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Mapping Land Suitability for Oil Palm Cultivation in Papua Using Geographic Information Systems

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Abstract

Land suitability analysis is essential to support sustainable oil palm cultivation and minimize environmental risks caused by inappropriate land use. This study aimed to evaluate land suitability for oil palm cultivation in Indonesia using a Geographic Information System (GIS)-based multi-criteria evaluation (MCE) approach. Spatial datasets related to climate, topography, and soil characteristics were obtained from open-source data providers, including WorldClim, CHIRPS, SoilGrids, and Indonesia Geospatial. The parameters used in this study included mean temperature, rainfall, wind speed, solar radiation, elevation, soil texture, soil pH, and organic carbon content. Datasets were processed and analyzed using QGIS through several stages, including data pre-processing, parameter reclassification based on oil palm growth requirements, weighting of parameters, and raster-based spatial overlay analysis. The resulting suitability index was classified into four land suitability classes: highly suitable (S1), moderately suitable (S2), marginally suitable (S3), and not suitable (N). Results of this study were presented in the form of thematic maps and a final land suitability map for oil palm cultivation, along with area statistics for each suitability class. This study demonstrates that GIS-based multi-criteria analysis is an effective tool for land suitability assessment and can support spatial planning and decision-making for sustainable oil palm development.

Keywords: Land Suitability, *Elaeis guneensis*, Oil Palm, Papua

1. Introduction

Oil palm (*Elaeis guineensis* Jacq.) is one of the most strategic plantation commodities, contributing substantially to the global supply of vegetable oil. Biologically, this species is characterized by high photosynthetic efficiency, a strong capacity for biomass accumulation, and oil productivity per unit area that surpasses that of other oil-producing crops (Corley & Tinker, 2016). The growth and productivity of oil palm are strongly influenced by complex interactions between genetic factors and environmental conditions, particularly climate, soil physicochemical properties, and water availability, which collectively regulate key physiological processes such as cell division, tissue differentiation, and primary metabolic activity (Hartley, 1988). From an ecological perspective, oil palm requires relatively specific biophysical conditions to achieve optimal performance, including an annual mean temperature of 24–28 °C, annual rainfall of 2000–3000 mm with a well-distributed pattern, sufficient soil depth, soil texture that supports adequate aeration and water retention, and land slopes that allow proper root system development and plant stability (Woittiez et al., 2017). Deviation from these conditions may induce abiotic stress, leading to reduced photosynthetic efficiency, impaired nutrient uptake, and ultimately a decline in fresh fruit bunch productivity.

Over the past two decades, land suitability evaluation approaches have advanced rapidly through the integration of plant ecological concepts with Geographic Information Systems (GIS) and remote sensing technologies. Numerous studies have demonstrated that land suitability mapping based on biophysical parameters provides a comprehensive spatial representation of environmental potentials and constraints for oil palm cultivation (Sys et al., 1993; Vijay et al., 2016). This approach not only supports production optimization but also serves as a critical instrument for sustainable, ecosystem-based land-use planning. Previous studies have assessed oil palm land suitability across various tropical regions, including Southeast Asia and Latin America, emphasizing climate, soil, and topographic variables as primary determinants of productivity (Pirker et al., 2016; Woittiez et al., 2017). However, most of these studies have focused on regions with well-established plantation systems that are relatively homogeneous in terms of infrastructure and land management. In contrast, Papua, characterized by high ecological complexity, heterogeneous landscapes, and distinct socio-environmental dynamics, remains underrepresented in integrated biologically and spatially based land suitability assessments for oil palm.

The main knowledge gap lies in the limited availability of spatially explicit information that directly links the biophysical characteristics of Papua's landscapes with the ecological requirements of oil palm. The lack of detailed land suitability studies may lead to suboptimal land use, which in turn can trigger environmental degradation, loss of ecosystem functions, and conflicts between production objectives and biodiversity conservation (Fitzherbert et al., 2008). Therefore, this study has high scientific urgency and biological relevance. From a theoretical perspective, it contributes to a deeper understanding of the relationships between land biophysical factors and the ecological responses of oil palm within complex tropical landscapes. From an applied perspective, the findings are expected to provide a scientific basis for land-use planning, informed decision-making in the sustainable development of oil palm plantations, and the mitigation of ecological impacts in Papua.

