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The relationship between soil properties in pedogenesis dynamics: A study of pedons on slopes and basins

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ABSTRACT

Soil formation and weathering are essential processes influencing natural fertility, yet the combined role of particle size distribution, texture, and organic carbon content at the profile scale remains understudied. Earlier research has focused chiefly on soil properties at the landform or regional scale, without examining interhorizon variations, leading to a limited understanding of their interactions in pedogenesis under different environments. This study compared the physical and chemical characteristics of soils in two contrasting pedons, Jatinangor (slope) and Tanjungsari (depression), both located in Sumedang Regency, West Java, Indonesia, with similar soil-forming factors. A descriptive-comparative method was employed using horizon-based sampling, laboratory analysis, and Principal Component Analysis (PCA) to reveal relationships and dominant factors. Results indicated that clay fractions dominated the JTN (Jatinangor) pedon with a clay texture due to intensive weathering under well-drained conditions. In contrast, the TJN (Tanjungsari) pedon was dominated by silt fractions resulting from fine material deposition under waterlogged conditions. Organic carbon content was lower in JTN due to leaching on slopes, whereas higher accumulation occurred in TJN due to depression settings. PCA identified sand fraction as the main discriminating factor, while fine fractions (silt and clay) were positively associated with organic carbon. These findings highlight that integrated analysis of these variables at the pedon scale provides a sensitive indicator of pedogenesis, weathering, and soil fertility.

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1. INTRODUCTION

Soil development and weathering are fundamental processes that determine the formation of soil horizons, influence nutrient availability, and natural soil fertility, which is influenced by complex interactions between physical, chemical, and biological factors. Among these factors, particle size distribution, soil texture, and organic carbon (C-organic) play a significant role in soil formation, weathering dynamics, and soil fertility (Dewangan et al., 2024; Du et al., 2022; Mishra & Singh, 2025; Mourya et al., 2021; Phayo, 2023; Ren et al., 2019; Sun et al., 2018; Wang et al., 2023; Z. Wang et al., 2024). Numerous studies have shown that soil particle size distribution is an important physical property of soil and determines many other chemical, physical, and biological properties of soil (Qiao et al., 2021; Rodríguez-Lado & Lado, 2017). Particle size distribution plays a crucial role in estimating soil hydraulic properties (Rahman & Amin, 2023), such as water retention curves and saturated hydraulic conductivity, as well as bulk density (Satyanaga et al., 2024).

Changes in particle size distribution can be used as indicators of the intensity of pedogenesis and soil formation processes (Darder et al., 2021; Richer-de-Forges et al., 2022; Sun et al., 2018). Shete et al. (2019) explain that variations in sand, silt, and clay fractions can be important indicators in assessing the level of soil development. Furthermore, organic carbon content has been shown to contribute to aggregate stability (Habibi et al., 2019; Udom et al., 2021) and cation exchange capacity (Du et al., 2024; Ratnayake et al., 2019; Solly et al., 2020), thus directly influencing soil fertility.

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However, most of these studies emphasize descriptive approaches at the regional scale. For example, studies by Doetterl et al. (2025); Eger et al. (2021); and van der Meij et al. (2020) highlight soil-forming factors at the landscape scale, while Bhatt et al. (2024); Dhruw et al. (2022); R. Wang et al. (2024) only compare soil properties based on different landforms without examining detailed relationships at the profile level. Existing studies tend to highlight differences in soil properties based on landforms in general, without delving in detail into the relationship between particle size distribution, texture variation, and organic carbon content with soil weathering intensity at the horizon level. Therefore, there is still a research gap at the soil profile scale to understand how these three factors directly influence the weathering process and soil horizon development.

This research is important to understand the influence of landform on soil formation process in tropical volcanic environment with other soil forming factors that are relatively uniform. The research was conducted in Jatinangor (Pedon JTN) and Tanjungsari (Pedon TJN) areas, Sumedang District, West Java, Indonesia which have similarities in four main soil forming factors, namely young volcanic ash parent material (Qyu), C3 type climate, dryland vegetation, and Holocene age, but differ in topography factor (slope gradient). The difference in slope gradient between Pedon JTN (8%, gentle slope class) and Pedon TJN (1%, flat slope class) provides an opportunity to specifically analyze the role of topography on the dynamics of pedogenesis process.

