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Identification of Soil Chemical Properties in Producing Oil Palm Plants in Kota Pinang District (Barumun Watershed Case Study)

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Abstract−Identification of soil chemical properties is the scientific basis for efficient and sustainable fertilizer management in oil palm plantations. This study aims to identify the status of soil chemical properties and determine the main limiting factors in a productive oil palm plantation (Mature Stage/MS) in the Barumun Sub-Watershed, Kota Pinang District. The method used was a survey with composite soil sampling at a depth of 0-20 cm from 20 sample points determined by purposive random sampling. Samples were analyzed in the laboratory for parameters of pH H_2O, organic-C, total N, available P (Bray I), exchangeable K, Ca, Mg, Cation Exchange Capacity (CEC), and Base Saturation (BS). The results show that the soil at the research location is very acidic to acidic (average pH 4.6) with very low exchangeable Potassium status (average 0.15 me/100g) and low Base Saturation (average 22.5%). Organic-C and total N content were classified as moderate, while available P varied greatly from very low to moderate. In conclusion, the main limiting chemical factors are a triad of problems: (1) high soil acidity, (2) acute Potassium deficiency, and (3) low Base Saturation, which are interrelated and limit nutrient availability. The proposed suggestions are the immediate implementation of a lime application program based on analysis, increasing the dose and frequency of split Potassium fertilizer application, and adopting site-specific soil fertility management approaches for plantation productivity sustainability.

Keywords: Identification; Soil Chemical Properties; Productive Oil Palm; Limiting Factors; Barumun Sub-Watershed; Pinang City

1. INTRODUCTION

Oil palm plantations (Elaeis guineensis Jacq.) are one of the strategic sectors in the Indonesian economy, both as a source of foreign exchange and as an absorber of labor. In 2023, the area of oil palm plantations in Indonesia reached about 15.3 million hectares with crude palm oil (CPO) production of about 46.7 million tons (Directorate General of Plantations, 2023; GAPKI, 2024). North Sumatra Province, as one of the main production centers, contributes significantly to this national achievement. However, the sustainability of production is highly determined by supporting factors, one of which is soil fertility as a growing medium. Productive oil palm plants (Mature Stage/MS) have high nutrient requirements to support flowering, fruit maturation, and vegetative growth simultaneously (Fairhurst & Härdter, 2016).

Chemical degradation of soil fertility is a serious threat to the long-term productivity of oil palm plantations. Intensive cultivation practices, such as imbalanced fertilization, minimal addition of organic matter, and erosion, can cause a decrease in soil pH, a decrease in organic matter content, macro and micronutrient deficiencies, and acidity that increases the solubility of toxic elements such as aluminum (Al) (Guillaume et al., 2018). A study by Adeni et al. (2022) in smallholder plantations in Riau showed that 65% of soil samples had organic matter content classified as low to very low, and 40% had acidic soil pH (< 5.0). This condition has the potential to reduce fertilizer efficiency and plant productivity.

The Barumun Sub-Watershed in Kota Pinang District, South Labuhanbatu Regency, is an area with rapid development of oil palm plantations. This region is dominated by Ultisol and Inceptisol soil orders which are naturally low in chemical fertility, characterized by acidic pH, low cation exchange capacity (CEC), and limited base saturation (BS) (Brady & Weil, 2016). These characteristics require specific and precise soil management so that the productivity of MS oil palm can be maintained optimally. A comprehensive understanding of the status of soil chemical properties is a crucial scientific foundation for formulating efficient and sustainable fertilization recommendations.

Previous research in the Sumatra region generally focused more on evaluating soil fertility in the development stage or immature plants (Immature Stage/IS). Meanwhile, comprehensive data on the dynamics of soil chemical properties in the more critical MS phase of the production cycle are still limited, especially in the Barumun Sub-Watershed area. In fact, in the MS phase, nutrient extraction by plants is very large. Research results in Central Kalimantan show that MS oil palm plants can transport more than 200 kg N, 30 kg P, 300 kg K, 60 kg Mg, and 50 kg Ca per hectare per year (Goh et al., 2021). If not balanced with good inputs and soil conditions, nutrient deficiency will occur.