The objective of this study is to analyze and map land suitability levels for oil palm cultivation in Papua based on key biophysical parameters, including climate, soil characteristics, and topography, using a Geographic Information System approach. The resulting maps are expected to align with the empirical findings presented in the Results and Discussion sections and to offer science-based recommendations for sustainable land resource management.

2. Materials and Methods

2.1. Software

This study utilized QGIS (Quantum Geographic Information System) latest version as the primary platform for spatial data processing, visualization, and analysis. QGIS was used to manage raster and vector datasets, perform spatial preprocessing, generate thematic maps for each environmental factor, and conduct spatial statistics related to land suitability assessment for oil palm cultivation.

2.2. Materials and Data Sources

The materials used in this study consisted of spatial and environmental datasets obtained from reliable open-source providers in raster and vector formats. All datasets were standardized to a uniform coordinate reference system to ensure spatial consistency across analyses.

Administrative boundary data of Indonesia were obtained from INDONESIA GEOSPASIAL and served as the base layer to define the study area and to clip all environmental raster datasets. This boundary ensured that all analyses were spatially restricted to the national territory of Indonesia.

Climatic and topographic data were obtained from WORLDCLIM in raster (.tif) format. These datasets included annual mean temperature, wind speed, solar radiation, and elevation, which represent key environmental conditions influencing oil palm growth. Annual rainfall data were obtained from CHIRPS, providing spatial information on precipitation distribution and intensity across Indonesia.

Soil characteristics data were obtained from SOILGRIDS, including soil texture, soil pH, and organic carbon content. Soil texture data were used to assess soil physical properties related to drainage and root development, pH to represent soil acidity conditions, and organic carbon content to indicate soil fertility status.

2.3. Research Type and Approach

This study employed a quantitative descriptive research approach using Geographic Information System (GIS)-based spatial analysis to evaluate land suitability for oil palm cultivation. The analysis focused on assessing individual environmental factors that influence oil palm growth, without integrating multiple factors into a composite suitability index. Each environmental variable was analyzed independently to describe its spatial distribution and its suitability level for oil palm cultivation based on established agronomic criteria.

2.4. Study Area and Research Period

The study area encompassed the entire territory of Indonesia, as defined by administrative boundary data obtained from INDONESIA GEOSPASIAL. The research period included data collection, preprocessing, spatial analysis, map generation, and interpretation of results.

2.5. Research Variables

The variables analyzed in this study consisted of climatic, topographic, and soil-related factors relevant to oil palm cultivation. Climatic variables included annual mean temperature, rainfall, wind speed, and solar radiation. Topographic conditions were represented by elevation, while soil characteristics included soil texture, soil pH, and organic carbon content. These variables were selected based on their relevance to oil palm growth requirements as reported in previous studies and national land suitability guidelines.

2.6. Data Processing and Analysis

Spatial data analysis was conducted using QGIS through a series of preprocessing and analytical steps. All raster and vector datasets were first standardized to the WGS 84 coordinate reference system. Environmental raster data were clipped to the Indonesian administrative boundary to ensure spatial consistency.

Each environmental factor was then analyzed separately. Raster datasets were reclassified into land suitability classes based on oil palm cultivation requirements, namely S1 (Highly Suitable), S2 (Moderately Suitable), S3 (Marginally Suitable), and N (Not Suitable). Reclassification thresholds were determined using criteria synthesized from the Indonesian Ministry of Agriculture Decree No. 131/2013, Gaol et al. (2023), and Corley and Tinker (2015) (Table 1).

The analysis focused on describing the spatial distribution of suitability classes for each factor independently. Thematic maps were produced for annual rainfall, mean temperature, wind speed, solar radiation, elevation, soil texture, soil pH, and organic carbon content to illustrate areas that meet or do not meet oil palm suitability requirements for each parameter.