Topography, especially slope gradient, plays an important role in influencing the physicochemical properties of soil by controlling the processes of runoff, drainage, soil erosion (Pitta-Osses et al., 2022), and is an important determinant of the spatial distribution of soil properties, including nutrient retention and availability (Okebalama et al., 2025). Variations in slope gradient can cause redistribution of soil properties and soil organic matter, thus affecting overall soil fertility (Assefa et al., 2020). The results of the study Ewunetu et al. (2025) showed that variations in slope gradient affect most of the physicochemical properties of the soil, including texture, specific gravity, porosity, pH, organic matter, available phosphorus, total nitrogen, cation exchange capacity, and exchangeable cations. This allows researchers to more accurately identify the influence of topography/slope gradient on variations in soil physical and chemical properties, such as particle size distribution, texture, and organic carbon content. Slope gradient is directly related to landforms, and both influence soil physical and chemical properties, water dynamics, erosion, deposition, and weathering intensity.

Landforms have a significant influence on the physical and chemical properties of soil because they determine the dynamics of soil formation and development. Variations in landforms, such as peaks, slopes, toes, and depressions, result in differences in erosion, weathering, organic matter accumulation, and drainage conditions (Mourya et al., 2021). On slopes, the soil experiences intensive erosion and leaching so that fine fractions such as clay and dust are carried down and the organic matter content is low (Ao et al., 2024; Osman, 2018a; Ray et al., 2023; Zhang & Wang, 2017). Meanwhile, on flat or concave land forms, there is an accumulation of fine and organic materials, due to the accumulation of erosion results from slopes and slow drainage conditions, so that the decomposition of organic materials takes place more slowly (Alamu & Dada, 2025; Feng et al., 2025; Wang et al., 2020).

This study aims to analyze the differences in particle size distribution, soil texture, and C-organic content between horizons in pedons with different landforms, namely slopes (Jatinangor) and basins (Tanjungsari) in Sumedang Regency, West Java, Indonesia and to reveal the relationship between variables and dominant factors through the Principal Component Analysis (PCA) approach. The results of this study are expected to provide new contributions in strengthening the understanding of pedology at the soil profile scale, which is useful as a scientific basis for sustainable land management.

2. MATERIAL AND METHODS

2.1. Study area

A comparative-descriptive study was conducted in two sub-districts, Jatinangor sand Tanjungsari, Sumedang Regency (Fig. 1). A soil pedon was established at each location: JTN ((06^o 54’44”S 107^o 46’ 10”E) in Jatinangor and TJN (6^o 54’10”S 107^o 49’27”E) in Tanjungsari (Table 1). The parent material at both locations was the same, namely Qyu, a young, undecomposed volcanic product derived partly from Mount Tangkuban Parahu and partly from Mount Tampomas, and characterized by andesitic-basaltic properties (Djuri, 1995) The field equipment used in this study was descriptive paper, Munsell Soil Color Chart, GPS (Global Position System), meter, labels, plastic bags, knife, clinometer, axe, shovel, push pin, and photo camera. The software used in this research is the GIS application, GraphPad Prism 10 and R-Studio. Each pedon was described, and soil samples were taken from each horizon for analysis of its physical and chemical properties, including particle size distribution, texture, and organic carbon content. Analysis of particle size distribution and texture was conducted at the Testing Laboratory of the Soil and Fertilizer Assembly and Testing Center, Bogor. In contrast, organic carbon analysis was performed at the Testing Laboratory of the Vegetable Plant Assembly and Modernization Center, Lembang, Bandung, West Java, Indonesia.

2.2. Soil samples and analysis

Soil sampling was carried out at each horizon in one JTN pedon and one TJN pedon. The JTN pedon consists of eight horizons, while the TJN pedon has seven horizons, so the total number of samples obtained was 15. Furthermore, the samples were analyzed for particle size distribution and texture using the pipette method, and the C-organic content was determined using the Walkley and Black method. The relationship between parameters, and the zonation visualization were analyzed using the PCA (Principal Component Analysis) method.

2.3. Statistical analysis

Principal Component Analysis (PCA) is helpful in simplifying complex data with many variables into a few, more easily understood main components without losing essential information (Salem & Hussein, 2019).

