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Soil Physical Characteristics of Community-Managed Agroforestry Systems Surrounding Wera Nature Tourism Park, Central Sulawesi, Indonesia

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Abstract

Agroforestry systems play an important role in maintaining soil quality and supporting sustainable land management in buffer zones surrounding conservation areas. This study aimed to evaluate soil physical properties under simple and complex agroforestry systems on community-managed agroforestry lands surrounding Wera Nature Tourism Park, Central Sulawesi, Indonesia. A field survey was conducted using purposive sampling. Two observation plots were established for each agroforestry system, resulting in four plots in total. Disturbed and undisturbed soil samples were collected at a depth of 0–20 cm and analyzed for soil texture, bulk density, total porosity, saturated hydraulic conductivity (Ksat), and soil color using standard laboratory procedures. The results showed clear differences in soil physical properties between the two agroforestry systems. The complex agroforestry system exhibited a sandy clay loam texture, higher bulk density (1.27 g cm⁻³), lower total porosity (39.49%), higher saturated hydraulic conductivity (9.85 cm h⁻¹), and darker soil color (7.5 YR 2.5/3, very dark brown). In contrast, the simple agroforestry system showed a sandy loam texture, lower bulk density (1.18 g cm⁻³), higher total porosity (47.69%), lower saturated hydraulic conductivity (2.66 cm h⁻¹), and lighter soil color (10 YR 7/4, dark yellowish brown). These findings indicate that differences in agroforestry system complexity significantly influence soil physical conditions. The study highlights the importance of agroforestry management practices that enhance organic matter input and maintain soil structural integrity to support sustainable land use in conservation buffer zones.

Keywords: Agroforestry system; Soil physical properties; Bulk density; Porosity; Saturated hydraulic conductivity; Wera Nature Tourism Park

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1. Introduction

Community-managed agroforestry lands surrounding Wera Nature Tourism Park (WNTP), Central Sulawesi, Indonesia, play an important role as buffer zones for conservation areas. These lands are managed by local communities to meet economic needs, primarily through agricultural and plantation activities (Rerkasem, Yimyam, & Rerkasem, 2009). Agroforestry is the dominant land-use system applied in this area, as it is considered capable of balancing production objectives with environmental protection in landscapes adjacent to conservation areas (Zulkaidhah, Hapid, Ariyanti, & Fadilah, 2025). The adoption of agroforestry systems by local communities is closely associated with the ecological and economic benefits they provide (Zulkaidhah et al., 2021). Agroforestry is widely recognized as a sustainable land-use system due to its ability to reduce land degradation, minimize soil erosion and landslide risks, and enhance soil fertility. In addition, agroforestry promotes product diversification and contributes to improving local livelihoods (Awazi, Njamnjubo, & Ambebe, 2025; Zulkaidhah et al., 2021). The presence of trees within agroforestry systems improves soil structure, increases organic matter inputs, and creates favorable microclimatic conditions that support land productivity (Ollinaho & Kröger, 2021).

In practice, agroforestry systems exhibit varying levels of complexity (Awazi et al., 2025; Ollinaho & Kröger, 2021). Based on their structural complexity, agroforestry systems can be classified into simple agroforestry and complex agroforestry (Latue et al., 2018). Simple agroforestry typically involves a limited integration of agricultural crops and trees, such as trees planted along field boundaries or between crop rows (Awazi et al., 2025; Lestari & Dewi, 2023). In contrast, complex agroforestry integrates multiple plant species, trees, and occasionally livestock within a multilayered structure that resembles natural forest ecosystems, resulting in higher vegetation diversity (Asase & Tetteh, 2010). Differences in system complexity are likely to generate variations in environmental conditions, including soil properties. Soil is a key component that determines the success of land-use systems, including agroforestry (Fahad et al., 2022; S. Li, Gong, Hou, Li, & Wang, 2022). It functions as a growth medium that provides rooting space, water, and nutrients required for plant development (Dreschel & Sager, 1989). Therefore, soil characteristics strongly influence plant growth, productivity, and the long-term sustainability of land management practices in areas surrounding conservation zones (Y. Li, Shi, Wu, Li, & Li, 2013).

