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The Relationship Between Certain Physical Properties and The Infiltration Rate of Ultisols in Oil Palm, Rubber, and Areca Nut Plantations in Maro Sebo Village, Jambi Luar Kota Subdistrict, Muaro Jambi Regency

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Abstract

Ultisols are widely distributed in Indonesia and are commonly utilized for plantation activities, including oil palm, rubber, and areca nut cultivation. However, intensive land-use changes and management practices can affect soil physical properties, particularly infiltration processes, which are essential for regulating water availability, reducing surface runoff, and maintaining soil sustainability. This study aimed to evaluate the relationship between soil physical properties and infiltration characteristics of Ultisols under different plantation types in Maro Sebo Village, Jambi Luar Kota Subdistrict, Muaro Jambi Regency. The research employed a survey method with random sampling based on land use types and slope characteristics. Soil samples were collected from oil palm, rubber, and areca nut plantations, while infiltration measurements were conducted using a double-ring infiltrometer. The observed parameters included organic matter content, bulk density, total porosity, soil water content, infiltration rate, and infiltration capacity. Data were analyzed using the Horton infiltration model, independent-sample mean comparison tests, and multiple linear regression analysis. The results showed that rubber and areca nut plantations had better soil physical conditions than oil palm plantations, as indicated by higher organic matter content, lower bulk density, and greater total porosity. Areca nut plantations exhibited the highest infiltration rate, followed by rubber and oil palm plantations. Regression analysis revealed a strong relationship between soil physical properties and infiltration characteristics, with an average coefficient of determination (R^2) value of 0.86. This study concluded that vegetation type and soil management practices significantly influenced the infiltration capacity of Ultisols. Therefore, sustainable plantation management practices are required to maintain soil physical quality and enhance water conservation functions.

INTRODUCTION

Oil palm plantations are among the most dominant forms of land use in Indonesia and have expanded in response to increasing global demand for palm oil. Changes in land use from forests, shrublands, or rubber plantations to oil palm plantations can affect soil physical properties, particularly infiltration characteristics. Infiltration is a critical process because it determines the soil's ability to absorb water, reduce surface runoff, and maintain groundwater availability (Bronstert et al., 2023; Zewide, 2021). Most oil palm plantations are located in regions with relatively high rainfall, making effective water management essential. Pancen et al. (2024) stated that one of the impacts of oil palm land development is the increasing limitation of water availability.

Marginal land conditions characterized by imbalances in water and nutrient availability can negatively affect oil palm productivity (Seidel, 2018). Oil palm requires annual rainfall ranging from 2,000 to 2,500 mm with relatively uniform distribution and without prolonged dry periods (Arsyad et al., 2012).

Rubber (Hevea brasiliensis) is one of the important plantation commodities in Indonesia, contributing to non-oil and gas foreign exchange earnings and serving as a primary raw material source for the rubber industry (Kularathna et al., 2024). Effective rubber plantation management is essential to improve productivity and sustainability. One of the key factors influencing rubber plant growth is soil nutrient status, as soil nutrients play an important role in supporting plant growth, development, and production (Akinmutimi et al., 2023; Nabayi et al., 2018; Saengwilai et al., 2023).

Areca nut (Areca catechu L.) plays an important role in influencing soil physical properties through its canopy characteristics, root system, and litter production (Hu et al., 2023; Vrignon-Brenas et al., 2019). The relatively upright and dense canopy of areca nut reduces the impact energy of raindrops on the soil surface, thereby minimizing soil compaction and maintaining aggregate stability. The accumulation of areca nut leaf litter on the soil surface contributes to increased organic matter content, which improves soil structure, enhances porosity, and reduces bulk density (Sung et al., 2017). These conditions support the formation of a looser soil environment with improved water storage capacity. In addition, the fibrous root system of areca nut spreads within the upper soil layers and contributes to the formation of macropores that facilitate water and air movement within the soil profile (Bagus, 2011).