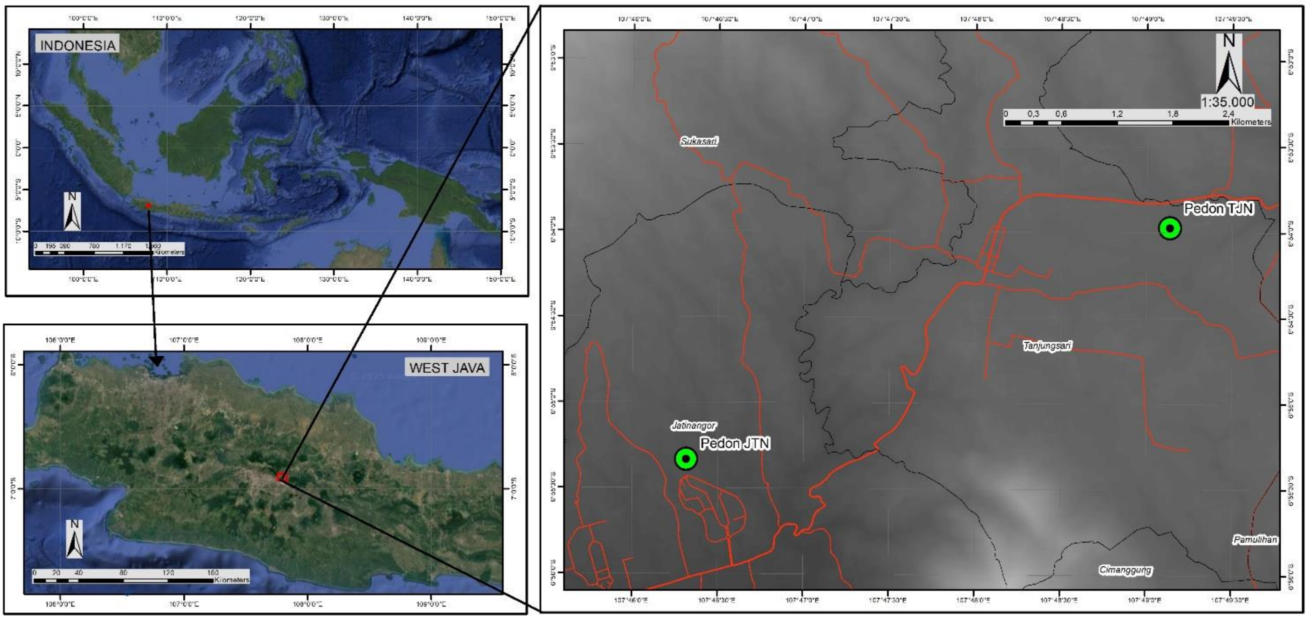

Figure 1. Location of Pedon JTN and Pedon TJN.

Table 1. Characteristics of the research location

Location	Coordinates	Height	Slope	Gradient Slope	Parent Material	Climate	Age	Vegetation
Pedon JTN	06° 54'44"S 107° 46' 10"E	825,81 m asl	8%	Flat	Qyu	C3	Holocene	Dryland
Pedon TJN	6° 54'10"S 107° 49'27"E	875,26 m asl	1%	Flat	Qyu	C3	Holocene	Dryland

Notes: Qyu = Quarter young undifferentiated, C3 = Areas with 3–4 wet months (≥ 200 mm), 3–4 humid months (100–200 mm), and ≥ 4 dry months (≤ 100 mm). Includes a semi-dry zone with one rain-fed rice planting period and one secondary crop planting period

Through PCA, we can identify the most influential variables, observe patterns of relationships between variables, and group samples based on similar characteristics (Souza, 2025). In this study, PCA was analyzed using GraphPad Prism 10 and R-Studio to explain the relationship between particle size distribution, texture, and organic matter content, thus helping researchers understand the dominant factors that influence soil development and fertility.

3. RESULTS

3.1. Soil particle size distribution

The particle size distribution analysis in Table 2 shows that the JTN Pedon is dominated by the clay fraction (fraction X) with a range of 30.3–77.5% along the profile. In the upper horizons (Ap_1–Bw_2; 0–102 cm depth), the clay content is relatively high, ranging from 64.1–77.5%, with the highest value in the Bw_2 horizon (84–102 cm) at 77.5% and the lowest in the BC_1 horizon (102–132 cm) at 30.3%. In addition to clay, the silt fraction (fractions VIII–IX) also contributes significantly, particularly in the BC_1 horizon (39.9%) and BC_2 horizon (6.6%). In the lower horizons (BC_1–BC_3, 102–200 cm depth), the clay content tends to decrease, while the fine sand and silt fractions increase. The BC_3 horizon again shows clay dominance (66.7%), indicating textural variations influenced by the parent material.

Particle size distribution data in the TJN Pedon show variations between horizons, with a shift in fraction dominance from clay to silt and sand with depth. In the Ap horizon (0–23 cm), the dominant fractions are silt (23.5%) and clay (24.6%), accompanied by fine-medium sand. In the Bw_1 horizon (23–51 cm), the silt content increases (±38.8%) with a decrease in clay (15.5%). The Bw_2 (51–83 cm) and Bw_3 (83–111 cm) horizons show a silt fraction dominance (±85%) with low clay (3.0–3.4%). In the Bw_4 horizon (111–148 cm), silt remains high (28.5%), but clay begins to increase (6.7%). Significant changes are seen in the 2AB (148–181 cm) and 2Bw (181–200 cm) horizons, where the sand fraction increases drastically (>45%), while clay is very low (1.3–4.5%).

