

EVALUATING SOIL QUALITY ACROSS MULTIPLE SOIL TYPES FOR SUSTAINABLE OIL PALM PLANTATIONS IN CENTRAL KALIMANTAN, INDONESIA

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ABSTRACT

Assessing soil quality is essential to ensuring the long-term sustainability of oil palm plantations by aligning agricultural productivity with environmental and social dimensions. This study examines the influence of soil type on soil quality in Kotawaringin Timur District, Central Kalimantan, Indonesia. Specifically, it evaluates four representative soil types (Histosols, Inceptisols, Ultisols and Entisols) using the soil quality index (SQI) framework, identifies key indicators through a minimum data set (MDS), and proposes soil-specific management strategies. The methodology includes field surveys, biological and physicochemical soil analyses, SQI computation and statistical evaluation, with six replications per soil type. Results demonstrate significant variation in SQI values: Low for Histosols (0.245) and very low for Ultisols (0.178), Inceptisols (0.180) and Entisols (0.182). Soil organic carbon (SOC), exchangeable magnesium (Ex-Mg) and available phosphorus (Av-P) were identified as critical indicators influencing soil function. To improve soil quality, the application of organic amendments such as compost, biochar and biofertilisers derived from oil palm residues is recommended. Integrating weed biomass may further enhance nutrient availability and soil resilience, supporting sustainable plantation management tailored to site-specific conditions.

Keywords: minimum data set, palm oil, regression, soil quality index, sustainable plantation.

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INTRODUCTION

Oil palm is a pivotal sector in Indonesia. As the world's largest producer, the country generates over 50 million tonnes of crude palm oil (CPO) annually and contributes more than 55% of global supply (Dadi, 2021). The industry supports over 16 million livelihoods, reduces rural poverty by up to

12%, and provides wages that are 30%–50% higher than those in subsistence agriculture (Judijanto, 2025). Despite occupying only 8% of Indonesia's total land area (Purwanto et al., 2020), oil palm plantations have positioned Indonesia (alongside Malaysia) as the dominant global producer (Soo et al., 2022). Indonesia also became the world's largest palm oil exporter in 2021, with refined palm oil generating USD23.62 billion in export value (Setiajiati et al., 2024). However, the share of crude palm oil exports has declined sharply from 37.5% in 2003 to 8.5% in 2021, driven by inconsistent sustainability compliance and increasing competition from Malaysia (Dermoredjo et al., 2025). Export flows to major markets such as India have also fluctuated substantially, ranging

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from USD1.89 billion in 2021 to USD4.63 billion in 2017 (Setyoyuniyanto et al., 2025), reflecting broader structural challenges, including low smallholder productivity and tightening international sustainability regulations, particularly from the European Union (Dermoredjo et al., 2025).

While the palm oil sector delivers substantial socio-economic benefits, it continues to face persistent scrutiny for its environmental footprint. Concerns include deforestation, peatland degradation, greenhouse gas emissions, biodiversity loss, and long-term soil deterioration. These issues are especially pronounced in frontier regions where plantation expansion has been rapid and often poorly regulated. Among these regions, Central Kalimantan stands out as one of Indonesia's most dynamic and ecologically sensitive oil palm landscapes. The province has experienced some of the highest rates of plantation expansion nationally, with more than 632,000 ha of oil palm plantations located within forest estate areas and an additional ~265,000 ha established across the Ex-Mega Rice Project (EMRP) landscape (Sumarga & Hein, 2016). This expansion has occurred across a mosaic of peat, mineral, and transitional soils, each with distinct vulnerabilities to compaction, nutrient depletion, subsidence and hydrological disruption.

Such rapid land-use change raises critical questions about the long-term sustainability of oil palm production in Central Kalimantan. Soil degradation has been widely reported in oil palm systems across Southeast Asia (Guillaume et al., 2016). These processes threaten not only environmental integrity but also the productive capacity of plantations, particularly in regions where soils are inherently fragile or have been subjected to repeated cycles of land clearing and intensive management. Although sustainable oil palm development has been promoted as a pathway to balance economic viability, social equity and environmental stewardship, its success ultimately depends on maintaining soil functions that support long-term productivity.

Ensuring sustainable production, therefore, requires a robust understanding of soil quality dynamics across different soil types and management contexts. Soil quality assessment frameworks, including soil quality index (SQI) and minimum data set (MDS), have been increasingly applied to evaluate soil functioning, monitor degradation, and guide sustainable land management in tropical agricultural systems (Bünemann et al., 2018). In Indonesia, SQI approaches have been used to compare forest and oil palm land uses (Palupi et al., 2019), assess soil fertility under specific management regimes, or characterise soil constraints in single soil types such as acid sulphate soil (Boafo et al., 2020) or peat (Simanullang et al., 2024).

However, several important knowledge gaps remain. First, most existing studies focus on single soil types or isolated sites, limiting understanding of how soil quality varies across the diverse soil groups that coexist within oil palm landscapes, particularly in heterogeneous regions such as Central Kalimantan. Second, many SQI applications emphasise chemical indicators, with limited integration of physical and biological properties that are essential for capturing soil functioning under perennial crops. Third, few studies explicitly link soil quality metrics to sustainability criteria, such as long-term productivity, erosion risk, peat subsidence, or nutrient-use efficiency. Finally, soil-type-specific management recommendations remain scarce, leaving plantation managers with generic guidelines that may not adequately address the unique constraints of each soil group.

Addressing these gaps is essential for supporting sustainable intensification in Indonesia's oil palm sector. A comprehensive evaluation of soil quality across multiple soil types can provide critical insights into degradation risks, productivity constraints and the potential for targeted interventions. This is particularly important in Central Kalimantan, where rapid expansion, diverse soil conditions and ecological sensitivity converge to create complex sustainability challenges. Moreover, because oil palm plantations in Kalimantan increasingly extend into marginal lands (including peatlands, drylands and nutrient-poor mineral soils), understanding soil potential and limitations becomes indispensable for designing sustainable land-use strategies.

