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Research Article

Assessment of fertility status in mature oil palm plantations under different soil types

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Abstract

Soil fertility is a main factor influencing the productivity and sustainability of oil palm plantations. This study evaluated the fertility status of mature oil palm plantations across peat and mineral soils in Muaro Jambi Regency, Indonesia. A survey with purposive sampling was conducted in plantations managed by smallholders and a company. Soil samples were collected at depths of 0-30 cm and 30-60 cm and analyzed for key physical and chemical properties, including bulk density, pH, organic carbon, nitrogen, phosphorus, potassium, cation exchange capacity (CEC), base saturation (BS), and exchangeable aluminum (Al). Peat soils exhibited lower bulk density and higher organic carbon content than mineral soils, while bulk density increased with soil depth. All soils were acidic, with fertility status ranging from very low to moderate. Low fertility in mineral soils was mainly associated with low organic carbon, CEC, BS, and nutrient availability, whereas peat soils were primarily constrained by low BS despite their high organic carbon content and CEC. The results indicated that soil type was a major determinant of soil fertility in oil palm plantations. Site-specific management strategies, including organic matter addition in mineral soils and improvement of base saturation in peat soils, are needed to support sustainable oil palm production.

Keywords: Soil fertility, Peat soil, Mineral soil, Oil palm plantation, Cation exchange capacity, Base saturation

Introduction

In Indonesia, oil palm (*Elaeis guineensis* Jacq.) has become one of the most important plantation crops that has huge contribution in supporting the national economy and to the world as a major source of vegetable oil. It plays a vital role in providing livelihoods for both large-scale plantation companies and smallholder farmers. With its high productivity and economic value, oil palm continues to expand across various soil types, including mineral soils and peat ones. However, sustaining productivity over time remains a major challenge, particularly in areas where soil fertility is inherently low and prone to degradation. Recent studies have highlighted that oil palm production systems are often established on nutrient-poor and acidic soils, which can limit long-term productivity if not properly managed (Murphy *et al.,* 2021; Thompson-morrison *et al.,* 2023).

Soil fertility is a key factor determining the growth and yield of oil palm plantations, as it directly influences nutrient availability, root development, and overall plant performance. In tropical environments, soil fertility is closely linked to organic matter dynamics, nutrient cycling, and soil biological activity. For instance, improved management practices such as organic matter application and residue recycling have been shown to enhance soil fertility and microbial activity in oil palm systems (Hidayat *et al.,* 2024). However, many plantations still experience low nutrient efficiency due to poor soil conditions, including high acidity, low base saturation, and limited nutrient retention (Smith *et al.,* 2016).

The type of soil also plays an important role in shaping fertility conditions. The mineral soils, which serve as the primary growing medium for oil palm plantations exhibit both low organic carbon levels and poor nutrient retention capabilities. Peat soils possess high organic matter content and excellent water retention capabilities, however they face restrictions due to their low base saturation levels and nutrient distribution problems (Nuryani *et al.,* 2024). The different soil types exhibit distinct productivity requirements which need specific management methods for effective maintenance (van Straaten *et al.,* 2015).

Plantation management practices together with soil type create significant differences in soil fertility across different areas. Intensive management systems that involve intensive fertilizer application can boost productivity but create environmental issues through nutrient runoff and greenhouse gas emissions when not properly managed (Chen *et al.,* 2024). Smallholders who use low-input systems do not adequately replace the nutrients that their harvests take away which causes their soil fertility to decrease over time. Understanding the interactions between soil types and management practices is fundamental to the development of sustainable plantation management systems (Lal, 2016).

Current research on oil palm production predominantly focuses on individual soil characteristics and specific soil types, with limited attention given to the comprehensive assessment of soil fertility. Furthermore, existing integrated field assessments are constrained by their inadequate evaluation of soil physical and chemical properties across varying soil types, soil depths, and management practices. Addressing this gap is essential for developing site-specific management recommendations that enhance soil fertility and support sustainable oil palm production (Herdiansyah *et al.,* 2020).

Therefore, this study aims to evaluate the fertility status of mature oil palm plantations under different soil types and management practices in Muaro Jambi, Indonesia. The results provide useful insights for improving soil management and supporting more sustainable and productive oil palm cultivation. Accordingly, this study undertakes a comparative plantation-based assessment that integrates soil type, soil depth, and management practices, an approach that remains underrepresented in oil palm research.

