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Geomorpho-Pedological Characteristics and Physicochemical Properties Under Different Agricultural Practices in the Fluvio-Marine Landscape, East Halmahera, Indonesia

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Abstract

The phenomenon of environmental degradation threatens various sectors, including agriculture in coastal ecosystems, thereby weakening the land's carrying capacity. On the other hand, information about soil resources in fluvial-marine landscapes has formed a complex, unique system that influences geomorpho-pedological characteristics. This study aims to (1) investigate variations in soil morphological characteristics under different agricultural practices and (2) interpret the results of soil genesis processes within the framework of geomorpho-pedological evolution in fluvio-marine landscapes. The research was conducted in Tobo Ino Village, Wasile Subdistrict, Subaim, East Halmahera Regency, North Maluku Province, Indonesia. The methodology used was a stratified sampling method to identify soil profiles based on USDA standards for two different land-use practices. This was followed by laboratory-scale physicochemical analysis of the soil in accordance with the Agricultural Instrument Standardization Agency, Ministry of Agriculture, Indonesia. The results show that land use activities affect soil morphology and classification. Fluvaquentic Endoaquepts soil classification is found in rice paddy field practices, while Typic Eutrudepts is found in mixed plantations. Along with similar geomorphological conditions but different soil evolution processes, this results in different land resource management practices. This approach offers a process-based understanding that is essential for sustainable agricultural planning in dynamic coastal-alluvial landscapes in wet tropical regions to achieve the Sustainable Development Goals (SDGs) and the Eight Goals of the Unitary State of the Republic of Indonesia.

1. Introduction

Geomorpho-pedological studies provide insight into how human activities change the evolutionary form of land. Furthermore, in the modern era, this idea offers knowledge of digital mapping (Huggett, 2007). Human life depends, among other things, on information about land resources to help provide terrestrial ecosystem services (Jannah and Pagiu, 2021; Telo Da Gama, 2023; Aji et al., 2025). Understanding soil's long-term effects on how ecosystems produce biomass (Aji et al., 2020), as well as on soil health and fertility (Yang et al., 2021; Morizet-Davis et al., 2023; Hartati et al., 2023). Policymakers can use this information to inform decisions on sustainable land management through geoinformation-based digital soil mapping or by examining relationships among anthropogenic factors, soil genesis, and geomorphological processes (Mikhailova et al., 2021; Chen et al., 2022). Geomorpho-pedological studies can also provide information on the relationship between the level of vulnerability

to land degradation in river basins (Piégay et al., 2023). Recent studies show that geomorpho-pedological analyses using the Random Forest Algorithm (RFA) approach and multiscale geomorphometric variables achieve high accuracy in interpreting soil texture, lithological conditions, and topography, as demonstrated in a case study in the Amazon River basin in Brazil (Araújo et al., 2021). The same is true in the Beijing-Tianjin-Hebei region of China, where this study was linked to digital elevation model (DEM) analysis using the upscaling method, resulting in a more detailed geomorphological classification (Zhang et al., 2020). According to Keller et al. (2020), these studies are thought to support sustainable land management. This means that this study can be linked to other geoscience fields and create new developments.

The fluvio-marine landscape in East Halmahera was formed during the Holocene geological period (Suparan et al., 2001). This has resulted in a diverse distribution of soil resources and physicochemical properties in this region. According to Gani et al. (2024), based on field observations, the soil in this landscape generally has a fine texture (Ø < 0.002 mm), an acidic pH, high availability of soil organic matter (SOM), and diverse nutrient availability. However, spatial and temporal land conversion occurs, affecting the morphological and physicochemical characteristics of the soil, which in turn influence its function. Therefore, comprehensive research is needed to ensure that the soil classification system can function properly as part of sustainable land management efforts.

To assist stakeholders in sustainable resource management, a comprehensive understanding of geomorphology and pedology is required, both vertically and horizontally. This study aims to (1) investigate variations in soil morphological characteristics under different agricultural practices and (2) interpret the results of soil genesis processes within the framework of geomorpho-pedological evolution in fluvio-marine landscapes. By providing a scientific foundation for sustainable land-use planning in East Halmahera, the research output is anticipated to advance understanding of the relationship between soil and landscape in tropical coastal environments.