Therefore, this study evaluates soil quality across multiple soil types within oil palm plantations in Central Kalimantan using an integrated SQI framework that incorporates physical, chemical and biological indicators. By comparing soil quality among soil types and interpreting SQI values in relation to sustainability thresholds, the research provides a soil-type-specific diagnosis of constraints and potentials for sustainable oil palm cultivation. The findings offer a regional baseline for soil quality and generate differentiated management recommendations tailored to each soil type, thereby contributing to evidence-based strategies for sustaining long-term productivity in one of Indonesia's most critical plantation regions.

MATERIALS AND METHODS

Study Sites

The study was undertaken at two locations in Central Kalimantan, Indonesia, namely Kotawaringin Timur Regency (1° 51' 14.46" S, 112° 41' 26.41" E) and Seruyan Regency (2° 23' 30.65" S, 112° 13' 51.80" E). The research activities were

conducted between July and December 2024, comprising soil surveys and laboratory analyses. Soil analyses were carried out at the Soil Chemistry and Fertility Laboratory, as well as the Soil Physics and Conservation Laboratory, within the Faculty of Agriculture, Universitas Sebelas Maret. The research process encompassed several key stages, including field surveys and soil sampling, soil analysis, selection of the MDS, determination of the SQI and subsequent data analysis.

Field Surveys and Soil Sampling

The soil survey was conducted in oil palm plantations, encompassing four distinct soil types: Histosols, Entisols, Inceptisols and Ultisols, with six replicates for each type. The study sites were located on flat to gently sloping terrain (<3%–8%) with annual rainfall ranging from 2,405 to 2,748 mm, which is suitable for oil palm growth as reported by Goenadi et al. (2021). Oil palm trees in these plantations have a lifespan of 15–20 years. In 2023, total production was approximately 88 t ha⁻¹, showing a decline compared to 2022, when yields reached around 154 t ha⁻¹. Sampling was carried out at two locations, with each location comprising 12 sampling points (Figure 1 and 2).

The survey employed a descriptive-exploratory approach, with purposive sampling used to

determine the sampling points. Soil samples were collected from inter-row areas, positioned away from drainage ditch edges and excluded from reclaimed or heaped soils. Several sites were vegetated with *Nephrolepis* and grasses, while others were located in frond-pile zones; however, all sites were carefully cleared before soil profile construction. Soil profile characterisation was conducted by describing the profile to a depth of 60 cm (Tinuntun et al., 2025). Root distribution data in oil palm plantations showed that medium root biomass declined significantly between 60 and 140 cm, indicating reduced root activity in deeper layers (Obrador-Olán et al., 2021). Thus, limiting soil sampling to 60 cm is justified, as this depth captures the most biologically active zone for nutrient uptake and soil-plant interactions. The samples were then composited for analysis.

Soil Analysis

Samples were air-dried for 2–3 days in open shade to avoid direct sunlight exposure. Once dried, the soil was sieved to meet analytical standards. The indicators observed included bulk density (BD), particle density (PD), porosity, electrical conductivity (EC), permeability, pH in H₂O, total nitrogen (Total-N), available phosphorus (Av-P), available potassium (Av-K), soil organic

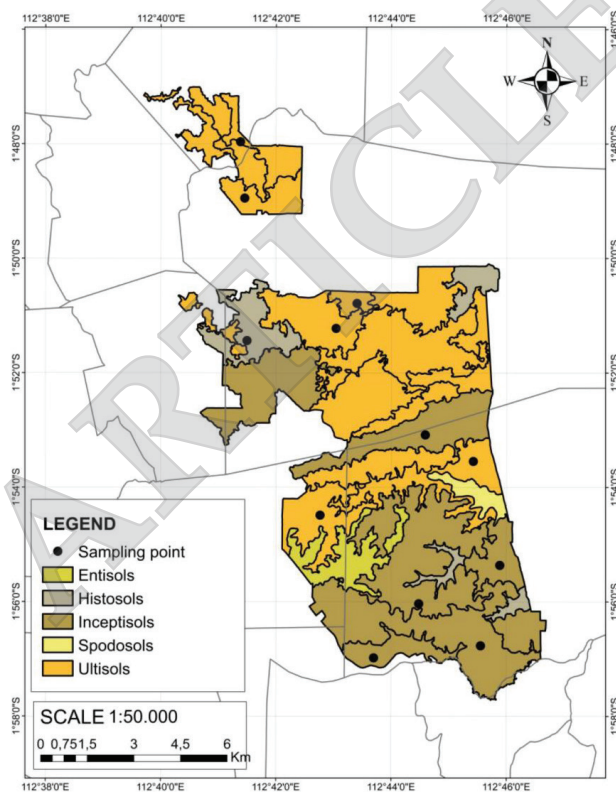


Figure 1. Sampling point distribution in Kotawaringin Timur Regency, Central Kalimantan, Indonesia.

