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Model of the Relationship Between Selected Soil Physical Properties of Oil Palm Soil

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ABSTRACT

Soil, water, and plants are interrelated elements in agricultural production. An in-depth understanding of the characteristics and interactions of these three aspects is essential in effective agricultural system management. The study aims to examine the relationship between soil's water-holding capacity and different land-slope levels and to identify the physical soil characteristics that affect it. The research was conducted in a community oil palm plantation in Talang Tengah I Village, Pondok Kubang District, Central Bengkulu Regency, Bengkulu Province. The method used was a survey with purposive sampling across five slope levels: flat (0-8%), sloping (8-15%), slightly steep (15-25%), steep (25-45%), and very steep (45-100%). The data were statistically analyzed using *Partial Least Squares Structural Equation Modelling* (PLS-SEM) with WarpPLS 7.0. The results showed that slope had a significant effect on various soil physical characteristics and soil water *holding capacity*. The steeper the slope, the greater the decrease in soil permeability, total pore space, and soil organic carbon, and the greater the increase in soil volume weight, which results in a decrease in soil water holding capacity. The resulting model shows agreement in describing the relationships between variables: slope affects organic matter, sand %, and permeability, and volume weight affects total pore space and permeability, which in turn affects the soil's capacity to hold water.

Keywords: Bulk density, permeability, slope, total soil porosity

INTRODUCTION

Soil, water, and plants are important interrelated components in agricultural production systems. Soil serves as a growing medium and supports plant life, while water supports plant growth and development (Zuhaida, 2018). Additionally, soil operates as a water reservoir, accounting for 3.8% of the total freshwater surface (Qiu et al., 2024; White, 1993). Furthermore, groundwater formed by infiltration significantly influences plant growth, especially during the early stages of development. Finally, adding water is often used on full-season agroeconomic or high-value specialty crops to ensure a dependable yield every year. It is also used on crops such as potatoes, flowers, vegetables, and fruits, where water stress affects yield quality (Scherer et al., 2022).

Oil palm, as one of the plantation crops, has a relatively high water requirement, with an ideal rainfall of 1.750-2.000 mm yr^{-1}, evenly distributed throughout the year (Harahap et al., 2021). It has a fibrous root system consisting of numerous fine roots spread throughout the soil. This plant is vulnerable to drought stress, an unavoidable factor in many environments. Evapotranspiration (ET), the combined process of water loss from soil (evaporation) and plant surfaces (transpiration), is part of the hydrological cycle and is directly related to energy balance (Guan et al., 2017; Teh et al., 2024). The soil's capacity to retain water is a critical factor influenced by physical characteristics such as texture (the proportion of sand, silt, and clay), permeability (how easily water moves through soil), bulk density (soil mass relative to its volume), total pore space (the volume of spaces between soil particles), and organic matter content. The soil's capacity to store water, known as water holding capacity, is considered equivalent to land capacity (Haridjaja et al., 2013). Field capacity is the level of soil moisture in the field at which drainage water flow has stopped or nearly stopped due to gravity after the soil reaches full saturation.

Topographical aspects, especially slope, affect the distribution and availability of groundwater. Slope is a major factor that creates spatial variation, leading to differences in vegetation growth and distribution. Steep slopes tend to have lower water-absorption rates than flat land. It can affect the soil's capacity to retain water. Water content influences the physical, chemical, and biological properties of soil. It is a major factor in regulating mass and energy exchange at the soil-air interface (Hermawan, 2004; Sheng et al., 2025). An in-depth understanding of soil's water-holding capacity is essential for optimizing water use in oil palm cultivation. (Mohamed et al., 2024) Montane ecosystems are remarkably diverse, mainly characterised by hillslope asymmetry, i.e., hillslope variation as a function of slope angle and aspect. Slope angle, aspect, and elevation are considered the primary factors driving spatial variation, influencing vegetation growth and distribution, and ecosystem function. The purpose of this study is to examine and develop a model of the relationship between soil water-holding capacity and various land-slope levels, and to identify the physical soil characteristics that affect it.

The vertical movement of water can cause soil materials to sink and accumulate downslope. The slope's angle also affects the amount of surface runoff; the more water that flows, the higher the speed at the bottom of the slope. The research by Fitriani et al. (2022) showed a very strong negative linear relationship between the slope of the land and the growth and yield variables of the observed oil palm plants. It is about 70% of the variation in stem diameter, 60% of the variation in plant height, 62% of the variation in the number of FFB per tree, and 72% of the variation in FFB weight that the variation in slope can explain. Oil palm will affect the amount of land and water management costs required to achieve optimal growth and yield, limiting the slope of the land to the suitability of the land.