2. Research Methods

2.1. Research Location

The research was conducted in Toboino Village, Wasile subdistrict, East Halmahera Regency, North Maluku Province (Figure 1). Geographically, the research location is located between 1°07'05" N - 1°18'50" N and 128°09'35" E - 128°27'20" E. The geomorphological conditions in the study area are fluviomarine landforms. Geologically, the area lies within the alluvial formation, consisting of gravel, sand, mud, and boulders, as well as terrace deposits. Analysis of rainfall data from the Meteorology, Climatology, and Geophysics Agency (MCGA) over the past 10 years revealed that rainfall in the study area ranged from 1200 to 2100 mm $year^{-1}$. The study area is located in East Halmahera Regency, North Maluku Province, Indonesia, within a fluvio-marine transitional landscape shaped by the interaction among fluvial processes, coastal dynamics, and tropical climatic forcing. This region represents a typical humid tropical lowland system, where agricultural activities increasingly intersect with geomorphological instability and soil degradation risks. Geographically, the area occupies the downstream sector of river systems draining from low-relief uplands toward coastal plains, estuaries, and nearshore marine environments. This transitional position renders the landscape highly dynamic, both geomorphologically and pedologically. These landforms differ markedly in terms of surface stability, sediment texture, drainage conditions, and depositional history, resulting in pronounced spatial heterogeneity. Younger geomorphic surfaces, particularly recent alluvial and tidal deposits, are characterized by weak structural development and high susceptibility to erosion, compaction, and inundation. In contrast, older and slightly elevated surfaces exhibit more stable morphologies and longer pedogenic development.

The research materials used included the Administrative Map, Lithology Map, and Land Use Map of Toboino Village at scale 1:50,000. These maps are used as spatial support for the study area's conditions. Laboratory analysis was conducted at the Soil Laboratory of the Agricultural Instrument Standardization Agency, Ministry of Agriculture, Indonesia.

2.2. Research Implementation and Data Analysis

Soil sampling activities began with the creation of an administrative map at scale 1:50,000 and a land-use map at scale 1:50,000, based on differences in agricultural practices, namely mixed plantations and rice paddy cultivation areas. Soil sampling was conducted using a stratified sampling method based on land use type and soil profile interpretation based on guidelines from the USDA Field Book for Describing and Sampling Soils (Soil Survey Staff, 2024). Furthermore, soil samples are taken at each depth for analysis on a laboratory scale. All measurements of soil physicochemical properties were based on guidelines from the Agricultural Instrument Standardization Agency, Ministry of Agriculture, Indonesia. The physicochemical properties of the soil analyzed included soil texture using granular analysis and pipetting methods, bulk density using the ring sample method, particle density using the picnometer method, porosity using the ratio between bulk density and particle density, soil pH (1:5) using the pH meter electrometric method, soil organic carbon (SOC) using the Walkley and Black wet oxidation method, total soil nitrogen (TN) using the Kjeldahl titrimetric method, phosphorus (P_2O_5) using the

spectrophotometer method, potassium (K_2O) using the Atomic Absorption Spectrophotometry (AAS) method, CEC using Percolation method NH_4OAc 1 M, pH 7 + NaCl 10%; Titrimetric, Base saturation calculated based on the proportion of CEC values filled by base cations. Data analysis was conducted after tabulation. The results of the data tabulation were interpreted and directly linked to the field events.

