

Geomorphological Controls on Soil Fertility Across Potential Rice Expansion Areas in Tropical Lowlands

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Abstract

Geomorphological variability strongly influences soil fertility conditions in tropical lowland environments and plays an important role in determining the potential for rice expansion. This study evaluated geomorphological controls on soil fertility across potential areas for rice expansion in Makroman, East Kalimantan, Indonesia, using a pedogeomorphic approach. Geomorphic units were delineated through visual interpretation of satellite imagery, field observations, and DEMNAS-derived elevation data. The study area was classified into four major geomorphic units: floodplains, undulating plains, rolling plains, and slopes. Soil fertility characteristics, including soil pH, soil organic carbon (SOC), and cation exchange capacity (CEC), were obtained from field-based soil observations and laboratory analyses across representative geomorphic units. The results revealed a clear fertility gradient across geomorphic units associated with dominant geomorphic processes. Floodplain environments exhibited the highest pH (5.8), SOC (1.7%), and CEC (32.4 cmol(+) kg⁻¹), whereas slopes showed lower pH (4.9), SOC (0.8%), and CEC (27.3 cmol(+) kg⁻¹). Intermediate conditions were observed in undulating and rolling plains, reflecting transitional redistribution and runoff-dominated processes. Depositional environments favored the accumulation of fine particles, organic matter, and exchangeable base cations, while erosional and leaching processes progressively reduced nutrient retention in elevated landscapes. These findings demonstrate that soil fertility variability in tropical lowlands is controlled not only by geomorphic position but also by the dominant geomorphic processes operating across the landscape. The study highlights the importance of geomorphology-based approaches for supporting sustainable rice expansion and land management in tropical agricultural environments.

1. Introduction

Rice is the staple food for most of the Indonesian population and plays a central role in national food security. However, rapid population growth and urban expansion continue to reduce the extent of productive paddy fields, forcing agricultural development into more marginal tropical lowland environments (Mulyani et al., 2023). However, humid tropical soils often exhibit low fertility – for example, strongly weathered Ultisols in Borneo typically exhibit acidic conditions and relatively low to moderate organic carbon content. These fertility constraints (acidic pH/Al toxicity, low soil organic matter, low CEC, and drainage limitations) are intrinsically linked to

geomorphic processes such as erosion, deposition, and water flow. Drawing on the principles of pedogeomorphology, which emphasize the interaction between landforms and soil formation processes (Gerrard, 1988; Zinck et al., 2023), we examine field-derived soil characteristics to evaluate how geomorphic processes influence variability in soil fertility across tropical lowland environments. This geomorphology-based analysis aims to reveal soil fertility patterns and limitations obscured by traditional land-suitability classes, thereby providing new insights for planning rice expansion in tropical lowlands.

Demand for rice in Indonesia is outpacing the conversion of existing paddy lands, making new cultivation areas a critical policy issue. Analyses suggest that replacing one hectare of highly productive irrigated rice land may require roughly two hectares of less fertile upland or swamp land to match the output. In response, agricultural planning has turned to the remaining lowland areas. However, many of these expansion zones were originally forested or swampy, with inherently poorer soils. In Makroman (Samarinda, East Kalimantan), for example, recent suitability mapping showed that only floodplain landforms were classified as highly suitable, while sloping upland and rolling plains were marginal (Nugroho et al., 2025), limitations attributed to soil factors (low pH and organic C) and drainage. This highlights why soil fertility is a central concern for tropical rice expansion (Purwanto et al., 2020; Ur Rahman et al., 2024) and motivates a deeper look at the soil landscape.