MATERIAL AND METHODS

The research implementation consists of two time series, which will be carried out in August 2023 and June 2024. The research was conducted at a 15-hectare community oil palm plantation in Talang Tengah I Village, Pondok Kubang District, Central Bengkulu Regency, Bengkulu Province. Soil sample analysis was carried out at the Soil Science Laboratory, Faculty of Agriculture, University of Bengkulu.

The tools used in this study are GPS *(Global Positioning System),* Avenza map *application*, sample ring, clinometer, soil drill, field knife, plastic, marker, *mobile phone,* permeameter, oven, analytical balance, *hydrometer*, and cylinder tube. Meanwhile, the materials used in this study include intact soil samples, disturbed soil, and a 5% Calgon solution.

The study used a survey method with purposive sampling across several different slopes*, all* with the same land use (oil palm plantations) and soil type (Ultisols). Soil analysis in the laboratory to study the results of soil water holding capacity analysis and is related to several soil physical properties on various slopes, namely on flat land (0-8%), sloping (8-15%), slightly steep (15-25%), steep (25-45%) and very steep (45-100%). Seven samples were collected per slope, for a total of 35 soil samples. The research variables and methods are a) soil water retention ability, b) permeability, c) volume weight, d) total pore space, all four using the gravimetric method, e) soil texture method, *hydrometer,* and f) C-Organic method, *Walkley and Black.* The laboratory data were then analyzed quantitatively using the PLS-SEM *(Partial Least Squares Structural Equation Modelling)* method in WarpPLS 7.0.

This method aims to determine the relationship between a dependent variable and an independent variable. Results from Khodijah and Soemarno (2019) show that there is a relationship between the total pore space, the weight of the soil volume, and the soil's capacity to hold water. Then, research by Yulina *et al.* (2015) shows a relationship between slope soil permeability and soil texture. Based on the research by Khodijah and Soemarno (2019) and Yuliana *et al.* (2015), a conceptual model of the relationships among soil's water-holding capacity, slope, and selected soil physical characteristics was developed, as presented in Figure 1.

Based on the conceptual model of the relationship between soil capacity holding water and soil physical properties and slopes, the research hypothesis is as follows:

Hypothesis 1: Slope affects Organic-C
Hypothesis 2: Slope affects % sand
Hypothesis 3: Slope affects permeability
Hypothesis 4: Organic-C affects Bulk Density
Hypothesis 5: Organic-C affects % sand
Hypothesis 6: Organic-C affects permeability
Hypothesis 7: % sand affects permeability
Hypothesis 8: % sand affects Total Pore Space
Hypothesis 9: Bulk Density affects permeability
Hypothesis 10: Bulk Density affects Total Pore Space
Hypothesis 11: Bulk Density affects Water Holding Capacity

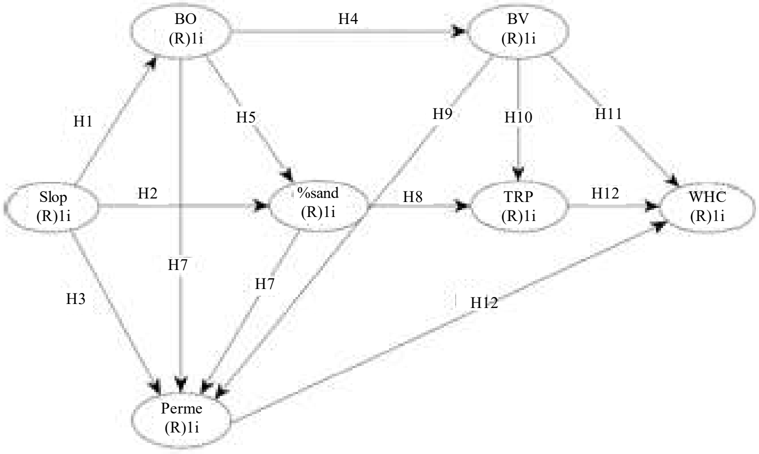


Figure 1. Conceptual model hypothesis.

