talenta PUBLISHER

InJAR
Indonesian Journal of Agricultural Research
Journal homepage: https://injar.usu.ac.id

Analysis of oil palm land characteristics in Muting District, Merauke Regency, South Papua Province

Diapari Siregar[1], Ratna Mauli Lubis[1], Benny Hidayat[2*]
[1]*Department of Agrotechnology, Faculty of Agriculture, Islamic University of Sumatera Utara, Medan, Indonesia*
[2]*Department of Agrotechnology, Faculty of Agriculture, Universitas Sumatera Utara, Indonesia*
[*]Corresponding author: bennyhidayat@usu.ac.id

ARTICLE INFO
Article history:
Received 17-04-2025
Revised 28-02-2026
Accepted 18-03-2026
Available online 31-07-2026

E-ISSN: 2615-5842
P-ISSN: 2622-7681

How to cite:
D. Siregar, R. M. Lubis, and B. Hidayat, "Analysis of Oil Palm Land Characteristics in Muting District, Merauke Regency, South Papua Province", *Indonesian J. Agric. Res*, vol. 9, no. 2, pp. 103-109, Jul. 2026.

https://doi.org/10.32734/injar.v9i2.20510

ABSTRACT
The growth and productivity of oil palm are strongly influenced by land characteristics. Merauke Regency, particularly Muting District, South Papua Province, has extensive land potential for oil palm development but requires a detailed evaluation of land suitability. This study aimed to analyze field land characteristics to determine land suitability classes for oil palm plantations. Field surveys and laboratory analyses were conducted in October 2022, using secondary climate data, direct soil morphological observations, and soil physical–chemical analyses. The parameters evaluated included rainfall and the number of rainy days over the past five years, as well as soil physical and chemical properties, and soil morphological characteristics. The results indicate that the study area is classified as Type-B climate according to the Schmidt and Ferguson (1951) classification. The dominant soil type is Acrustoxic Kanhaplustults, characterized by clay-dominated texture and generally low to very low chemical fertility status. These soil conditions suggest inherent limitations for optimal oil palm growth. Based on the land suitability evaluation following the criteria of the Palm Oil Research Center, the study area is classified as S3 (marginally suitable) for both actual and potential suitability classes. Light-limiting factors include rainfall, soil texture, and drainage, while moderate-limiting factors consist of dry months, effective soil depth, and soil pH. These constraints indicate the need for appropriate land management and soil improvement strategies to enhance productivity. Overall, this study provides essential baseline information for sustainable land development planning for oil palm plantations in Muting District, Merauke Regency.
Keywords: Kanhaplustults, land characteristics, limiting factors, marginal sustainability

1. Introduction

Indonesia has prioritized palm oil exports as one of its major non-oil and gas commodities in response to steadily increasing global demand. This condition has driven the implementation of both intensification and extensification strategies in oil palm plantation development. Currently, oil palm plantations in Indonesia cover approximately 14.99 million hectares, predominantly located in Sumatra and Kalimantan, with smaller proportions in Sulawesi and Java [1]. However, land availability in these regions has become increasingly limited, prompting the exploration of new potential development areas, including Muting District, Merauke Regency, South Papua Province. Land suitability assessment was based on integrated climatic, soil, topographic, and hydrological parameters [2]. Climatic variables included mean annual temperature, rainfall amount and distribution, solar radiation, potential evapotranspiration, and climatic hazards. Soil parameters comprised texture, effective soil depth, drainage condition, soil reaction (pH), organic matter content, and nutrient availability. Topographic conditions were represented by slope gradient, while hydrological conditions were evaluated through water availability and drainage status [3].

Land classified as S1 exhibited optimal conditions with no significant limitations for oil palm growth. S2 land presented moderate limitations that may reduce productivity but remain manageable through appropriate agronomic interventions. S3 land was characterized by severe limitations resulting in marginal productivity and high management inputs. Land categorized as N possessed very severe limitations that could not be corrected economically or technically [4]. Land suitability analysis was conducted using a matching and limiting factor approach, in which the lowest suitability rating among evaluated parameters determined the overall land suitability class. This method enabled the identification of dominant limiting factors affecting oil palm cultivation in the study area [5].