Table 1. Land Suitability Criteria for Oil Palm (*Elaeis guineensis*) Development

No	Parameter	S1	S2	S3	N
1	Annual Rainfall (mm/year)	1,750 – 3,000	1,500 – 1,750	1,250 – 1,500	< 1,250 / > 3,500
2	Average Temperature (°C)	25 – 28	22 – 24	20 – 22	< 18 / > 32
3	Elevation	0 – 200	200 – 400	400 – 500	> 500
4	Solar Radiation (MJ/m^2/day)	> 16	14 – 16	12 – 14	< 12
5	Wind Speed (m/s)	< 2	2 – 4	4 – 6	> 6
6	Soil Texture	Fine (Loamy)	Medium	Coarse	Very Coarse (Sand)
7	Organic Carbon (%)	> 2.0	1.2 – 2.0	0.5 – 1.2	< 0.5
8	pH	5.0 – 6.0	4.2 – 4.9	4.0 – 4.1	< 4.0 / > 7.0

Source: Data synthesized and adapted from Indonesian Ministry of Agriculture Decree No. 131/2013, Gaol et al. (2023), and Corley & Tinker (2015).

2.7. Research Outputs

The outputs of this study consisted of individual thematic maps for each environmental factor, spatial descriptions of land suitability classes for oil palm cultivation per parameter, and summary tables presenting the areal extent of suitability classes for each factor across Indonesia.

3. Results

The land suitability analysis for oil palm (*Elaeis guineensis*) across six provinces in Papua was conducted by integrating eight biophysical parameters. Based on the spatial data processing, the discussion is categorized into three main strategic factors.

3.1. Climatic Factors (Rainfall, Temperature, Solar Radiation, and Wind Speed)

The climatic profile across the study area shows exceptional potential for oil palm growth. Annual Rainfall in all provinces, including Papua, West Papua, and South Papua, consistently ranges between 2,000–3,005 mm/year. According to Permentan 131/2013, this range falls into the S1 (Highly Suitable) category, providing optimal water availability for the crop.Solar Radiation is a primary advantage for this region, with values ranging from 14,263 to 18,000 kJ/m²/day. South Papua recorded the highest radiation intensity (up to 18,000 kJ/m²/day), visualized in Red on the suitability map. According to Corley & Tinker (2015), such high radiation is crucial for efficient photosynthesis and oil biosynthesis. Average Temperature in the lowlands remains optimal at 25–28°C; however, in the Papua Mountains and Central Papua, temperatures drop significantly to 6°C in highland areas, acting as a permanent limiting factor. Wind Speed is generally low and safe (0.9–2.8 m/s), although it reaches 5.6 m/s in mountainous regions, it remains within the threshold to prevent mechanical damage to the fronds (Figure 1).