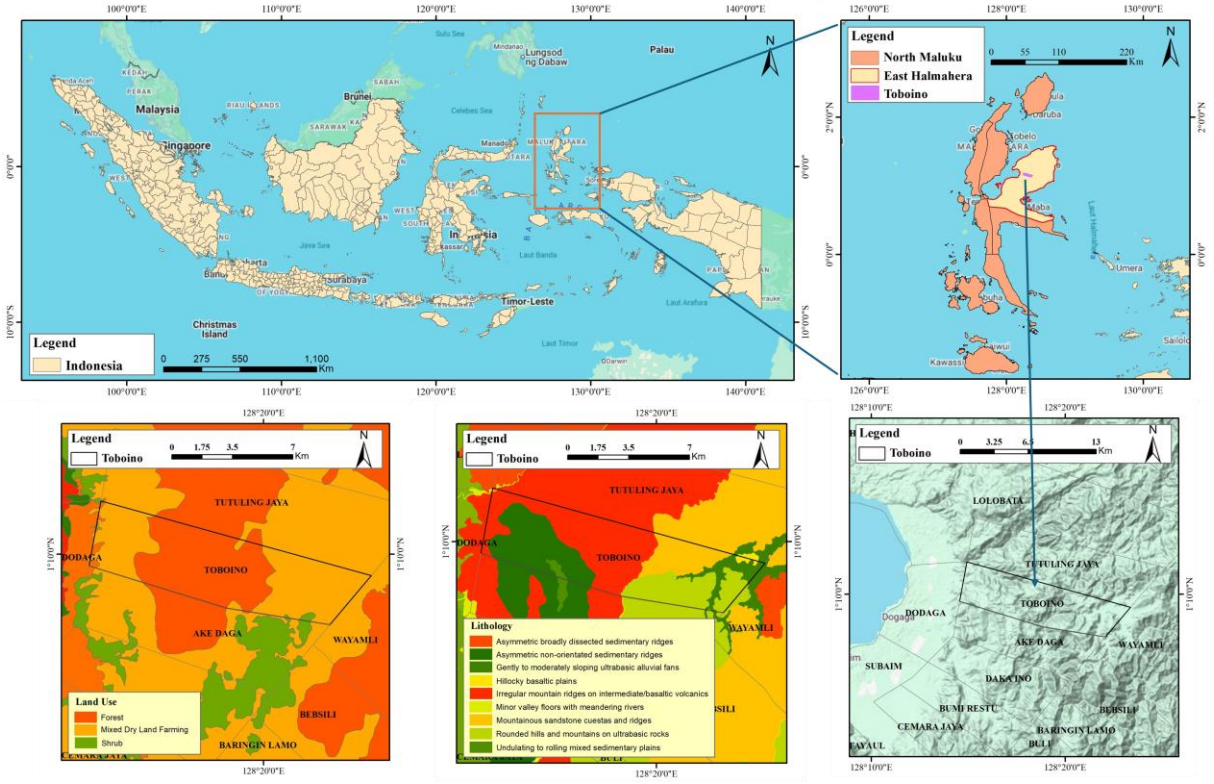

Figure 1. Administrative map, lithology map, and land use map of the study area.

3. Results and Discussion

3.1. Soil Morphological Characteristics and Classification

The results of the study are shown in Table 1. The soil classification for both profiles falls under the subgroup category of Fluvaquentics Endoaquepts for profile 1 and Typic Eutrudepts for profile 2. Both are types of Inceptisols soil. However, this soil classification shows differences in soil morphological characteristics.

Fluvaquentic Endoaquepts are a subgroup of Inceptisols commonly found in floodplains, wetlands, and paddy fields. They are characterized by poor drainage, high water tables, and moderate to low inherent fertility, with properties shaped by fluvial (river) deposition and frequent saturation. In addition, their aquic moisture regime means they are saturated with water for extended periods, and the presence of a cambic horizon indicates some soil development, but not enough to form more mature soil orders. They are classified under the USDA Soil Taxonomy as a great group within the Aquepts suborder of Inceptisols (Mansyur et al., 2019; Panti et al., 2024). Then, Eutrudepts are moderately developed, fertile soils with high base saturation, supporting agriculture in diverse climates and landscapes (Siwi et al., 2023). Their classification includes several subgroups based on drainage and parent material.

The soil solum in the study area is shallow (<60 cm). Geomorphological processes influence the thickness of this soil through sedimentation of parent material. Fluvio-marine soils are formed from a mix of marine and fluvial (river) sediments, often resulting in sandy clay loam textures with variable mineral content. The nature of these parent materials, especially when dominated by sand or marine-derived sediments, limits the development of thick, well-differentiated soil horizons, leading to a shallow solum (Alnaimy et al., 2023). In addition, the movement of erosion processes on the surrounding slopes also affects the degree of soil thickness variation (Sarastika et al., 2025).

There is a difference in the second layer in both soil profiles (Figure 2). In P1L2 in soil profile 1, a Bg horizon was found, while in P2L2 in soil profile 2, there was a Bw horizon. The gleic horizon (Bg) is a diagnostic subsurface horizon that slows down the rate of organic matter (OM) degradation and pedogenesis. It occurs in anaerobic environments. Another characteristic of this horizon is its gray color with bright patches. Accordingly, oxidation-reduction processes are the mechanisms by which pedogenesis occurs (Bedard-Haughn, 2011). Soil

morphology is closely related to key environmental processes and ecosystem services. Soil architecture significantly controls water, carbon, and nutrient dynamics, while being continuously shaped by climate, biology, and land use. In cultivation activities, horizon gleic (Bg) forms as a result of gleization, in which high groundwater or continuous waterlogging reduces Fe^{3+} to Fe^{2+} under anaerobic conditions, affecting plant productivity and crop yields (Liu et al., 2015).