2. Materials and Methods

This study was conducted at the oil palm plantation of PT. Agriprima Citra Persada, Muting District, Merauke Regency, South Papua Province, Indonesia, from September to October 2022. A descriptive–comparative approach was applied, in which land characteristics were analyzed and compared among land units. Data were collected through a field survey using flexible observation spacing and an identification-based observation method. The study area was delineated into land units based on similarities in elevation and topographic conditions. Soil samples were collected from representative observation points within each land unit using purposive sampling to capture variations in land characteristics. At each sampling point, disturbed soil samples were taken for laboratory analysis, while field observations were conducted to record morphological characteristics, slope, drainage conditions, and other site attributes relevant to land evaluation.

Land characteristics evaluated included soil, topography, geology, and geomorphology. Observed variables comprised soil physical properties, slope gradient and length, rock hydraulic conductivity, landform types, and land unit attributes. Field equipment included a 1:5,000 scale field map, soil auger, Munsell Soil Color Chart, GPS, measuring tape, altimeter, digital camera, hand lens, and data sheets. Laboratory analyses were performed to determine key soil chemical and physical properties, including soil pH, organic carbon, total nitrogen, available phosphorus, exchangeable potassium, cation exchange capacity, base saturation, and soil texture, following standard analytical procedures. These parameters were used to evaluate soil fertility status and their suitability for oil palm cultivation.

Data analysis involved: (1) delineating and describing land characteristics for each land unit; (2) comparing measured land characteristics with established land suitability criteria using the matching method; (3) identifying limiting factors affecting oil palm growth; (4) climatic type determination using the Schmidt–Fergusson classification (1951); (5) soil classification based on Soil Taxonomy (2016); (6) soil fertility assessment following Sahetapy (1989); and (7) land suitability classification for oil palm using criteria established by IOPRI [6]. The final land suitability class for each land unit was determined based on the most limiting factor according to the FAO land evaluation framework.

3. Results and Discussion

3.1. Land characteristics

3.1.1. Temperature and soil moisture regime

The temperature conditions in the study area generally fall within the optimal range for oil palm growth. Mean annual air temperatures support physiological processes such as photosynthesis, vegetative growth, and fruit development. Based on temperature requirements for oil palm, the study area can be classified as **S1** in terms of thermal suitability [9]. Favorable temperature conditions also enhance nutrient uptake efficiency and promote the formation of fresh fruit bunches (FFB), thereby contributing to higher productivity. Moreover, stable temperatures throughout the year minimize thermal stress, allowing oil palm to maintain continuous growth and reproductive development. Therefore, temperature is not considered a limiting factor for oil palm cultivation in the study area, and current thermal conditions are highly supportive of sustainable plantation management. Soil moisture conditions are characterized by an ustic moisture regime, indicating a seasonal pattern of water availability with alternating wet and dry periods. While soil moisture is generally adequate during the rainy season, moisture deficits may occur during consecutive dry months, particularly from June to August. These temporary moisture limitations may reduce land suitability to S2 or S3, depending on soil water-holding capacity and the duration of the dry period [7].

The interaction between temperature and soil moisture plays a critical role in determining oil palm productivity. Although temperature does not represent a limiting factor, seasonal soil moisture stress may constrain growth and yield if not properly managed. Therefore, appropriate soil and water management practices are required to maintain optimal growing conditions and sustain oil palm productivity under variable climatic conditions [8].

3.2. Soil type and land characteristics

In accordance with the distribution of physiographic units derived from secondary data, soil classification based on the Soil Taxonomy system (USDA–NRCS, 2016) indicates that the study area is predominantly occupied by Kanhaplustults, specifically the Acrustoxic Kanhaplustults subgroup. These soils occur mainly in gently convex to undulating flat areas with good drainage. A smaller portion of the area is occupied by Aquic Kanhaplustults, which are located in depressional areas that are prone to waterlogging, particularly during the rainy season [9]. These soils developed on Permo-Carboniferous geological formations (older than the Tertiary period) with a peneplain physiography. A peneplain is a very old land surface formed through long-term planation processes acting on formerly undulating terrain over hundreds of thousands of years, rather than through fluvial alluviation or sediment deposition [10].