Hypothesis 12: Total Pore Space affects Water Holding Capacity
Hypothesis 13: Permeability affects Water Holding Capacity

RESULTS AND DISCUSSIONS

Soil capacity to hold water

The soil capacity to hold water decreases as the slope increases, from 38.78% on flat slopes to 21.72% on very steep slopes (Figure 2). This decline is related to the slope, which affects the movement of water on the surface (runoff). On steep slopes, water tends to flow vertically and laterally, parallel to the soil surface. It moves down along the soil contours, resulting in greater surface flow, whereas on flat slopes it moves more vertically, increasing water absorption into the soil (Kalembiro et al., 2018). Steeper slopes result in greater surface flow, while on flatter surfaces it tends to be smaller. Steep slopes often experience more intense erosion, which can remove the topsoil layers that contain abundant organic matter. Organic matter is very important in increasing the capacity to hold groundwater. It aligns with Siregar (2023), who states that organic matter plays an important role in increasing groundwater absorption. When the soil is enriched with organic matter, its ability to hold and store water increases significantly compared to soil with minimal organic matter.

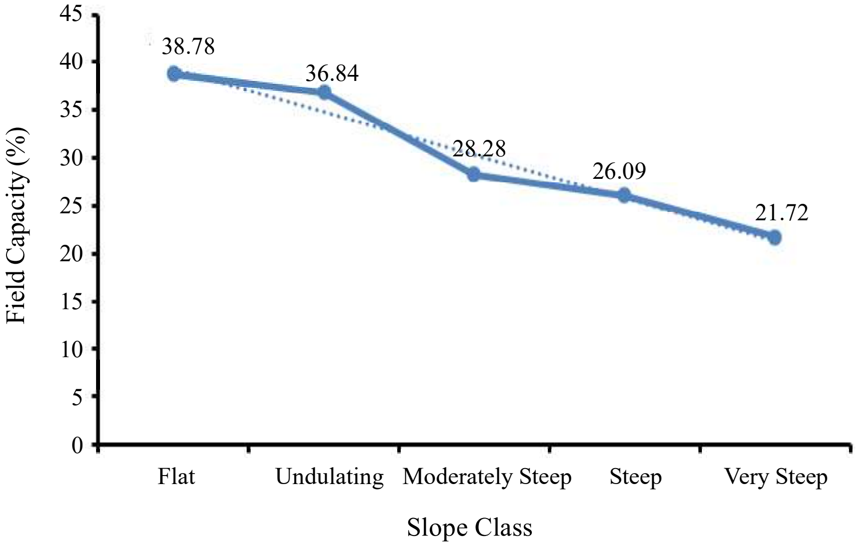


Figure 2. The curve of the relationship between slope level and soil capacity to hold water in smallholder oil palm plantations in Central Bengkulu Regency.

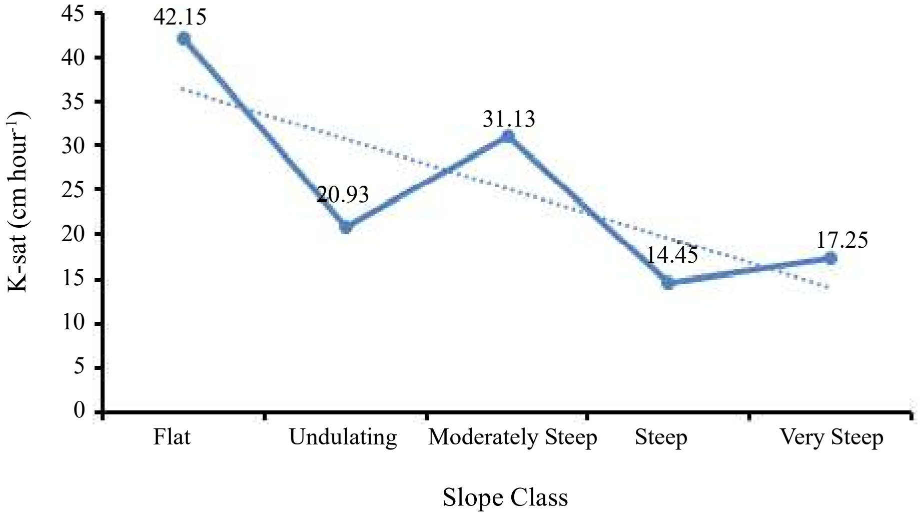


Figure 3. The curve of the relationship between slope level and soil permeability in smallholder oil palm plantations in Central Bengkulu Regency.

