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Soil Sulfur Status of Inceptisols in Oil Palm Plantations in Riau, Indonesia

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Abstract. *Oil palm requires sulfur (S) in amounts comparable to phosphorus. However, most fertilization Standard Operating Procedures (SOP) in plantations neglect sulfur application. Notably, sulfur accumulation in soils can lead to base cation depletion, surface water acidification, and hydrogen sulfide toxicity. This study aims to assess soil sulfur status based on its physical and chemical characteristics. This descriptive quantitative study analyzed sulfur levels in soil samples from six- and eight-year-old oil palm plantations. A preliminary study was conducted before the implementation of sulfur fertilization trials in oil palm plantations in Riau to assess sulfur status in Inceptisol soils and sulfur content in plant tissues. The measured parameters included exchangeable acidity (Al and H-dd), soil pH (H_2O) using a pH meter, Cation Exchange Capacity (CEC) using ammonium acetate extraction, organic carbon (extracted with $K_2Cr_2O_7$ and H_2SO_4) Total N (Kjeldahl method), total nutrients (P, K, Ca, Mg, S, Al, and Fe) using XRF, and available sulfur using a spectrophotometer with Morgan Wolf extraction. Results showed that total soil sulfur in both study locations was moderate to high, whereas sulfate levels as available S for plants were very low (<20 ppm). Total soil sulfur ranged from 40-70 ppm internationally, while available sulfur ranged from only 1.59-6.27 ppm. Correlation analysis revealed a strong positive relationship between soil sulfate concentration and pH, cation exchange capacity (CEC), and bulk density. These findings indicate that soil fertility management should focus on nutrient addition and increasing the nutrient availability in the soil.*
Keywords: Inceptisols, nutrient adequacy; production; sulfate, acidic soil.

Type of the Paper: Regular Article.

1. Introduction

In Indonesia, yield disparities in oil palm plantations are substantial, presenting opportunities to increase productivity. Globally, Indonesia is the largest supplier of palm oil, yet it does not have the highest Crude Palm Oil (CPO) productivity. According to Jenkins [1], Indonesia ranks fifth in CPO productivity, following Papua New Guinea, Colombia, Thailand, and Malaysia.

Agricultural crop productivity is significantly influenced by agroclimatic conditions, which also affect fertilizer efficiency. The top five palm oil-producing countries have distinct agroclimatic patterns, potentially explaining production differences. Woittiez e tal. [2] highlighted that nutrition management and rainfall as key factors influencing oil palm productivity. Their study suggested that Fresh Fruit Bunch (FFB) yields could reach 20-30 tons/ha/year under optimal Photosynthetically Active Radiation (PAR) conditions. However, according to Vos et al. [3], FAO

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data indicate that actual FFB yields in Indonesia have ranged from 17 tons/ha since 2007, indicating a significant yield gap.

The primary oil palm products, CPO and Palm Kernel Oil (PKO), are influenced by factors beyond PAR, including nutrients such as sulfur, which is crucial for oil synthesis. Jamal et al. [4] reported that oil-producing crops require sulfur up to 300% more than cereals and legumes. However, sulfur fertilization is often overlooked in most plantations because soil and plant sulfur analyses are not routinely conducted, and annual sulfur fertilization is not reported. Instead, kieserite is typically applied only at the initial planting stage, neglecting the essential role of sulfur that is as important as nitrogen (N) and phosphorus (P) in forming the fundamental components of palm oil production. Sulfur deficiency affects nitrogen and phosphorus transport due to its structural role in amino acids such as methionine and cysteine, as reported by Gilbert et.al [5] and Naryan et al. [6]. For instance, Narayan et al. [6], Marschner [7], Ijaz et al. [8] found that sulfur fertilization significantly increased oil content in *oilseed rape*. Similarly, Aisyah et al. [9] reported that 61.22 kg.ha^{-1} sulfur application enhanced corn growth and sulfur uptake. Sulfur uptake varies with crop type, variety, yield levels, and soil sulfur status [10]. It also contributes to the formation of compounds such as lipids and fatty acids, which are essential components of palm oil [10]. Therefore, sulfur's role in FFB and CPO productivity is significant, as evidenced by the current average CPO content of 20-22% in Indonesia [11].