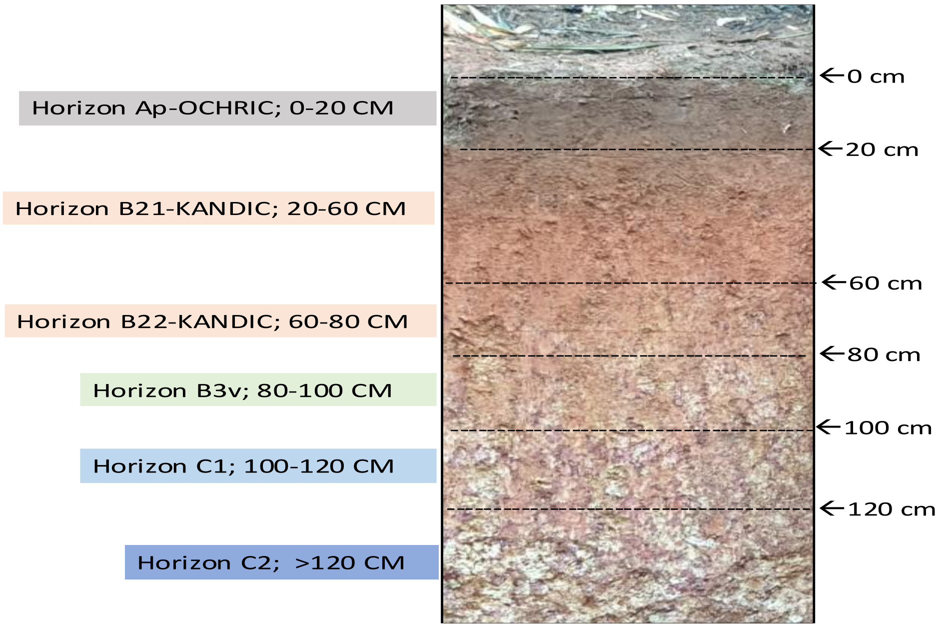

Figure 1. Soil profile of Acrustoxic Kanhaplustults excavated to a depth of 200 cm. The profile dimensions (width x length x depth) are 1.5 x 2.5 x 2.0 m

The soils are classified as Ultisols, which are very old soils characterized by the presence of a kandic horizon. A kandic horizon is a subsurface soil horizon distinguished by a higher clay content compared to adjacent horizons. Unlike an argillic horizon, the kandic horizon does not exhibit clay skins. The kandic horizon represents an advanced stage of soil development from an argillic horizon, in which clay skins coat soil ped faces. Through prolonged pedogenic processes, the removal of clay skins leads to the transformation of an argillic horizon into a kandic horizon [11].

The occurrence of a kandic horizon indicates an advanced stage of weathering and pedogenic development, typically associated with prolonged leaching under humid tropical conditions. During this process, silica and exchangeable base cations are progressively removed from the soil profile, while low-activity clay minerals such as kaolinite and Fe–Al oxides become dominant [12]. Both kandic and argillic horizons are diagnostic horizons characteristic of Ultisols and indicate long-term soil-forming processes. Conceptually and empirically, soils characterized by a kandic diagnostic horizon generally exhibit lower inherent fertility compared to soils with an argillic horizon. The transformation from an argillic to a kandic horizon is estimated to require pedogenic processes operating over hundreds of thousands of years [13].]. Figure 1 presents the soil profile of Acrustoxic Kanhaplustults, while its detailed description is provided in Table 1, and the results of soil analysis are shown in Table 2.