Furthermore, the spatial variability of soil chemical properties within a plantation, even within the same block, is often high. A preliminary survey in several locations in Kota Pinang District indicated soil pH variations from 4.2 to 5.8 in a relatively narrow area. This variability is influenced by factors of topography, land use history, and non-uniform fertilizer management (Corley & Tinker, 2015). Therefore, a case study approach at the Sub-Watershed level with representative sampling is needed to map the actual conditions and identify the dominant soil fertility limiting factors.

The use of inorganic fertilizers that are often not based on soil analysis results (putative) is a common problem. Data from the Ministry of Agriculture (2021) shows that the efficiency of N fertilizer use in smallholder oil palm plantations is still below 40% on average. One of the main causes is non-ideal soil chemical conditions, such as very acidic pH which causes high P fixation and leaching of base cations. Soil reconditioning through amelioration and

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balanced fertilization based on soil chemical property data is the key to increasing efficiency (Nelson et al., 2021). Without accurate identification, fertilization efforts can become technically ineffective and uneconomical.

Based on the description above, research entitled "Identification of Soil Chemical Properties in Productive Oil Palm Plants (MS) in Kota Pinang District (Case Study of Barumun Sub-Watershed)" is very relevant and urgent to carry out. This research is expected to provide a comprehensive scientific picture and measurable statistical data regarding the status of soil chemical fertility, so that it can be the basis for decision-making in precise and sustainable soil and fertilization management in the region.

The Objectives of this Research are: To identify and analyze the status of soil chemical properties (pH, organic-C, total N, available P, exchangeable K, Ca, Mg, CEC, and BS) in MS oil palm plantations in the Barumun Sub-Watershed, Kota Pinang District. To evaluate the level of soil chemical fertility based on standard soil fertility criteria for oil palm and to identify the main limiting factors.

2. RESEARCH METHODS

This research was conducted for 6 (six) months, from August to November 2025. Soil sampling and field observations were carried out in September 2024. Soil sample analysis was carried out at the Soil Chemistry and Fertility Laboratory, Faculty of Agriculture, Universitas Sumatera Utara.

Figure 1. Location Is In MS Oil Palm Plantations

The research location is in MS oil palm plantations (aged 8-15 years) in the Barumun Sub-Watershed area, Kota Pinang District, South Labuhanbatu Regency, North Sumatra Province. Geographically located at coordinates 1°42'00" - 1°55'00" North Latitude and 100°05'00" - 100°15'00" East Longitude.Figure 1.

The materials used in this study were composite soil samples from 20 sampling points in MS oil palm plantations, aquadest, and various chemical analysis materials for soil parameters according to laboratory standards. The tools used included: soil auger, sample bag, Garmin GPS, labels, oven, analytical balance, pH-meter, spectrophotometer, flame photometer, and standard laboratory glassware.

To identify and analyze the status of soil chemical properties (pH, organic-C, total N, available P, exchangeable K, Ca, Mg, CEC, and BS) in MS oil palm plantations in the Barumun Sub-Watershed, Kota Pinang District. To evaluate the level of soil chemical fertility based on standard soil fertility criteria for oil palm and to identify the main limiting factors.

Research Methode Preparation Literature study and preparation of a work map, Field Survey: Identification and determination of sampling points, composite soil sampling, Sample Preparation: Soil samples were air-dried, ground, and sieved with a 2 mm sieve to obtain fine earth, Laboratory Analysis: Measurement of all soil chemical property parameters according to standard methods, Data Analysis: Data were analyzed descriptively (average, standard deviation, minimum, maximum) and compared with standard soil fertility criteria for oil palm.