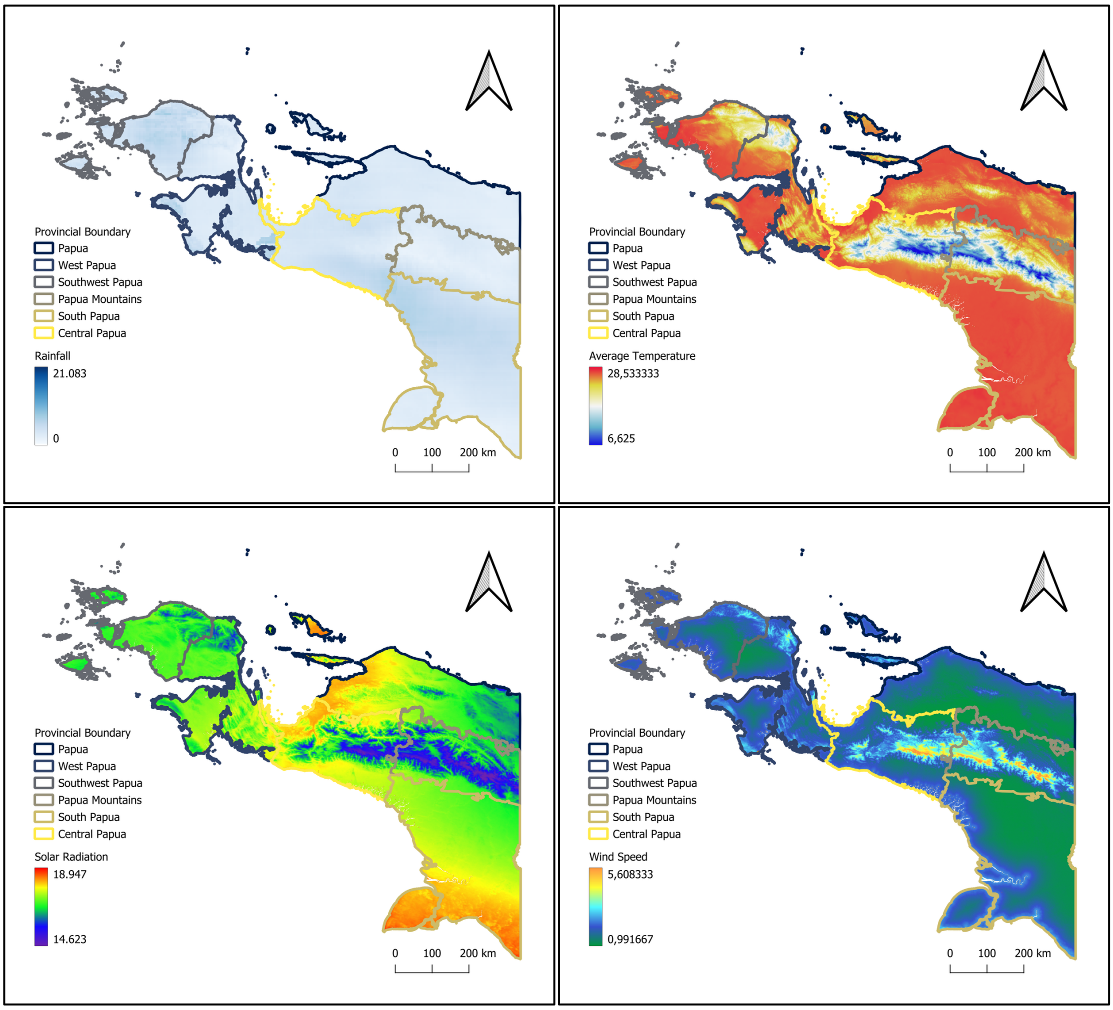

Figure 1. Climatic factors affecting land suitability for oil palm: (a) rainfall, (b) temperature, (c) solar radiation, and (d) wind speed.

3.2. Topographic Factors (Elevation and Soil Texture)

Topography serves as the primary filter for determining potential plantation areas in Papua. Elevation in coastal provinces like Southwest Papua and South Papua ranges from 0–1,000 m.asl. However, following the criteria of Permentan 131/2013 and Gaol et al. (2023), only areas below 500 m.asl are classified as suitable. Data shows that the Papua Mountains reach extreme elevations of up to 4,401 m.asl, which are automatically categorized as N (Not Suitable). Regarding physical properties, the Soil Texture in Papua's lowlands is dominated by fine to medium textures (clay loam). This supports the oil palm root system in water absorption and tree stability. The combination of low elevation and favorable soil texture in the southern and northwestern regions identifies these areas as priority zones for development (Figure 2).