3.2. Soil texture

The soil texture analysis in Table 3 shows that clay fractions dominate the JTN Pedon throughout the 0–200 cm depth. In the Ap_1 (0–16 cm) to BC_1 (102–132 cm) horizons, the clay content is very high, ranging from 70–86%. Furthermore, in the BC_2 (132–157 cm) horizon, the silt fraction increases to 45%, shifting the soil texture to silty clay. However, in the BC_3 horizon, the soil texture is again dominated by clay fractions. In general, the texture distribution pattern shows an increase in clay content from the upper horizon (Ap_1) to Bw_2, then decreases in the BC_1 to BC_3 horizons as the sand fraction content increases due to the weathering of the parent material.

Table 2. Particle size distribution in pedon JTN dan TJN

Pedon	Horizon	Depth	Fract I	Fract II	Fract III	Fract IV	Fract V	Fract VI	Fract VII	Fract VIII	Fract IX	Fract X
JTN	Ap_1	0-16	1.4	0.6	0.8	0	0.1	5.5	1.0	12.5	14.1	64.1
	Ap_2	16-32	1.8	0.1	1.1	0.8	0.0	2.6	1.0	12.9	9.4	70.3
	AB	32-54	0.6	0.6	0.9	0.1	0.1	1.4	1.4	12.1	8	74.8
	Bw_1	54-84	0.5	0.7	1.9	0.3	0.1	2.2	0.3	8.0	13.3	72.6
	Bw_2	84-102	0.7	0.6	1.0	0.4	0.0	1.4	0.4	11.1	6.9	77.5
	BC_1	102-132	0.7	0.1	0.1	0.4	0.0	14.2	8.9	5.4	39.9	30.3
	BC_2	132-157	0.7	0.5	0.7	0.1	0.0	24	14.9	6.0	6.6	46.5
	BC_3	157-200	0.9	0.5	0.8	0.3	0.1	1.6	3.1	16.1	9.8	66.7
TJN	Ap	0-23	4.9	1.1	3.3	0.1	0.1	16.2	11.3	23.5	15	24.6
	Bw_1	23-51	8.3	1.1	3.1	0.3	0.1	25.4	7.6	19.4	19.4	15.5
	Bw_2	51-83	6.3	1.9	2.9	0.3	0.2	34	11.1	25.6	14.7	3.0
	Bw_3	83-111	3.7	2.6	2.7	0.3	0.1	37.8	9.3	26	14.1	3.4
	Bw_4	111-148	9.7	1.4	4.9	0.2	0.6	29.2	10.3	28.5	8.6	6.7
	2AB	148-181	10.8	11.4	13.4	14.7	0.5	18.6	8.7	14	3.5	4.5
	2 Bw	181-200	19.4	0.9	18.4	6.7	2.3	20.9	7.5	14.7	7.8	1.3

Description: size of fraction I = 2.00 – 1.00 mm; fraction II = 1.00 – 0.50 mm; fraction III = 0.50 – 0.25 mm; fraction IV = 0.25 – 0.10 mm; fraction V = 0.10 – 0.05 mm; fraction VI = 0.05 mm; fraction VII = 0.02 mm; fraction VIII = 0.005 mm; fraction IX = 0.002; fraction X = 0.0005 mm

Table 3. Results of soil texture analysis in pedon JTN dan TJN

Pedon	Horizon	Depth (cm)	Texture			Texture Criteria
			Sand	Silt	Clay	
JTN	Ap_1	0-16	3	19	78	Clay
	Ap_2	16-32	4	17	80	Clay
	AB	32-54	2	15	83	Clay
	Bw_1	54-84	4	11	86	Clay
	Bw_2	84-102	3	13	84	Clay
	BC_1	102-132	1	29	70	Clay
	BC_2	132-157	2	45	53	Silty clay
	BC_3	157-200	3	21	77	Clat
TJN	Ap	0-23	10	51	40	Silty clay loam
	Bw_1	23-51	13	52	35	Silly clay loam
	Bw_2	51-83	12	71	18	Silly clay loam
	Bw_3	83-111	9	73	18	Silly clay loam
	Bw_4	111-148	17	68	15	Silly clay loam
	2AB	148-181	51	41	8	Clay
	2Bw	181-200	48	43	9	Clay

The results of the soil texture analysis in the TJN Pedon show differences in texture distribution patterns. The Ap to Bw_1 horizons (0–51 cm) have a silty clay loam texture, then change to silt loam in the Bw_2 to Bw_4 horizons (51–148 cm). In the lower horizons, namely in the 2Ab to 2Bw horizons (148–200 cm), the soil texture returns to clay. Vertically, from the Ap_2 to the Bw horizons, there is a regular increase in clay content as a characteristic of horizon development. However, at the transition from the Bw_4 to 2Ab horizons, there is a quite significant textural change, indicated by an increase in the sand fraction from 17% to 51%, a decrease in the silt fraction from 68% to 41%, and a reduction in the clay fraction from 15% to 8%. This phenomenon indicates a difference in parent material (lithological discontinuity) between the lower and upper layers.