The measured soil chemical property parameters along with analysis methods and units are presented. Prior to further analysis, the research data were subjected to the Parameters, Analysis Methods, and Units of Measurement for Soil Chemical Properties test, the results of which are shown in the following table;

Table 1. Parameters, Analysis Methods, and Units of Measurement for Soil Chemical Properties

No.	Parameter	Analysis Method	Unit	Reference
1.	pH H_2O	Electrometry (ratio 1:2.5)	-	Rayes & Lumbanraja (2019)
2.	C-Organic	Walkley and Black	%	Nelson & Sommers (2018)

No.	Parameter	Analysis Method	Unit	Reference
3.	N-Total	Kjeldahl	%	Bremner (1996)
4.	P-Available	Bray I	ppm	Bray & Kurtz (1945)
5.	Exchangeable K	Extraction with 1N NH_4OAc pH 7.0, Flame Photometry	me/100g	Helmke & Sparks (1996)
6.	Exchangeable Ca & Mg	Extraction with 1N NH_4OAc pH 7.0, Titration/AAS	me/100g	
7.	CEC	Extraction with 1N NH_4OAc pH 7.0	me/100g	Sumner & Miller (2018)
8.	Base Saturation (BS)	(K+Ca+Mg)/CEC x 100%	%	Brady & Weil (2016)

3. RESULTS AND DISCUSSION

Results of Soil Analysis on Soil Chemical Properties in Productive Oil Palm Plants (MS) in Kota Pinang District (Case Study of Barumun Sub-Watershed) are presented. Prior to further analysis, the research data were subjected to the Results of Soil Chemical Property Analysis at Depth 0-20 cm in MS Oil Palm Plantations, Barumun Sub-Watershed (n=20), the results of which are shown in the following table;

Table 2. Results of Soil Chemical Property Analysis at Depth 0-20 cm in MS Oil Palm Plantations, Barumun Sub-Watershed (n=20)*

Parameter	Average ± SD	Range	Status*
pH H_2O	4.6 ± 0.3	4.1 - 5.2	Very Acidic - Acidic
C-Organic (%)	1.8 ± 0.5	1.0 - 2.8	Moderate - High
N-Total (%)	0.18 ± 0.06	0.09 - 0.30	Moderate
P-Available (ppm)	12.5 ± 8.2	3.0 - 35.0	Very Low - Moderate
Exchangeable K (me/100g)	0.15 ± 0.07	0.05 - 0.30	Very Low
Exchangeable Ca (me/100g)	2.1 ± 1.2	0.5 - 5.0	Low - Moderate
Exchangeable Mg (me/100g)	0.9 ± 0.5	0.2 - 2.1	Low
CEC (me/100g)	14.2 ± 3.5	8.5 - 20.0	Moderate
BS (%)	22.5 ± 9.8	8.0 - 45.0	Low

Based on laboratory analysis of 20 soil samples from MS oil palm plantations in the Barumun Sub-Watershed, a comprehensive picture of soil chemical fertility status was obtained. The discussion of each parameter is described in detail below, integrating the findings of this research, previous research results, and the underlying scientific mechanisms.

Soil pH values ranged from 4.1 to 5.2 with an average of 4.6 ± 0.3, which is classified as very acidic to acidic. This condition is an intrinsic characteristic of acidic mineral soils (Ultisols and Inceptisols) in humid tropical regions that have experienced intensive leaching of base cations (Ca^{2+}, Mg^{2+}, K^{+}) and accumulation of aluminum (Al^{3+}) and hydrogen (H^{+}) ions (Brady & Weil, 2016). pH below 5.0 has critical implications for nutrient dynamics: (a) increases the solubility of Al^{3+} and Fe^{3+} to toxic levels that can inhibit root growth and reduce nutrient uptake, (b) causes phosphate (P) fixation by insoluble Al and Fe oxides (forming Al-P and Fe-P), so that P availability for plants decreases drastically even though P fertilizer is applied, and (c) decreases the activity and diversity of soil microorganisms, especially decomposer bacteria that play a role in organic matter mineralization and the nitrogen cycle (Kochian et al., 2015; Guo et al., 2019). This finding is in line with research by Nelson et al. (2021) in Kalimantan oil palm plantations which reported an average pH of 4.3-4.8 in plantations with productivity below potential. Therefore, amelioration with lime material (calcite/dolomite) is a main and non-negotiable intervention to raise soil pH close to the optimal range of 5.0-5.5 for oil palm plants (Fairhurst & Härdter, 2016).