Soil quality and fertility are governed by the interaction of physical, chemical, and biological properties (Delgado & Gómez, 2024). Soil physical properties such as texture, structure, porosity, and bulk density play a crucial role in regulating water and air movement within the soil and in supporting root system development (Dexter, 2004). Variations in soil physical properties directly affect the soil's capacity to supply water and nutrients to plants (Delgado & Gómez, 2024). Soil fertility is defined as the ability of soil to provide essential nutrients in adequate quantities and in forms available for plant uptake (Octavia et al., 2023). Nutrient availability is strongly influenced by the interaction between soil physical, chemical, and biological properties; thus, soil physical conditions play a fundamental role in controlling nutrient dynamics and uptake processes (Dexter, 2004). Furthermore, soil physical conditions are critical determinants of plant growth and yield, as they influence root penetration, water-holding capacity, drainage, aeration, and nutrient distribution (Octavia et al., 2023). Poor soil physical conditions can restrict air and water circulation within the soil profile, thereby limiting optimal plant growth (Dexter, 2004; Jose, Malla, Renuka, Bux, & Kumari, 2024). Consequently, differences between simple and complex agroforestry systems are expected to result in distinct soil physical conditions (S. Li et al., 2022).

Based on these considerations, it is essential to investigate soil physical properties under different agroforestry systems managed by local communities around Wera Nature Tourism Park. The findings of this study are expected to provide insights into how variations in agroforestry system complexity influence soil physical conditions and to serve as a scientific basis for sustainable land management in conservation buffer zones. This study aims to assess the soil physical properties under simple and complex agroforestry systems on community-managed agroforestry lands surrounding Wera Nature Tourism Park, Central Sulawesi, Indonesia.

2. MATERIALS AND METHODS

2.1 Research sites

This study was conducted on community-managed agroforestry lands surrounding Wera Nature Tourism Park (WNTP), West Dolo District, Sigi Regency, Central Sulawesi, Indonesia. The study area comprised two land-use types, namely simple agroforestry and complex agroforestry systems. Laboratory analyses of soil physical properties were carried out at the Soil Science Laboratory, Faculty of Agriculture, Tadulako University, Central Sulawesi, Indonesia.

2.2 Research Design and Plot Establishment

The study employed a field survey method. Study sites were selected using purposive sampling, whereby locations were deliberately chosen based on land characteristics relevant to the objectives of the study. For each agroforestry type (simple and complex), two observation plots were established, resulting in a total of four plots. Each plot measured 20 m × 20 m, which was considered representative for assessing soil physical conditions under each agroforestry system.

2.3 Sampling

Disturbed Soil Samples

Disturbed soil samples were collected for the analysis of soil texture and soil color. In each plot, samples were taken from five sampling points arranged diagonally. Approximately 1 kg of soil was collected from each point. The five subsamples were then thoroughly mixed to form a composite sample, from which approximately 1 kg was taken as the final sample for laboratory analysis. All samples were labeled according to sampling location and agroforestry type.

Undisturbed Soil Samples

Undisturbed soil samples were used for the analysis of bulk density, total porosity, and saturated hydraulic conductivity. Sampling was conducted using a core ring sampler at a single point located at the center of each plot. The ring sampler was vertically inserted into the soil to a depth of 0–20 cm, carefully removed, and trimmed to ensure a flat surface. The ring was then sealed and labeled. One undisturbed sample was collected from each plot, resulting in a total of four undisturbed soil samples for laboratory analysis.

2.4 Laboratory Analysis

All collected soil samples were analyzed to determine soil physical

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properties, including:

1. Bulk density
2. Saturated hydraulic conductivity
3. Soil color
4. Total porosity
5. Soil texture

Laboratory analyses were conducted following standard soil analysis procedures applied at the Soil Science Laboratory.

2.5 Data Analysis

Data obtained from laboratory analyses were evaluated using a descriptive quantitative approach. Soil physical property values were compared between simple and complex agroforestry systems to assess differences in soil physical conditions between the two land-use types. The results were presented in the form of tables accompanied by descriptive explanations.