Methods

Study area and experimental design

The study was conducted on mature oil palm plantations in Muaro Jambi Regency of Jambi Province, Indonesia representing various soil types and management systems. The locations of the sites were peat soils in Ramin Village and mineral soils in Kedemangan Village and Tanjung Harapan Village. Ramin and Kedemangan Villages are smallholder-managed plantations, while Tanjung Harapan Village is a company-managed plantation. These sites were chosen to represent variation in soil properties and management practices.

A survey-based approach using purposive sampling was employed to select representative plots at each site. Plant age, management history and access issues influenced the selection of sampling locations and it was ensured that plots sampled reflected typical field conditions for each plantation system.

Soil sampling procedure

Soil sampling was carried out at two depths, namely 0–30 cm (topsoil) and 30–60 cm (subsoil). At each study site, three subsamples were collected at each depth and combined into one composite sample. Consequently, two composite samples (topsoil and subsoil) were obtained from each study site for chemical analyses. This approach was adopted to reduce spatial variability and improve the representativeness of soil fertility assessment. Intact soil samples were collected separately using ring samplers for the determination of bulk density and soil water content.

Soil analysis

After collection, the soil samples were transported to the laboratory and processed according to standard soil sample preparation and analytical procedures. From the intact samples, bulk density was assessed and the disturbed samples were examined for soil pH (H_2O), organic carbon, total nitrogen, total phosphorus (P), total potassium (K), cation exchange capacity (CEC), base saturation (BS), and exchangeable aluminum (Al). These soil parameters were selected to assess soil chemical characteristics and the soil fertility status of each oil palm plantation.

Particularly, The Van Vost method, commonly used for the classification of peat decomposition, was applied to indicate the level of maturity of the sampled peat soils.

Data analysis

The soil analysis results were interpreted using descriptive statistics and compared according to soil type, soil depth, and management system. Soil fertility status was assessed based on the criteria developed by the Indonesian Soil Research Center (1995), which classify selected soil properties into five categories: very low, low, medium, high, and very high. A comparative analysis was used to identify key limiting factors affecting soil fertility in each location. The interpretation focused on understanding how soil type, depth, and management practices influence soil physical and chemical characteristics in oil palm plantations.

Result and discussion

Soil physical properties and their implications for oil palm growth

Analysis of soil physical properties revealed that oil palm plantations were established on both mineral and peat soils. The analysis results indicate that, in general, bulk density (BD) values in both the topsoil (0–30 cm) and subsoil (30-60 cm) layers were lowest in the oil palm plantations of Ramin Village, followed by Kedemangan Village, and highest in Tanjung Harapan Village (Tables 1 and 2). Meanwhile, at all observation sites, the trend was the same, namely the BD value was higher in the 30-60 cm layer compared to the 0-30 cm layer (Figure 1).

Oil palm land in Ramin Village has a low bulk density (BD) value because the soil is classified as Histosol which is rich in organic matter with BD values ranging from

Table 1: Value of bulk density (BD) (g/cm^3), total pore space (%) and water content (%) at each location at a depth of 0-30 cm

Location (Village)	Sampling Number	BD (g/cm^3)	Total Pores (%)	Water Content (%)
Kedemangan (KD)	1	1.08	59.25	45.5
	2	1.17	55.85	42.5
	3	1.26	52.45	37
Ramin (R)	1	0.19	92.83	341.8
	2	0.54	79.62	91.2
	3	0.7	73.58	97.2
Tanjung Harapan (TH)	1	1.35	49.06	20.5
	2	1.28	51.7	9.8
	3	1.33	49.81	7.5

Table 2: Value of bulk density (BD) (g/cm^3), total pore space (%) and Water Content (%) at each location at a depth of 30-60 cm

Location (Village)	Sampling Number	Bulk Density (g/cm^3)	Total Soil Pores (%)	Water Content (%)
Kedemangan (KD)	1	1.28	51.7	40.7
	2	1.21	54.34	41.9
	3	1.36	48.68	33.7
Ramin (R)	1	0.14	94.72	610.9
	2	1.03	61.13	47.8
	3	0.84	68.3	80.2
Tanjung Harapan (TH)	1	1.48	44.15	18
	2	1.36	48.68	5.9
	3	1.08	59.25	28.3

0.1-0.9 g/cm^3. In contrast, the oil palm plantations in Kedemangan and Tanjung Harapan Villages are located on mineral soils with a BD value of 1.2-1.5 g/cm^3. Moreover, total pore space (%) has a close relationship with the value of bulk density. Lower BD values corresponded to greater total pore space (Tables 1 and 2, respectively).

