assessment. This fragmented approach limits the understanding of the overall condition of soil systems and reduces the effectiveness of rehabilitation planning. Furthermore, comparative analyses between pre-mining (initial) and post-mining (production) conditions are still relatively scarce, making it difficult to accurately assess the magnitude and direction of soil quality changes.

These limitations highlight a clear research gap in the evaluation of soil quality in post–oil mining areas, particularly within ecologically sensitive conservation zones such as Zamrud National Park. There is a need for integrated studies that simultaneously assess physical and chemical soil properties, incorporate comparative analysis between initial and production conditions, and link evaluation results to practical recommendations for land rehabilitation and environmental management. Without such comprehensive approaches, efforts to restore degraded lands may remain ineffective and unsustainable.

In response to these gaps, this study offers a novel contribution by providing an integrated evaluation of soil physical and chemical properties in post–oil mining areas within a conservation zone. Unlike previous studies, this research combines multiple soil quality indicators into a single analytical framework, enabling a more holistic understanding of soil degradation processes. The study also employs a comparative approach

between initial (pre-mining reference) and production (post-mining) conditions, allowing for a clearer assessment of the impact of oil mining activities on soil quality. Furthermore, the research focuses on a unique and underexplored context, namely post–oil mining land within the Zamrud National Park area, which is characterized by peatland and wetland ecosystems with high ecological sensitivity.

Based on these considerations, this study aims to evaluate the physical and chemical properties of soils in post–oil mining areas at PT Bumi Siak Pusako by comparing initial and production land conditions. The study seeks to identify the extent of soil degradation, analyze key limiting factors affecting soil quality, and provide scientific recommendations for sustainable land rehabilitation and environmental management. By integrating ecological evaluation with practical management considerations, this research is expected to contribute to the development of more effective and adaptive strategies for restoring degraded lands and supporting sustainable environmental management in conservation areas.

2. METHOD

2.1 Location and Time of Activity

The activity was conducted from September 2025 to January 2026 in the Zamrud Oil Field operated by PT Bumi Siak Pusako, located in Dayun District, Siak Regency, Riau Province, Indonesia. The study area is situated within the buffer and utilization zones of Zamrud National Park, an ecologically sensitive conservation area dominated by peatland and wetland ecosystems. Soil evaluation was carried out at three inactive oil wells, namely SEB, BRK 24, and BRK 26, which represent areas previously affected by oil and gas production activities**.**

2.2 Activity Design and Approach

This activity employed an environmental evaluation approach to assess soil quality conditions in post–oil mining areas as a basis for supporting land rehabilitation and environmental management planning. Field surveys were conducted to observe site conditions and identify sampling locations. Soil sampling points were determined using purposive sampling based on land disturbance characteristics and accessibility.

Two land conditions were evaluated at each well location: (1) Initial condition (RA), representing relatively undisturbed soil conditions used as reference points, and (2) Production condition (RP), representing soils affected by oil mining operations, including land filling and operational activities.

2.3 Soil Sampling Procedure

Soil samples were collected from the topsoil layer at a depth of 0–20 cm, which is the most responsive layer to physical and chemical changes caused by land-use disturbance. At each sampling point, several subsamples within a small radius were collected and composited to represent soil conditions at the location. Sampling was conducted using soil augers and ring samplers for physical analysis. All samples were labeled, stored in clean containers, and transported to the laboratory for further analysis.

Prior to sampling, field observations were recorded using a field observation form (borlist) to document site morphology, land surface conditions, drainage characteristics, vegetation cover, and signs of land disturbance. This information was used to support the interpretation of laboratory analysis results.

`2.4 Soil Physical and Chemical Analysis

Soil physical properties analyzed included soil texture, bulk density, particle density, and total porosity. Soil texture was determined using the hydrometer method, while bulk density and particle density were measured using core and pycnometer methods, respectively. Total soil porosity was calculated based on bulk density and particle density values.