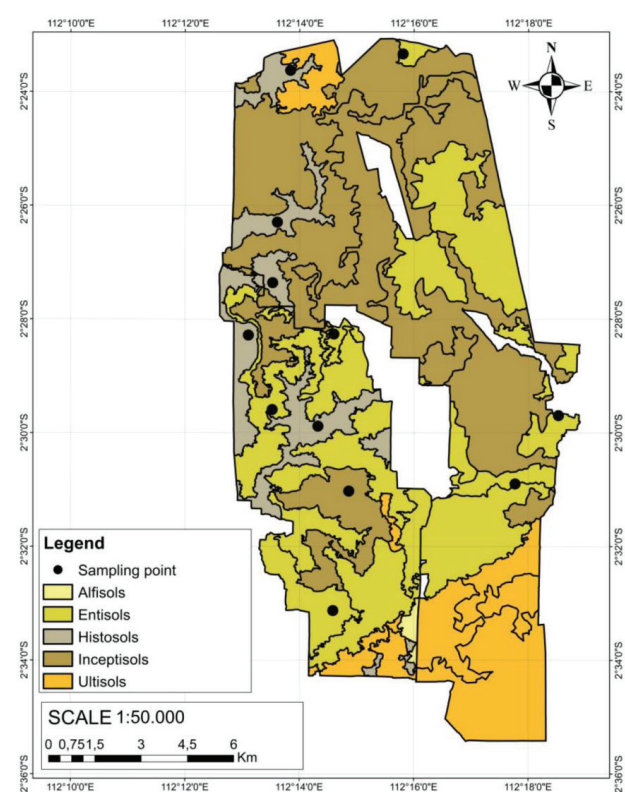


Figure 2. Sampling point distribution in Seruyan Regency, Central Kalimantan, Indonesia.

carbon (SOC), cation exchange capacity (CEC), exchangeable calcium (Ex-Ca), exchangeable magnesium (Ex-Mg), exchangeable sodium (Ex-Na), base saturation (BS) and microbial biomass carbon (MBC).

The parameters were assessed following standardised procedures: BD was determined through gravimetric analysis (Hikouei et al., 2021), PD using a pycnometer (Santos et al., 2022), and porosity calculated using an equation that relates BD and PD (Alhaj Hamoud et al., 2019). EC was measured with a conductivity meter (Hossain et al., 2020), permeability following the constant head method (Barbero et al., 2020), and soil pH determined in H₂O suspension (Hale et al., 2020). Total-N was analysed using the Kjeldahl method (Gautam et al., 2023), Av-P and Av-K were extracted with the Bray and ammonium acetate methods, respectively (Suchithra & Pai, 2020), and SOC was quantified using the Walkley-Black method (Wani et al., 2023). CEC, Ex-Ca, Ex-Mg and Ex-Na were measured by NH₄OAc extraction (Nel et al., 2023), BS was calculated as the proportion of exchangeable bases relative to CEC (Bouajila et al., 2023), and MBC was determined through fumigation-extraction (Hua et al., 2021).

Data Analysis

The MDS indicators were determined through correlation analysis and principal component analysis (PCA). These indicators represent the most relevant soil parameters for evaluating the SQI, ensuring that the assessment captures the essential aspects of soil functionality. Pearson's correlation analysis evaluated the strength and direction of interrelationships among soil variables. PCA identified principal components with eigenvalues >1 for further analysis (Dewi et al., 2024). Indicators showing strong component loadings and significant target correlations were selected, reflecting high sensitivity in characterising soil properties (Dewi et al., 2022). The final indicators were assigned respective weights and scores, which were then incorporated into the SQI calculation as shown in Equation (1), following Abd-Elwahed (2019);

$$SQI = \sum_i^n W_i \times S_i^n \quad (1)$$

where, SQI represents the overall assessment of soil quality, W_i denotes the weight assigned to each indicator, derived from the proportion divided by the cumulative value in PCA. S_i corresponds to the indicator score, while n signifies the total number of soil quality indicators considered in the analysis. The classification of soil quality was presented in Table 1.

TABLE 1. CRITERIA FOR SOIL QUALITY INDEX (SQI) CLASSIFICATION

No.	SQI	Classification
1	0.00–0.19	Very low
2	0.20–0.39	Low
3	0.40–0.59	Moderate
4	0.60–0.79	High
5	0.80–1.00	Very high

Source: Abdel-Fattah et al. (2021).

Statistical Analysis

Statistical analyses were conducted using Minitab Statistical Software version 22 (Minitab, USA) and RStudio 4.2.2 (R Core Team, Austria). Analysis of variance (ANOVA) was carried out to determine the effect of soil type on soil quality. Pearson correlation analysis aimed to determine the relationship between soil indicators and SQI. Stepwise regression analysis was subsequently applied to identify the key determinants of soil quality. All statistical analyses were performed at a 95% confidence level.

RESULTS AND DISCUSSION

Soil Characteristics at Research Site

The results of the soil characterisation analysis presented in Table 2 indicate that each soil type within the oil palm plantations exhibits distinct properties. Soil types that influence the physical, chemical and biological characteristics of the soil (Dewi et al., 2024); however, soil acidity and nutrient deficiency remain the primary concerns.

Variation in soil type had a highly significant effect on pH, SOC, CEC, BS, MBC, EC, PD and BD ($p < 0.01$), and a significant effect on Total-N and porosity ($p < 0.05$). Overall, soil pH tended towards acidity, with the exception of Entisols, which ranged from 4.01 to 6.56. BS levels varied widely, ranging from very low to high (18.21%–54.66%). The lowest pH and BS values were recorded in Histosols, which were not significantly different from Ultisols. The extremely low pH in Histosols is attributed to elevated SOC, which releases organic acids during decomposition, thereby lowering soil pH. Humic and fulvic acids, as by-products of organic matter (OM) breakdown, contribute to soil acidification (Kumar et al., 2024). Additionally, Histosols possess minimal mineral content, resulting in low base cation retention. Excessive rainfall further promotes leaching, diminishing base cation levels (Parjono et al., 2021).