This study had revealed that changes in soil type and soil depth impact physical properties and are important for the growth of oil palm. Peat soils have lower bulk density compared to mineral soils, likely due to their porosity and large quantities of organic matter. Peaty soil conditions are conducive for the growth of oil palm, as they help with the penetration of roots, soil aeration, and holding of water. High growth resistance and low soil permeability are likely caused by high bulk densities of mineral soils, especially in their deeper layers systems. Similarly, Hidayat *et al.* (2024), reported findings where root development in oil palm plantations improved due to enhanced physical soil quality and higher organic matter content.

Soil depth correlates with bulk density across all the surveyed locations, with almost all the soil depth layers in the study being very compact. This high level of compaction is common in soil layers with little biological activity and low organic matter, especially deeper soil layers. Very compact subsoil impedes the growth of roots in depth and breadth, and this affects the productivity of the plant, especially when nutrients in the soil layer that is nearer the surface are at a low availability. This condition is very significant in case of the tropics, as soil degradation at the surface reduces the depth of proliferation roots and the ability of the soil to provide nutrients.

Soil acidity and aluminum toxicity as limiting factors

Soil acidity showed a similar pattern across all study sites where the pH value was usually within the range of acidity. The results of the soil pH and exchangeable Al were analyzed at the different study sites and the different depths which were presented in Table 3. The average value of the soil pH at a depth of 0-30 cm at all the study locations was in the range of being acid with the lowest value of 4.70 at Tanjung Harapan Village and 4.91 at Ramin Village followed by Tanjung Harapan Village with a high value of 5.42. At a layer of 30-60 cm, Ramin Village had the lowest pH value (4.70) followed by Kedemangan Village (4.91) and Tanjung Harapan (5.54) where all locations had an acidic soil pH.

This situation is characteristic of tropical soils and can have a serious implication on nutrient availability and plant growth. Acidic soils reduce the availability of the essential nutrients such as phosphorus and increase the solubility of the toxic elements, especially aluminum. It is also reported that previous research in oil palm plantations has found that acidic soil status is usually correlated with low base saturation and low nutrient availability, directly affecting the crop productivity (Christian *et al.,* 2024).

The results of soil sample analysis for exchangeable Al at each study location showed variation (Table 3). The average

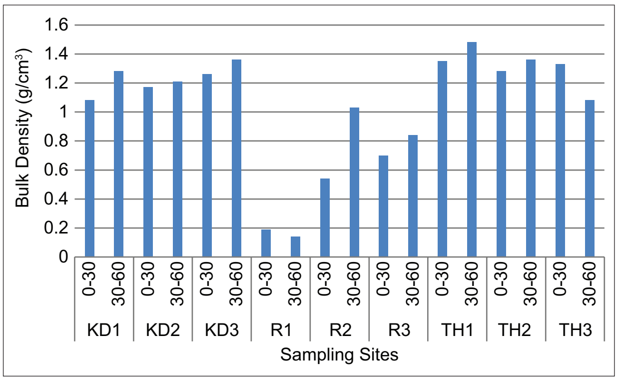

Figure 1: Variation in bulk density (g/cm^3) of oil palm plantations at different locations and management at depths of 0-30 cm and 30-60 cm

Table 3: Soil pH and exchangeable Al of oil palm plantations at different soil types and depths

Location*	Depth (cm)	pH (H_2O)	Exchangeable Al (cmol(+)/kg)
KD1	0-30	4.61 (A)	3.25
	30-60	4.94 (A)	6.31
KD2	0-30	4.63 (A)	4.35
	30-60	4.99 (A)	5.46
KD3	0-30	4.85 (A)	2.55
	30-60	4.81 (A)	5.53
TH1	0-30	5.06 (A)	1.25
	30-60	5.04 (A)	1.86
TH2	0-30	5.37 (A)	0.30
	30-60	6.06 (MA)	<0.12
TH3	0-30	5.82 (MA)	<0.12
	30-60	5.51 (MA)	<0.12
R1	0-30	3.77 (VA)	12.00
	30-60	4.40 (VA)	3.87
R2	0-30	6.15 (MA)	7.03
	30-60	4.64 (A)	3.52
R3	0-30	4.81 (A)	3.55
	30-60	5.07 (A)	3.85