Although sulfur is recognized as a crucial nutrient necessary for optimal plant growth, with requirements similar to those of phosphorus, it has historically garnered limited attention. This is primarily due to the prevailing assumption that sulfur is adequately supplied through atmospheric deposition and various fertilizers such as Kieserite. However, Hinckley et al. [12] reported that declining atmospheric S deposition in the Westwestern United States has resulted in a 29-fold increase in sulfur fertilizer use since 2009 until now. In this case, he suggests the need for sulfur fertilizer management to maintain crop yields while minimizing the environmental consequences of excess sulfur. Similarly, a study [13] found that atmospheric S deposition in Germany over three decades has occurred by 2000 percent.

A comprehensive study by Muhammad et al. [14] investigated sulfur concentrations in two soil types in South Sulawesi, revealing unquantified levels (uq) in both Inceptisol and Vertisol soils. For instance, in palm cultivation, the utilization of fertilizers in Malaysia and Indonesia differs considerably concerning sulfur availability. In Malaysia, the predominant nitrogen source of ammonium sulfate [$(NH_4)_2SO_4$] along with organic fertilizers and industrial effluents, generally secures a sufficient sulfur supply. This practice has historically sustained adequate sulfur concentrations in both soils and plants. Conversely, in Indonesia, urea serves as the primary nitrogen source for oil palm cultivation, and the application of sulfur-containing fertilizers such as

single superphosphate remains infrequent. Although some plantations use Kieserite, its application has not been prioritized in any land assessments [15]. These shifts have contributed to deterioration of sulfur status within Indonesian soils, principally due to sulfur extraction through harvested fruits and losses via leaching. Consequently, sulfur status in Indonesia is considered marginal, with concentrations frequently dipping below the critical threshold for optimal oil palm growth [15].

On the other hand, sulfur accumulation in soils can deplete soil base cations, acidify surface waters, and cause hydrogen sulfide toxicity. The duality between the benefits of sulfur for oil palm production and its effects on environmental quality requires precise studies to support sustainable production while minimizing adverse effects on the environment.

The specific objective of this study was to reveal the soil sulfur status in oil palm plantations in Riau Province and assess whether its availability is closely related to its transport in the plants, thereby providing a basis for more sustainable nutrient management.

2. Materials and Methods

2.1. Study Sites

The study was conducted from June to August 2024 at Sei Pagar plantation, East District Regional III, owned by PT Perkebunan Nusantara IV (formerly known as PTPN V), approximately 26 km southwest of Pekanbaru City, Riau Province, Indonesia (0°19'34.7"N, 101°21'08.1"E).