Rubber plant root activity can improve soil structural stability and reduce the risk of compaction caused by rainfall and human activities (Ali et al., 2025). Improved porosity and soil structure can enhance infiltration rates and soil permeability. According to Rossie and Rinto (2024), land cover influences soil physical properties associated with infiltration rate and infiltration capacity. Root systems and vegetation density can improve soil structure by increasing pore formation, thereby enhancing soil porosity. A well-developed soil structure facilitates the infiltration process. Research by Niya et al. (2023) showed that the infiltration rate in a 5-year-old oil palm plantation was 0.1 cm h^{-1}, which increased to 0.4 cm h^{-1} at 10 years of plant age. However, no further increase in infiltration rate was observed between 10 and 15 years of plant age. The relatively slow infiltration rate was associated with soil physical properties, including high clay content and low soil porosity, although oil palm plantations aged 10 and 15 years were classified as having good infiltration conditions.

Maro Sebo Village is one of the villages located in Jambi Luar Kota Subdistrict, Muaro Jambi Regency. The village was established in 1979 and covers an area of 773,857.09 ha. Maro Sebo Village is dominated by Ultisol soils, which have considerable potential for smallholder plantation development. Soil tillage during land conversion activities can alter the original soil structure. A well-developed soil structure consists of stable aggregates that support air and water circulation. However, excessive soil compaction due to intensive tillage can restrict water movement and reduce infiltration capacity.

According to Ardiansyah (2019), land conversion can reduce soil capacity to absorb rainfall due to inappropriate land management practices and soil compaction caused by heavy machinery, which negatively affects infiltration rates. Soils with poor infiltration capacity generate surface runoff even under relatively low rainfall conditions.

High surface runoff occurs when a large proportion of rainfall is unable to infiltrate into the soil, potentially causing flooding and erosion. Maro Sebo Village has diverse land-use types, partly resulting from community-based land management and conservation activities. Variations in vegetation cover among different land uses are expected to influence soil infiltration capacity. Several studies have demonstrated that different land-use systems produce different infiltration capacities. According to Billing et al. (2020), variations in land use can result in differences in soil infiltration rates.

Shrubland areas generally exhibit relatively high infiltration capacity due to diverse vegetation cover and fibrous root systems that support water absorption processes. The importance of evaluating soil infiltration capacity under different vegetation covers motivated this research, entitled "The Relationship Between Certain Physical Properties and the Infiltration Rate of Ultisols in Oil Palm, Rubber, and Areca Nut Plantations in Maro Sebo Village, Jambi Luar Kota Subdistrict, Muaro Jambi Regency."

METHOD

The research was conducted in oil palm, rubber, and areca nut plantations located in Maro Sebo Village, Jambi Luar Kota Subdistrict, Muaro Jambi Regency, for six months. Soil analyses were performed at the Soil Science Laboratory, Faculty of Agriculture, Universitas Jambi.

The study was conducted on Ultisol soils under oil palm, rubber, and areca nut plantations with slope gradients ranging from 9–15%. The equipment used included ring samples, a double-ring infiltrometer, field knives, measuring tapes, hoes, buckets, watering cans, plastic ropes, analytical balances, writing instruments, and cameras.

The research employed a survey method involving three land-use types: rubber plantations, oil palm plantations, and areca nut plantations, covering an area of approximately 700 ha. The research area consisted of community-owned land in Maro Sebo Village. Sampling points were determined using a random sampling method based on homogeneous land units classified according to land use and slope characteristics.

The selected sampling areas had slope gradients ranging from 15–30%. Infiltration measurements were conducted at the plant basin (dish) and canopy areas of rubber, oil palm, and areca nut plants. The measurements were conducted at 10 points for each plantation type. Intact and disturbed soil samples were collected from a depth of 0–20 cm. Intact soil samples were obtained using ring samples, while disturbed soil samples were collected using a soil auger. Field infiltration measurements were performed directly using a double-ring infiltrometer.

The observed parameters included soil organic matter content, bulk density, total porosity, soil water content, infiltration rate, and infiltration capacity of Ultisols under oil palm, rubber, and areca nut plantations. Data obtained from field infiltration measurements were analyzed using the Horton infiltration model and presented as infiltration curves. Soil physical property data were analyzed using independent-sample mean comparison tests to evaluate differences among land-use types. Multiple linear regression analysis was conducted to determine the relationship between infiltration characteristics and soil physical properties.