KD=Kedemangan Village, Jambi Luar Kota Sub District; TH=Tanjung Harapan Village, Sungai Bahar Sub District; R=Ramin Village, Kumpeh Ulu Sub District; A=Acid; MA=Moderately Acid; VA=Very Acid.
*Number following village code as number of samplings

exchangeable Al concentration varied among villages and soil depths. In the topsoil layer (0–30 cm), Ramin Village recorded the highest average value (7.53 cmol(+)/kg), followed by Kedemangan Village (3.38 cmol(+)/kg), while Tanjung Harapan Village had the lowest value (0.56 cmol(+)/kg). In the subsoil layer (30–60 cm), the highest average exchangeable Al concentration was observed in Kedemangan Village (5.77 cmol(+)/kg), followed by Ramin Village (3.75 cmol(+)/kg), with Tanjung Harapan Village remaining the lowest (0.70 cmol(+)/kg).

Exchangeable aluminum (Al) is especially found in acidic soils with a pH < 5.5 (Hartono *et al.,* 2022). Table 3 shows that generally the exchangeable Al levels will be higher at lower pH. Aluminum is very active because it is in the form of Al^{3+}, a monomer that is very harmful by poisoning plants or binding to phosphorus (Abreu Jr. *et al.,* 2003).

The relatively high levels of exchangeable Al in several locations, especially in peat and some mineral soils, indicate a potential risk of aluminum toxicity. Under acidic conditions, Al^{3+} becomes more soluble and can interfere with root development, inhibit nutrient uptake, and reduce overall plant growth. In addition, aluminum can bind with phosphorus, making it less available to plants. This interaction is a major constraint in tropical soils, where phosphorus fixation reduces its availability despite sufficient total P content (Abreu Jr. *et al.,* 2003; Iswahyudi & Bakri, 2019).

These findings suggest that soil acidity management, particularly through liming, is a critical strategy for improving soil fertility and enhancing nutrient availability in oil palm plantations.

Soil chemical fertility and key limiting factors

The analysis of soil chemical properties indicates that fertility status varies across locations but generally ranges from very low to moderate (Indonesian Soil Research Center, 1995). In mineral soils, low fertility is primarily associated with low organic carbon content, low cation exchange capacity (CEC), and low base saturation. Similar constraints have been widely reported in highly weathered tropical soils, where low CEC and organic matter limit nutrient retention and reduce fertilizer efficiency (Christian *et al.,* 2024). The classification criteria for soil chemical properties used in this study are summarized in Table 4, while the analytical results for each sampling site are presented in Table 5.

Table 4: Criteria for assessing soil chemical properties (Indonesian Soil Research Center, 1995)

Parameter	Very Low	Low	Moderate	High	Very High
Organic Carbon (OC) (%)	<1.00	1.00-2.00	2.01-3.00	3.01-5.00	>5.00
Base Saturation (%)	<20	20-35	36-50	51-70	>70
Phosphorus (P) (mg/100 g)	<10	10-20	21-40	41-60	>60
Potassium (K) (mg/100 g)	<10	10-20	21-40	41-60	>60
CEC (me/100 g)	<5	5-15	17-24	25-40	>40

The analysis results showed that soil chemical fertility parameters varied among the study locations and between the topsoil (0-30 cm) and subsoil (30-60 cm) layers. In Kedemangan Village, the assessed soil fertility parameters were classified within the very low, low, and medium fertility categories. A detailed evaluation of soil fertility parameters and the corresponding fertility status for each location and soil depth is presented in Table 5.