3.3. C-organic

C-organic values in the JTN Pedon show quite clear variation. The highest value is found in the Ap_1 horizon at 2.65%, while the lowest value is found in the Bw_2 horizon at 0.64%. In the TJN Pedon, the highest C-organic value is found in the Ap horizon at 3.29%, while the lowest value is found in the Bw1 horizon at 2.07%. Interestingly, in the Bw_2 horizon, the C-organic value increases again to 3.15%, before decreasing in the 2AB horizon to 2.71% (Fig. 2).

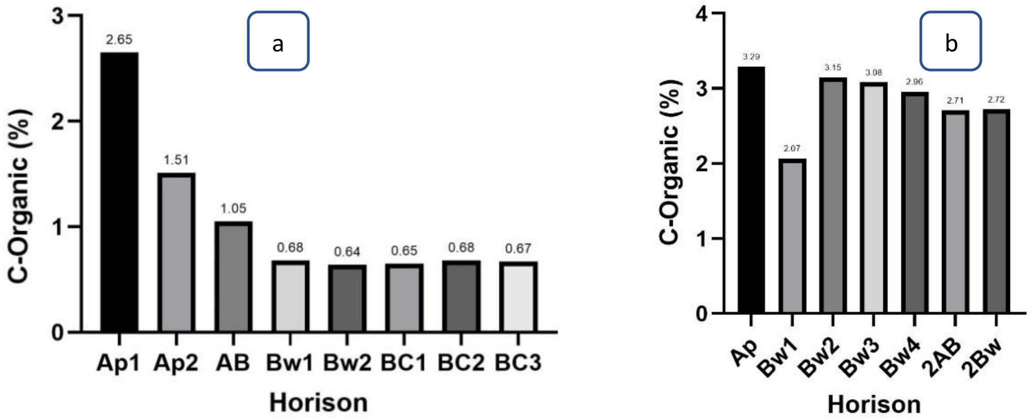

Figure 2. C-Organic content in pedon JTN (a) dan TJN (b)

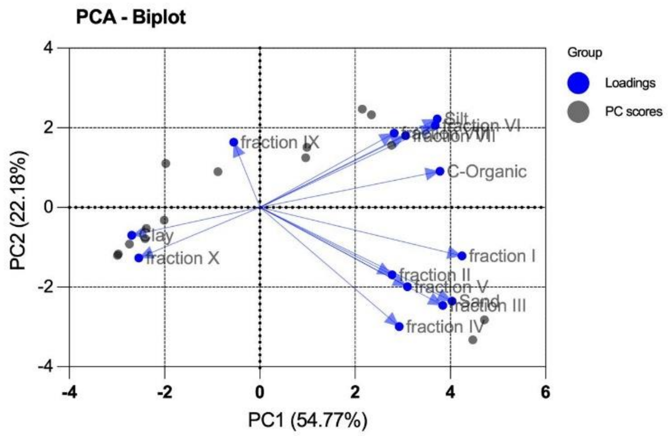

Figure 3. Biplot curve

Table 4. Variance of physical and chemical properties of soil based on the main components

	PC1	PC2
Eigenvalue	7.668	3.105
Variability (%)	54.77%	22.18%
Cumulative (%)	54.77%	76.95%

3.4. Principal Component Analysis (PCA) method

The results of the Principal Component Analysis (PCA) with the Biplot Curve in Figure 3 show that two main components can explain most of the data variability, with PC1 at 54.77% and PC2 at 22.18% (Table 4). The first component (PC1) is dominated by the contribution of the sand fraction (fraction I–V), which is closely associated with sand texture. In contrast, the second component (PC2) is influenced by the intermediate fractions (fractions VI, VII, IX) and the C-organic content (Table 5). This indicates that sand texture is the main factor differentiating between soil samples, while the silt fraction and C-organic content provide additional contributions in explaining variations in soil properties. The distribution pattern of variables in the biplot shows that the sand fraction (fraction I–V) has a long vector and is in the same direction as PC1, indicating its dominant role in the variation of the first component. In contrast, the clay fraction and fraction X are in the opposite direction to sand, indicating a clear negative relationship. The dust fraction groups (fraction VI, VII) and fraction IX are in the same quadrant as C-organic, which confirms the existence of a positive association between these variables.