TABLE 2. SOIL CHARACTERISTICS OF THE STUDY AREA

Indicator	<i>p</i> -value	Ultisols	Inceptisols	Entisols	Histosols
		Mean $\pm$ standard deviation			
pH	0.00**	4.88 ^{ab} $\pm$ 0.45	5.52 ^b $\pm$ 1.03	6.56 ^c $\pm$ 0.24	4.01 ^a $\pm$ 1.17
SOC (%)	0.00**	2.21 ^a $\pm$ 0.27	2.60 ^a $\pm$ 1.32	1.95 ^a $\pm$ 1.78	31.06 ^b $\pm$ 9.26
CEC (cmol kg ⁻¹)	0.00**	34.75 ^b $\pm$ 4.81	19.53 ^a $\pm$ 2.55	13.25 ^a $\pm$ 6.06	110.60 ^b $\pm$ 37.60
Ex-Ca (cmol kg ⁻¹)	0.46	6.25 ^a $\pm$ 1.38	6.59 ^a $\pm$ 1.31	5.19 ^a $\pm$ 3.97	10.79 ^a $\pm$ 1.18
Ex-Mg (cmol kg ⁻¹)	0.11	1.37 ^{ab} $\pm$ 0.39	0.64 ^a $\pm$ 0.25	1.23 ^{ab} $\pm$ 0.49	7.75 ^b $\pm$ 1.08
Ex-Na (cmol kg ⁻¹)	0.36	0.41 ^a $\pm$ 0.13	0.56 ^a $\pm$ 0.17	0.45 ^a $\pm$ 0.20	0.85 ^a $\pm$ 0.38
BS (%)	0.00**	25.62 ^a $\pm$ 1.85	43.93 ^b $\pm$ 4.41	54.66 ^b $\pm$ 5.83	18.21 ^a $\pm$ 1.80
Total-N (%)	0.04*	0.06 ^a $\pm$ 0.02	0.05 ^a $\pm$ 0.01	0.05 ^a $\pm$ 0.02	0.34 ^b $\pm$ 0.08
Av-P (mg kg ⁻¹)	0.11	2.68 ^a $\pm$ 0.70	2.60 ^a $\pm$ 1.59	3.34 ^a $\pm$ 0.50	9.32 ^a $\pm$ 0.67
Av-K (cmol kg ⁻¹)	0.13	1.45 ^{ab} $\pm$ 0.88	0.66 ^{ab} $\pm$ 0.41	0.29 ^a $\pm$ 0.15	3.46 ^b $\pm$ 1.69
MBC (μ g g ⁻¹)	0.00**	0.07 ^a $\pm$ 0.02	0.06 ^a $\pm$ 0.01	0.14 ^a $\pm$ 0.07	0.41 ^b $\pm$ 0.14
EC (μ S cm ⁻¹)	0.00**	0.35 ^a $\pm$ 0.04	0.28 ^{ab} $\pm$ 0.02	0.52 ^c $\pm$ 0.14	0.44 ^{bc} $\pm$ 0.09
BD (g cm ⁻³)	0.00**	1.41 ^b $\pm$ 0.11	1.33 ^b $\pm$ 0.28	1.23 ^b $\pm$ 0.16	0.67 ^a $\pm$ 0.37
PD (g cm ⁻³)	0.00**	1.98 ^b $\pm$ 0.22	1.98 ^b $\pm$ 0.16	2.35 ^{bc} $\pm$ 0.35	0.93 ^a $\pm$ 0.67
Porosity (%)	0.02*	27.28 ^a $\pm$ 9.16	36.74 ^{ab} $\pm$ 9.51	44.29 ^b $\pm$ 10.9	28.35 ^a $\pm$ 9.74
Permeability (%)	0.37	13.56 ^a $\pm$ 13.59	13.10 ^a $\pm$ 7.18	34.31 ^a $\pm$ 5.43	6.17 ^a $\pm$ 6.05

Note: SOC - soil organic carbon; CEC - cation exchange capacity; BS - base saturation; Ex-Ca - exchangeable calcium; Ex-Mg - exchangeable magnesium; Ex-Na - exchangeable sodium; Total-N - total nitrogen; Av-P - available phosphorus; Av-K - available potassium; MBC - microbial biomass carbon; EC - electrical conductivity; BD - bulk density; PD - particle density; * - *p*-value <0.05; ** - *p*-value <0.01; numbers followed by the same letter in the same column indicate statistically non-significant differences.

Histosols exhibited very high SOC (31.06%), while other soil types demonstrated moderate levels (1.95%–2.60%). CEC ranged from low to very high (19.53–110.60 cmol kg⁻¹), reflecting varied retention capacities. MBC values across all soils were categorised as very low (0.06–0.07 μ g g⁻¹). Histosols recorded the highest MBC, CEC and SOC traits linked to carbon accumulation supporting microbial activity (Slukovskaya et al., 2021). In contrast, mineral soils such as Inceptisols, Ultisols, and Entisols had low SOC. High CEC in Histosols is a result of continuous OM input, slow decomposition and accumulation of humus containing negatively charged carboxyl and phenolic groups, which facilitate cation adsorption (Herviyanti et al., 2025).

The availability of both macro- and micro-nutrients is essential for oil palm growth. Differences in soil type did not significantly affect the availability of nutrients (Av-K, Av-P, Ex-Ca, Ex-Mg, Ex-Na). Soil fertility levels at sites were compared against the critical thresholds suggested by Mutert (1999). Nitrogen (N) is essential for oil palm growth, supporting frond development, vegetative expansion and fresh fruit bunch (FFB) production that determines oil yield (Permatasari et al., 2025). However, field observations revealed that total-N ranged from 0.05% to 0.34%, with adequate levels only in Histosols, while other soils were below the threshold of 0.15%–0.25%

(Mutert, 1999), indicating a potential limitation for optimal growth and yield. Phosphorus (P) is vital for oil palm growth as it supports root development, crown formation, trunk diameter and FFB production (Viégas et al., 2023). Nevertheless, the analysis revealed that Av-P was very low (2.60–9.32 mg kg⁻¹), far below the recommended 20.00–25.00 mg kg⁻¹ (Mutert, 1999). This severe deficiency is likely to limit nutrient uptake, ultimately leading to smaller bunches, reduced crown size and lower yields. In contrast, Av-K ranged from 0.29 to 3.46 cmol kg⁻¹, generally above the minimum requirement of 0.25 to >0.30 cmol kg⁻¹. Potassium (K) is crucial for oil palm as it regulates photosynthesis, carbohydrate metabolism and nutrient transport, thereby sustaining fruit development and oil yield (Mirande-Ney et al., 2020).