Humid tropical climates promote intense weathering and leaching, producing deeply developed soils (Ultisols/Oxisols) that are generally acid-rich and nutrient poor. A key constraint is low pH with associated aluminum toxicity: at pH below ~5.5, soluble Al^{3+} inhibits root growth and nutrient uptake (Ur Rahman et al., 2024). Indeed, Indonesian Ultisols are typically very acidic and aluminum-rich. These soils also have low inherent fertility, organic carbon levels tend to be low under hot, wet conditions, and available phosphorus is quickly fixed by iron and aluminum oxides. Tropical lowland soils are typically highly weathered and acidic, resulting in inherently low cation exchange capacity (CEC), particularly where sand content is high, and base cations have been extensively leached. Aprile and Lorandi (2012) reported that tropical soils generally exhibit low CEC due to the dominance of Al and Fe oxides, while recent studies have confirmed that CEC is strongly influenced by soil organic matter, clay content, and soil pH (Oyebi et al., 2026; Xiao et al., 2021). Consequently, nutrient retention is often limited, increasing the dependence on external fertilizer inputs. In addition, drainage conditions vary considerably with microtopography. Floodplain environments are commonly affected by prolonged saturation and waterlogging, requiring effective drainage management, whereas upland positions tend to experience rapid drainage and a greater risk of erosion (Ritzema et al., 2014). These constraints highlight the strong influence of geomorphic processes on soil fertility and agricultural suitability in tropical lowland landscapes. For example, lowland peat domes in Borneo remain waterlogged year-round, limiting cultivation. Thus, the classic fertility constraints (acidity/Al, low OM, low CEC, and drainage issues) are each linked to how landforms control soil genesis and water flux.

Soil properties exhibit substantial spatial variability across landscapes as a result of interactions among topography, climate, parent material, organisms, and time. Among these factors, relief plays a particularly important role because it influences infiltration, erosion, runoff, and microclimatic conditions that govern soil formation and development (Jenny, 1994; Zinck et al., 2023). Under this pedogeomorphic viewpoint, a soil on a convex hillside will lose material and bases downslope, becoming shallower, sandier, and more acid; in contrast, concave footslopes and floodplains accumulate finer sediments and organic matter. As Gerrard (1988) emphasizes, “soil acts as a buffer zone between the landform and the atmospheric and surface processes,” so the soil profile often reflects landscape history. In practice, many studies (from catenas to digital soil mapping) use terrain attributes (slope, wetness index, elevation) to predict soil properties. Modern pedogeomorphic studies commonly integrate terrain attributes and field observations to evaluate spatial variability of soil properties across landscapes. Detailed geomorphic analysis can reveal how floodplains, plains, and upland positions influence soil development and fertility patterns within tropical environments. However, global models may smooth or miss fine local patterns. For tropical lowlands, detailed pedogeomorphic analysis can reveal how ancient floodplain vs. upland landforms control fertility. For instance, older alluvial plains often have thicker carbon-rich topsoils than adjacent colluvial slopes, a contrast only apparent when soils are examined by landform unit rather than broad classes.

Despite this knowledge, many land suitability studies (including those in East Kalimantan) have treated fertility as one of several “limiting factors” within a suitability class framework, rather than exploring its geomorphic causes. For example, Nugroho et al. (2025) evaluated potential rice expansion areas in Makroman based on landform units but did not specifically investigate the geomorphological processes that drive soil fertility variability. Although studies have reported differences in soil properties across landforms, limited research has examined the geomorphological controls on soil fertility variability in areas of tropical lowland rice expansion. Consequently, the relationships between geomorphic processes, landscape position, and soil fertility remain insufficiently understood in these environments. Addressing this gap could improve understanding of terrain-driven variability in soil fertility and provide a stronger scientific basis for sustainable rice expansion planning in tropical lowlands.

This study aims to quantify how soil fertility indicators (pH, SOC, and CEC) vary across geomorphic environments and to evaluate geomorphological controls on soil fertility patterns within tropical lowland landscapes. While previous studies in Makroman primarily focused on land suitability classification, the present study adopts a pedogeomorphological perspective to examine the mechanisms by which geomorphic processes influence soil fertility variability. Rather than simply identifying suitable and unsuitable areas for rice cultivation, this study investigates how depositional, erosional, runoff, and leaching processes contribute to differences in soil acidity, organic matter accumulation, nutrient retention, and overall fertility across geomorphic units. By explicitly linking soil fertility characteristics to geomorphic processes and landscape position, this study provides a process-based explanation of fertility variability that can support more effective and sustainable rice expansion planning in tropical lowland environments.