The correlation strength can be interpreted using the absolute value of r: very strong (0.90-1.00), strong (0.70-0.89), moderate (0.40-0.69), weak (0.10-0.39), and negligible (0.00-0.10) (Pengphorm et al., 2024). The results of the correlation analysis in Figure 4 support the PCA findings. Fractions I–V have a very strong positive correlation (0.77–0.97) and are identical to the sand fraction. Fractions VI–VIII show a very strong positive correlation with silt (0.78–0.97), while fraction IX has a weak positive correlation with silt (0.34). Fraction X has a strong negative correlation with sand (–0.59 to –0.89) and a very strong positive correlation with clay (0.96).

The correlation between texture and organic matter is also clearly visible. Organic C had a strong positive correlation with silt (0.73) and a moderate positive correlation with sand (0.51), but a strong negative correlation with clay (–0.78). The highest positive correlation of organic C was shown in fraction VIII (0.79) and fraction VI (0.65), while a negative correlation was seen in fraction X (–0.75).

Table 5. Analysis of the main components of the physical and chemical properties of soil

	PC1	PC2
Fract I	0.883	-0.277
Fract II	0.577	-0.386
Fract III	0.799	-0.560
Fract IV	0.608	-0.681
Fract V	0.645	-0.454
Fract VI	0.766	0.572
Fract VII	0.636	0.501
Fract VIII	0.586	0.519
Fract IX	-0.201	0.455
Fract X	-0.930	-0.289
Sand	0.839	-0.536
Silt	0.775	0.618
Clay	-0.984	-0.160
C-Org	0.787	0.252

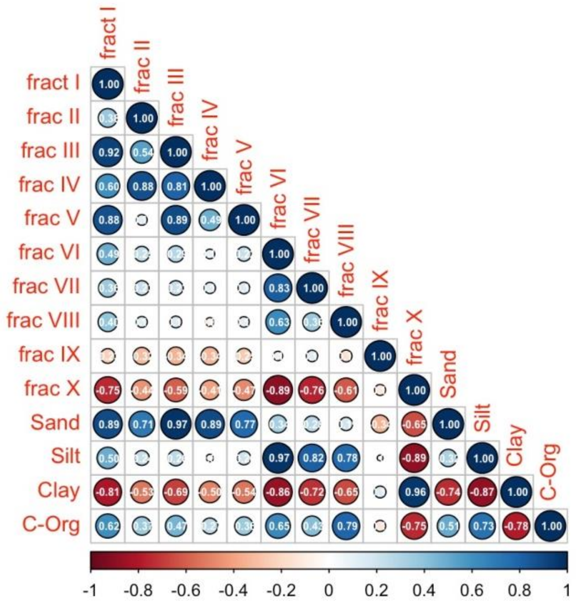

Figure 4. Correlation matrix between particle size distribution, soil texture, and organic C. Colors reflect the correlation coefficient (r) on a scale of -1 to 1. High positive correlation values are indicated by dark to very dark blue, while values close to zero are indicated by light blue to pink

4. DISCUSSION

The particle size distribution patterns in the two pedons indicate differences in pedogenesis processes and the influence of parent material. In the JTN Pedon, the high clay content in the upper to middle layers of the profile (Ap_1-Bw_2, 0–102 cm depth) indicates illuviation, where clay is leached from the upper layers and accumulates in the lower horizons. However, the drastic decrease in clay content in the BC_1–BC_2 horizons, followed by an increase in sand and silt fractions, indicates the influence of different parent materials in the lower layers. The clay fraction again increases in the BC_3 horizon (66.7%), confirming the heterogeneity of the parent material in this pedon. Meanwhile, in the TJN Pedon, the distribution pattern indicates that the upper to middle layers of the profile (Ap–Bw_4, 0–148 cm depth) are dominated by silt and clay fractions. The high silt content in the Bw2–Bw3 horizons indicates intensive clay eluviation, shifting the texture from silty clay to clayey silt. The most prominent changes occur in the 2AB–2Bw horizon, which exhibits a lithological discontinuity with a significant increase in the sand fraction. This indicates a difference in the coarser parent material compared to the overlying layers, thus making soil development more influenced by external factors in the form of variations in the parent material.