The results of the independent-sample mean comparison tests showed that organic matter content, bulk density, total porosity, and soil water content in rubber plantations were similar to those in areca nut plantations but differed from oil palm plantations. Meanwhile, infiltration rate and infiltration capacity differed among rubber, oil palm, and areca nut plantations. Multiple linear regression analysis indicated that infiltration rate was associated with soil organic matter content, bulk density, and total porosity across the three plantation types.

RESULTS AND DISCUSSION

Organic Matter Content, Soil Bulk Density, Total Pore Space, Water Content, Infiltration Rate, and Infiltration Capacity of Ultisol in Rubber, Oil Palm, and Areca Nut Plants

Based on the unpaired mean value test on organic matter content, bulk density, and soil water content in rubber, oil palm, and areca nut plants, the results can be seen in Table 1 below.

Table 1. Average organic matter content, bulk density, and total pore space of Ultisol in rubber, oil palm, and areca nut plants

Plant	Organic Matter (%)	Bulk Density (g/cm^3)	Total Pore Space (%)
Rubber	3.71 a	1.20 a	47.24 a
Oil Palm	2.82 b	1.47 b	37.97 b
Areca Nut	3.79 a	1.22 a	46.66 a

Note: Numbers followed by the same letter in the same column indicate no significant difference according to the Unpaired Mean Value Test at the 5% level.

In Table 1, based on the unpaired mean value test analysis on organic matter, bulk density, and total pore space, rubber plants were the same as areca nut plants but significantly different from oil palm plants. The difference in organic matter, bulk density, and total pore space between rubber and areca nut plants versus oil palm plants is due to the fact that rubber and areca nut plants have high organic matter content. This is because of the return of organic matter during dry seasons through leaf shedding as litter, and between plant spacings vegetation still grows and is allowed to cover the soil surface, so the organic matter content is quite high. This is consistent with the research of Erlina et al. (2017), who found that the higher organic matter in rubber plantation land use compared to oil palm land use is because rubber plants shed their leaves more often, especially during the dry season. The same applies to soil bulk density because of the soil organic matter content. According to Nursanta et al. (2024), soil with high organic matter content will improve soil physical properties and lead to a decrease in soil bulk density.

The results of the unpaired mean value test analysis showed that rubber plants and areca nut plants were the same but significantly different from oil palm plants in total pore space. The difference in total pore space between oil palm plants versus rubber and areca nut plants is because in oil palm, soil compaction increases, which causes an increase in soil bulk density. In addition, the oil palm root system is fibrous and only spreads on the soil surface around the plant base, and there is no return of litter on the soil surface, resulting in low organic matter. This is supported by the statement of Rahmayanti et al. (2019) that soil with a low total bulk density value has a high total pore space value, and conversely, soil with a high bulk density has a low total pore space value. According to Nursanta et al. (2024), the high total pore space of the soil is caused by the areca nut plantation having diverse vegetation growing on it, whose roots can break the soil and then form many cavities within the soil.

Water Content, Infiltration Rate, and Infiltration Capacity

Based on the unpaired mean value test on rubber, oil palm, and areca nut plants for water content, infiltration rate, and infiltration capacity of Ultisol, the results can be seen in Table 2 below.

Table 2. Water Content, Infiltration Rate, and Infiltration Capacity of Ultisol in Rubber, Oil Palm, and Areca Nut Plantations

Plant	Water Content (%)	Infiltration Rate (cm/hr)	Infiltration Capacity (cm/hr)
Rubber	40.77 a	40.96 a	220.48 a
Oil Palm	35.36 b	34.37 b	161.08 b
Areca Nut	39.82 a	52.11 c	178.42 c

Note: Numbers followed by the same letter in the same column indicate no significant difference according to the Unpaired Mean Value Test at the 5% level.

Based on Table 2, the soil water content in rubber plants is the same as the water content in areca nut soil and significantly different from the water content in oil palm plants. The difference in soil water content in oil palm land compared to rubber and areca nut plants is because oil palm land use has non-dense vegetation and overlapping canopies, so if rainwater falls it does not directly hit the soil; and the surface soil in oil palm plantations is quite compact because many oil palm roots are fibrous, resulting in small pores, making it difficult for water to seep into the soil, and transpiration and evaporation rates are higher, resulting in little water stored in the soil. Meanwhile, the soil water content in rubber plantation land is similar to that in areca nut plants because they have considerable amounts of litter and vegetation growing beneath them, so much organic matter falls on the soil, resulting in rainwater being stored within the soil.