2. Research Methods

2.1. Study Area

The study was conducted in Makroman Village, Sambutan District, Samarinda City, East Kalimantan, Indonesia, covering approximately 2,438 ha and located between 0°28'0"–0°34'0" S and 117°13'0"–117°17'0" E (Figure 1; Nugroho et al., 2024). The study area represents a tropical lowland landscape influenced by the Mahakam River system and exhibits considerable geomorphic variability associated with differences in relief, drainage, and landscape position. Makroman experiences a humid tropical climate with annual rainfall ranging from 2,000 to 3,000 mm and mean temperatures of approximately 27–30 °C (Nugroho et al., 2025), providing generally favorable conditions for rice cultivation. The area is dominated by sedimentary parent materials and highly weathered tropical soils, particularly Ultisols, which generally exhibit acidic pH, relatively low to moderate organic carbon content, and moderate natural fertility (Nugroho et al., 2025). These environmental conditions make Makroman suitable for evaluating geomorphological controls on soil fertility across potential areas of rice expansion in tropical lowlands.

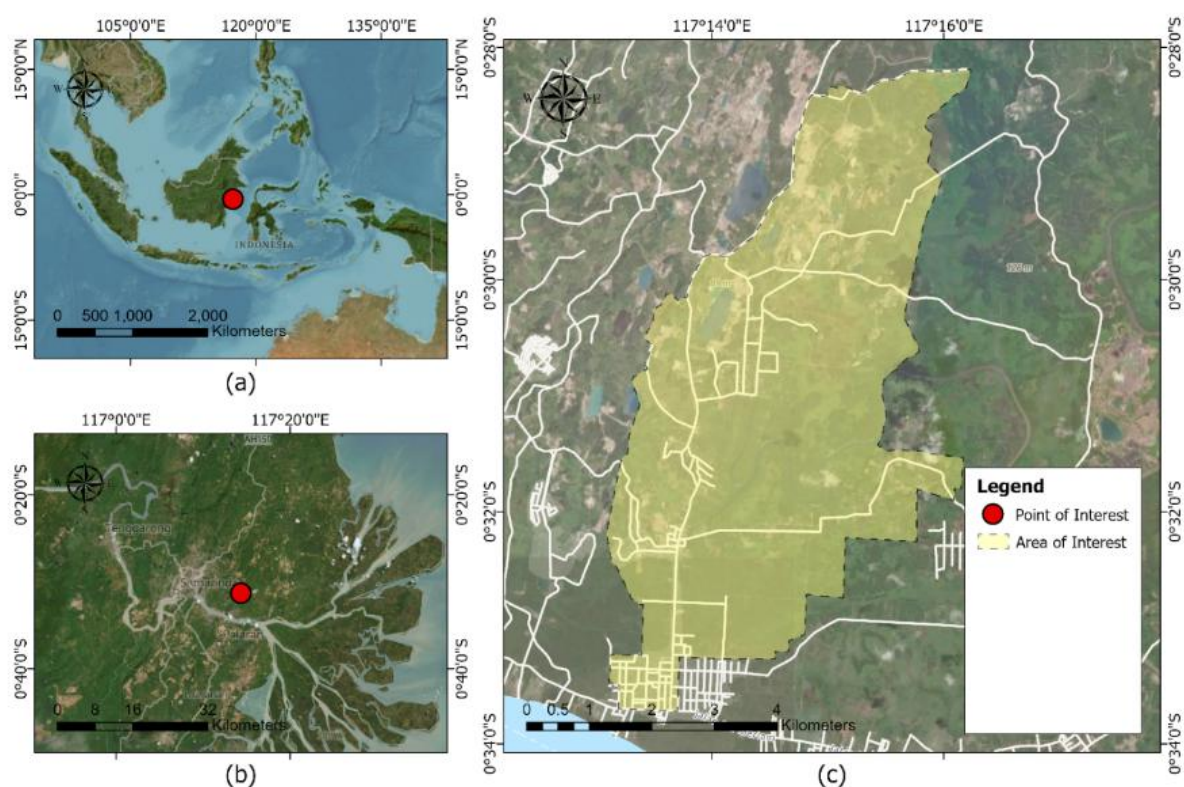


Figure 1. Study area location of Makroman Village, Sambutan District, Samarinda City, East Kalimantan, Indonesia: (a) regional location within Indonesia, (b) location within Samarinda City, and (c) detailed boundary of the Area of Interest (AOI)/Makroman Village.

2.2. Geomorphic Unit Delineation

Geomorphic unit delineation was conducted to establish a geopedological framework linking landscape morphology with soil fertility characteristics relevant to potential rice expansion areas. The delineation integrated

visual interpretation of high-resolution satellite imagery, field observations, and elevation data derived from the Indonesian National Digital Elevation Model (DEMNAS) to capture relative relief, landscape position, and drainage conditions across the study area. DEMNAS provides a nationally consistent elevation dataset generated by integrating multiple elevation sources and has been widely applied in geomorphological and land evaluation studies in Indonesia (De Feudis et al., 2021; Geospatial Information Agency of Indonesia, 2018; Julzarika and Harintaka, 2019).