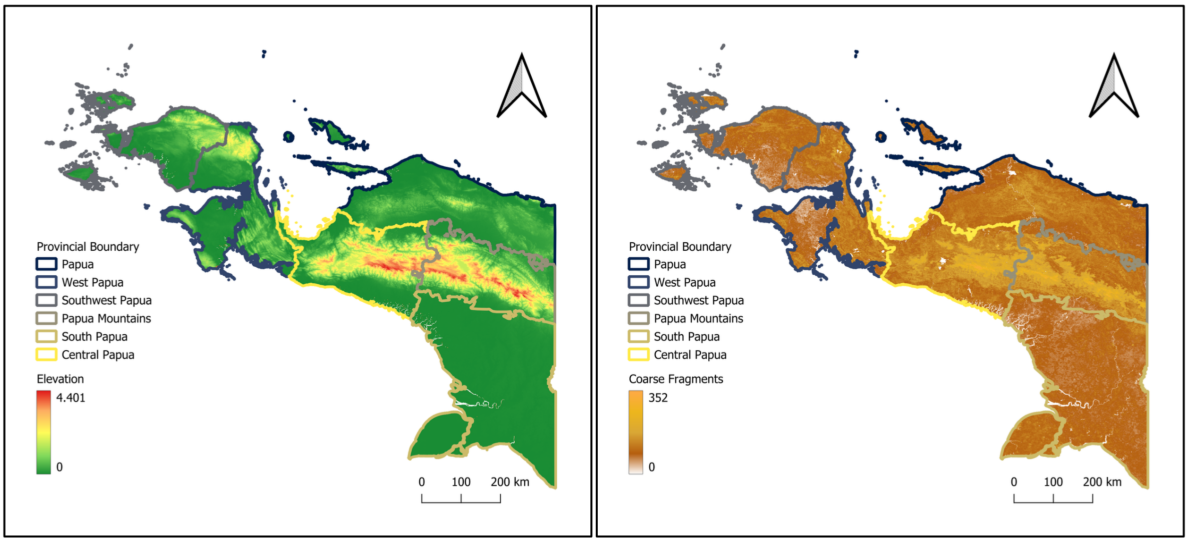

Figure 2. Topographic factors affecting land suitability for oil palm: (a) elevation and (b) soil texture

3.3. Soil Chemical Factors (pH and Organic Carbon)

The soil chemical conditions in the study area indicate excellent stability for nutrient availability. The Water/Soil pH is consistently recorded between 5.0 and 6.0, visualized in Light Green. According to the criteria by Gaol et al. (2023), this value is within the optimal range (S1), ensuring that macro-nutrients such as Nitrogen and Phosphorus are highly soluble and accessible to the plants without aluminum toxicity risks.

The Organic Carbon parameter, measured as Carbon Density in hg/m^3 shows values between 233 and 1,000 hg/m^3, with the highest density found in Papua and Southwest Papua provinces. High carbon density indicates superior cation exchange capacity and soil water retention. Nevertheless, in accordance with the sustainability mandate of Permentan 131/2013, areas with extremely high organic content (indicating peatlands) must be managed with controlled drainage systems to comply with peat depth regulations (< 3 meters) (Figure 3).

The integration of the eight biophysical parameters through spatial analysis yields a comprehensive overview of land suitability for oil palm development across the six provinces in Papua. The distribution of suitability classes, identified limiting factors, and the overall development status for each region are summarized in (Table 2). This classification highlights the significant contrast between the highly productive coastal lowlands and the constrained mountainous interior regions.

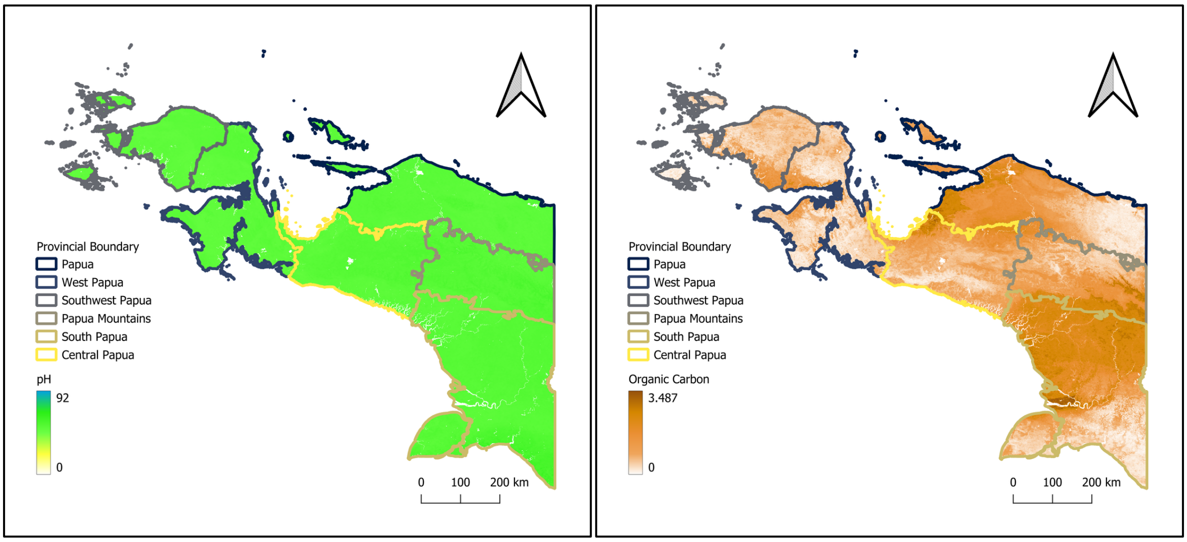

Figure 3. Soil chemical factors affecting land suitability for oil palm: (a) pH and (b) organic carbon