Calcium (Ca) is a secondary but essential nutrient that strengthens cell walls, supports membrane stability and enhances fruit set and quality (Mayzaitul-Azwa et al., 2025). In this study, Ex-Ca ranged from 5.19 to 10.79 cmol kg⁻¹, indicating sufficient levels that were generally above the critical threshold of 0.9 cmol kg⁻¹ required for oil palm growth (Shamshuddin et al., 2024). Ex-Mg varied between 0.64 and 7.75 cmol kg⁻¹, a range considered sufficient for oil palm plantations. This result is consistent with the findings of Ayanda et al. (2020), who reported Ex-Mg levels of 0.23 cmol kg⁻¹ in oil palm plantation soils in Bera, Pahang, Malaysia,

which were similarly categorised as moderate for supporting oil palm growth. Ex-Na ranged from 0.41 to 0.85 cmol kg⁻¹; although not essential for oil palm, its presence requires monitoring due to potential antagonistic effects on K and Ca uptake.

EC showed an average range of 0.28–0.52 $\mu\text{S cm}^{-1}$, with the highest values observed in Entisols, indicating increased salinity and alkalinity risk (Krishnapriya et al., 2023). BD ranged from 0.67 to 1.41 g cm⁻³, whereas PD ranged from 0.93 to 2.35 g cm⁻³. Histosols demonstrated the lowest BD and PD due to their organic nature and large pore spaces. With decomposition, BD increases due to reduced OM and structural collapse, while PD remains low owing to humus's lower density and higher surface area (Gui et al., 2021). Porosity ranged from 27.28% to 44.29%, with the highest values observed in Entisols, which were not significantly different from Inceptisols. In contrast, permeability was not significantly affected by soil type ($p > 0.05$), with values ranging from 6.17% to 34.31%.

Minimum Data Set (MDS)

The weighting of selected soil indicators (W_i) was determined through PCA. The MDS method was applied using correlation analysis and PCA to identify key patterns and relationships within the dataset. A correlation analysis was conducted on each soil physical, chemical and biological indicator to evaluate the relationships among parameters.

The correlation test results (Figure 3) indicate the presence of significant and highly significant correlations among soil indicators. Out of the 16 selected indicators, 14 were identified as relevant for soil quality assessment. These indicators exhibited strong correlations with one another, except for EC and permeability, which showed weak or no significant associations.

Based on the PCA results (Table 3), three principal components (PCs) meet the criteria for representing the entire dataset, each with an eigenvalue >1 for both soil layers. These three PCs cumulatively explain 87.5% of the data variance. PC1 accounts for 57.2% of the total variance and is represented by seven soil indicators, namely SOC, CEC, Ex-Mg, Total-N, Av-P, MBC and PD. PC2 explains 22.4% of the total variance and is characterised by pH, Ex-Ca, Ex-Na, BS and Av-K. PC3 explains 7.9% of the total variance and is characterised by BD and porosity.

Soil Quality Index (SQI)

Based on the SQI assessment results in Figure 4, all values fall within the very low to low categories, with averages ranging from 0.178 to 0.245. This aligns with findings from Nusantara et al. (2018), who reported a low SQI (0.37) in oil palm plantations in Rasau Jaya, Kubu Raya District, West Kalimantan, and reflects the broader evidence that long-term intensive cultivation triggers soil degradation, which in turn contributes to declining

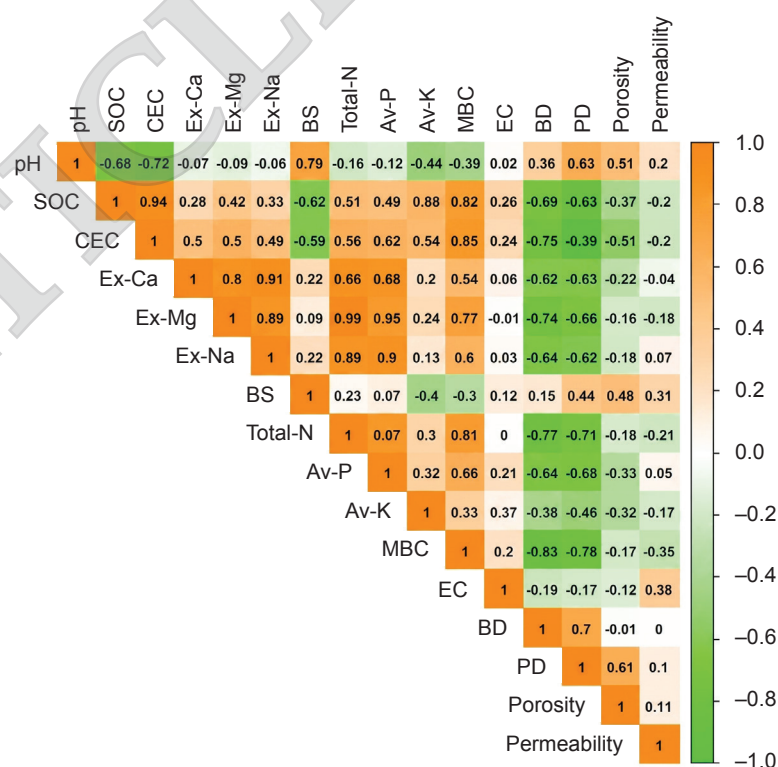


Figure 3. Correlation between soil indicators.