2.3. Soil Fertility Characteristics

Soil fertility characteristics used in this study were obtained through field-based soil survey observations conducted across representative geomorphic units in the study area. Soil samples were collected from floodplains, undulating plains, rolling plains, and slope environments to characterize spatial variability in soil fertility. Soil pH, soil organic carbon (SOC), and cation exchange capacity (CEC) were selected as important indicators controlling nutrient availability, nutrient retention, and soil productivity in tropical agricultural environments (Amoakwah et al., 2024; Paramesh et al., 2023). Soil pH was used to indicate soil acidity conditions associated with weathering and leaching intensity (Purwanto et al., 2020; Regasa et al., 2025), while SOC represented organic matter accumulation influenced by erosion–deposition processes (Dalzell et al., 2022; Quine et al., 2022). CEC was used to assess nutrient retention capacity under contrasting geomorphic settings (Aprile and Lorandi, 2012; Oyebiyi et al., 2026). These indicators were selected because they represent fundamental chemical properties that strongly influence nutrient availability, nutrient retention, and crop productivity in highly weathered tropical soils (Amoakwah et al., 2024; Paramesh et al., 2023). Although additional fertility parameters such as total N, available P, available K, base saturation, exchangeable Al, and soil texture may provide a more comprehensive assessment, pH, SOC, and CEC were considered sufficient to evaluate dominant fertility constraints associated with contrasting geomorphic environments. Soil samples were collected from representative locations within each geomorphic unit at a depth of 0–20 cm. Soil pH was measured in H₂O suspension, SOC was determined using the Walkley–Black method, and CEC was analyzed using the NH₄OAc extraction method at pH 7.

A reconnaissance-level pedogeomorphic sampling approach was employed to characterize soil fertility conditions across contrasting geomorphic environments. One representative soil observation point was selected within each geomorphic unit (floodplain, undulating plain, rolling plain, and slope) based on geomorphic homogeneity, landscape position, drainage characteristics, and field observations. Soil samples were collected from the 0–20 cm depth at each observation point. Because the objective of the study was to characterize representative soil fertility conditions across different geomorphic environments rather than to statistically compare geomorphic units, no within-unit replicates were collected, and no inferential statistical analyses were performed. Therefore, soil fertility indicators (pH, SOC, and CEC) were evaluated using descriptive analysis and interpreted in relation to the dominant geomorphic processes operating within each landform unit.

3. Results and Discussion

3.1. Geomorphic Characteristics of the Study Area

The study area in Makroman is characterized by diverse tropical lowland geomorphic environments consisting of floodplains, undulating plains, rolling plains, and slopes (Figure 2). These geomorphic units reflect variations in topographic position, relief, drainage conditions, and surface morphology across the landscape. Floodplain environments are generally distributed in low-lying areas adjacent to drainage systems and are characterized by relatively flat topography, imperfect drainage, and higher moisture accumulation. Undulating plains represent transitional geomorphic environments with gentle relief variability and moderate drainage conditions. Rolling plains exhibit more pronounced surface undulation and greater runoff potential, associated with increased relief variability, whereas slopes are characterized by steeper terrain, stronger surface runoff, and higher susceptibility to erosion processes.

The contrasting geomorphic characteristics indicate differences in hydrological conditions and erosion–deposition dynamics within the study area. Floodplain environments are associated with depositional processes and finer material accumulation, whereas rolling plains and slopes are more strongly affected by runoff, leaching, and surface erosion. Undulating plains represent intermediate geomorphic conditions between low-relief floodplains and more elevated landscapes (Zinck et al., 2023). These geomorphic differences potentially influence soil acidity, organic carbon accumulation, and nutrient retention through contrasting erosion–deposition and hydrological processes (Dalzell et al., 2022; Quine et al., 2022; Wu et al., 2022).