Table 2. Summary of Land Suitability Classification by Province in the Study Area

Region (Province)	Dominant Class	Limiting Factors	Status
South Papua	S1	None (Optimal Radiation & pH)	Highly Suitable
Southwest Papua	S1	None	Highly Suitable
West Papua	S1	None	Highly Suitable
Papua	S1 - S2	Slight Soil Texture variations	Suitable
Central Papua	S2 / N	Elevation (Mountains)	Fragmented
Papua Mountains	N	Temperature (6°C), Elevation (4401m)	Unsuitable

4. Discussion

Based on the results of the study, South Papua, West Papua, and Southwest Papua Provinces were identified as the most optimal regions for oil palm plantation development and were classified under the S1 suitability category (Table 2). This classification is consistent with the evaluation parameters applied in this study, including climatic conditions, topography, and soil characteristics. These provinces meet the land suitability criteria stipulated in the Regulation of the Minister of Agriculture No. 131/2013, which defines optimal environmental requirements for oil palm cultivation. Similar findings have been reported in previous land suitability assessments, indicating that lowland regions of Papua possess favorable agroecological conditions for oil palm development (Gaol et al., 2023; Corley & Tinker, 2015). Another province, Papua, was classified as S1–S2, indicating that oil palm cultivation is feasible but not fully optimal, mainly due to limitations in soil texture and soil quality. Meanwhile, Central Papua and Highland Papua Provinces were found to be unsuitable for oil palm plantation development because they do not meet the environmental thresholds outlined in the Ministerial Regulation No. 131/2013. Central Papua was classified as S2/N due to relatively high elevation and fragmented terrain, which constrain optimal oil palm growth, while Highland Papua was categorized as unsuitable (N) owing to its predominantly rocky soils, excessive elevation, and low temperatures that are unfavorable for oil palm cultivation (Hartley, 1988; Sys et al., 1993).

From a climatic perspective, oil palm exhibits optimal growth under humid tropical conditions characterized by high and evenly distributed rainfall and warm temperatures. The optimal annual rainfall requirement for oil palm ranges from 2,000 to 2,500 mm, with minimal drought stress and continuous water availability throughout the year (Corley & Tinker, 2015; Woittiez et al., 2017). South Papua, Southwest Papua, and West Papua Provinces fall within this optimal rainfall range, with average annual precipitation of approximately 2,000 mm. Oil palm is a crop with high water demand throughout its growth cycle, and insufficient water availability can significantly restrict physiological processes and biomass accumulation (Hartley, 1988). Temperature also plays a crucial role in oil palm productivity, with optimal growth occurring at mean temperatures of 24–28 °C. Temperatures below this range can suppress photosynthesis, slow vegetative growth, and reduce yield (Corley & Tinker, 2015). Highland Papua and Central Papua Provinces are the least suitable regions in this respect, as average temperatures can reach as low as 6 °C, which severely limits oil palm growth. In contrast, South Papua Province exhibits climatic conditions that closely align with the optimal temperature range for oil palm cultivation.

Solar radiation is a key driver of oil palm growth because it directly influences photosynthetic efficiency, flowering, and fresh fruit bunch production. Adequate solar radiation enhances carbon assimilation and biomass accumulation, whereas limited radiation reduces yield potential (Woittiez et al., 2017). Wind speed also affects oil palm performance by influencing transpiration rates, gas exchange, and pollination efficiency. Moderate wind conditions are beneficial, but high and persistent wind speeds may cause mechanical damage, excessive water loss, and reduced productivity (Corley & Tinker, 2015). Papua Mountains and Central Papua Provinces were identified as suboptimal for oil palm cultivation due to relatively high wind speeds and lower solar radiation levels, which limit photosynthetic activity and overall crop performance.