Chemical soil analysis included soil pH (measured using a pH meter), organic carbon content, total nitrogen, C/N ratio, available and potential phosphorus, exchangeable potassium, base cations (Ca, Mg, and Na), and cation exchange capacity (CEC). All laboratory analyses were conducted following standard procedures commonly applied in soil science laboratories.

2.5 Data Analysis

Data obtained from soil physical and chemical analyses were evaluated using descriptive analysis. Soil

quality parameters were compared between initial (RA) and production (RP) conditions to identify the direction and magnitude of changes caused by oil mining activities. The interpretation of soil quality status and degradation levels was based on soil fertility and soil property criteria established by the Indonesian Soil Research Institute. The results were used to formulate recommendations for soil rehabilitation and sustainable environmental management in post–oil mining areas.

3 RESULT AND DISCUSSION

3.1 Overview of Laboratory Analysis Results

Laboratory analysis results comparing initial (RA) and production (RP) soil conditions across all sampling locations are presented in Table X. The table integrates physical and chemical soil properties to provide a comprehensive overview of soil quality changes following oil mining activities. Overall, soils in production areas showed consistent degradation compared to initial conditions, indicated by changes in soil physical structure and a decline in chemical fertility status.

Table 1. Laboratory Results for Physical and Chemical Soil Properties

Parameter	Unit	SEB–RA	SEB–RP	BRK 24–RA	BRK 24–RP	BRK 26–RA	BRK 26–RP
PHYSICAL PROPERTIES							
Sand	%	n.a. (peat)	23.06	n.a. (peat)	n.a.	n.a. (peat)	n.a.
Silt	%	n.a. (peat)	11.01	n.a. (peat)	n.a.	n.a. (peat)	n.a.
Clay	%	n.a. (peat)	65.03	n.a. (peat)	n.a.	n.a. (peat)	n.a.
Bulk density	g cm^{-3}	n.a. (peat)	↑ (compacted)	n.a. (peat)	↑	n.a. (peat)	↑
Particle density	g cm^{-3}	n.a.	↑	n.a.	↑	n.a.	↑
Total porosity	%	High	↓	High	↓	High	↓
CHEMICAL PROPERTIES							
pH (H_2O)	–	3.74	7.20	4.30	4.83	3.82	4.72
Organic carbon	%	High	Low–very low	High	Low–very low	High	Low–very low
Total nitrogen	%	Moderate	Low	Moderate	Low	Moderate	Low
C/N ratio	–	57.2	30.2	33.8	31.4	53.1	15.2
Available P_2O_5	ppm	13.3	2.11	3.9	2.73	10.0	2.82
Potential P_2O_5	mg 100 g^{-1}	8.66	1.93	11.6	0.67	8.87	2.48
Exchangeable K (K-dd)	cmol kg^{-1}	0.78	0.30	1.02	0.30	0.46	0.32
Base cations (Ca+Mg+Na)	cmol kg^{-1}	Moderate	Low	Moderate	Low	Moderate	Low
Cation exchange capacity (CEC)	cmol kg^{-1}	Moderate	Very low	Moderate	Very low	Moderate	Very low

3.2 Changes in Physical Soil Properties

The evaluation results showed distinct differences in physical soil properties between the initial condition (RA) and the production condition (RP) across all observed well locations. Soils under initial conditions were generally characterized by organic-dominated materials with low bulk density and high porosity, indicating favorable physical conditions for root growth and water movement. In contrast, soils in production areas showed increased bulk density and reduced total porosity, reflecting soil compaction caused by land filling and operational activities.

As summarized in Table 2, bulk density increased while total porosity decreased in production areas compared to initial conditions. Increased bulk density is a common indicator of soil compaction, which negatively affects soil structure, limits root penetration, and restricts soil aeration. Reduced porosity further constrains water infiltration and gas exchange, creating unfavorable conditions for plant establishment. These findings are

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consistent with reports that post-mining soils frequently experience structural degradation due to heavy machinery traffic and soil disturbance (Sheoran et al., 2010; Brady & Weil, 2017).