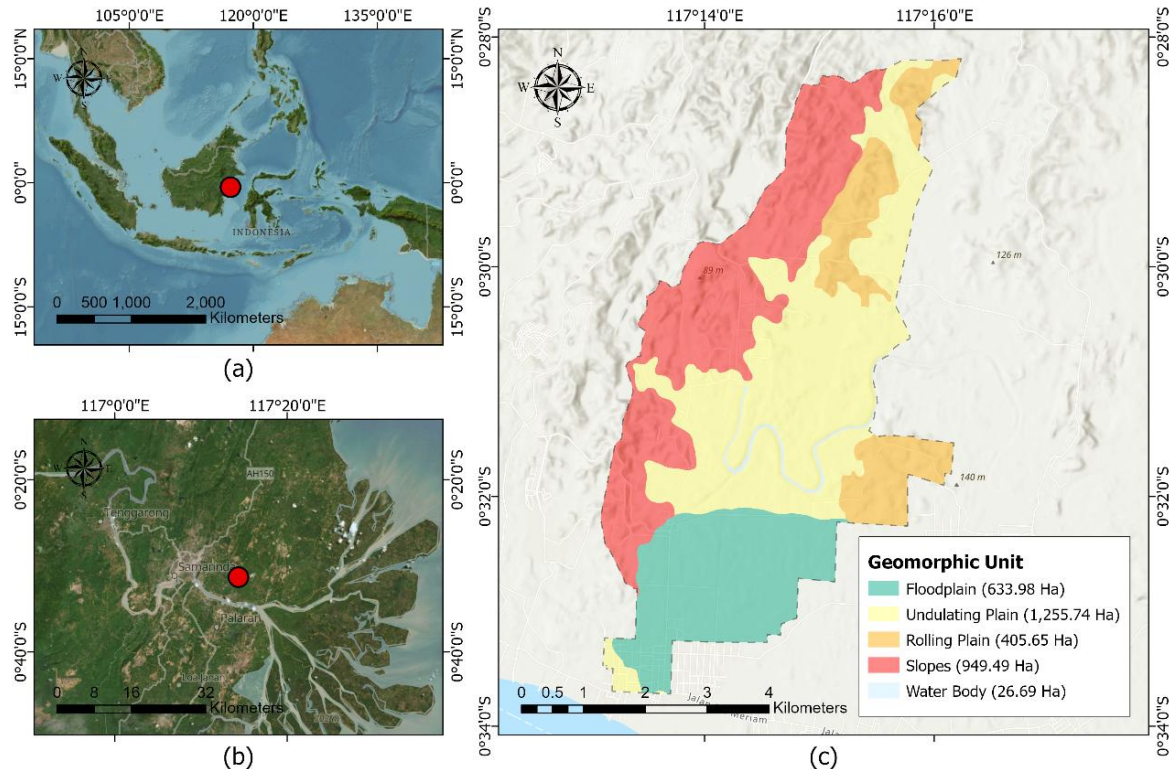


Figure 2. Geomorphic units of potential rice expansion areas in Makroman, East Kalimantan, Indonesia: (a) regional location within Indonesia, (b) location within Samarinda City, and (c) spatial distribution of floodplain, undulating plain, rolling plain, and slope geomorphic units within the study area.

3.2. Fertility Characteristics Across Geomorphic Units

Soil fertility characteristics varied considerably across geomorphic units within the study area (Table 1). Floodplain environments exhibited relatively higher soil pH, soil organic carbon (SOC), and cation exchange capacity (CEC) than other geomorphic settings. Soil pH ranged from 4.9 to 5.8 across the study area, indicating substantial variation in soil acidity associated with differences in geomorphic position and dominant landscape processes. SOC values ranged from 0.8 to 1.7%, indicating variability in organic matter accumulation associated with geomorphic processes across the landscape. CEC showed notable variability among geomorphic units, ranging from 27.3 to 32.4 cmol(+) kg⁻¹, with the highest values observed in floodplain environments and the lowest values occurring on slopes.