Cation Exchange Capacity (CEC)

Cation exchange capacity (CEC), a key indicator of soil fertility, varied considerably among the study locations and soil depths. In the topsoil layer (0-30 cm), Ramin Village recorded the highest average CEC (39.66 me/100 g), corresponding to the high fertility category. Kedemangan Village exhibited an average CEC of 11.72 me/100 g, classified as low, whereas Tanjung Harapan Village had the lowest average CEC (1.95 me/100 g), falling within the very low category. In the subsoil layer (30-60 cm), Ramin Village again recorded the highest average CEC (34.13 me/100 g), classified as high. In contrast, Kedemangan Village (11.57 me/100 g) and Tanjung Harapan Village (5.00 me/100 g) both exhibited CEC values within the low fertility category. The observed differences in CEC among the study sites can be attributed to variations in soil organic matter content and clay mineral composition, both of which are key factors influencing soil CEC (Table 5) (Anda, 2008; Sufardi *et al.,* 2020). Soils dominated by hydrous oxides of aluminum (Al) and iron (Fe) generally possess a low negative charge on colloidal surfaces, resulting in lower CEC values (Brady & Weil, 2008). This is consistent with the characteristics

Table 5: Results of analysis of variable soil fertility assessment and soil fertility status of several oil palm plantations in Muaro Jambi Regency at different soil types and depths

Location*	Depth (cm)	CEC (me/100 g)	Base Saturation (%)	Phosphorus (P) (mg/100 g)	Potassium (K) (mg/100 g)	Organic Carbon (%)	Soil Fertility Criteria
KD1	0-30	11.83 (L)	20.11 (L)	100.85 (VH)	203.07 (VH)	1.74 (L)	Low
	30-60	10.74 (L)	7.18 (VL)	118.95 (VH)	211.75 (VH)	0.88 (VL)	Low
KD2	0-30	10.52 (L)	21.6 (L)	49.66 (H)	174.71 (VH)	1.5 (L)	Low
	30-60	11.99 (L)	23.16 (L)	72.35 (VH)	164.85 (VH)	0.66 (VL)	Low
KD3	0-30	12.81 (L)	22.6 (L)	104.57 (VH)	131.41 (VH)	2.05 (M)	Low
	30-60	11.99 (L)	11.63 (VL)	82.61 (VH)	115.66 (VH)	0.65 (VL)	Low
TH1	0-30	3.55 (VL)	7.11 (VL)	9.87 (VL)	24.93 (M)	1.15 (L)	Very Low
	30-60	4.13 (VL)	6.64 (VL)	6.6 (VL)	31.69 (H)	0.6 (VL)	Very Low
TH2	0-30	1.26 (VL)	18.04 (VL)	4.17 (VL)	2.49 (VL)	0.51 (VL)	Very Low
	30-60	2.64 (VL)	71.63 (VH)	3.81 (VL)	1.15 (VL)	0.27 (VL)	Very Low
TH3	0-30	1.04 (VL)	27.26 (L)	4.18 (VL)	1.37 (VL)	0.4 (VL)	Very Low
	30-60	8.23 (VL)	1.41 (VL)	17.69 (L)	2.31 (VL)	2.9 (M)	Very Low
R1	0-30	69.48 (VH)	5.72 (VL)	110.21 (VH)	16.12 (L)	40.99 (VH)	Low
	30-60	66.29 (VH)	16.53 (VL)	94.48 (VH)	26.59 (M)	40.84 (VH)	Medium
R2	0-30	24.71 (M)	3.86 (VL)	134.11 (VH)	204.57 (VH)	11.52 (VH)	Medium
	30-60	15.4 (L)	34.9 (L)	31.41 (M)	157.65 (VH)	2.23 (M)	Low
R3	0-30	24.79 (M)	17.64 (L)	144.84 (VH)	200.67 (VH)	11.91 (VH)	Medium
	30-60	20.71 (M)	22.27 (L)	79.21 (VH)	171.76 (VH)	7.69 (VH)	Medium

KD=Kedemangan Village, Jambi Luar Kota Sub District; TH=Tanjung Harapan Village, Sungai Bahar Sub District; R=Ramin Village, KecamatanKumpeh Ulu Sub District; VL/L/M/H/VH=VeryLow/Low/Medium/High/Very High. *Number following village code as number of sampling point of the study sites, where the mineral soils of Kedemangan Village and Tanjung Harapan Village exhibited relatively low organic matter content, whereas the organic soil (Histosol) in Ramin Village contained substantially higher levels of organic carbon.