Soil permeability

Soil permeability, or K-sat, is the ability of soil to drain water in saturated soil conditions. It shows how easily water can seep into the soil. Soil permeability is important because it determines how quickly rainwater is absorbed by the soil, thereby influencing plant growth. The average results of soil permeability analysis across five slope classes indicate a decrease in permeability with increasing slope. On flat soils, permeability was recorded at 42.15 cm hour^{-1}, whereas on very steep slopes it decreased to 17.25 cm hour^{-1} (Figure 3). It has to do with the varying soil textures at different slope levels, which affect how well the soil absorbs and transmits water. Sand-dominated soils have larger pores than clay-dominated soils. As a result, water seeps more easily through sandy soils (Fadel et al., 2021).

Bulk density and total pore space

Bulk Density (BD) is a parameter that indicates the level of soil density or indicates how much soil mass is contained in a given volume (Table 1). The volume weight at each slope level shows an increasing trend with slope, from 1.07 g cm^{-3} on flat soils to 1.21 g cm^{-3} on very steep soils (Figure 4). It

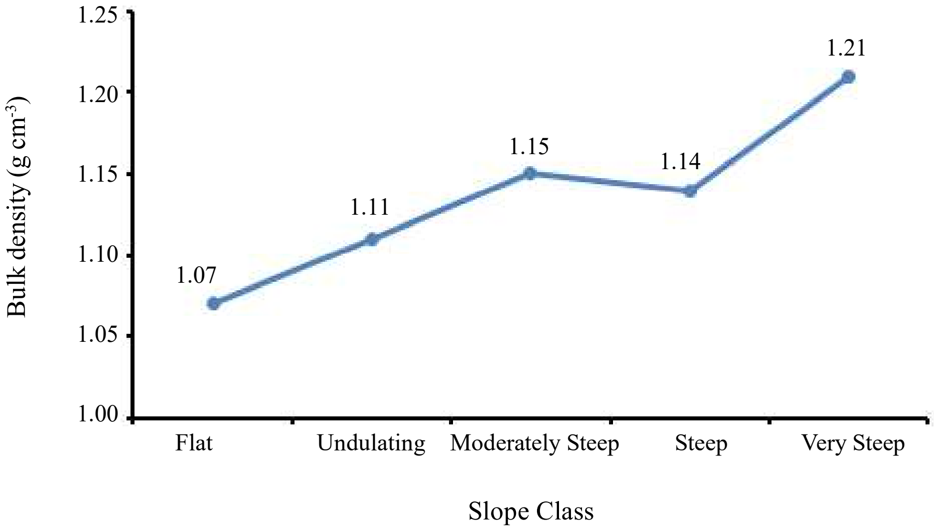


Figure 4. The curve of the relationship between slope level and soil volume weight in smallholder oil palm plantations in Central Bengkulu Regency.

Table 1. The average value of the analysis of soil water holding capacity and some soil physical characteristics on different slopes in the Bengkulu Tengah oil palm plantation, with 35 observation samples in the laboratory.

Slope class (%)	Field capacity (%)	K-sat (cm hour^{-1})	Bulk density (g cm^{-3})	Total pore space (%)	Texture (%)			Texture Class	Organic-C (%)
					Sand	Silt	Clay		
Flat to gentle undulating (0-8%)	38.78	42.15	1.07	59.37	55.6	21.2	23.1	SCL	4.93
Undulating (8-15%)	36.84	20.93	1.11	58.16	54.6	17.0	28.4	SCL	3.97
Moderately steep (15-25%)	28.28	31.13	1.15	56.84	44.2	25.3	30.5	SL	3.74
Steep (25-45%)	26.09	14.45	1.14	56.95	39.8	28.1	32.1	SL	3.44
Very steep (45-100%)	21.72	17.25	1.21	54.33	44.0	24.7	31.3	SL	2.63

Description: SCL= sandy clay loam, SL = sandy loam

indicates that soils in steeper areas tend to be denser. It is related to the condition of the topsoil layers, which generally have high organic matter on steep land and are more susceptible to erosion than on relatively flat land. According to Andrian et al. (2014) and Pathirana *et al.* (2024), the length and steepness of the slope are directly proportional to the erosion potential. It is due to the increased surface flow rate (runoff) on longer, steeper slopes, leading to more intensive soil erosion. Natural and artificial soil compaction caused by agricultural machinery is a major issue in sustainable agriculture. Another cause is that four interrelated factors influence the weight of soil volume. The organic matter content tends to lower BD by increasing porosity. The texture of the soil, including the proportions of sand, dust, and clay, affects its density. The number and distribution of soil pores directly determine the soil's pore space, thereby affecting BD. The root system of plants also plays a role in shaping the soil structure and creating channels, which can lower the BD (Megayanti et al., 2022).