Table 1. Soil fertility indicators across geomorphic units in potential rice expansion areas of Makroman, East Kalimantan

Geomorphic Unit	pH	SOC (%)	CEC (cmol(+) kg ⁻¹)	Dominant Geomorphic Process
Floodplain	5.8	1.7	32.4	Deposition
Undulating plains	5.5	1.4	31.1	Transitional redistribution
Rolling plains	5.2	1.1	27.9	Surface runoff
Slopes	4.9	0.8	27.3	Erosion and leaching

Floodplain environments exhibited the most favorable fertility conditions, with pH, SOC, and CEC values of 5.8, 1.7%, and 32.4 cmol(+) kg⁻¹, respectively. These characteristics are associated with depositional processes that promote the accumulation of finer materials and nutrients. Undulating plains exhibited intermediate conditions with relatively high pH (5.5) and CEC (31.1 cmol(+) kg⁻¹), reflecting transitional redistribution processes across the landscape. Rolling plains showed slightly lower fertility, characterized by reduced SOC and moderate CEC values, likely associated with increasing surface runoff influence. In contrast, slopes exhibited the lowest pH (4.9), SOC (0.8%), and CEC (27.3 cmol(+) kg⁻¹), indicating stronger effects of erosion and leaching processes that contribute to nutrient and organic matter depletion. The representative soil observations indicate potential differences in selected soil fertility indicators across geomorphic units. Floodplain environments exhibited relatively higher pH, SOC, and CEC values, whereas slope environments showed lower values. These patterns are consistent with the influence of depositional and erosional processes on soil properties, as sediment redistribution,

organic matter accumulation, runoff, and leaching are known to affect soil chemical characteristics across landscapes (Dalzell et al., 2022; Quine et al., 2022; Wu et al., 2022; Zinck et al., 2023). The observed patterns therefore suggest that geomorphic variability may contribute to the spatial distribution of soil fertility indicators within potential rice expansion areas in Makroman.

3.3. Geomorphological Controls on Soil Fertility

The observed differences in soil fertility indicators among geomorphic units are consistent with established pedogeomorphic concepts. Floodplain environments are commonly associated with depositional processes and greater moisture retention, which can promote the accumulation of organic matter and nutrient-bearing sediments, whereas upland slopes are more susceptible to runoff, erosion, and leaching losses (Gerrard, 1988; Jenny, 1994; Dalzell et al., 2022; Quine et al., 2022; Zinck et al., 2023). In the present study, the representative floodplain profile exhibited higher pH, SOC, and CEC values than the representative slope profile, suggesting that geomorphic position may influence the spatial distribution of selected soil fertility indicators.

The observed fertility gradient across the study area follows a process-based geomorphic sequence extending from depositional environments (floodplains) toward erosional environments (slopes). Floodplain units dominated by depositional processes tend to accumulate fine-textured sediments due to repeated sedimentation during flooding, which are rich in organic matter and exchangeable base cations. This process enhances pH, SOC, and CEC values (Quine et al., 2022; Sao et al., 2023). Transitional redistribution processes in undulating plains produce intermediate fertility conditions, whereas rolling plains increasingly experience surface runoff, which may reduce nutrient retention. At higher landscape positions, erosion and leaching on slopes progressively remove fine particles, organic matter, and nutrient reserves, resulting in lower fertility. Research by Mengiste et al. (2025) showed that the upper slope had the higher sand percentage and bulk density, while the lower slope had higher clay content, pH, CEC, exchangeable cations, and trace elements. This sequence suggests that soil fertility variability is governed not only by geomorphic position itself, but also by the dominant geomorphic processes operating across the landscape.

The higher soil pH and CEC values in floodplain units (Table 1) can be linked to depositional accumulation of fine sediments and base cations. In tropical lowlands, alluvial and colluvial deposition brings clays and organic matter downslope. These finer, moisture-retentive sediments buffer acidity and increase the number of cation exchange sites (Aprile and Lorandi, 2012). By contrast, slopes lose these materials to runoff. Continuous erosion strips away nutrient-rich topsoil, leaving coarse-textured, Fe–Al–oxide-rich subsoil characteristic of Indonesian Ultisols. This process results in lower SOC and CEC on slopes, as observed. Lower pH on slopes reflects depletion of base cations and accumulation of exchangeable Al associated with prolonged leaching and erosion processes. Slope environments (pH 4.9) are more likely to experience exchangeable Al toxicity risks, whereas floodplain environments (pH 5.8) approach more favorable conditions for rice cultivation due to reduced acidity constraints (Ur Rahman et al., 2024). The substantially higher pH observed in floodplain units (5.8) relative to slopes (4.9) suggests stronger accumulation of base cations and buffering effects associated with depositional environments and periodic sediment inputs (Jenny, 1994; Regasa et al., 2025; Schaetzl and Thompson, 2015). In sum, our results align with the theory of soil catenas: upper slopes (high relief) show intensified leaching and acidity, while depositional lows accumulate organic matter and bases (Jenny, 1994; Nugroho et al., 2026; Zinck et al., 2023).