Table 1. Morphological description of the Acrustoxic Kanhaplustults soil profile

Number Horizon	Depth (cm)	Symbol Horizon	Morphological Description
I	0-20	Ap	Reddish-brown coating (5YR4/4), dusty clay texture, crumb structure, friable consistency, very coarse-medium-fine rooting, real straight switch to
II	20-60	B21	The yellowish-red coating (5YR4/6), dusty clay texture, angular strong-medium-lumpy structure, firm consistency, medium and fine roots are rather numerous, gradually switching straight to
III	60-80	B22	Yellowish-red coating (5YR4/6), dusty clay texture, angular strong-medium-lumpy structure, very firm consistency, medium and fine roots of medium amount, gradually straight over to
IV	80-100	B3v	Reddish-brown (5YR4/4) and white (2.5YR4/0) coating, dusty clay texture, angular strong-medium-clumpy structure, very firm consistency, gradually straight switch to
V	100-120	C1	The coating is red (2.5YR4/6) and white (2.5YR4/0), clay texture, massive structure, hard consistency, gradually straight switch to
VI	120+	C2	The coating is red (2.5YR4/6) and white (2.5YR4/0), clay texture, massive structure, very hard consistency.

The occurrence of a kandic horizon reflects an advanced stage of soil weathering and pedogenic development that typically forms under warm and humid climatic conditions over prolonged geological periods. Both argillic and kandic horizons are recognized as diagnostic subsurface horizons in Ultisols; however, they differ substantially in their degree of weathering, mineralogical composition, and fertility status. Argillic horizons are characterized by the accumulation of translocated clay through illuviation and may retain relatively greater nutrient reserves and cation exchange capacity, whereas kandic horizons represent a more advanced stage of pedogenesis marked by intensive desilication, prolonged leaching of exchangeable base cations, and the dominance of low-activity clay minerals such as kaolinite together with iron and aluminum oxides. Continuous weathering under high rainfall conditions progressively removes silica and nutrient-bearing minerals from the soil profile, resulting in lower cation exchange capacity, lower base saturation, increased soil acidity, greater phosphorus fixation, and reduced nutrient retention capacity. Consequently, soils containing kandic horizons generally exhibit lower inherent fertility and require more intensive management interventions, including liming, balanced fertilization, and organic matter amendments, to sustain agricultural productivity. From a geomorphological perspective, the presence of a well-developed kandic horizon is widely regarded as evidence of long-term landscape stability and advanced pedogenesis, commonly occurring on old geomorphic surfaces such as peneplains that have experienced prolonged weathering with minimal disturbance from erosion or sediment deposition. Pedogenic studies indicate that the transformation of an argillic horizon into a kandic horizon may require hundreds of thousands to several million years, depending on climate, parent material, drainage conditions, and landscape stability. Therefore, the identification of a kandic horizon not only signifies a highly weathered and nutrient-depleted soil environment but also provides valuable evidence regarding the age, evolutionary history, and long-term pedogenic development of tropical landscapes [14]. Soil properties of the study area indicate advanced weathering and impose moderate to severe limitations on oil palm cultivation. The soils are dominated by clay across all horizons (41–60%), reflecting highly developed Ultisols with fine texture. Soil reaction is strongly acidic, with pH values decreasing from 4.7 in the surface horizon to 4.5 in the subsoil, indicating intensive base leaching and dominance of Al and Fe cations [15].

Surface soil organic carbon remains moderate (2.76–3.26%) but declines sharply with depth (0.33–0.97%), accompanied by moderate surface nitrogen content (0.24–0.26%) and low subsoil values. The C/N ratio (8–12) is optimal, although rapid organic matter decomposition under an ustic moisture regime may accelerate carbon depletion if not replenished through organic amendments [16].

Indonesian Journal of Agricultural Research Vol. 09, No. 02 (2026) 103 – 109

Table 2. The results of mechanical and chemical analysis of the soil from each horizon "layer" of soil