Topographic factors, particularly elevation, exert a strong influence on oil palm growth by modifying temperature regimes, solar radiation availability, and physiological processes. Oil palm grows optimally in lowland areas below 300 m above sea level, where warmer temperatures support efficient photosynthesis and biomass accumulation (Hartley, 1988; Sys et al., 1993). At higher elevations, cooler temperatures and reduced radiation constrain metabolic activity and reduce yield. Soil texture is another critical determinant of oil palm suitability because it affects water retention, aeration, and root penetration. Loam to clay-loam soils are considered optimal, as they provide sufficient moisture while maintaining adequate drainage and oxygen supply for roots (Sys et al., 1993; Gaol et al., 2023). In contrast, sandy soils have low water- and nutrient-holding capacity, while heavy clay soils often exhibit poor drainage, both of which limit oil palm productivity. Central Papua and Highland Papua Provinces are therefore considered unsuitable due to their high elevations and predominantly rocky or compact soil textures, which restrict root development and water availability.

Soil chemical properties, particularly soil pH and organic carbon content, play a fundamental role in oil palm growth by influencing nutrient availability, root activity, and soil biological processes. Oil palm grows optimally in slightly acidic soils with pH values ranging from 4.0 to 6.5, where nutrient availability is maximized and aluminum toxicity is minimized (Corley & Tinker, 2015; Sys et al., 1993). Soil pH values outside this range can reduce nutrient uptake and impair root development. Organic carbon content is essential for maintaining soil fertility, as it improves soil structure, enhances water-holding capacity, increases nutrient retention, and supports beneficial microbial activity (Woittiez et al., 2017). Papua and Papua Mountains Provinces exhibit relatively high organic carbon content, indicating fertile soils capable of supporting long-term oil palm cultivation. Adequate organic carbon levels contribute to sustained productivity by improving soil physical and chemical properties.

Despite these findings, this study has certain limitations. The datasets used are temporal in nature and may not fully reflect recent environmental changes. Moreover, oil palm growth and productivity are influenced by additional factors not addressed in this study, including planting material quality, fertilization regimes, and plantation management practices (Woittiez et al., 2017). Future studies should incorporate these factors and utilize updated datasets to improve the accuracy of land suitability assessments. The results of this study can serve as a preliminary reference for identifying environmentally suitable regions for oil palm development on the island of Papua. Based on the findings, South Papua, Papua, and Southwest Papua Provinces are recommended as the most suitable areas due to their favorable environmental conditions. However, Papua Island is recognized as a global biodiversity hotspot with high levels of endemism and ecological significance. Therefore, oil palm expansion must be carefully planned and managed to minimize deforestation and biodiversity loss, in line with previous studies highlighting the environmental risks associated with oil palm expansion (Fitzherbert et al., 2008; Vijay et al., 2016; Pirker et al., 2016). Sustainable plantation development should also prioritize the involvement and rights of local and indigenous communities, whose cultural diversity and traditional knowledge are integral to the long-term sustainability of land-use practices in Papua.

5. Conclusions

This study evaluated the suitability of oil palm cultivation across provinces on the island of Papua based on climatic, topographic, and soil characteristics. The results indicate that South Papua, Papua, and Southwest Papua Provinces exhibit the most favorable conditions for oil palm development, including optimal rainfall, temperature, solar radiation, wind speed, elevation, soil texture, soil pH, and organic carbon content. In contrast, Central Papua and Highland Papua Provinces were identified as less suitable to unsuitable for oil palm cultivation due to limiting factors such as high elevation, low temperatures, unfavorable soil texture, reduced solar radiation, and relatively high wind speeds. Overall, the findings of this study provide a scientific reference for identifying environmentally suitable areas for oil palm plantation development on the island of Papua. However, oil palm expansion should be conducted responsibly, with careful consideration of environmental sustainability, biodiversity conservation, and the socio-cultural values of local communities, to ensure long-term agricultural productivity and ecological balance.

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