Floodplains have higher moisture and stable surfaces, favoring organic matter retention (e.g., from decayed vegetation). Slopes, by contrast, shed organic residues with runoff. Although SOC values remained relatively moderate across the study area, floodplain units contained approximately twofold higher SOC than slopes (1.7% vs. 0.8%). This pattern likely reflects greater organic matter accumulation and reduced loss of material in depositional environments, whereas erosional settings continuously remove organic residues through runoff and surface processes. The floodplain has low flow velocity and transport energy, causing the deposition of fine sediments and organic materials, while upper slopes are characterized by higher erosive energy and sediment transport that enhance SOC removal and redistribution downslope (Dalzell et al., 2022; Wu et al., 2022). The same depositional textural effect also enhances CEC by increasing the accumulation of finer particles and exchange sites (Aprile and Lorandi, 2012). Overall, observed patterns – higher fertility in depositional units, lower on erosional slopes – mirror findings from other tropical areas (Gerrard, 1988; Purwanto et al., 2020; Zhang et al., 2022) and showcase how terrain-driven processes control nutrient distribution.

These geomorphic influences have practical consequences. Rice fields on floodplains should benefit from relatively higher inherent fertility, but drainage management may be needed in waterlogged areas (Ritzema et al., 2014). On sloping lands, persistently low pH (high Al saturation) calls for liming to raise pH above critical thresholds (~5.5) for rice (Ur Rahman et al., 2024). Relatively lower SOC and CEC values on slopes suggest that organic amendments (compost or green manure) may improve nutrient retention and maintain long-term soil productivity. Soil conservation is crucial: terraces, grassed waterways, or cover cropping can reduce erosion and sustain fertility (Mulyani et al., 2023). In summary, nutrient management (lime and fertilizer) and erosion/drainage

controls must be tailored to landform: floodplains need drainage and water management; slopes need erosion control and soil amendments.

Although pH, SOC, and CEC are widely recognized as important indicators of soil fertility because they influence nutrient availability, nutrient retention, and soil chemical functioning, they do not fully represent all dimensions of soil fertility. Other important properties, including total nitrogen, available phosphorus, available potassium, base saturation, exchangeable aluminum, and soil texture, were not evaluated in this study. Consequently, the results should be interpreted as an assessment of selected soil fertility indicators rather than a comprehensive evaluation of overall soil fertility status. Future studies incorporating a broader range of chemical and physical soil properties would provide a more complete understanding of geomorphological controls on soil fertility variability in tropical lowland environments.

We note several caveats. Our analysis was based on representative soil observations within each geomorphic unit and may not fully capture small-scale spatial variability occurring within landform boundaries (Jenny, 1994; Schaetzl and Thompson, 2015; Zinck et al., 2023). This reconnaissance-level approach may smooth internal variability and obscure localized extremes. Moreover, without repeated sampling, temporal changes associated with land-use dynamics or seasonal variability were not captured. Therefore, while the observed patterns are consistent with established pedogeomorphic concepts (Gerrard, 1988; Zinck et al., 2023), the results should be interpreted as indicative of dominant fertility conditions rather than precise estimates of within-unit variability.

3.4. Implications for Potential Rice Expansion Areas

The observed fertility differences have clear planning consequences. Floodplain units with higher pH and CEC are naturally better suited to rice. Soil chemical properties such as CEC and pH are important aspects that affect fertilization effectiveness (Gumilang et al., 2025). Floodplain environments exceeded the commonly reported critical pH threshold (~ 5.5) for mitigating Al toxicity, suggesting relatively lower chemical constraints for rice cultivation (Ur Rahman et al., 2024). Higher SOC and CEC also contributed to higher capacity to retain important cations such as K^+ , Mg^{2+} , Ca^{2+} , and NH_4^+ . Recent studies have shown that high SOC levels result in higher microbial activity and nutrient availability, thereby increasing rice productivity (Iqbal et al., 2022; Paramesh et al., 2023). Planners should therefore prioritize these areas while ensuring proper drainage management to avoid prolonged waterlogging (Ritzema et al., 2014). Sloping uplands have poorer soils and must be treated as marginal. Converting one hectare of prime paddy requires roughly two hectares of such marginal land to equal production, underscoring that using slopes will demand substantial inputs (Mulyani et al., 2023). Smallholders aiming to farm slopes will therefore need targeted support.