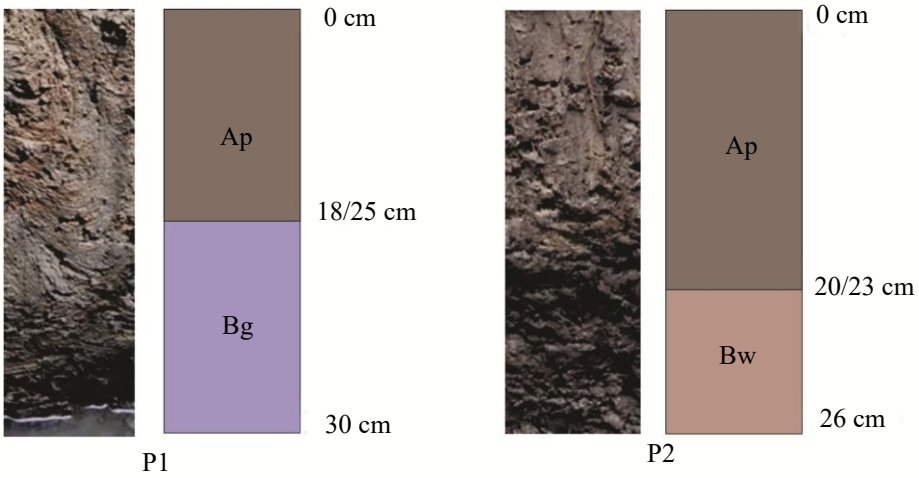

Figure 2. Soil profile.

Table 1. Soil morphological characteristic

Code	Parent Material	Land-Use	Soil Horizon	Soil Depth (cm)	Color	Soil Texture
P1L1	Alluvial Deposits	Paddy rice fields	Ap	0-18/25	10 YR 3/1	Clay Loam
P1L2			BG	18/25-30	5 GY 3/2	Clay Loam
P2L1	Alluvial Deposits	Mixed plantations	Ap	0-20/23	10 YR 4/1	Clay
P2L2			Bw	20/23-26	10 YR 3/1	Clay

Table 1. Continued

Code	Structure	Consistency	Root	Root Total	Soil Classification (SubGroups)
P1L1	Granular	Slightly sticky	Meso	Meso	Fluvaquentic Endoaquepts
P1L2	Subangular Blocky	Sticky	-	-	
P2L1	Granuler	Sticky	Meso	Meso	Typic Eutrudepts
P2L2	Subangular Blocky	Sticky	Meso	Moderately Few	

Furthermore, horizon Bw is a subsoil diagnostic horizon characterized by weak soil structures and color changes in the subsoil (40 cm), and a less clear clay illuviation process (Noviyanto et al., 2020; Aji et al., 2020; Aji et al., 2024). In addition, in the Bw horizon, in certain types of soil, clayey minerals such as muscovite and vermiculite are sometimes coated with hydroxyaluminum (Bruand and Reatto, 2022). According to recent research, biological processes, such as the excavation of ant nests, often produce microgranular structures in the Bw horizon. The bioturbation process between natural fragmentation and the mixing of soil components creates a biomantle with unique physico-chemical properties (Reatto et al., 2009)

Qualitative soil texture measurements on both soil profiles indicate a predominance of fine texture (Ø < 0.002 mm). The fine soil texture (Ø < 0.002 mm) is believed to result from geomorphic processes, with sediment

accumulating over a period of time to form the soil body. In addition, external factors such as wind erosion and salinization affect the retention or removal of fine particles at the soil surface, which, in turn, influences soil texture in fluvio-marine landscapes (Li and Guo, 2022). The soil structure of both soil types tends to be similar, namely granular in the upper layer and gradually forming clumps in the lower layer. The structure in the topsoil is generally due to anthropogenic activities, while the clumps in the subsoil are due to pedogenesis.