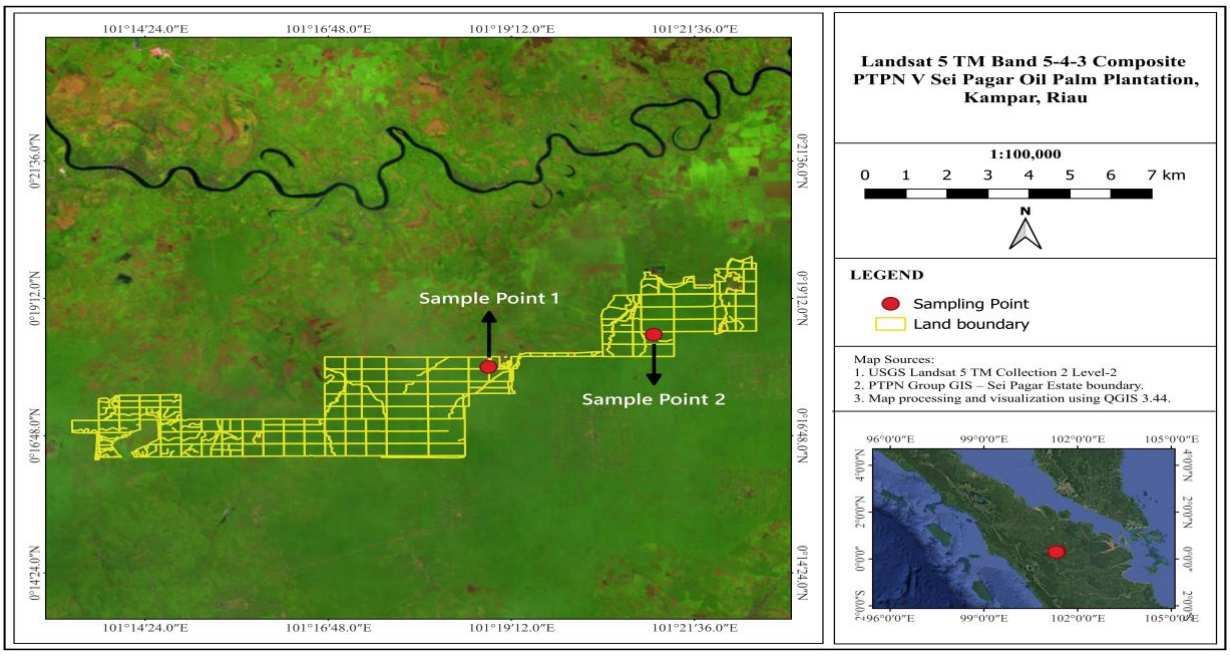


Fig. 1. Study site, the soil sampling points sites in Sei Pagar Oil Palm.

The plantation slope is flat to undulating at altitudes of 7-50 meters above sea level, and is traversed by two major sub-watersheds: Kampar Kanan and Kampar Kiri Rivers.

Soil and plant samples were collected from two plantation blocks with six- and eight-year-old oil palms (Fig. 1), located in blocks 25R1 (Afdeling II) and 21N1 (Afdeling I). The soils are

classified as Typic and Humic Dystrudepts, with some areas identified as Typic Haplosaprist, according to the PTPN V Annual Report 2022 and [16].

The plantation represents the second generation of oil palm cultivation (variety DxP tenera), initially planted in 1986 and covering 2,813 hectares. Both study sites are classified as Inceptisols, with sandy clay loam textures and volumetric soil water contents ranging from 19.05-26.55%. Average annual rainfall from 2019-2024 was 1,798 mm. Fertilization recommendations are based on annual soil and plant analyses conducted by the Indonesian Oil Palm Research Institute. Fertilizers are applied biannually during months with 100-200 mm rainfall. In 2024, fertilization for eight-year-old palms included Urea (3.5 kg), TSP (1 kg), MOP (3 kg), and Dolomite (1 kg) per plant, while six-year-old palms received Urea (3.5 kg), TSP (1 kg), MOP (3.5 kg), and Dolomite (0.75 kg). PTPN IV. (2024). Annual Fertilization Report. Unpublished internal document.

2.2. Field Survey and Analytical Methods

Soil surveys were conducted at two sites within the oil palm plantation, representing six- and eight-year-old palms. Soil samples were collected from a depth of 0-40 cm at 16 sampling points across 20 ha and composited into four samples for laboratory analysis. Each soil composite sample represents 5 hectares, with 4 sample trees. However, at third and fourth soil sampling points, only two trees were taken as samples at each point because they did not meet the criteria for a leaf sampling unit, as they were located right next to the drainage ditch. Therefore, 14 leaf sampling units represented the 20 hectares of the study sites. Soil parameters included exchangeable acidity (KCl extract), pH H_2O (pH meter), cation exchange capacity (ammonium acetate extraction), organic carbon (extracted with $K_2Cr_2O_7$ and H_2SO_4 and measured with a spectrophotometer), and total nutrient content (S, P, K, Ca, Mg, Al, and Fe) determined using X-ray fluorescence (XRF). Sulfate content was analyzed using a spectrophotometer method with Morgan Wolf solvent. Plant nutrient levels were determined using XRF, except for total nitrogen, which was analyzed using the Kjeldahl method.

Leaf samples were collected randomly from 14 oil palm trees in each plantation area to represent 20 ha. Sampling followed the "Leaf Sampling Unit" criteria, with samples taken from the 17th frond in the phyllotaxis system. From these fronds, six leaflets were selected from the midsection. The observed variables included total sulfur content, nitrogen, phosphorus, potassium, calcium, and magnesium levels. Data on nutrient adequacy status were interpreted following [17-19]. Graphs and statistical analyses of soil characteristics and nutrient leaf content parameters were performed using IBM SPSS Statistics 25.0. Correlation analysis was employed to evaluate the influence of soil characteristics on soil sulfate concentration. In addition, an independent-samples t-test was conducted to compare leaf nutrient concentrations of oil palm at 6 and 8 years of age.

The significance level α was set at 0.05 OriginLab 2024 was used to visualize the data in correlogram.