TABLE 3. PRINCIPAL COMPONENT ANALYSIS (PCA) RESULTS FOR THE MINIMUM DATA SET (MDS) INDICATORS OF SOIL QUALITY INDEX (SQI)

Indicator	PC1	PC2	PC3	W _i (P/C)
pH	-0.18	0.42*	-0.05	0.06
SOC	0.28*	-0.27	-0.23	0.09
CEC	0.32*	-0.21	-0.06	0.09
Ex-Ca	0.27	0.29*	0.25	0.06
Ex-Mg	0.30*	0.25	-0.03	0.09
Ex-Na	0.27	0.30*	0.14	0.09
BS	-0.10	0.49*	0.01	0.06
Total-N	0.31*	0.22	-0.03	0.09
Av-P	0.29*	0.21	0.18	0.09
Av-K	0.17	-0.22*	-0.02	0.06
MBC	0.31*	-0.01	-0.32	0.09
BD	-0.29	-0.05	0.41*	0.05
PD	-0.32*	0.13	-0.13	0.09
Porosity	-0.14	0.24	-0.72*	0.05
Eigenvalue	8.013	3.139	1.105	
Proportion (P)	0.572	0.224	0.079	
Cumulative (C)	0.572	0.797	0.875	

Note: SOC - soil organic carbon; CEC - cation exchange capacity; BS - base saturation; Ex-Ca - exchangeable calcium; Ex-Mg - exchangeable magnesium; Ex-Na - exchangeable sodium; Total-N - total nitrogen; Av-P - available phosphorus; Av-K - available potassium; MBC - microbial biomass carbon; EC - electrical conductivity; BD - bulk density; PD - particle density; W_i - weight; * - minimum data set.

SQI in tropical agroecosystems (Mandal et al., 2021; Manorama et al., 2021). The poor soil quality at the study site is attributed to soil degradation, as evidenced by extremely low levels of MBC, Total-N and Av-P across all soil types, compounded by suboptimal PD conditions. This clearly indicates that soils in the oil palm plantations are nutrient-deficient. According to Boafo et al. (2020), although the SQI in oil palm plantations in Pattani Province, Thailand, was classified within the moderate category, only one of the three sites, Ban Lipasango (BL), had nutrient inputs that met the standard requirements for oil palm cultivation.

Soil microorganisms are vital to the carbon cycle and ecosystem stability, with fluctuations in MBC reflecting OM decomposition, microbial turnover and environmental influences (Onwosi et al., 2020). MBC, as a key SOC indicator, regulates nutrient dynamics and supports ecosystem productivity, organic cycling and long-term monitoring (Evangelou & Giourga, 2024). Soil bacteria influence ecosystem intricacy and plant biomass by linking subsurface conditions with above-ground growth (Dewi & Nurhutami, 2023). Low MBC reduces microbial activity and nutrient cycling across all soil types, leading to lower SQI. Even soils with high SOC or CEC, such as Histosols, often show low SQI due to limited Total-N and Av-P, compounded by low MBC that restricts

mineralisation and nutrient cycling. This biological limitation, driven by low MBC, is a key factor underlying the reduced SQI observed in these soils.

Based on the ANOVA results, soil type had a highly significant effect on SQI ($p = 0.002$). Histosols exhibited the highest SQI value (0.25), clearly exceeding that of other soil types (average SQI = 0.18). This superiority is largely attributed to their elevated SOC, high CEC, substantial MBC, and the lowest PD among all soil groups (Table 2). Although not statistically different, indicators such as Ex-Ca, Ex-Mg, Ex-Na, Total-N, and Av-P also contributed to the higher SQI observed in Histosols (Figure 4). Collectively, these characteristics underpin their enhanced soil quality compared with mineral soils. The high SOC content reflects abundant OM, which reduces BD due to its low-density fibrous components that promote pore formation (Hammad et al., 2020). SOC plays a crucial role in improving soil physical, chemical and biological properties (Page et al., 2020). OM, being less dense than mineral particles, increases porosity and further decreases BD (Meurer et al., 2020).

CEC is essential for nutrient retention, preventing leaching by binding cations. This reversible exchange process directly influences nutrient availability for plant uptake (Ćirić et al.,

2023). One of the key factors controlling CEC is the presence of OM. OM contains polar functional groups capable of releasing and absorbing protons, generating negative charges and increasing cation exchange sites (Liu et al., 2020). The high CEC observed in Histosols primarily results from their abundant OM content, whereas other soil types generally exhibit lower CEC due to limited OM

availability. High CEC in Histosols reflects their nutrient retention capacity. While it is one of the factors influencing soil quality, it does not alone indicate suitability for oil palm cultivation, as low pH, poor drainage, and low base saturation often constrain productivity in Histosols. The spatial distribution of SQI status across plantations in Central Kalimantan is illustrated in Figure 5 and 6.

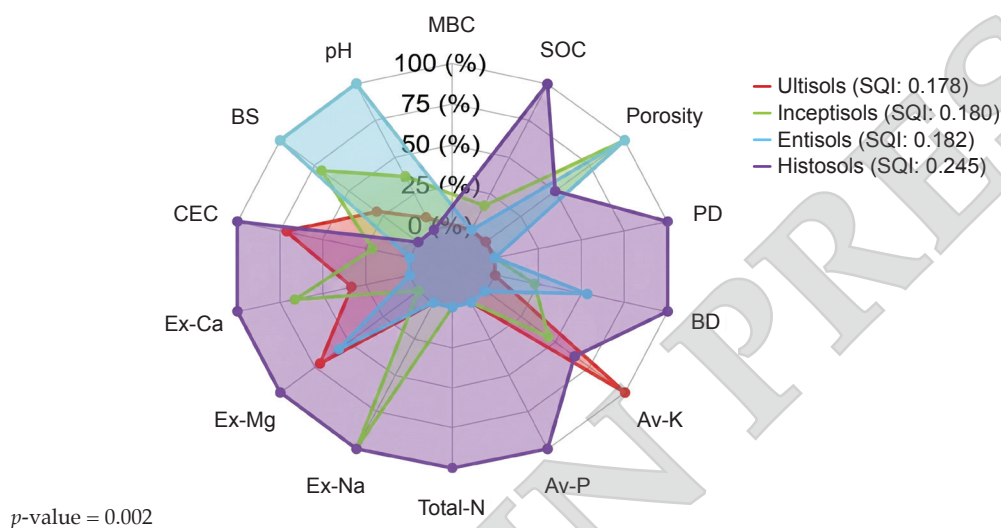


Figure 4. Spider plot of soil quality index (SQI) values for each soil type.