Peat soils are characterized by high organic carbon content and relatively high CEC, reflecting their organic nature. However, despite these favorable properties, soil fertility in peatlands may still be constrained by low base saturation. This indicates that although peat soils have a high capacity to retain nutrients, the proportion of essential base cations such as Ca, Mg, and K may be insufficient to support optimal plant growth (Nuryani *et al.,* 2024).

Low base saturation further limits nutrient availability and reduces the effectiveness of ion exchange processes in the soil. Consequently, low soil fertility remains one of the primary constraints to agricultural production on marginal lands, as chemical limitations can restrict plant growth and productivity (Javed *et al.,* 2022). To improve soil quality and enhance fertility, the application of organic amendments is recommended alongside inorganic fertilizers. Organic inputs can increase soil organic matter, improve nutrient retention, and support more sustainable soil fertility management (Sufardi *et al.,* 2020).

Soil base saturation (BS)

Base saturation (BS) is defined as the proportion of exchangeable base cations relative to the soil's cation exchange capacity (CEC), expressed as a percentage. At the 0-30 cm soil depth, the average BS values across the study sites were generally classified as low to very low. Kedemangan Village recorded a low BS value, with an average of 21.44%, whereas Ramin Village and Tanjung Harapan Village were classified as very low, with average values of 9.07% and 17.44%, respectively (Table 5).

At the 30-60 cm depth, Kedemangan Village maintained a low average BS value of 26.56%, while Tanjung Harapan Village (26.56%) and Ramin Village (24.57%) exhibited BS values within the moderate category (Table 5). Previous studies have reported a positive relationship between CEC and BS, as base saturation reflects the proportion of exchange sites occupied by base cations within the soil colloidal complex (Rawal *et al.,* 2019; Embe & Asriani, 2021).

Low BS values are often associated with intensive leaching processes. During leaching, essential alkaline cations such as Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+} are dissolved and transported downward with percolating water, reducing their availability within the root zone and consequently lowering soil fertility (Jin *et al.,* 2015).

Soil organic carbon

The results showed substantial differences in soil organic carbon (OC) content among the study sites, particularly between the mineral soils of Kedemangan Village and Tanjung Harapan Village and the organic soil of Ramin Village. Tanjung Harapan Village recorded the lowest average OC content (0.69%), which was classified as very low, followed by Kedemangan Village with an average value of 1.76%. In contrast, Ramin Village exhibited a very high average OC content of 21.47%, reflecting the organic nature of its Histosol soil (Table 5).

The low OC content observed in the mineral soils may be attributed to the limited application of organic amendments in the oil palm plantations, where management practices primarily relied on inorganic fertilizers. Conversely, organic soils naturally contain high levels of organic carbon due to the accumulation of partially decomposed plant residues. Low soil organic carbon content can indirectly reduce oil palm productivity, as soil organic matter plays a crucial role in maintaining soil quality, nutrient availability, water retention, and overall plant growth (Herdiansyah *et al.,* 2020; Murphy *et al.,* 2021).

Soil phosphorous and potassium

The total soil phosphorus (P) content varied considerably among the study sites and soil depths, ranging from very low to very high fertility categories. At the 0–30 cm depth, total P levels in Kedemangan Village and Ramin Village were classified as very high, with values of 85.03% and 129.72%, respectively. In contrast, Tanjung Harapan Village exhibited a very low P content of 6.07%. A similar pattern was observed in the 30–60 cm layer, where Kedemangan Village and Ramin Village maintained very high total P values of 91.30% and 68.37%, respectively, while Tanjung Harapan Village remained in the very low category with a value of 9.37% (Table 5).

The relatively high phosphorus content observed in Kedemangan and Ramin Villages may be associated with greater organic matter accumulation and nutrient retention capacity. Phosphorus in soils is derived from both organic sources, such as decomposing plant residues and litter, and inorganic sources, particularly phosphate-containing minerals such as apatite (Balemi & Negisho, 2012; McLauchlan, 2006). The high organic matter content in the peat soil of Ramin Village likely contributes to enhanced phosphorus availability and retention.

A similar trend was observed for total potassium (K_2O) content. At the 0–30 cm depth, Kedemangan Village and Ramin Village recorded very high K_2O values of 169.73% and 140.45%, respectively, whereas Tanjung Harapan Village was classified as very low, with a value of 9.60%. In the 30–60 cm layer, Kedemangan Village and Ramin Village again exhibited very high K_2O contents, with values of 164.09% and 118.67%, respectively. In contrast, Tanjung Harapan Village showed a low K_2O status, with a value of 11.72% (Table 5).