From Table 2, the infiltration rate and infiltration capacity among oil palm, rubber, and areca nut plants differ significantly. This is due to differences in each plant's ability to allow water into the soil, which is related to the infiltration rate and infiltration capacity; root movement and the litter produced are sources of organic matter, thus affecting the infiltration speed at the time of rain. This condition is consistent with the research of Rifco et al. (2022), which states that there are several factors affecting infiltration, including soil type and soil physical properties such as organic matter content, water content, texture, and structure affecting the infiltration rate.

The difference in infiltration rate and infiltration capacity between oil palm and areca nut plants is due to the role of a non-dense canopy and the taproot system, which allows roots to spread in the upper soil layer, which can slow down water entering the soil during rainfall. This condition is consistent with the opinion of Aini et al. (2021), who stated that rainwater that does not directly hit the soil surface will be intercepted by vegetation such as the canopy and plants, resulting in high infiltration. In addition, the presence of tree vegetation causes roots to improve their water absorption, which also increases soil infiltration.

Relationship of Organic Matter, Bulk Density, Total Pore Space, and Water Content to Infiltration Rate and Infiltration Capacity

The results of the multiple linear regression test, where the X variables are soil organic matter (X1), bulk density (X2), total pore space (X3), and soil water content (X4) against infiltration rate and infiltration capacity as Y, can be seen in Table 3 below.

Table 3. Results of Multiple Linear Regression Test of Ultisol Physical Properties against Soil Infiltration Rate in Rubber, Oil Palm, and Areca Nut Plants

Plant	Multiple Regression Equation	R^2
Rubber	Y = -213 + 233(X1) + 23.54(X2) - 221.44(X3) - 63.11(X4) Y = 21.45 + 0.45(X1) + 1.22(X2) - 0.78(X3)	0.90 0.82
Oil Palm	Y = -213 + 233(X1) + 23.54(X2) - 221.44(X3) - 63.11(X4) Y = 11.55 - 0.65(X1) - 0.456(X2) + 13.67(X4)	0.82 0.86
Areca Nut	Y = -131 - 212(X1) - 25.1(X2) + 41.56(X3) + 671(X4) Y = -123.267 + 7.893(X1) - 45.89(X2) + 2.068(X3)	0.86 0.81

Note: X1 (organic matter content), X2 (soil bulk density), X3 (total soil pore space), X4 (soil water content), Y (soil infiltration rate), R^2 (strength of relationship), Yp (partial relationship strength.

Based on Table 3, the multiple linear regression showed a very strong relationship of organic matter content, soil bulk density, and total pore space with soil infiltration in rubber, oil palm, and areca nut plants, with an average R^2 = 0.86. The differences in the strength of the relationship between the physical factors of organic matter content, bulk density, and total pore space in these three types of plants are greatly influenced by the shape of the plant canopy, the range of root penetration through the soil mass, and the water content stored in the soil, which facilitates the soil infiltration rate. This is in line with the opinion of Autum et al. (2021), which states that high organic matter content from fallen leaves, stems, and plant litter will be easily decomposed by microorganisms and can create balanced soil pores, so the soil infiltration rate increases.

Based on Table 3, there is a predictive strength relationship in rubber plants and areca nut plants where the soil water content factor had no effect; after elimination, the predictive strength of the relationship increased. This is because water content will cause soil aggregate bonds to break more easily, thereby reducing the infiltration rate. This is consistent with the opinion that on soils easily dispersed by water, the soil pores will be covered by dust, making it difficult for water to enter the soil pores, and consequently the infiltration rate decreases (Yasinta et al., 2024).

To see the strength of the relationship between several physical properties and infiltration capacity, based on the multiple linear regression test for soil infiltration capacity with variables organic matter (X1), bulk density (X2), total pore space (X3), and soil water content (X4) for rubber, oil palm, and areca nut plants, the equations can be seen in Table 4.