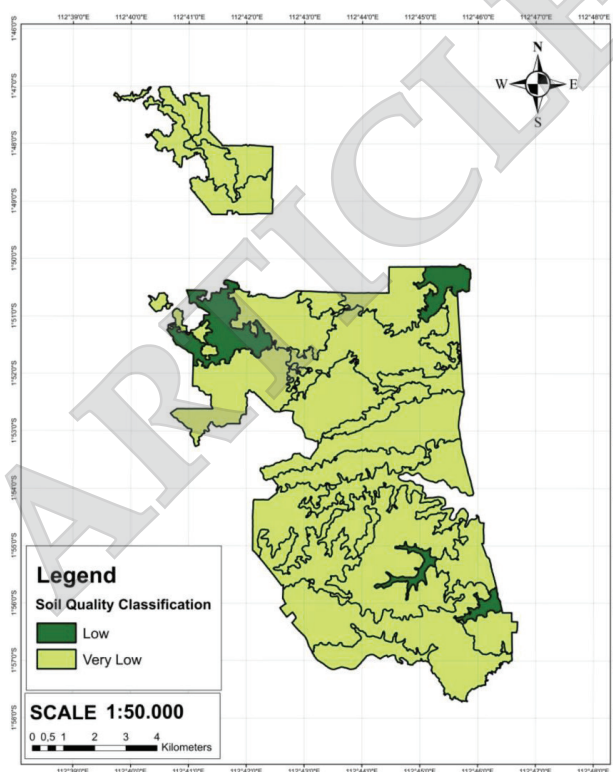


Figure 5. Map of soil quality index (SQI) for different soil types palm oil plantation in Kotawaringin Timur Regency, Central Kalimantan, Indonesia.

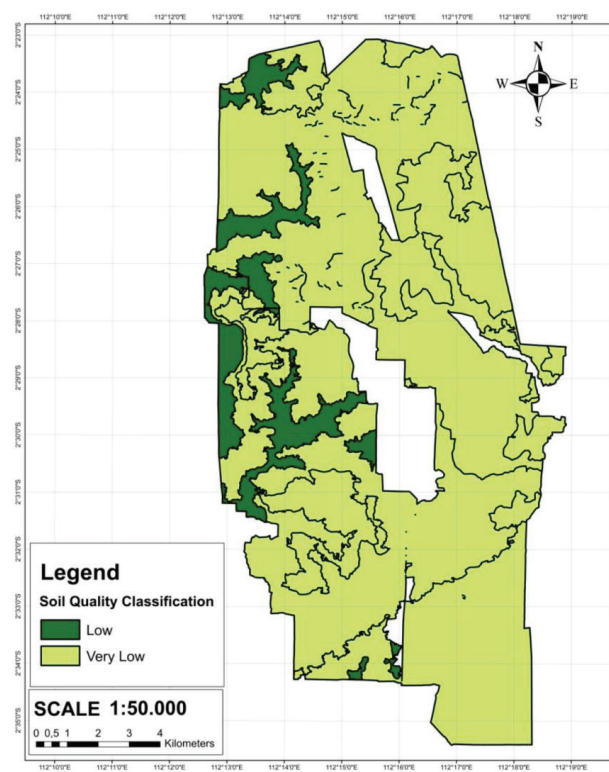


Figure 6. Map of soil quality index (SQI) for different soil types palm oil plantation in Seruyan Regency, Central Kalimantan, Indonesia.

Although peat soils consistently yield high SQI values, these scores primarily represent the inherent nature of Histosols (extremely high SOC, strong CEC, active microbial processes and very low BD). These carbon-rich attributes enhance ecological functioning and elevate SQI scores, yet they do not necessarily reflect agronomic suitability for oil palm cultivation.

In reality, peat soils remain fundamentally constrained by extremely acidic pH, low base saturation, weak bearing capacity, poor aeration and high vulnerability to subsidence and fire. These limitations directly restrict long-term plantation productivity and structural stability. Similar discrepancies between ecological quality and crop suitability in peatlands have been reported (Page & Hooijer, 2016).

Therefore, SQI interpretation in oil palm systems must clearly distinguish between mineral soils and peat soils to avoid overestimating the productive potential of Histosols. While peatlands may score highly in ecological functioning, their intrinsic biophysical constraints demand careful, adaptive and conservation-oriented management when used for plantation agriculture. Ensuring sustainable peat management is essential not only for maintaining plantation performance but also for safeguarding long-term peat ecosystem functions, carbon storage and landscape resilience.

Determinant Factor of Soil Quality

The SQI assessment was followed by correlation analysis with MDS to determine the strength of relationships between individual indicators and SQI. Indicators showing significant correlations were further analysed using regression. The correlation test results between soil indicators and SQI are presented in Table 4.