3. Results and Discussion

3.1. Soil Characteristics based on age

Analysis of samples from the two study sites (Table 1) revealed that soil from the eight-year-old plantation had lower organic matter, total nitrogen, sulfate, and cation exchange capacity than soil from the six-year-old plantation. These differences were significant according to the criteria of Eviati et al. [19]. Both plantation sites exhibited C:N ratios below 10, indicating high soil mineralization rates. According to Itanna [20], tropical climates facilitate high mineralization, which impact soil sulfur fractions. Consequently, tropical soils generally have lower total sulfur content than subtropical soils due to increased mineralization rates. Furthermore, the acidic nature of tropical soils reduces sulfur solubility. Both sites showed high soil acidity potential, as evidenced by very high exchangeable aluminum (Al) and hydrogen (H) levels. These parameters significantly influence soil cation exchange processes, soil pH, and fertility.

Table 1. Characteristics of Soil Site.

Variables	Units	Analysis Method	Planting Ages		UCC*
			8 years	6 years	
Bulk Density (BD)	gr/cm3	Sample Ring	1.15	1.05	
C-org	%	Walkley- Black	1.85 l	2.36 s	
Total N	%	Kjehldhal	0.186 l	0.267 s	
C:N ratio			9.91 l	9.04 l	
SOM	%	Conversion: C-org	3.18 l	4.06 l	
Extractable-Al	$cmol.kg^{-1}$	KCl Extraction	4.03 h	2.85 h	
Extractable-H	$cmol.kg^{-1}$	KCl Extraction	2.53	1.80	
pH		pH meter	4.44 acid	4.30 acid	
CEC	$cmol.kg^{-1}$	Ammonium Acetate Extraction	21.32 m	27.03 h	
Bulk Density (BD)	gr/cm3	Sample Ring	1.15	1.05	
SO_4	Ppm	Turbidimetric	1.589 l	6.265 l	
Major Oxides					UCC
P_2O_5	%	XRF	4.393	4.446	0.16
K_2O	%	XRF	2.577	2.474	2.8
CaO	%	XRF	9.562	9.276	4.2
MgO	%	XRF	0.463	0.119	2.48
SO_3	%	XRF	0.470	0.392	$6{,}2.10^{-5}$
Al_2O_3	%	XRF	10.918	10.957	15.4
Fe_2O_3	%	XRF	30.196	30.547	5.04

l, low, m, medium, h, high Criteria according to BSIP Ministry of Agriculture 2023. UCC Upper Continental Crust for the analysis criteria of S-total, CaO, MgO, SO3, Total (Al and Fe) (Rudnick & Gao, 2003) using the XRF method.

XRF analysis showed variations in soil mineral content (oxide form) among the elements. Levels of P, Ca, and S were significantly higher than upper continental crust (UCC) values, indicating that these elements accumulate in the soil layer likely due to fertilization practices, as this plantation represents the second planting cycle. Phosphorus has lower solubility in acidic or alkaline soils, limiting its uptake efficiency by oil palm plants. Conversely, magnesium

concentrations decreased, likely due to changes in aluminum mineral stability such as feldspar, mica, or kaolinite. Ginting et al. [21] reported that oil palm plants' phosphorus uptake efficiency is lower than magnesium uptake, which reaches 56%, contributing to differences in soil fertility status compared to UCC data [22]. Additionally, lower total aluminum levels than UCC values at the site suggest that aluminum release from primary minerals into the solution, followed by leaching to deeper layers beyond the sampling depth (40 cm). In sandy clay loam Inceptisols, the low water and nutrient retention capacity further supports this hypothesis. Conversely, the sixfold increase in iron content indicates secondary minerals, such as hematite and goethite dominate clay composition in these soils, which are rich in iron. High rainfall in the area likely causes leaching of calcium, magnesium, and potassium, resulting in relatively higher levels compared to other total elements during XRF analysis.

3.2. Plant Nutrients Based on Age

The independent samples t-test was conducted to assess differences in leaf nutrient concentrations between 6- and 8-year-old oil palm trees, using a significance threshold of $\alpha = 0.05$. The analysis revealed that nitrogen ($p = 0.021$) were significantly higher in the younger palms, whereas potassium ($p = 0.034$) was significantly greater in the older palms. In contrast, no significant differences were observed for phosphorus ($p = 0.412$), calcium ($p = 0.287$), magnesium ($p = 0.563$), or sulfur ($p = 0.478$), as all p-values exceeded 0.05. These results suggest that nitrogen and potassium concentrations are influenced by palm age, while the other nutrients remain relatively consistent between the two age groups. Consequently, nutrient management practices should prioritize adequate nitrogen availability in younger palms and sufficient potassium supply in older palms to promote optimal growth and productivity. These findings indicate that nitrogen and potassium are age-sensitive nutrients, whereas the other elements remain stable.