Particle density values in production areas tended to be higher than those in initial conditions, indicating a greater influence of mineral soil materials. This change suggests the replacement or mixing of organic soil layers with mineral materials during operational activities. Although mineral materials may contribute to higher soil pH, they often lack sufficient organic matter to support soil aggregation and biological activity.

Overall, the physical soil changes presented in Table 2 indicate that post–oil mining areas have a reduced capacity to function as effective growing media. Soil compaction and altered pore systems represent major physical constraints that must be addressed to support vegetation establishment and ecosystem recovery.

Table 2. Summary of Physical Soil Property Changes in Post–Oil Mining Areas

Soil Physical Parameter	Initial Condition (RA)	Production Condition (RP)	Implication for Land Rehabilitation
Soil texture	Organic-dominated (peat soil)	Mineral soil dominated by clay fraction	Reduced root penetration and aeration
Bulk density	Low	Increased	Indicates soil compaction due to operational activities
Particle density	Lower	Higher	Reflects dominance of mineral materials in RP
Total porosity	High	Decreased	Limited water infiltration and soil aeration

3.3 Changes in Chemical Soil Properties

Chemical soil properties also differed markedly between initial and production conditions. Soils under initial conditions exhibited higher organic carbon content and relatively better nutrient status, reflecting the natural characteristics of organic soils within the Zamrud National Park area. In contrast, soils in production areas were characterized by low to very low organic carbon content, low total nitrogen, and very low cation exchange capacity.

As shown in Table 3, the decline in organic carbon content represents a critical aspect of soil degradation in post–oil mining areas. Organic matter plays a key role in improving soil structure, enhancing nutrient retention, and supporting microbial activity. Low organic matter levels in production areas contributed to reduced nutrient availability and limited soil buffering capacity. Consequently, essential nutrients such as nitrogen, phosphorus, and potassium were present at low levels, constraining plant growth and soil biological processes. Soil pH values in production areas tended to increase compared to initial conditions due to the influence of mineral materials introduced during operational activities. However, the chemical status summarized in Table 3 indicates that this increase in pH was not accompanied by improvements in soil fertility. This finding highlights that soil pH adjustment alone is insufficient to restore soil quality when organic matter content and nutrient retention capacity remain low.

The very low cation exchange capacity observed in production areas further indicates limited ability of soils to retain and supply nutrients for plant uptake. Under such conditions, added nutrients are prone to leaching losses, reducing the effectiveness of rehabilitation interventions if not accompanied by organic matter enhancement.

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Table 3. Summary of Chemical Soil Properties and Their Implications for Rehabilitation

Soil Chemical Parameter	General Status in Production Areas (RP)	Implication for Soil Management
Soil pH	Increased (from very acidic to acidic–neutral)	pH improvement not followed by fertility recovery
Organic carbon	Low to very low	Requires organic matter enrichment
Total nitrogen	Low	Limits plant growth and microbial activity
C/N ratio	Low to moderate	Indicates limited organic matter input
Available phosphorus (P_2O_5)	Low	Requires phosphorus management
Exchangeable potassium (K-dd)	Low	Indicates poor nutrient availability
Base cations (Ca, Mg, Na)	Low	Limited buffering capacity
Cation exchange capacity (CEC)	Very low	Low nutrient retention capacity

4 CONCLUSIONS

This study concludes that post–oil mining soils in the Zamrud National Park area have undergone significant physical and chemical degradation compared to initial conditions, as indicated by increased soil compaction, reduced porosity, low organic matter content, limited nutrient availability, and very low cation exchange capacity. Although soil pH in production areas tended to increase due to the influence of mineral materials, this change did not correspond to an improvement in overall soil fertility. These findings indicate that soil compaction and organic matter depletion are the primary constraints to vegetation establishment and ecosystem recovery. The integrated evaluation of soil physical and chemical properties provides essential baseline information to support sustainable land rehabilitation and environmental management in post–oil mining areas within conservation zones.

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