The higher potassium levels in Kedemangan and Ramin Villages are consistent with their relatively greater cation exchange capacity (CEC), particularly in Ramin Village, where the organic soil exhibited high nutrient-holding capacity. Conversely, the low CEC observed in Tanjung Harapan Village limits the soil's ability to retain and supply potassium to plants. As a result, potassium is more susceptible to leaching losses in soils with low CEC, reducing its availability for plant uptake (Cornell University Cooperative Extension, 2007).

Furthermore, the substantial variation in phosphorus and potassium contents among the study sites suggests differences in fertilization practices and nutrient management strategies. In some mineral soils, low nutrient levels may be attributed to nutrient leaching and limited retention capacity. Conversely, elevated phosphorus and potassium concentrations in certain locations may reflect recent fertilizer applications rather than sustained improvements in inherent soil fertility. These findings highlight the importance of site-specific nutrient management to maintain soil fertility and support sustainable oil palm production.

Assessment of soil fertility

Soil fertility refers to the capacity of a soil to supply essential nutrients in adequate amounts and appropriate proportions to support plant growth under favorable environmental conditions (Assefa & Tadesse, 2019; Sanchez *et al.,* 2003). According to Lambers *et al.* (2010), fertile soils provide sufficient plant-available nutrients and are free from major constraints that limit plant growth. Soil fertility status, meanwhile, describes the fertility condition of a soil at a specific location and time and is commonly assessed using standardized evaluation criteria (Asmarhansyah & Hasan, 2020). The criteria for determining soil fertility status are shown in Table 6, whereas the fertility classification of each study site is presented in Table 5.

The evaluation results indicated that the fertility status of oil palm plantation soils varied among the study locations but remained relatively consistent across soil depths. At both the 0–30 cm and 30–60 cm depths, soils in Kedemangan Village were classified as having low fertility status, while those in Tanjung Harapan Village fell within the very low fertility category. In contrast, soils in Ramin Village exhibited fertility levels ranging from low to moderate (Table 5). The generally low fertility status observed across the study sites, particularly in the mineral soils of Kedemangan Village and Tanjung Harapan Village, was primarily associated with low soil organic matter content and low base saturation.

Soil organic matter plays a fundamental role in maintaining soil fertility and productivity through its influence on biological activity and nutrient cycling. Numerous soil properties, including physical, chemical, and biological characteristics, are directly or indirectly affected by organic matter. In addition, organic matter contributes to soil aggregate formation, thereby improving soil structure, water retention, and nutrient availability (Six *et al.,* 2000; Torres-Sallan *et al.,* 2017). Consequently, the application of organic amendments is essential for sustaining and improving soil fertility, particularly in intensively managed agricultural systems (Ross, 1993; Lal, 2015).

Table 6: Criteria for assessing soil fertility status (Indonesian Soil Research Center, 1995)

No	CEC	Base Saturation	P, K, OC	Soil Fertility Criteria
1	H	H	2 H without L	High
2	H	H	2 H without L	Medium
3	H	H	2 M without L	High
4	H	H	2 M without L	Medium
5	H	H	H, M, L	Medium
6	H	H	2 L with H	Medium
7	H	M	2 L with M	Low
8	H	M	2 H without L	High
9	H	M	2 H with L	Medium
10	H	M	2 M without L	Medium
11	H	M	Other combination	Low
12	H	L	2 H without L	Medium
13	H	L	2 H with L	Low
14	H	L	Other combination	Low
15	M	H	2 H without L	Medium
16	M	H	2 H with L	Medium
17	M	H	Other combination	Low
18	M	M	2 H without L	Medium
19	M	M	2 H with L	Medium
20	M	M	Other combination	Low
21	M	L	3 H	Medium
22	M	L	Other Combination	Low
23	L	H	2 H without L	Medium
24	L	H	2 H with L	Low
25	L	H	2 M without L	Medium
26	L	H	Other Combination	Low
27	L	M	2 H with L	Medium
28	L	M	Other Combination	Low
29	L	L	All Combination	Low
30	VL	H, M, L	All Combination	Very Low