Organic Carbon (C-Organic) Soil organic-C content showed variation from low to high (1.0 - 2.8%) with an average of 1.8% (moderate category). This value reflects a moderate level in the organic matter cycle. The main source of organic matter in plantations comes from frond litter and empty fruit bunches. The average value of 1.8% is still better than the report by Adeni et al. (2022) in smallholder plantations in Riau which were mostly below 1.5%, but has not reached the ideal target of >3.0% to support long-term soil health (Utomo, 2019). Organic matter is key to improving soil physical (structure, infiltration), biological (microbial activity), and chemical properties, especially as a slow-release nutrient source and increasing Cation Exchange Capacity (CEC) (Lehmann & Kleber, 2015). Low organic-C content at several sample points (<1.5%) indicates a decomposition rate that may be faster than the addition of organic matter or surface erosion. This reinforces the importance of conservation practices such as regular placement of empty fruit bunches in the inter-row.

Soil total N content ranged from 0.09% to 0.30% with an average of 0.18% (moderate category). This value shows a significant positive correlation (r=0.82) with organic-C content, because more than 95% of soil N is bound in organic matter. The observed average soil C/N ratio was 10:1, indicating that the organic matter has decomposed well and is ready to release N through the mineralization process (Murphy, 2015). Although the status is moderate, N availability for plants in acidic pH is often inhibited because the activity of decomposer microbes such as Nitrosomonas and Nitrobacter decreases at pH <5.5. Furthermore, the risk of N loss through ammonia volatilization from urea fertilizer could increase in soils with low pH and low clay content. Therefore, additional N fertilization is still needed, with consideration of using more efficient N sources such as ammonium sulfate or coated urea under site-specific conditions (Sutedjo & Kartasapoetra, 2019).

This parameter showed the highest variability, ranging from very low (3.0 ppm) to moderate (35.0 ppm), with an average of 12.5 ppm (low category). 60% of samples were below 15 ppm, which is the critical limit for MS oil palm. This wide variation is strongly influenced by local P fertilization history and the strong P fixation nature in acidic soils. At pH <5.0, phosphate ions ($H_2PO_4^-$) react quickly with dissolved Al^{3+} and Fe^{3+} ions to form Al-phosphate and Fe-phosphate compounds (such as variscite and strengite) which are very stable and unavailable to plants (Hinsinger, 2001). This condition explains why the efficiency of P fertilizer (such as SP-36) in acidic soils rarely exceeds 20%. This finding is consistent with research in the Serdang Bedagai region, North Sumatra, which reported that the application of 100 kg P_2O_5/ha only increased available soil P by 5-8 ppm in soil with pH 4.5 (Sitorus & Daulay, 2020). Management strategies must focus on: (1) raising soil pH as a basic step, (2) applying P fertilizer in smaller doses but higher frequency (split application), and (3) adding organic matter to bind Al and Fe, thereby reducing fixation sites (Zaharah & Lim, 2017).

Potassium status is in a very critical condition, with an average of only 0.15 me/100g (very low category). This is the most concerning finding because K is a primary nutrient for fruit filling, sugar translocation, and stress tolerance. The K requirement of MS oil palm is very large, reaching 200-300 kg K_2O/ha/year (Goh et al., 2021). Low exchangeable K indicates: (a) limited soil mineral K reserves (e.g., from illite), (b) inadequate or inefficient K fertilizer (KCl) application, and (c) high K loss through leaching on sandy textured soils or through run-off. Soils with low CEC (<16 me/100g) like those found at the research location have a weak capacity to retain K, so applied K fertilizer is easily leached (Situngkir et al., 2021). An urgent recommendation is a significant increase in K fertilizer dose and split application (at least 2 times a year) to match the plant's demand pattern and reduce losses.