Table 4. Results of Multiple Linear Regression Test of Ultisol Physical Properties against Infiltration Capacity of Ultisol in Rubber, Oil Palm, and Areca Nut Plants

Plant	Multiple Regression Equation	R^2
Rubber	Y = +324 + 0.99(X1) + 21.71(X2) - 0.99(X3) - 74.96(X4) Y = -22.23 + 0.75(X1) + 2.872(X2) + 0.86(X3)	0.86 0.90
Oil Palm	Y = -21.89 + 0.45(X1) + 23.54(X2) - 0.87(X3) - 67.45(X4) Y = 11.55 - 0.65(X1) - 0.456(X2) + 13.67(X4)	0.79 0.86
Areca Nut	Y = -34.78 - 0.68(X1) - 25.1(X2) + 34.56(X3) - 62.66(X4) Y = -17.88 + 0.78(X1) - 45.89(X2) + 2.068(X4)	0.78 0.81

Note: X1 (organic matter content), X2 (soil bulk density), X3 (total soil pore space), X4 (soil water content), Y (soil infiltration capacity), R^2 (strength of relationship), Yp (partial relationship strength)

Based on Table 4, the predictive strength relationship in rubber and areca nut plants showed that the soil water content factor had no effect; after elimination, the predictive strength of the relationship increased. This is because water content will cause soil aggregate bonds to break more easily, thereby reducing the infiltration rate. This is consistent with the opinion that on soils easily dispersed by water, the soil pores will be covered by dust, making it difficult for water to enter the soil pores, and consequently the infiltration rate decreases (Damanik et al., 2021).

Based on the pattern of these three plants, namely rubber plants, oil palm plants, and areca nut plants, the planting pattern based on canopy and root distribution can affect the rate of water infiltration into the soil (Bhat et al., 2024). This is due to the presence of organic matter that can easily bind and store water and the stable total pore space resulting from the work of the root system and balanced total pore space, thereby facilitating water entry into the soil, and as a result the soil infiltration rate becomes good and fast. This is also supported by the research of Austin et al. (2022), where oil palm produces diverse canopy cover and fibrous roots; the diverse canopy and lack of litter can protect the soil surface from direct rain impact, and fibrous roots cause the soil to become compact, so the soil becomes dense, affecting infiltration. According to Sari (2020), the effectiveness of vegetation in suppressing surface runoff and erosion is influenced by canopy height, canopy area, and vegetation density. Vegetation plays an important role in protecting the soil from direct rain impact by breaking its kinetic energy through the canopy, twigs, and stems.

CONCLUSION

Based on the research findings, this study concluded that differences in land-use types among oil palm, rubber, and areca nut plantations significantly influenced the physical properties and infiltration characteristics of Ultisol soils in Maro Sebo Village, Jambi Luar Kota Subdistrict, Muaro Jambi Regency. Rubber and areca nut plantations exhibited better soil physical conditions compared with oil palm plantations, as indicated by higher organic matter content, lower bulk density, and greater total porosity. These conditions contributed to improved soil water retention, infiltration rate, and infiltration capacity. The infiltration rate and infiltration capacity differed significantly among the three plantation types, with areca nut plantations showing the highest infiltration performance, followed by rubber and oil palm plantations. Furthermore, multiple linear regression analysis demonstrated that soil organic matter content, bulk density, and total porosity were strongly associated with soil infiltration characteristics, with an average coefficient of determination (R^2) of approximately 0.86, indicating that these soil physical properties explained a substantial proportion of the variation in infiltration performance. The findings highlighted the important roles of vegetation characteristics, root systems, canopy structure, and litter accumulation in maintaining soil structure and enhancing water infiltration processes in Ultisol soils.

Future research should expand the investigation by incorporating additional environmental factors, such as soil texture, microbial activity, land management practices, rainfall intensity, and seasonal variations, to obtain a more comprehensive understanding of infiltration dynamics. Further studies should also evaluate the long-term effects of different plantation management systems, including conservation practices such as organic matter application, cover cropping, agroforestry systems, and reduced soil disturbance, on improving soil hydraulic properties. Research conducted across broader spatial scales and different Ultisol regions is also needed to validate the applicability of these findings and support sustainable plantation management strategies, particularly for reducing surface runoff, preventing erosion, and maintaining groundwater availability in agricultural landscapes.

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