3. RESULTS AND DISCUSSION

3.1 Results

Table 1. Soil Physical Properties under Simple and Complex Agroforestry Systems around Wera Nature Tourism Park, Central Sulawesi, Indonesia

Soil Physical Parameter	Unit	Complex Agroforestry	Interpretation	Simple Agroforestry	Interpretation
Bulk Density	g cm^{-3}	1.27	High (Dense)	1.18	Moderate
Saturated Hydraulic Conductivity (Ksat)	cm h^{-1}	9.85	Moderately rapid	2.66	Moderate
Soil Color (Munsell notation)	–	7.5 YR 2.5/3	Very dark brown	10 YR 7/4	Dark yellowish brown
Total Porosity	%	39.49	Poor	47.69	Poor
Soil Texture (USDA)	–	Sandy clay loam	–	Sandy loam	–

3.2 Discussion

3.2.1 Bulk Density

Bulk density is a key indicator of soil physical condition because it is closely related to soil compaction, porosity, and the ability of soil to support root growth and water movement. The results of laboratory analysis showed that bulk density values differed between the two agroforestry systems. Bulk density in the complex agroforestry system reached 1.27 g cm^{-3}, which falls into the high (dense) category, whereas the simple agroforestry system had a bulk density of 1.18 g cm^{-3}, classified as moderate. This difference indicates variations in soil physical conditions influenced by different agroforestry management systems around Wera Nature Tourism Park. The higher bulk density observed in the complex agroforestry system suggests that the soil in this system is more compacted compared to the simple agroforestry system. High soil compaction is generally associated with a reduction in macropore space, which limits air exchange and water movement within the soil. Such conditions can restrict root penetration and reduce the efficiency of water and nutrient uptake, potentially leading to lower land productivity.

The difference in bulk density between the two agroforestry systems is likely influenced by vegetation structure and land management practices. Complex agroforestry systems are typically characterized by denser and multilayered vegetation. Over time, the accumulation of biomass and repeated human activities related to crop maintenance and harvesting may exert mechanical pressure on the soil surface, increasing soil compaction, particularly in the topsoil layer. In contrast, the lower bulk density value observed in the simple agroforestry system indicates a relatively looser soil condition. According to Rauf et al. (2015), lower bulk density values reflect better soil structure and higher soil friability, which are more favorable for plant growth. Moderately compacted soils allow roots to develop more freely, improve root system expansion, and enhance the capacity of plants to absorb water and nutrients.

Increasing soil compaction, as reflected by higher bulk density values, has a direct impact on root penetration. (Unger & Kaspar, 1994) reported that increasing soil compaction reduces root penetration depth and plant height growth. This occurs because roots experience greater mechanical resistance when penetrating compacted soils, resulting in restricted root development and suboptimal plant growth. Disruption of root system development due to high bulk density also affects plant physiological processes (Houlbrooke, Thom, Chapman, & McLay, 1997). Poorly developed root systems limit the uptake of water and nutrients from the soil, thereby impairing metabolic processes within plant tissues. As a consequence, essential processes such as photosynthesis and vegetative growth may be inhibited, ultimately reducing overall crop productivity.

Bulk density is also closely related to the soil's ability to transmit water (Archer & Smith, 1972). (Yu et al., 2024) stated that soil water transmission capacity is strongly influenced by soil compaction, with soils exhibiting high bulk density generally having lower permeability. Such conditions may lead to surface waterlogging during the rainy season and reduced soil water availability during the dry season, both of which are unfavorable for plant growth. In the context of agroforestry lands surrounding conservation areas such as Wera Nature Tourism Park, high bulk density values in complex agroforestry systems deserve special attention. Although complex agroforestry systems offer ecological benefits through higher vegetation diversity, inappropriate management practices may lead to degradation of soil physical properties, particularly increased soil compaction in the upper soil layers (Zulkaidhah et al., 2025).