Total Pore Space (TPS) is the sum of all pores, both macro and micro pores, in the soil. The magnitude of the total value of soil pore space indicates the level of soil looseness, expressed as a percentage. In the TPS measurement, the average percentage of total pore space decreased slightly with increasing slope, from 59.37% on flat soil to 54.33% on very steep soil (Figure 5). Fewer pore

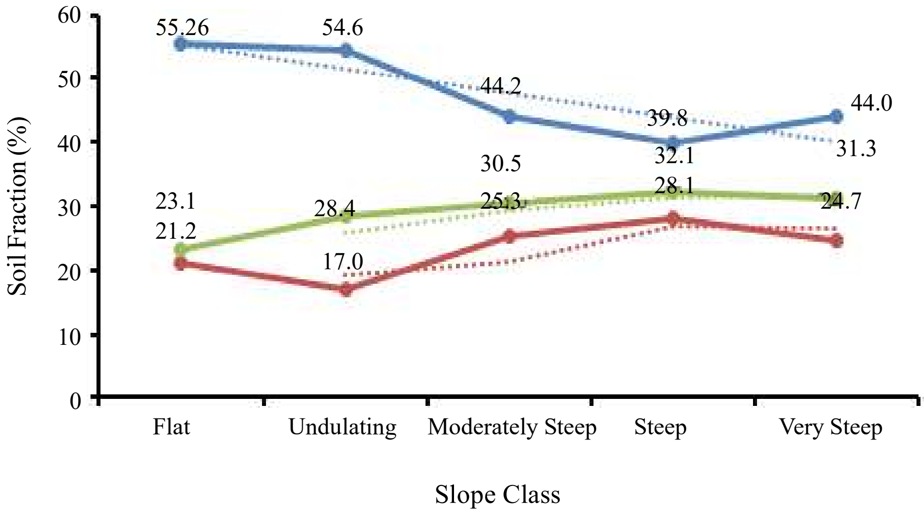
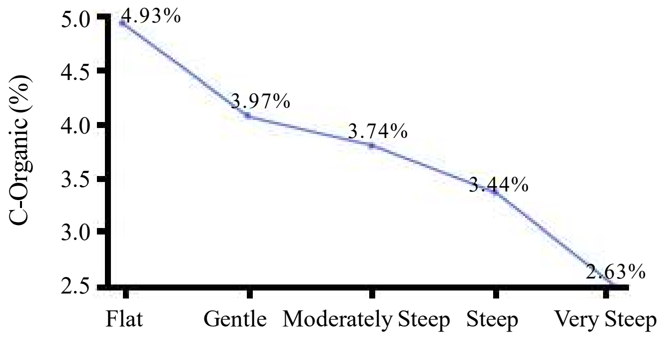


Figure 5. The curve of the relationship between slope level and soil texture in smallholder oil palm plantations in Central Bengkulu Regency. ●: sand, ●: silt, ●: clay.



Slope category

Figure 6. The curve of the relationship between slope level and organic-C soil in smallholder oil palm plantations in Central Bengkulu Regency. ▬◆▬ : C-organic (%), ┅ : Trendline.

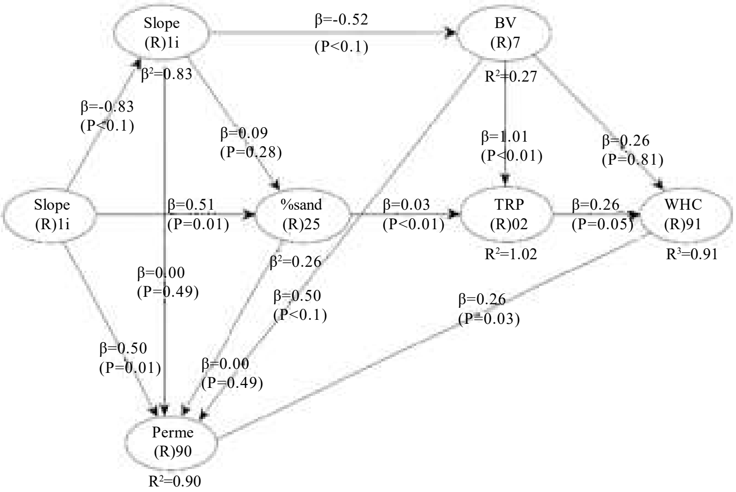


Figure 7. Results of conceptual model testing.