Based on the results of XRF analysis of 28 samples, the average S content was 0.53% - 0.66%, where the S content of 8-year-old oil palm leaves is higher than 6 years. [18] stated that the critical S level of the 17th leaf of oil palm plants was 0.22%. Fig. 2. show the nutrient levels in 8-year-old and 6-year-old oil palm plants had sufficient nutrients.

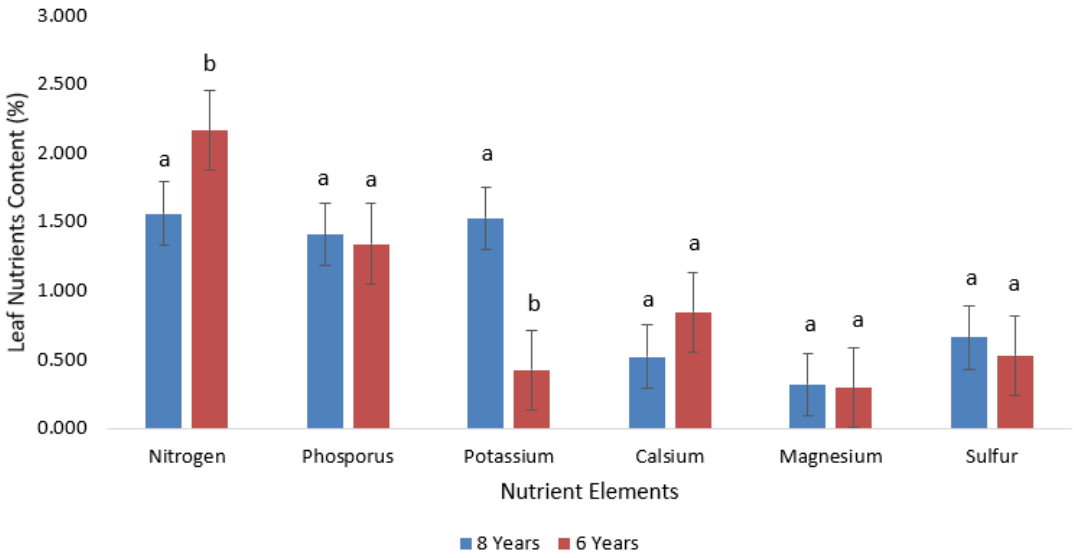


Fig. 2. Nutrient Leaf Content at 8 and 6 Plant Age.

According to Fairhurst and Mutert [18] soil analysis indicated low S levels, but absorption in plants does not correlate with the results of the analysis. This indicates that oil palm plants can absorb SO_2 and H_2S in gas form [23]. In addition, atmospheric sulfur deposition occurs throughout the year through rainfall. Viégas [24] reported that there was the highest S accumulation in oil palm leaves aged 8 years, with accumulation increasing quadratically from 2 to 8 years. The percentage of S extraction also increased with plant age. Doruk and Sarangthem [25] reported a significant increase in S absorption in the vegetative tissue of 12-year-old oil palm with standard fertilization with increased frequency of application. Kalala et al. [26] and Doruk and Sarangthem [25] have also reported that sulfur concentrations in oil palm leaves can vary widely. For instance, leaf sulfur concentrations ranged from 0.02% to 0.35% in a study conducted in West Godavari district of India. Another study in Karnataka, India, reported leaf sulfur concentrations ranging from 0.72% to 1.09%. These results are similar to those reported by Behera et al. [27] and Chang et al. [28], who emphasized that proper sulfur management is crucial for enhancing oil yield. The addition of sulfur through fertilizers, such as ammonium sulfate, has been shown to improve fresh fruit bunch yield significantly. Based on the guidelines by Dibb et al. [17] and Peng et al. [29], [30] overall the nutrient adequacy of oil palm plants fertilized using the Universiti Putera Malaysia fertilization system has been met except for the element of sulphur, compared to the standard oil palm fertilization system in Malaysia [21].