Parameters	Analysis results and status at each soil depth (cm)					
	0-20	20-40	40-60	60-80	80-120	120+
Mechanical analysis						
Sand fraction (%)	9	6	6	10	13	6
Dust fraction (%)	43	53	52	49	31	34
Clay fraction (%)	48	41	42	41	56	60
Texture	Dusty clay	Dusty clay	Dusty clay	Dusty clay	Clay	Clay
Chemical analysis						
pH-H2O	4.7 (AR)	4.7 (AR)	4.7 (AR)	4.5 (R)	4.5 (R)	4.5 (R)
C (%)	3.26 (AT)	2.76 (S)	0.97 (R)	0.59 (R)	0.49 (R)	0.33 (R)
N (%)	0.26 (S)	0.24 (S)	0.10 (R)	0.07 (R)	0.06 (R)	0.04 (R)
C/N	13 (AT)	12 (AT)	10 (S)	8 (S)	8 (S)	8 (S)
P-bray 1 (ppm)	10.5 (AR)	1.4 (R)	0.4 (R)	0.2 (R)	0.2 (R)	0.6 (R)
P_2O_5 HCl 25% (mg/100g)	7 (SR)	5 (SR)	5 (SR)	6 (SR)	5 (SR)	4 (SR)
K2O HCl 25% (me/100g)	6 (SR)	10 (R)	12 (R)	4 (SR)	3 (SR)	3 (SR)
K-dd (me/100g)	0.07 (SR)	0.13 (R)	0.24 (R)	0.04 (SR)	0.03 (SR)	0.04 (SR)
Ca-dd (me/100g)	1.72 (SR)	0.97 (SR)	0.44 (SR)	0.34 (SR)	0.32 (SR)	0.29 (SR)
Na-dd (me/100g)	0.04 (SR)	0.09 (SR)	0.13 (SR)	0.11 (SR)	0.13 (SR)	0.12 (SR)
Mg-dd (me/100g)	0.64 (R)	0.62 (R)	0.38 (SR)	0.32 (SR)	0.30 (SR)	0.26 (SR)
CEC (me/100g)	16.57 (S)	12.67 (R)	8.37 (R)	7.75 (R)	8.17 (R)	6.32 (R)
KB (%)	15 (R)	14 (R)	14 (R)	10 (R)	10 (R)	11 (R)
DHL (mmhos)	0.050 (SR)	0.044 (SR)	0.06 (SR)	0.044 (SR)	0.027 (SR)	0.030 (SR)

Note: Analysis at the Bogor Soil Center Laboratory (2022), SR= very low; R= low; AR= bit low; S= medium; AT= somewhat high.

Available phosphorus is low to very low (10.5 ppm at the surface and 0.2–1.4 ppm in the subsoil), consistent with very low total P_2O_5, indicating limited phosphorus reserves in the parent material and strong phosphorus fixation under acidic conditions. Exchangeable K, Ca, and Mg are also low to very low, while cation exchange capacity is moderate only in the surface horizon and decreases in the subsoil, reflecting advanced weathering and prolonged leaching of base cations. The low base saturation (10–15%) further confirms the poor inherent fertility of these soils and suggests limited nutrient retention and availability for plant growth. Such characteristics are typical of highly weathered Ultisols and constitute important constraints for oil palm cultivation, requiring appropriate fertilization and soil amelioration practices to sustain productivity [17]. Based on these characteristics, the soils are classified as moderately suitable (S2) for oil palm in well-drained areas with intensive fertility management, and marginally suitable (S3) in locations where nutrient limitations and subsoil constraints are more pronounced.

3.3. Land suitability class

Based on the evaluation results, the land suitability class (LSC) of the oil palm plantation in the Muting District and surrounding areas is classified as S3 (marginally suitable), with a subclass designation of S3-h1.k2.s2.t1.d1.a2. This land unit is constrained by six limiting factors (h, k, s, t, d, and a), consisting of three moderate limitations and three light limitations. The assessment indicates that the land suitability class cannot be improved and will remain at S3 even under potential management interventions.

The moderate limitations include: (1) the occurrence of dry months averaging three months per year, (2) shallow effective soil depth of approximately 80 cm, and (3) acidic soil conditions with pH values ranging from 4.5 to 4.7. Among these factors, only soil acidity is technically amendable through the application of dolomite to increase soil pH toward neutral conditions. However, soil pH improvement is considered difficult, as it requires repeated dolomite applications for at least three consecutive years at a rate of 2.5 kg per tree per year [18].