spaces can indicate a decrease in the soil's capacity to store air and water, which can affect root growth and the activity of soil microorganisms. The data show that the TPS value is inversely proportional to BD.

Soil texture

The results of soil texture analysis revealed variations in soil texture composition at the research site. At different levels of the slope, there are fluctuations in the values of sand, dust, and clay fractions. In the steep-slope class, there is a decrease in the sand fraction, followed by an increase in the dust and clay fractions (Figure 6). The erosion process can explain this phenomenon. Erosion on steep slopes removes the upper soil layer, which is generally richer in sand fractions. It aligns with a study by Fajeriana & Risal (2023), which found that sandy soils have many large pores, allowing water to permeate quickly. However, the structure of these sandy soils tends to be unstable because the particles are less well-bonded. As a result, this type of soil is more susceptible to erosion. At the same time, this tendency to increase the clay and dust content occurs because the erosion process has brought the upper soil layer to the surface, leaving the soil surface closer to the argillaceous horizon. The argillaceous-like horizon itself is the main feature of ultisol soils.

Organic carbon

The content of soil organic matter indicates the level of fertility and soil quality. The higher the organic matter content, the better the soil's ability to store water, provide nutrients for plants, and support the activity of beneficial microorganisms. Based on the data presented in Figure 7, a clear

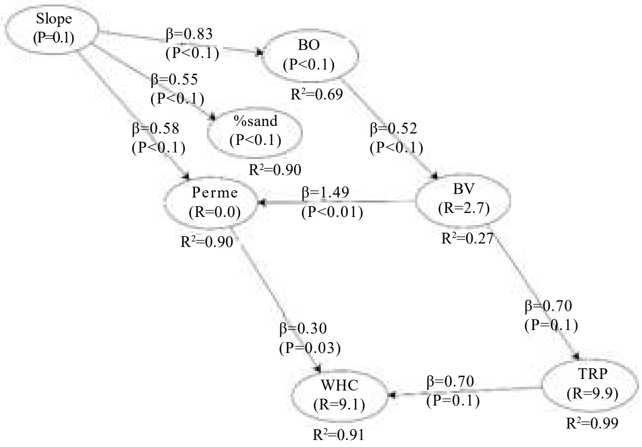


Figure 8. Final conceptual model of soil water holding capacity with slopes and some soil characteristics

downward trend in the percentage of soil organic matter is evident, along with an increase in slope from flat to very steep.

Data shows that soil on flat slopes has the highest organic matter content of 4.93%. This percentage gradually decreases across the categories of steeper slopes: 3.97% for slopes, 3.74% for slightly steep slopes, 3.44% for steep slopes, and 2.63% for very steep slopes. This decrease indicates a negative correlation between slope steepness and soil organic matter content. This phenomenon can be explained by several factors, such as more intensive erosion on steeper slopes, leading to greater loss of organic matter than on flatter slopes (Refliaty & Marpaung, 2010).

Relationship model

We can analyze the results of the modeling hypothesis test through three important values, namely Path Coefficients (β), Coefficients of Determination (R^2), and P-value (Figure 8). Path Coefficients show how strong and directional (positive or negative) the relationship between the variables being analyzed is. Coefficients of determination indicate how well an independent variable can explain the variation in the dependent variable as a whole. Meanwhile, the P-value indicates the significance of the model's relationship; values less than 0.05 indicate statistical significance.

The final model conformity evaluation was conducted using four test parameters: *Average Path Coefficient* (APC), *Average R-Squared* (ARS), *Average Adjusted R-Squared* (AARS), and *Average Block VIF* (AVIF). The model is considered appropriate if the APC, ARS, and AARS have *a P-value* < 0.005 and an AVIF value of < 5. The analysis showed that all parameters met the set criteria, with APC = 0.621 ($p<0.001$), ARS = 0.679 ($p<0.001$), AARS = 0.668 ($p<0.001$), and AVIF = 2.24. Thus, it can be concluded that the model has matched the data and can be used for further analysis.