The results of this study indicate that the simple agroforestry system exhibits relatively better bulk density conditions than the complex agroforestry system (Zulkaidhah et al., 2021). This suggests that simple agroforestry may provide a more favorable soil environment for root growth and water movement. Nevertheless, sustainable management practices are still required to prevent further soil compaction caused by intensive land-use

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activities. Overall, differences in bulk density between simple and complex agroforestry systems reflect the influence of land-use systems on soil physical properties. These findings emphasize the importance of soil conservation-oriented management in agroforestry lands around Wera Nature Tourism Park, particularly in maintaining soil bulk density within an optimal range to support plant growth and sustain ecological functions.

3.2.2 Saturated Hydraulic Conductivity (KSAT)

Saturated hydraulic conductivity (Ksat) is an important soil physical parameter that describes the ability of soil to transmit water under saturated conditions. This parameter plays a crucial role in regulating soil water dynamics, plant water availability, and the potential occurrence of surface runoff and erosion. The laboratory analysis results showed that saturated hydraulic conductivity differed between the complex and simple agroforestry systems around Wera Nature Tourism Park. The saturated hydraulic conductivity value in the complex agroforestry system was 9.85 cm h^{-1}, which is classified as moderately rapid, whereas the simple agroforestry system exhibited a value of 2.66 cm h^{-1}, falling within the moderate to slow category. This difference indicates variation in soil water transmission capacity, which is strongly influenced by differences in land-use systems and soil physical characteristics under each agroforestry type.

The higher saturated hydraulic conductivity observed in the complex agroforestry system is closely associated with denser and more continuous vegetation cover. Dense vegetation protects the soil surface from the direct impact of raindrops, thereby maintaining soil structure stability. This condition favors the formation and preservation of macropores, which serve as the primary pathways for rapid water movement within the soil profile. In addition to vegetation cover, well-developed root systems in complex agroforestry systems contribute significantly to increased saturated hydraulic conductivity. Plant roots create biopores that enhance pore continuity and enlarge macropore space. These root-induced channels facilitate faster downward water movement, resulting in higher Ksat values compared to systems with less developed root networks.

In contrast, the lower saturated hydraulic conductivity value recorded in the simple agroforestry system indicates a relatively limited capacity of the soil to transmit water. This condition may be attributed to less developed soil structure and reduced macroporosity. Under such circumstances, water tends to remain longer at the soil surface or within the upper soil layers, increasing the risk of surface runoff, particularly during periods of high rainfall. Saturated hydraulic conductivity is strongly influenced by other soil physical properties, particularly bulk density, particle density, and soil texture. Pachepsky & Park (2015)reported that soils with high bulk density and fine textured particles, such as clay, generally exhibit lower saturated hydraulic conductivity. Conversely, soils with lower bulk density and coarser textures, such as sandy soils, tend to have higher saturated hydraulic conductivity values.

The relationship between saturated hydraulic conductivity and bulk density is evident in this study (Pachepsky & Park, 2015; Yu et al., 2024). Although the complex agroforestry system exhibited a higher bulk density than the simple agroforestry system, the presence of extensive root activity and higher organic matter input likely improved effective soil porosity. This finding suggests that saturated hydraulic conductivity is not determined solely by soil compaction, but also by pore size distribution and pore connectivity within the soil matrix. According to (Asdak, 2002), soil surface cover by vegetation plays a critical role in enhancing soil water transmission capacity. Vegetation cover stimulates soil microbial activity, which promotes the formation of stable soil aggregates. Stable aggregates improve soil structure and porosity, thereby increasing saturated hydraulic conductivity and overall soil permeability.

In the context of agroforestry lands surrounding conservation areas such as Wera Nature Tourism Park, relatively high saturated hydraulic conductivity values in complex agroforestry systems provide important ecological benefits. Improved water infiltration reduces surface runoff, minimizes erosion risk, and enhances groundwater recharge. These processes are essential for maintaining hydrological balance in buffer zones adjacent to conservation areas. Overall, differences in saturated hydraulic conductivity between complex and simple agroforestry systems reflect the influence of land-use systems on soil physical properties. The complex agroforestry system demonstrated a greater capacity for water transmission than the simple agroforestry system, primarily due to dense vegetation cover and well-developed root systems. These findings emphasize the importance of conservation-oriented agroforestry management practices to maintain soil and water sustainability around Wera Nature Tourism Park.