Changes in fraction distribution in the JTN and TJN pedons are influenced by parent material and landform factors. In the JTN pedon, the increase in sand and silt fractions in the BC1 horizon indicates the influence of parent material weathering and particle accumulation from the overlying horizon. Meanwhile, in the TJN pedon, variations in particle distribution are caused by the presence of two different parent materials, thus affecting the mineral composition within the soil profile. Differences in parent materials lead to differences in mineral content and levels of resistance to weathering (Wilson, 2019) Given that mineral soils are largely composed of mineral particles and control many soil properties (Wilson, 2019). Furthermore, the distribution of secondary minerals is primarily determined by the parent material (mafic, felsic, or sedimentary), which varies with altitude (altitude 20–1700 m) (Watanabe et al., 2017). In addition to parent material factors (lithologic discontinuity), landforms also play a role (Wang et al., 2022) The soil formation process is closely related to topography, which influences soil morphology, mineralogy, and weathering processes. This is due to the topography or relief, which affects how water and other materials are added and removed from the soil (Tunçay & Dengiz, 2016)

In slope-based pedons (JTN), good drainage conditions lead to rapid weathering. Water easily seeps downward, creating aerobic conditions that accelerate the transformation of primary minerals (feldspar, mica) into secondary clay minerals (kaolinite, illite, smectite). This process increases the clay content, while physical weathering produces a silt fraction. Slopes with readily weathered parent materials (volcanic, tuff, claystone) generally produce higher silt and clay fractions. Conversely, in basin-based pedons (TJN), water flow slows due to frequent inundation. Under low-energy conditions, silt settles more quickly, while clay remains suspended longer and can be carried out of the basin. Therefore, basin-based areas tend to have a silt-clay or silt-clay texture, as they receive fine material and sediment that produce high amounts of secondary minerals in the silt fraction.

These findings are reinforced by the textural variations that developed in both pedons. The distribution patterns of soil texture in the two pedons reflect differences in dominant pedogenesis processes. In the JTN Pedon, the dominance of clay fractions across almost all horizons indicates intensive clay eluviation–illuviation processes. The consistent increase in clay content from the Ap_1 to Bw_2 horizons indicates clay accumulation in the lower horizons, which is a hallmark of argillaceous horizon formation (Soil Survey Staff, 2014). Conversely, the decrease in clay content accompanied by an increase in sand fractions in the BC_1 to BC_3 horizons reflects the role of parent material weathering in forming a coarser texture (Bayat et al., 2015). This suggests that soil development in the JTN Pedon is primarily controlled by internal processes, specifically the vertical transport of fine particles followed by parent material weathering in the lower part of the profile.

Unlike the JTN, soil development in the TJN Pedon is not only determined by internal processes such as clay leaching. Still, it is also influenced by external factors such as changes in parent material. This is evident from the lithological discontinuity at the transition from the Bw_4 horizon to the 2Ab horizon, which is characterized by a sharp change in texture, namely an increase in the sand fraction accompanied by a decrease in the clay and silt fractions. The presence of lithological discontinuity indicates that pedogenesis in the TJN Pedon did not occur uniformly, but was influenced by differences in the origins of the materials making up the soil profile (Sachan et al., 2023). Thus, the JTN Pedon reflects a more consistent soil development due to the clay eluviation-illuviation process, while the TJN Pedon shows a more complex development due to a combination of clay leaching and lithological changes.

Apart from the differences in texture that are influenced by pedogenesis and lithology processes, another dynamic that is no less important is the distribution of organic C, which displays a close relationship with biological factors, environmental conditions, and geomorphological position. The distribution pattern of organic C in both pedons shows a close relationship with horizon position, organic matter input, and soil microenvironmental conditions. The highest organic C content in the Ap horizon in both the JTN and TJN Pedons is due to the accumulation of surface organic matter in the form of leaf litter, plant debris, and microbial activity. Furthermore, the Ap horizon is the plow layer, so it receives more fresh organic matter input from agricultural activities and natural vegetation (Hartemink et al., 2020).

The decrease in organic C in the Bw1 horizon of the TJN Pedon (2.07%) reflects the reduced organic matter input due to the increasing distance from the soil surface. This Bw horizon is a transition zone, so organic matter content decreases because it no longer receives direct input from the surface, but there has also been no significant accumulation from below. Interestingly, organic C content increased again in the Bw_2 horizon of the TJN Pedon (3.15%). This is likely due to limited drainage or aeration conditions at this depth, resulting in slower decomposition of organic matter and relatively higher accumulation (Wang et al., 2017; Zhang & Wang, 2017). Furthermore, another factor that may play a role is the movement of dissolved organic matter (illuviation) from the overlying layers, which is then deposited in this horizon. In horizon 2AB of Pedon TJN, the organic C content decreased again to 2.71%. This may be attributed to the influence of the previous parent material, which was relatively poor in organic content, making it unable to support large amounts of carbon accumulation. Thus, the distribution of organic C in these two pedons indicates an interaction between biological factors (litter input and microbial activity), environmental conditions (drainage and aeration), and geological factors (parent material).