DISCUSSION

The results of the data test in Figure 8 indicate acceptance of hypotheses 1, 2, and 3. It shows that the slope variable significantly influences several other variables, namely organic matter, texture composition, and soil permeability level. In this case, soil texture is represented by the percentage of sand. The selection of this indicator is based on soil texture analysis of the samples studied, which showed that the sand fraction predominates. The degree of this influence is indicated by the R^2 values of 0.69, 0.31, and 0.90. It means that slope affects soil organic matter by 69%, soil sand % by 31%, and soil permeability by 90%. The relationship between *slope* and organic matter has a coefficient of -0.83 ($P<0.01$), indicating that slope has a significant negative influence on organic matter, with a higher slope associated with lower organic matter. The relationship between slope and % soil sand is also significant ($P < 0.01$). Similarly, *slope* also had a significant negative relationship with soil sand % ($\beta = -0.55$, $p < 0.01$) and soil permeability ($\beta = -0.58$, $p < 0.01$), indicating that steeper slopes were associated with lower soil sand % and soil permeability. These three results illustrate how slope can significantly affect soil physical characteristics.

The results of hypothesis 4 showed that soil organic matter significantly influences soil volume weight. The R-value of 0.27 indicates that soil organic matter accounts for 27% of the variation in soil volume weight. Further analysis revealed a negative relationship between soil organic matter and bulk density (BD), with a beta coefficient (β) of -0.52 and a P value of 0.01. It indicates that the change in soil organic matter is inversely proportional to the change in soil volume weight. Soil organic matter can increase the stability of soil aggregates, leading to a more crumbly soil structure. Soils with this loose structure tend to have a lower fill weight (Adrinal et al., 2021; Widodo & Kusuma, 2018).

Meanwhile, we accepted the results of hypothesis 9, indicating that BD had a negative relationship with permeability ($\beta = -0.49$, $P < 0.01$), with an R^2 of 0.90, indicating that the volume effect accounts for 90% of the variation in permeability. It shows that soils with high permeability tend to have lower volume weights. These results illustrate that soil volume weight plays an important role in determining other soil physical characteristics. Soils with high BD values are compact, which affects their capacity to absorb and drain water and, ultimately, the soil's overall structure and function.

We also accepted hypothesis 10, which stated that tulk density (BD) had a significant effect on total soil pore space (TPS), with an R^2 of 0.99. It means that BD affects TPS by 99%. Bulk density has a very strong, negative relationship with TPS ($\beta = 1.00$, $P < 0.01$), indicating that changes in BD fully explain TPS. It aligns with the opinion (Damanik et al., 2022) that there is an inverse relationship between total pore space and soil weight.

Hypotheses 12 and 13 were also accepted, indicating that total pore space and soil permeability significantly affect soil water-holding capacity ($R^2 = 0.91$). It means that the total pore space and soil permeability account for 91% of the soil's water-holding capacity (WHC). Permeability had a positive effect on WHC ($\beta = 0.30$, $P = 0.03$), suggesting that more permeable soils tended to have higher water-holding capacity. Similarly, TPS showed a positive relationship with WHC ($\beta = 0.70$, $P < 0.01$), indicating that increases in TPS were associated with increases in soil water-holding capacity. It is in line with the research (Guo et al., 2025; Suharto, 2006) that the distribution of micropore space and the size of clay and sand particles determine the capacity of the soil to hold water, where these two physical properties of the soil greatly affect the amount of soil percolation water and the conductivity of groundwater in a saturated state (permeability).

CONCLUSIONS

The results of this study indicated a significant relationship between slope and various soil physical characteristics, as well as the soil's water-holding capacity. The steeper the slope, the greater the decrease in soil permeability, total pore space, and soil organic carbon. As well as the % soil sand content, the increased weight of soil volume, and the clay and dust content. This results in a decrease in soil water holding *capacity* on steeper slopes.

The resulting model describes the complex relationships among various soil and topographic properties, with slope playing an important role in influencing soil organic carbon, % sand, and permeability. Soil organic carbon and bulk density also make important contributions to explaining total pore space and, in turn, permeability, which affects the soil's capacity to hold water. It will also directly affect the soil's chemical and biological conditions, thereby optimizing plant growth and production above it.

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