3.2. Soil Physicochemical Characteristics

The results for the soil's physical and chemical properties are summarized in Table 2. These results are based on laboratory test results. The soil texture in both soil layers is quantitatively dominated by the fine fraction (Ø <0.002 mm). Factors influencing the formation of clay soil texture include eluvial and illuvial processes and environmental conditions that shape clay soil texture (Badía-Villas et al., 2022). In addition, the parent material also plays an important role by providing a mineral composition that controls the vertical differentiation process of clay content in the soil horizon (Pereira et al., 2024). Furthermore, the Bulk Density (BD) and Particle Density (PD) values show a similar trend: an increase in the horizon-to-horizon difference. Similarly, soil porosity values show a trend consistent with differences in horizon type (Table 2, Figure 3).

Table 2. Soil physicochemical properties

Code	Soil Depth (cm)	Soil Texture			Soil Class Texture	BD (g cm^{-3})	PD (g cm^{-3})	n (%)	pH H_2O (1:5)
		Sand	Silt	Clay					
		%							
P1L1	0 – 18/25	11	40	49	Silty Clay	0.8	1.70	52	6.14
P1L2	18/25 – 30	10	46	44	Silty Clay	1.2	2.03	41	6.25
P2L1	0 – 20/23	23	38	39	Clay Loam	1.1	1.98	45	6.35
P2L2	20/23 – 26	27	42	31	Clay Loam	1.3	2.18	35	6.39

Note: BD: bulk density; PD: particle density; n: soil porosity; SOC: soil organic carbon; SOM: soil organic matter; TN: total nitrogen; CEC: cation exchange capacity; BS: base saturation.

Table 2. Continued

Code	SOC	SOM	TN	P_2O_5	K_2O	Base Cation				CEC (cmol(+) kg^{-1})	BS (%)
						Ca	Mg	K	Na		
	%			mg $100g^{-1}$		(cmol(+) kg^{-1})					
P1L1	1.53	2.63	0.13	23.63	10.95	30.2	1.3	0.1	2.5	42.4	80
P1L2	1.04	1.79	0.10	17.43	12.04	22.2	4.8	1.1	3.5	31.8	99
P2L1	1.38	2.37	0.12	22.45	12.01	5.5	0.6	1.8	2.2	14.6	70
P2L2	1.14	1.96	0.08	13.63	8.95	4.2	0.8	2.2	3.6	14.9	73

Bulk density is a physical property that reflects the mass of a given volume of material. Bulk density (BD) is also believed to serve as an indicator in assessing soil density, root system pathways, soil organic matter (SOM) content, and soil pore space (Hartati et al., 2023). In addition, particle density is generally related to soil's inherent properties and mineral content. In general, soils with coarse textures have higher dry density levels than those without. This is due to the composition of their characteristic particle structure (Jia and Zheng, 2024). The pH values of both soil profiles show a tendency toward neutral pH. Biological, chemical, and environmental factors influence soil pH. In addition, soil pH is believed to be one of the determinants of the criticality of nutrient content and soil health, thereby affecting plant growth and surrounding ecological conditions. The causes of soil pH variation can also be broadly categorized from natural processes to anthropogenic influences. For example, afforestation can lower pH in alkaline soils and raise it in acidic ones (Hong et al., 2018). At the research site, pH values were influenced by land management factors, including lime application, which increased pH. Furthermore, the soil organic carbon (SOC) and soil organic matter (SOM) values in each soil profile show similar trends (Table 2, Figure 3). Generally, SOM values are influenced by SOC values. SOM will increase when SOC values increase, and vice versa. However, SOC values decreased in both soil profiles. This was due to the pedogenetic process of leaching, which occurred within the soil body. (Aji et al., 2020; Noviyanto et al., 2020). The total nitrogen (TN) value in both cases tends to be low, but it decreases further to very low at P2L2. Soil total nitrogen is primarily affected by soil organic carbon, vegetation characteristics (ground cover), mean annual temperature (MAT), and topographical slope (Nie et al., 2020). In Agricultural practice, fertilization and irrigation practices can enhance TN content. Previous researchers have already revealed this at the coal mine site (Stickler, 2022). In addition, precipitation, elevation, soil organic matter (SOM), and silt content positively correlate with soil total nitrogen. Conversely, sand content and temperature negatively affect soil organic nitrogen and mineral nitrogen contents (Zhang et al., 2023).

The P_2O_5 and K_2O content in both soil profiles was categorized as low. Generally, low levels of phosphorus (P) and potassium (K) are caused by several factors, including soil type, fertilization, microbial activity, and soil chemical composition (Zhao et al., 2019). Low P content is also caused by Al-Fe fixation. Meanwhile, low K content is usually determined by 2:1 clay minerals such as illite and vermiculite. However, the combined application of lime with P- and K-solubilizing bacteria can increase soil P and K levels and improve nutrient availability (Abou-El-Seoud et al., 2012).