The light limitations consist of: (1) annual rainfall occasionally below 2000 mm or exceeding 3000 mm, (2) clay-dominated soil texture with high water-holding capacity that restricts water availability to oil palm roots under certain conditions, and (3) moderately to somewhat impeded drainage due to high clay content, which limits water percolation during periods of high rainfall. Additionally, the presence of plinthite in the subsoil horizons further degrades soil physical properties, causing the soil to become very hard during the dry season [19].

Table 3. The results of mechanical and chemical analysis of the soil from each horizon ("layer" of soil)

No.	Element of Conformity/symbol	Soil Type *Acrustoxic Kanhaplustults*	
1.	Precipitation (mm)/h	1992-3092	1
2.	Dry month (month)/k	3	2
3.	Elevation (m.dpl)/l	20-35	0
4.	Region shape/slope(%)/w	Flat – choppy	0
5.	Effective depth (cm)/s	80	2
6.	Rock content (%)/b	<3	0
7.	Soil texture/t	Dusty clays	1
8.	Drainage class/d	Medium-somewhat inhibited	1
9.	pH/a	4.5-4.7	2
	ACTUAL LSC	S3-h1,k2.s2.t1.d1.a2	
	POTENTIAL LSC	S3	

Note: LSC= land suitability class

3.4. Plant performance

The general plant performance and potential improvement measures can be summarized as follows. The nitrogen (N) status in the leaves, based on visual assessment, ranges from moderate to high, which is consistent with the still adequate soil N availability. However, considering the highly labile nature of nitrogen, which is susceptible to leaching, volatilization, and rapid mineralization, regular N fertilization at moderate rates is required to sustain optimal plant growth. Phosphorus (P) status is visually classified as deficient, as indicated by narrow frond angles relative to the trunk and a low proportion of female inflorescences across several areas. Despite these symptoms, the trunk exhibits optimal size and shape from the basal to upper sections, suggesting that typical P deficiency effects have not yet fully manifested structurally. Potassium (K) status appears near optimal in the current year; nevertheless, sporadic white stripe symptoms are still observed on the middle and lower fronds within the canopy, indicating the need for moderate to high K fertilization. Magnesium (Mg) status is considered optimal, as reflected by the generally fresh green coloration of the leaves; therefore, Mg fertilization at moderate rates is recommended to maintain this favorable condition. The calcium (Ca) status in the leaves is difficult to assess visually; however, it is likely to be low due to the advanced stage of soil weathering and strongly acidic soil conditions. Boron (B) status is visually deficient, characterized by crinkled leaflets and partially unopened fronds, symptoms that are also commonly associated with P deficiency and highlight the essential role of boron in plant development; consequently, moderate B fertilization is required. Other micronutrients are visually assessed to be at optimal levels under field conditions [20].

4. Conclusion

Oil palm plantations in Muting District, Merauke Regency, South Papua Province are developed under Climate Type B, characterized by an average of three dry months annually. More than 90% of the area is dominated by Acrustoxic Kanhaplustults, which exhibit unfavorable physical and chemical properties, including shallow effective soil depth, clay-dominated texture, moderate drainage, acidic soil reaction, and low to very low availability of P, K, Mg, and Ca. Although moderate organic matter content and optimal C/N ratios persist as a legacy of secondary forest conversion, these properties are highly susceptible to degradation following land-use change. Overall plant performance is near optimal, as indicated by vigorous growth and green foliage;

however, localized deficiencies of K, P, and B were observed. Based on integrated climatic, soil, and crop performance evaluations, the land is classified as marginally suitable (S3) for oil palm cultivation, with recurrent dry months, shallow soil depth, and acidic soil reaction as the main limiting factors, of which soil acidity is the most feasible constraint to ameliorate.

5. Conflict of Interest

The authors state no conflict of interest.