On slopes, liming is critical. Raising pH above ~ 5.5 neutralizes exchangeable Al, preventing root toxicity and improving nutrient availability (Ur Rahman et al., 2024). A typical recommendation is ~ 1 – 2 tonnes $CaCO_3$ per hectare (applied 3–6 months before planting) to shift pH by ~ 0.5 units. By lime application, Al can be kept in an unavailable form while increasing carbon stocks, lowering heavy metal availability, and increasing paddy land productivity (Amoakwah et al., 2024; Liu et al., 2025). Organic amendments (compost, manure, green manure) should be applied to upland fields to boost SOC and CEC (Aprile and Lorandi, 2012). For example, adding 5–10 t/ha of farmyard manure can significantly increase organic carbon. Increased organic matter in uplands resulted in better soil aggregation, reducing erosion susceptibility and increasing water retention (Linam et al., 2023). On floodplains, moderate organic inputs can sustain fertility, but drainage is key: installing control gates or raised beds prevents prolonged waterlogging and subsidence (Ritzema et al., 2014). In addition, intermittent irrigation management and amendments such as sulfate and limestone are recommended to maintain productive rice cultivation in floodplain areas (Fang et al., 2024).

Contour bunding, terraces, or vegetative strips on slopes will reduce topsoil loss. These structures trap eroding soil and maintain organic layers (Gerrard, 1988; Jenny, 1994; Zinck et al., 2023). For instance, grassed waterways or vetiver hedges intercept runoff. Combined with cover crops (e.g., leguminous cover between rice cycles), these measures help retain SOC and nutrients. Balanced fertilization is also needed: split N–PK applications or controlled-release formulations can match rice demand while reducing runoff in heavy rains.

Floodplain development may also face several environmental and management challenges. Waterlogging, peat subsidence, and changes in soil hydrology can occur when drainage systems are not properly managed. Lowering groundwater levels for agricultural purposes may accelerate peat oxidation, land subsidence, and fire susceptibility in organic-rich environments (Ritzema et al., 2014). In addition, excessive application of lime and fertilizers can increase production costs and potentially contribute to nutrient losses through leaching and runoff (Iqbal et al., 2022; Paramesh et al., 2023). The successful implementation of soil improvement measures may also depend on socioeconomic factors, including farmers' access to agricultural inputs, technical knowledge, credit, and land resources (Mulyani et al., 2023). Therefore, both biophysical and socioeconomic considerations should be integrated into planning strategies for sustainable rice expansion in tropical lowland environments.

4. Conclusion

This study demonstrates that geomorphological variability influences soil fertility characteristics across potential rice expansion areas in Makroman, East Kalimantan. Floodplain geomorphic units exhibited substantially higher pH (5.8), SOC (1.7%), and CEC (32.4 cmol(+) kg⁻¹), whereas slopes exhibited lower pH (4.9), SOC (0.8%), and CEC (27.3 cmol(+) kg⁻¹). In contrast, slopes showed lower SOC and CEC values due to stronger runoff, erosion, and leaching processes that accelerate nutrient and organic matter loss. These findings highlight the important role of geomorphic position in regulating soil acidity, nutrient retention, and organic matter accumulation within tropical lowland landscapes. The results also indicate that landform-specific management strategies are necessary for sustainable rice expansion, particularly through drainage management in floodplains and liming, organic amendments, and erosion control on sloping areas. Although based on representative field-derived soil observations across geomorphic units, the pedogeomorphic framework applied in this study provides additional insights into terrain-driven soil fertility processes in tropical agricultural environments. However, the study was based on one representative soil observation point for each geomorphic unit and evaluated only selected soil fertility indicators (pH, SOC, and CEC). Therefore, the results should be interpreted as indicative of dominant fertility conditions rather than comprehensive estimates of within-unit variability or overall soil fertility status. Future research should incorporate larger sample sizes, repeated observations, and additional soil properties, including total N, available P, available K, exchangeable Al, base saturation, and soil texture, to provide a more comprehensive understanding of geomorphological controls on soil fertility in tropical lowland landscapes.

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