The value of Cation exchange capacity (CEC) in soil profile 1 is higher than in soil profile 2. Land use factors influence the value of CEC. Rice fields usually have higher CEC values than non-rice fields. This is due to the management of hydrological systems, including irrigation, organic matter content, and integrated soil management (Cornish et al., 2020; Tang et al., 2024). Next, the Basic Saturation (BS) value for soil profile 1 is higher than that for soil profile 2. The alkaline saturation (BS) value is often influenced by soil type and environmental conditions. In addition, the content of Ca, Mg, and Al also plays an important role in the BS value (Wang et al., 2020). There is a relationship between CEC and BS value. BS and CEC are influenced by soil mineralogy. Soil types with mineralogy, such as kaolinite and halloysite, are considered to increase nutrient availability compared to soils with amorphous minerals because they have a high chelating power to bind alkaline cations, suggesting the need for better land management strategies (Anda et al., 2012).

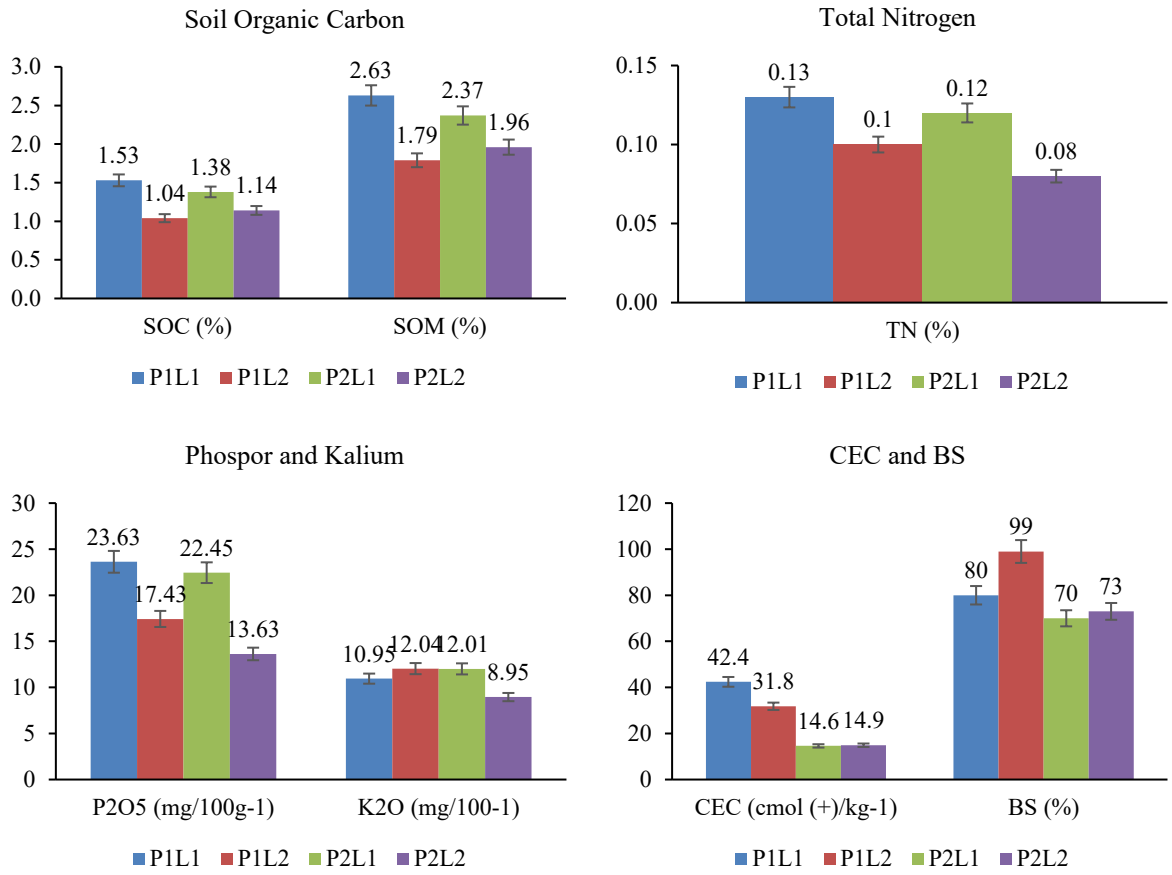

Figure 3. Soil chemical characteristic dynamics in soil profile

3.3. Discussion

It has been established that the idea of soil geomorphology in fluvio-marine landscapes is interconnected and directly affects soil characteristics. Different parent material compositions result from distinct sedimentation processes driven by dynamic geomorphological processes from upstream to downstream. The composition of the parent material of the environment it produces is one factor that determines the classification of soil types in a region (Nurcholis et al., 2019). These results can also serve as indicators for assessing crop suitability and land capability for different land uses. Areas with steep slopes or prone to erosion are used as conservation buffer zones in the form of secondary forests or production forests, whereas regions with mild slopes and fertile soils are better suited for intensive agriculture (Sarkar, 2019; Derakhshan-Babaei et al., 2021; Nykytiuk and Kravchenko, 2025).

The kind of sedimentation that creates new landforms is correlated with fluvio-marine landscapes. The formation of dunes in regions that lead to the sea is one example (Bera et al., 2025). The fluvio-marine landscape is also influenced by factors such as temperature, rainfall patterns, sea-level fluctuations, and landscape morphology. These elements are crucial in supplying materials that sustain soil properties and landscape dynamics (Henriques et al., 2022). Though the variety of lithological types and geomorphological processes must be taken into account when interpreting it, the chemical weathering index is also strongly correlated with rainfall, which influences soil characteristics and sedimentation outcomes (Dinis et al., 2020). At the mouth of the Sittang River, for example, hydro-morphodynamic interactions between wave energy and tidal cycles produce sediment distribution and coastal features (Shimozono et al., 2019).