The correlation test results presented in Table 4 indicate that eight out of 16 soil indicators demonstrate a highly significant positive correlation with SQI (p -value < 0.01), namely SOC ($r = 0.68$), CEC ($r = 0.78$), Ex-Ca ($r = 0.81$), Ex-Mg ($r = 0.90$), Ex-Na ($r = 0.86$), Total-N ($r = 0.93$), Av-P ($r = 0.86$), and MBC ($r = 0.84$). Conversely, two soil indicators, BD ($r = 0.16$) and PD ($r = -0.83$), show a highly significant negative correlation with SQI. The indicators that correlate with the SQI were further analysed using regression tests to determine the key contributors to SQI. The regression results for the first soil layer are presented in Equation (2).

$$\text{SQI} = 0.17025 + 0.000991 \text{ SOC} + 0.004266 \text{ Ex-Mg} + 0.001169 \text{ Av-P} \quad (2)$$

$$R^2 \text{ Adj} = 93.20\%; F\text{-value} = 106.16; P\text{-value} = 0.000$$

TABLE 4. CORRELATION BETWEEN MINIMUM DATA SETS (MDS) AND SOIL QUALITY INDEX (SQI)

No.	Indicators	r-value	p-value
1	pH	-0.26	0.20
2	SOC	0.68**	0.00
3	CEC	0.78**	0.00
4	Ex-Ca	0.81**	0.00
5	Ex-Mg	0.90**	0.00
6	Ex-Na	0.86**	0.00
7	BS	-0.09	0.66
8	Total-N	0.93**	0.00
9	Av-P	0.86**	0.00
10	Av-K	0.38	0.06
11	MBC	0.84**	0.00
12	BD	0.16	0.43
13	PD	-0.83**	0.00
14	Porosity	-0.80**	0.00

Note: SOC - soil organic carbon; CEC - cation exchange capacity; BS - base saturation; Ex-Ca - exchangeable calcium; Ex-Mg - exchangeable magnesium; Ex-Na - exchangeable sodium; Total-N - total nitrogen; Av-P - available phosphorus; Av-K - available potassium; MBC - microbial biomass carbon; EC - electrical conductivity; BD - bulk density; PD - particle density; * - significant; ** - very significant.

Based on Equation (2), the three indicators contributing most significantly to soil quality were identified as SOC, Ex-Mg, and Av-P. The applied regression model accounted for 93.20% of the variation in soil quality data, with a statistically significant *P*-value of 0.000. Increments in SOC, Ex-Mg, and Av-P were associated with respective increases in the SQI of 0.000991, 0.004266 and 0.001169.

SOC is a key indicator of soil quality due to its influence on biological, chemical, and physical properties, including MBC, respiration, CEC and nutrient availability (Romadhon et al., 2024). Enhancing CEC improves the soil's capacity to adsorb and retain nutrients, thereby increasing their effective availability. BD management is essential for maintaining soil porosity, providing favourable conditions for root development (Priori et al., 2020). MBC also plays a critical role in nutrient cycling and overall soil ecosystem health.

Soils at the study site are predominantly characterised by high acidity, except for Entisols. This pronounced acidity is likely to restrict phosphorus availability. Av-P typically declines in acidic soils due to aluminium phosphate (Al-P) and iron phosphate (Fe-P) deposition, but increases with OM input and improved soil processing (Istiqomah et al., 2025). Av-P is vital for plant productivity, supporting metabolic functions via adenosine triphosphate (ATP) and contributing to nucleic acid formation; deficiency can impede growth and restrict root systems (Amalina et al., 2023). Av-K, Total-N, and Ex-Mg are essential for oil palm seedlings (Osayande & Oviasogie, 2024). Mg deficiency disrupts cellular functions, induces stress responses, and reduces photosynthetic efficiency, which may compromise plant health and lower resistance to *Ganoderma boninense*, the pathogen responsible for basal stem rot (Mohd Yunus et al., 2024).

Recommendations for Oil Palm Plantation Management

Recommendations for improving soil conditions and mitigating degradation in oil palm plantations should be tailored to SQI status, particularly in areas with low fertility and critical soil health indicators. Based on SQI evaluations, oil palm cultivation may be viable on Histosols, which offer substantial productivity potential if effectively managed. Land management should target key indicators strongly associated with SQI, notably SOC, Ex-Mg, and Av-P. Enhancing CEC, MBC, nutrient content, and BD can be achieved through OM application.

The processing and maintenance of oil palm plantations generate approximately 70% of solid waste from post-harvest residues, including stems,

fronds, leaves, empty fruit bunches (EFB) and shells, all with potential for soil improvement (Pranolo et al., 2023). These residues can be combined with weeds or processed into compost, biochar, mycorrhizal fungi, or biofertiliser to enhance nutrient availability and improve soil conditions (Herawati et al., 2024). However, effective utilisation of these materials requires attention to their C/N ratios. Rejuvenation generates substantial organic residues, fronds, stems, rachis and leaves with respective C/N ratios of 25:1, 56:1, 90:1 and 77:1 (Shamsuddin et al., 2021). Post-harvest outputs such as EFB and palm shells have C/N ratios of 42.9:1 (Saroni et al., 2023). The optimal use of these residues involves shredding and application as mulch or conversion into compost.

Given the high C/N ratio of plantation waste, composting before soil incorporation is essential. This process can be improved by blending residues with low C/N weed species such as *Mucuna bracteata*, a vigorous leguminous cover crop noted for weed suppression and high N fixation capacity. Sakiah et al. (2021) recommended a 75% EFB to 25% *M. bracteata* composition for optimal nutrient balance, enhancing N availability while managing K uptake.

CONCLUSION

The soil quality of oil palm plantations in Central Kalimantan, Indonesia, is classified as low for Histosols and very low for Ultisols, Inceptisols and Entisols. Soil type differences significantly influence soil quality, MBC, EC, BD, PD, SOC, CEC, pH and BS. Key determinants of soil quality include SOC, Ex-Mg and Av-P. Although Histosols exhibit relatively higher SQI values, they remain marginal soils for oil palm cultivation without appropriate management interventions. Despite their high SOC and CEC content, nutrient availability remains limited, necessitating soil management strategies involving OM amendments derived from oil palm plantation residues. These residues can be combined with weeds or processed into compost, biochar, or biofertilisers to enhance nutrient availability and improve soil conditions. Further research can expand on these findings by incorporating biological parameters such as macrofauna diversity and soil respiration, alongside studies on the optimal application rates of organic amendments for sustainable land management.

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