References

[1] Statistics Indonesia (BPS), Area of Oil Palm Plantations in Indonesia by Province. Jakarta, Indonesia: Statistics Indonesia, 2022.
[2] Untari, "Availability of land, water, human and technology resources in the development of food estate areas in Merauke-Indonesia," *Technium*, vol. 17, no. 1, pp. 21–29, 2023.
[3] Food and Agriculture Organization (FAO), *A Framework for Land Evaluation*. Rome, Italy: FAO Soils Bulletin No. 32, 1976.
[4] Kementerian Pertanian Republik Indonesia, *Petunjuk Teknis Evaluasi Lahan untuk Komoditas Pertanian*. Bogor, Indonesia: Balai Besar Penelitian dan Pengembangan Sumberdaya Lahan Pertanian (BBSDLP), 2011.
[5] Verheye, *Growth and Production of Oil Palm*, in *Encyclopedia of Life Support Systems (EOLSS)*. Oxford, U.K.: EOLSS Publishers, 2010.
[6] Indonesian Oil Palm Research Institute (IOPRI), Soil Nutrient Status Criteria for Oil Palm Plantations. Medan, Indonesia: IOPRI, 1991.
[7] R. H. V. Corley and P. B. Tinker, "The Climate of the Oil Palm-Growing Regions," in *The Oil Palm*, 5th ed. Chichester, U.K.: Wiley-Blackwell, 2015, ch. 3, doi: 10.1002/9781118953297.ch3.
[8] N. Tani *et al.*, "Small temperature variations are a key regulator of reproductive growth and assimilate storage in oil palm (*Elaeis guineensis*)," *Scientific Reports*, vol. 10, No. 650, 2020. doi: 10.1038/s41598-019-57170-8.
[9] Soil Survey Staff, *Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys*, 2nd ed. Washington, DC, USA: U.S. Department of Agriculture, Natural Resources Conservation Service, 1999.
[10] R. Hall, *The Geology of Indonesia*. Chichester, U.K.: Wiley-Blackwell, 2012.
[11] A. R. Orme, "The Foundations of Geomorphology," in *Treatise on Geomorphology*, vol. 1, San Diego, CA, USA: Academic Press, 2013
[12] F. H. Beinroth, H. Eswaran, P. F. Reich, and E. Van den Berg, "Land Related Stress Factors for Sustainable Tropical Agriculture," in *Sustainable Management of Soil Resources in the Tropics*, Bangkok, Thailand: IBSRAM, 2001, pp. 13–30.
[13] Soil Survey Staff, *Keys to Soil Taxonomy*, 13th ed. Washington, DC, USA: United States Department of Agriculture, Natural Resources Conservation Service (USDA-NRCS), 2022.
[14] A. E. Hartemink *et al.*, "Soil horizon variation: A review," *Advances in Agronomy*, vol. 160. pp. 125–185, 2020. doi: 10.1016/bs.agron.2019.10.003.
[15] M. M. Pratamaningsih, D. P. Hati, E. Erwinda, R. Q. Muslim, M. Hikmat, and S. Purwanto, "Soil characteristics and management of ultisols derived from claystones of Sumatra," *Journal of Tropical Soils*, vol. 29, no. 3, pp. 115–125, 2024.
[16] T. D. Schowalter, "Decomposition and Pedogenesis," in Insect Ecology, 2nd ed. Amsterdam, The Netherlands: Academic Press, pp. 405–435, 2006.
[17] H. H. Gebrekidan, "Soil acidification: Sources, processes, impacts on soil properties, nutrient dynamics, crop health and yield: A review," *EQA–International Journal of Environmental Quality*, vol. 54, pp. 1–22, 2025.
[18] C. E. Sys, E. Van Ranst, and J. Debaveye, *Land Evaluation Part II: Methods in Land Evaluation*, Agricultural Publications No. 7. Brussels, Belgium: General Administration for Development Cooperation, 1991.
[19] M. K. V. Carr, "The Water Relations and Irrigation Requirements of Oil Palm (*Elaeis guineensis*): A Review," *Experimental Agriculture*, vol. 47, no. 4, pp. 629–652, 2011.
[20] H. Ifansyah, "Soil pH and solubility of aluminum, iron, and phosphorus in Ultisols: The roles of humic acid," *Journal of Tropical Soils*, vol. 18, no. 3, pp. 203–208, 2013. doi: 10.5400/jts.2013.18.3.203.