Sustainable agricultural land management in fluvio-marine landscapes must be comprehensive to create a sustainable environment. Effective and efficient strategies are essential, such as the use of Artificial Intelligence of Things (AIoT)- based land management technology to monitor soil fertility in suboptimal areas using soil sensors. In addition, the creation of ridges through soil conservation practices can increase crop productivity, soil health, and water availability for crops, while also addressing climate change (Ayyam et al., 2019). The application of biochar, one of the most effective technologies for retaining nitrogen in soil, is discussed. Biochar has microscopic pores that prevent nitrogen from being washed away by rainwater or irrigation. Planting legumes as nitrogen-fixing species between main crop cycles to naturally harvest nitrogen from the atmosphere. Furthermore, prioritizing the determination of conservation zones to maintain biomass production stability, minimize excessive nutrient loss, and improve clean water quality for agricultural activities (Müller et al., 2000; Nguyen Thi Ngoc et al., 2025).

In the pursuit of the Sustainable Development Goals (SDGs) and the Eight Principles of the Unitary State of the Republic of Indonesia, geoscience plays a significant role. SDG goals 2 (food security), 6 (clean water), 13 (climate change action in terrestrial ecosystems), and 15 (biodiversity preservation) are all directly tied to proficiency in the multidisciplinary fields of geomorphology and pedology. Asta Cita, on the other hand, is more concerned with Asta Cita Unitary State of the Republic of Indonesia number 2, which concerns independence and food security, and number 8, which concerns harmony between people and their surroundings. Therefore, it is thought that this study will be able to quantify how land development affects biodiversity, soil quality, and the health of terrestrial ecosystems, giving stakeholders and policymakers useful information (Mikhailova et al., 2023)

4. Conclusion

Based on the findings and descriptions above, it can be concluded that studies on geomorphological-pedological characteristics and physico-chemical properties of soil in fluvio-marine landscapes have resulted in different soil classifications due to differences in land use. The Fluvaquentic Endoaquepts soil classification is found in rice field land use, while Typic Eutrudepts is found in mixed plantation land use. This study demonstrates that a strong coupling between geomorpho-pedological settings and soil physicochemical properties characterizes the fluvio-marine landscape of East Halmahera. Variations in landform units, sedimentary environments, and pedogenic development have a decisive influence on the physicochemical properties of soil, thereby shaping the functional capacity of soil used for agriculture. The integration of geomorphological analysis with pedological and physico-chemical assessments provides a robust framework for identifying zones vulnerable to degradation and for distinguishing land units based on their intrinsic land quality. Soil management strategies, such as applying organic fertilizers, regulating the application of organic materials, and using vegetative conservation techniques, are essential. This approach offers a process-based understanding essential to sustainable agricultural planning in dynamic coastal-alluvial landscapes in wet tropical regions.

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