The difference in organic carbon content between the two pedons is influenced by geomorphological conditions and landforms. In the JTN Pedon, located on a slope, leaching by surface water flow is more dominant, resulting in rapid degradation of organic matter in the upper layers and low organic carbon content in the lower horizons. This is consistent with findings by Ashida et al. (2021) and Huang et al. (2021), which indicate that slope conditions accelerate the loss of organic matter from the soil profile.

Conversely, in the TJN Pedon, located in a basin, limited drainage conditions result in low aeration. This slows the rate of organic matter decomposition, resulting in higher organic carbon accumulation compared to soils on slopes (Osman, 2018b; Védère et al., 2022). Previous studies (Liang et al., 2019; Liu et al., 2024; Oliveira Filho et al., 2022; Wang et al., 2017) also confirmed that environments with limited aeration enhance the conservation of organic matter in the soil. Furthermore, the movement of dissolved organic matter from upper to lower horizons (organic matter illuviation) likely occurs, which then accumulates in lower horizons, thus explaining the variability in organic C values between horizons in the TJN Pedon. Overall, the JTN Pedon reflects the influence of slope geomorphology, which causes low organic C content in lower horizons. At the same time, the TJN Pedon shows higher organic matter accumulation due to basin conditions with limited drainage and the presence of organic matter illuviation processes.

The relationship between these factors is further emphasized through multivariate statistical analysis, which is able to reveal the fundamental relationship between particle distribution, texture, and organic C content (Fig. 4). Principal Component Analysis (PCA) and correlation results (Fig. 4) indicate that particle size distribution is a major determinant of soil texture variation (Polakowski et al., 2021; Wang et al., 2022), which is then closely related to organic C -content (Amorim et al., 2022; Mozaffari et al., 2022). Sand texture proved to be the primary differentiating factor in PC1, but finer fractions such as silt and clay played an important role in controlling organic C retention. The strong negative relationship between sand and clay confirms the substitutability of coarse and fine fractions in the soil profile.

The organic C content associated with the fine fractions (silt and clay) indicates that soil texture directly influences the soil's ability to retain organic matter (Franzluebbers, 2024; Gonçalves et al., 2017). The fine fraction has a larger specific surface area and a higher cation exchange capacity (Yan et al., 2023), making it able to bind and stabilize organic matter better than sand. Conversely, sandy soils tend to be poor in organic carbon due to the lower ability of the coarse fraction to retain organic matter (Yost & Hartemink, 2019).

Soil carbon storage is influenced by texture and aggregate formation, with silt and clay fractions playing a crucial role in protecting soil organic carbon (SOC) from decomposition (Cai et al., 2016; Mustafa et al., 2020). As organic matter decomposes, these compounds can bind to silt and clay particles, forming aggregates that protect the organic matter from further decomposition (Churchman, 2018; Findlay, 2021). Although Hassink (1997) did not find a direct relationship between total carbon and silt and clay content, the study did show an increase in carbon accumulation in fractions <20 µm in size as the proportion of silt and clay increased. Similar findings were also reported by Matus (2021), who found that the highest soil carbon content was found in the silt and clay fractions, while the sand fraction only retained low amounts.

In volcanic soils, the particle size distribution, dominated by fine fractions, particularly volcanic ash that weathers into amorphous clay minerals such as allophane and imogolite, contributes significantly to the stabilization of organic matter. This fine fraction has a high specific surface area and strong adsorption capacity, enabling it to bind and protect organic carbon from rapid decomposition. Thus, in line with the general concept, the delicate texture of volcanic soils plays a fundamental role in maintaining organic matter reserves, improving quality, and maintaining long-term soil fertility.

5. CONCLUSION

Based on the research results, pedogenesis in the Pedon JTN (slope) is influenced by the process of clay eluviation-illuviation and intensive weathering, resulting in a dominant clay texture. In contrast, the Pedon TJN (basin) shows a more complex development with the presence of lithological discontinuity and the dominance of the dust fraction due to the deposition of fine material. The organic C content is proven to be influenced by landform, where in the pedon JTN, the organic C value is lower than in the pedon TJN (due to accumulation under limited drainage conditions). The sand fraction is the main differentiating factor, while the fine fractions in the form of dust and clay play an essential role in the retention of organic C. The combination of internal factors, such as eluviation-illuviation and mineral weathering, together with external factors, such as lithology, topography, and drainage, synergistically form variations in the physicochemical properties of the soil that determine the level of natural fertility.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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