VL/L/M/H=Very Low/Low/Medium/High

Base saturation is another important indicator of soil fertility because it reflects the proportion of the soil's cation exchange sites occupied by essential base cations such as calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na). The availability of these nutrients to plants depends largely on the degree of base saturation, as higher base saturation generally facilitates the release of adsorbed nutrients into the soil solution (Cornell University Cooperative Extension, 2007). According to Sufardi *et al.* (2020), soils with base saturation values greater than 80% are considered highly fertile, those with values between 50% and 80% have moderate fertility, and soils with base saturation below 50% are classified as infertile. Therefore, the low base saturation values observed in the present study represent a significant constraint to soil fertility and may limit nutrient availability and oil palm productivity.

Influence of soil type and management practices and implications for sustainable soil management

The observed differences in soil fertility among the study locations highlight the combined influence of soil type and management practices on soil quality. Mineral soils, particularly those managed under low-input systems, exhibited more pronounced fertility constraints, primarily due to low organic matter content and limited nutrient retention capacity. In contrast, peat soils, although naturally rich in organic matter and characterized by higher cation exchange capacity (CEC), require careful nutrient management to address imbalances in base cations and improve nutrient availability.

Variations in soil fertility may also be influenced by differences in plantation management systems. Company-managed plantations generally employ more intensive management practices, including regular fertilizer application and soil management interventions, which can enhance nutrient availability in the short term. However, without addressing inherent soil limitations, such practices may not fully overcome long-term fertility constraints. Conversely, smallholder plantations often rely on lower input levels, which may contribute to gradual nutrient depletion and declining soil fertility over time (Chen *et al.,* 2024).

These findings demonstrate that soil fertility management in oil palm plantations cannot be based on uniform recommendations. Instead, management strategies should be tailored to local soil characteristics and plantation management conditions to effectively address site-specific fertility constraints.

The overall results of this study suggest several important strategies for improving soil fertility in oil palm plantations. In mineral soils, increasing organic matter inputs through the application of organic amendments is essential for improving soil structure, enhancing cation exchange capacity, and increasing nutrient retention. Long-term incorporation of organic materials has been shown to improve soil physical, chemical, and biological properties, stimulate microbial activity, and enhance nutrient availability in oil palm production systems (Hidayat *et al.,* 2024). In addition, balanced fertilization programs are necessary to correct deficiencies in essential nutrients, particularly phosphorus and potassium.

In peat soils, management efforts should focus on increasing base saturation through appropriate fertilization and soil amendment practices. Although peat soils possess high organic carbon content and nutrient-holding capacity, their productivity may be constrained by low levels of exchangeable base cations. Sustainable management of peat soils therefore requires careful nutrient balancing and targeted amendments to improve base saturation while maintaining long-term soil productivity (Ratai *et al.,* 2024).

Across all soil types, integrated soil fertility management practices—including the application of organic amendments, balanced fertilization, and soil conservation measures—are essential for maintaining soil health and sustaining long-term productivity in oil palm plantations. Adopting site-specific management strategies that account for differences in soil type, soil depth, and plantation management systems will be critical for improving soil fertility and supporting sustainable oil palm production.

Conclusion

This study demonstrates that soil type and soil depth are key factors influencing the physical and chemical properties of soils in oil palm plantations. Peat soils were characterized by lower bulk density and higher organic carbon content than mineral soils, while subsoil layers consistently exhibited higher bulk density than topsoil layers across all study locations.

Both soil types were generally acidic, with soil fertility status ranging from very low to moderate. The fertility of mineral soils was primarily constrained by low organic carbon content, low cation exchange capacity (CEC), low base saturation, and limited nutrient availability. In contrast, peat soils, despite their high organic matter content and relatively high CEC, were mainly limited by low base saturation, which restricted the availability of essential base cations.

The findings highlight the importance of adopting site-specific soil management strategies in oil palm plantations. In mineral soils, improving soil fertility should focus on increasing organic matter inputs, enhancing nutrient retention, and implementing balanced fertilization practices. In peat soils, management efforts should prioritize improving base saturation and maintaining nutrient balance to optimize soil productivity.

Overall, sustainable soil management practices tailored to soil type and site conditions are essential for improving soil fertility, enhancing nutrient use efficiency, and supporting the long-term productivity and sustainability of oil palm plantations.

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