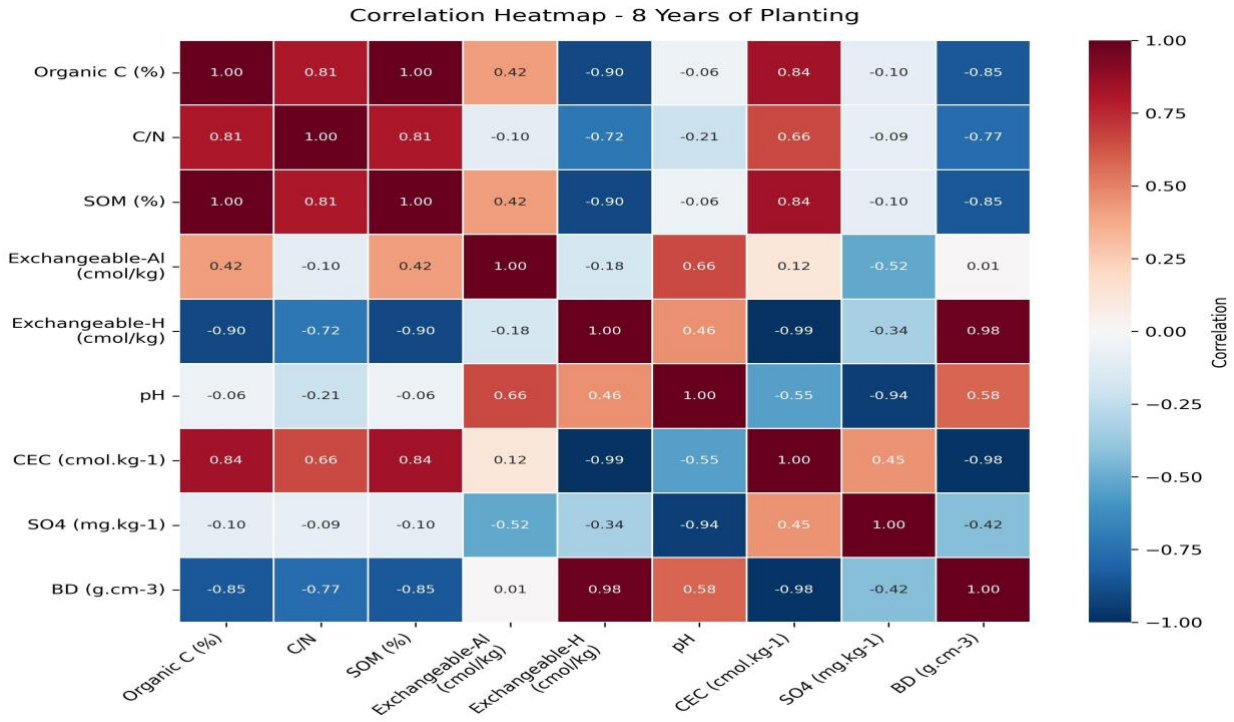


Fig. 3. Correlogram for Soil Characteristics of Oil Palm Plantations with Planting Age of 8 Years.

3.3. Correlation of soil properties with plants

To identify relationships among soil characteristics, data were analyzed using simple correlations, as shown in Fig. 3 and Fig. 4. Fig. 3 shows that 50% of soil characteristics showed strong correlations. Positive correlations were particularly evident among organic matter, C-organic content, CEC, and the C:N ratio, as well as between pH and exchangeable H-dd, Al-dd, and bulk density (BD). Conversely, negative correlations were observed between H-dd and C-organic, C:N ratio, and organic matter. A strong negative correlation was also found between CEC and H-dd, and between BD and organic matter and the C:N ratio. Meanwhile, sulfate availability in the eight-year-old plantations was strongly influenced by pH.

The correlation heatmap reveals that soil sulfate levels at the research site are closely related to cation exchange capacity, pH, and bulk density. The data indicate that higher sulfate level is associated with greater cation exchange capacity. This can occur because sulfate increases the negative charge on soil colloids, strengthening their ability to retain cations. The similar relationship was also reported by Srinivasarao et al. [30]; soils with a higher pH tend to have more dissolved sulfate. At low pH, sulfate can bind to Al (Aluminum) or Fe (Iron), reducing its free concentration. This aligns with the findings of Srinivasarao's research, who reported a negative correlation between pH and sulfate adsorption, indicating that lower the pH leads to higher sulfate adsorption. Conversely, there is a positive correlation between available S (sulfur) and soil organic carbon. The availability of S for plants is not solely determined by the total amount of S in the soil, but also by the interactions between organic fractions, pH, texture, and organic carbon, which are

further influenced by rainfall, the duration of wet periods, and air temperature.