Exchangeable Calcium is in the low to moderate category (average 2.1 me/100g), while exchangeable Magnesium is low (average 0.9 me/100g). Both of these base cations are important for soil structure stability (Ca), chlorophyll component (Mg), and enzyme activation. The observed average Ca/Mg ratio was 2.3:1, still within a tolerable range (3:1 to 5:1). However, the low absolute content of both, especially Mg, can cause deficiency symptoms such as chlorosis on old leaves. In acidic soils with low pH, the availability of Ca and Mg is also suppressed due to competition with Al^{3+} ions at root absorption sites (Mengel & Kirkby, 2012). Dolomite CaMg(CO3)2CaMg(CO3)2 application is a win-win solution strategy because it can simultaneously raise pH (amelioration) and supply both nutrients. Special attention needs to be paid to the balance between K, Ca, and Mg because excess K can cause antagonism and inhibit Mg uptake (nutrient imbalance).

Soil CEC ranged from 8.5 to 20.0 me/100g with an average of 14.2 me/100g (moderate category). CEC reflects the capacity of the soil as a "nutrient bank" to hold cations (K^+, Ca^{2+}, Mg^{2+}, Na^+, H^+, Al^{3+}) and prevent their leaching. This CEC value is highly determined by the type of clay mineral (kaolinite dominant in acidic soils has low CEC) and organic matter content (Brady & Weil, 2016). CEC below 16 me/100g is vulnerable to nutrient loss, especially under high rainfall like in the Barumun Sub-Watershed. Therefore, efforts to increase CEC through consistent addition of organic matter not only improve fertility but also increase the efficiency of applied inorganic fertilizers

Low base saturation (average 22.5%, low category) is a synthesis of all previous cation parameters. BS measures the percentage of the cation exchange complex occupied by bases (K, Ca, Mg, Na) compared to acid ions (H^+ and Al^{3+}). BS < 50% indicates that the soil adsorption complex is dominated by ions that are unfavorable for plants and is a strong indicator of chemical infertility of acidic soils (van Ranst et al., 2018). For optimal growth, oil palm requires BS above 50-60% (PPKS, 2018). This low BS directly limits the availability of cationic nutrients, because plant roots will exchange more with toxic H^+ and Al^{3+}. Increasing BS can only be achieved through a measured liming program and balanced fertilization of base cations in the medium term.

4. CONCLUSION

The status of soil chemical properties in MS oil palm plantations in the Barumun Sub-Watershed is generally in suboptimal to critical condition. Key parameters indicate: very acidic soil pH (average 4.6), very low exchangeable Potassium content (average 0.15 me/100g), and low Base Saturation (BS) (average 22.5%). Organic-C and total N content are in the moderate category, while available Phosphate and cations Ca and Mg vary from low to moderate with high spatial variability. This condition describes the characteristics of acidic mineral soils (Ultisol/Inceptisol) that have undergone cultivation intensification without adequate amelioration. The main limiting chemical factors threatening productivity and fertilization efficiency are a triad of interrelated problems: (a) Soil acidity (low pH) which triggers (b) high Aluminum toxicity and Phosphorus fixation, and (c) very severe Potassium (K) deficiency. Low BS is a synthetic indicator that the soil adsorption complex is dominated by unfavorable acid ions (H^+ and Al^{3+}), not by the base nutrients (K, Ca, Mg) needed by plants. The combination of these factors causes the potential availability of nutrients for plants to be very limited even though fertilization inputs may have been applied. Spatially, there is significant variability between sample points, especially for available P and base cation parameters. This indicates the influence of land management history, topography, and non-uniform application of inputs within the study area. Therefore, a uniform management approach (blanket recommendation) for the entire area will be less effective and efficient.

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