Higher C-organic content typically indicates a greater amount of organic material available for decomposition. Lower C:N ratios are often associated with increased organic matter decomposition and nitrogen availability to plants. Soils with higher organic matter content generally exhibit lower bulk density, as organic matter creates larger pore spaces, improving aeration and water retention. Thus, the negative correlation between C:N and BD suggests that increased organic matter reduces soil compaction, improving physical conditions for oil palm root growth. C-organic content also correlates positively with CEC because organic matter binds and stores essential cations such as calcium (Ca), magnesium (Mg), and potassium (K), crucial for plant growth. Higher CEC enables soils to efficiently store and release nutrients, including sulfur and nitrogen.

Soil pH strongly influences aluminum exchangeability. More acidic soils (lower pH) typically have higher aluminum concentrations, which can replace other cations during cation exchange processes. Similarly, acidic soils exhibit increased hydrogen exchange activity due to their higher H^+ ion concentrations.

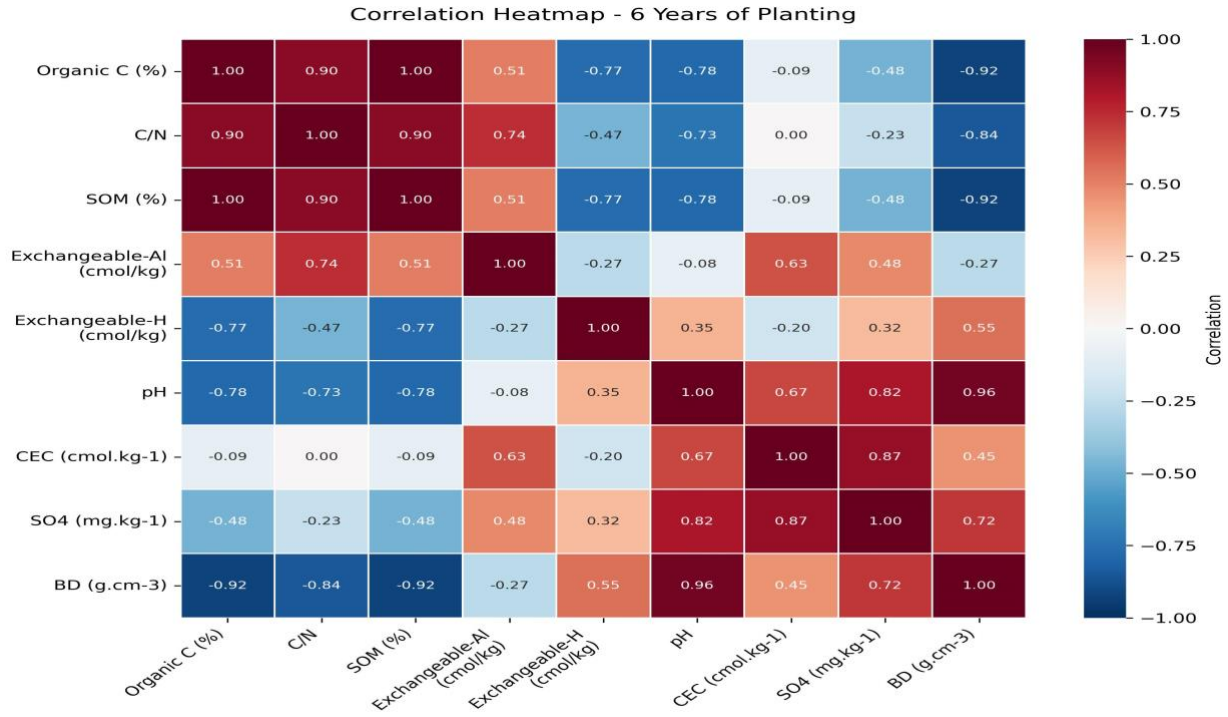


Fig. 4. Correlogram for Soil Characteristics of Oil Palm Plantations with Planting Age of 6 Years.

The correlation patterns observed in the six-year-old plantation were similar to those in the eight-year-old plantation. However, sulfate availability was more positively influenced by pH, CEC, and BD. Chaudhary et al. [31] noted that sulfur oxidation in soils is primarily mediated by microorganisms such as Thiobacillus sp. or Bacillus anthracis, which oxidize sulfur in acidic soils [24]. This process generates sulfuric acid (H_2SO_4), further reducing soil pH. Additionally, pH

affects sulfur adsorption and desorption. [32] reported that Fe_2O_3 and Al_2O_3 levels have a greater impact on sulfate retention than pH and Carbon in Inceptisols. Additionally, a study by Gao et al. [33] found that adding sulfur in the form of sodium lignosulfonate to highly acidic soil (pH 3.5) reduced Al solubility, thereby increasing soil pH and raising exchangeable base saturation by 1.45-fold. As suggested by He et al. [34], this effect stems from the presence of sulfonate (SO_3) functional groups, which carry a strong negative charge and therefore can adsorb positively charged cations such as Al^{3+}.

CEC and BD also exhibited significant correlations. Liu et al. [35] found that the rate of organic sulfur mineralization positively correlates with clay and silt content, while showing a significant negative correlation with sand content. This highlights the importance of soil texture and composition in influencing sulfur mineralization rates. Studies by Gourav et al. [36] and Kalala et al. [26] revealed a positive correlation between soil fraction composition and sulfate availability. Soil CEC is closely related to soil fractions, and clay content significantly affects sulfur release patterns. Higher clay content enhances sulfur release, as reported by Doruk and Sarangthem [25] and Minato et al. [37].

Table 1 Shows low N status soil (0.186%) in oil palms aged 8 years and moderate (0.267%) at the age of 6 years. Nitrogen supports vegetative growth and fruit production. N and K are the elements that are most widely absorbed during harvest. According Dibb et al. [17], each ton of Fresh Fruit Bunches (FFB) transports around 2.94 kg of N and 3.71 kg of K. If in one year oil palm produces 20 tons.ha-^{1}.yr^{-1}, then the plantation loses approximately 58.88 kg of N in 1 ha. Similarly, Mg, which has a high level of fertilization efficiency (56%) according to Ginting et al. [21], was present at low levels in the soil. The total Sulfur from the XRF test results showed a high amount, but the amount of available S was very low (1.59 - 6.23 g.kg^{-1}). These values differ from the critical limit of available S in the soil, which is approximately 9.5 - 13.5 mg.kg-1 according to Gourav et al. [36], Kalala et al. [26] and Shelke et al. [38]. This fact is related to the mineralization process of organic matter in the soil. Rosette et al. [39] states that more than 95% of the total S in the soil occurs in organic form. A lower C:S ratio (below 200) supports the sulfur mineralization, while a higher ratio (above 400) can cause bioimmobilization of organic sulfur [40]. Similarly, Rosette et al. [39] reported that 1 to 5% of organic sulfur in soil with field capacity water content is mineralized into sulfate during the growing season. The age of oil palm plants is one factor affecting soil S status; where Viégas et al. [24] stated that the efficiency of S use increases proportionally with the age of oil palm.

4. Conclusion

This study indicates that total soil sulfur levels at both research sites ranged from adequate

to high. However, the concentration of sulfate (SO_4^{2-}) that represent plant-available sulfur, was categorized as very low (<20 ppm). Sulfate (SO_4^{2-}) in 6–8-year-old oil palm plantations shows a positive relationship with soil pH through Al^{3+} immobilization, cation exchange capacity (CEC), and soil bulk density (BD). The sulfur concentration in oil palm leaf tissues—specifically in 6 and 8 year-old plants is deemed sufficient to support growth. These findings highlight the need for further investigation into the mechanisms of sulfur uptake in oil palm under field conditions.

Abbreviations

CPO Crude Palm Oil
FFB Fresh Fruit Bunch
XRF X-ray fluorescence
UCC Upper Continental Crush
PTPN Perusahaan Terbatas Perkebunan Nusantara (State-Owned Plantation Company, Indonesia)

Data Availability Statement

The data supporting this study are not publicly available due to ethical restrictions but may be available from the corresponding author upon reasonable request

CRediT Authorship Contribution Statement

Hermansah: was responsible for the conceptualization of the research and securing funding, and contributed to the preparation of the manuscript and intellectual property documentation. **Oksana**: conducted the writing original draft project administration, investigation, data curation and visualization. **Agustian**: carried out the formal data analysis and interpretation, and provided supervision during the analytical phase. **Syafrimen Yasin**: oversaw data validation and final reporting, and participated in the review of the manuscript.

Declaration of Competing Interest

The authors declare that there are no conflicts of interest that could have influenced the outcomes or interpretation of this research

Declaration of Use of AI in the Writing Process

Author used Microsoft Copilot, ChatPdf and Claude during preparation of this manuscript to improve grammar, paraphrase text and enhance clarity. After using these tools, the authors carefully reviewed and edited the content and take full responsibility for the content of the publication.

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