3.2.3 Soil Color (Munsell notation)

Soil color is an important soil physical property that can be used as an indicator to understand several key soil characteristics, including soil development stage, soil age, and weathering processes. According to Eviani and Priyono (2024), soil color reflects the combined effects of parent material, climate, organisms, topography, and time, making it a valuable parameter for preliminary soil assessment. The laboratory analysis results presented in Table 5 show clear differences in soil color between the complex and simple agroforestry systems around Wera Nature Tourism Park. Soil color in the complex agroforestry system was classified as 7.5 YR 2.5/3 (Very Dark Brown), whereas soil color in the simple agroforestry system was 10 YR 7/4 (Dark Yellowish Brown). These results indicate that soils under the complex agroforestry system exhibit a darker color compared to those under the simple agroforestry system.

The darker soil color observed in the complex agroforestry system suggests a more developed soil condition. Dark-colored soils are commonly associated with higher organic matter accumulation in the surface layer. Complex agroforestry systems are characterized by higher vegetation diversity and denser canopy cover, which promote greater and more continuous organic matter inputs to the soil. Vegetation diversity and stand density in complex agroforestry systems play a crucial role in increasing soil organic matter content. Continuous litterfall from leaves, branches, and root turnover contributes organic residues that undergo decomposition and become incorporated into the mineral soil matrix. This process leads to the formation of organic-rich topsoil horizons with darker coloration.

In contrast, the lighter soil color observed in the simple agroforestry system indicates relatively lower soil organic matter content. Simple agroforestry systems generally consist of fewer plant species and lower canopy density, resulting in reduced litter input and organic residue accumulation. Consequently, soil color tends to be lighter and more yellowish-brown. In general, variations in soil color are strongly influenced by differences in

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soil organic matter content. Higher organic matter concentrations result in darker soil colors, as organic compounds absorb light and mask the inherent color of mineral particles. Therefore, soil color is often used as a visual indicator of soil fertility and organic matter status.

Lapadjati (2016) reported that darker-colored soils are generally more productive than lighter-colored soils. Dark soils tend to contain higher levels of organic matter, which serve as a source of essential nutrients and enhance the soil's capacity to retain water. These properties contribute to improved soil structure and support optimal plant growth. In addition to fertility-related aspects, soil color also affects soil thermal properties. Dark-colored soils absorb more solar radiation than light-colored soils, leading to higher soil temperatures. Increased soil temperature can stimulate microbial activity and accelerate the decomposition of organic matter, thereby influencing nutrient cycling processes.

However, greater absorption of solar energy by dark-colored soils may also increase evaporation rates from the soil surface. As a result, despite their generally higher fertility, dark-colored soils require appropriate water management to minimize moisture loss, particularly during dry periods. Overall, differences in soil color between complex and simple agroforestry systems reflect variations in ecological conditions and land management practices. The darker soil color observed under complex agroforestry indicates higher organic matter content and greater soil fertility potential. These findings highlight the important role of complex agroforestry systems in improving soil quality and supporting sustainable land management around Wera Nature Tourism Park.

3.2.4 Total Porosity

Soil porosity is a fundamental soil physical property that represents the percentage of soil volume not occupied by solid particles, including mineral particles and organic matter. Total porosity consists of pore spaces between sand, silt, and clay particles, as well as pores formed between soil aggregates (Tolaka et al., 2013). These pore spaces play a crucial role in regulating the movement of water and air within the soil and in determining water availability and oxygen supply for plant roots. The laboratory analysis results indicate that total soil porosity in the complex agroforestry system was 39.49%, which falls into the poor category, whereas the simple agroforestry system exhibited a higher porosity value of 47.69%. Although the latter is still classified as poor, it shows a relatively better soil physical condition compared to the complex agroforestry system. This variation reflects differences in soil physical characteristics associated with distinct agroforestry land-use systems around Wera Nature Tourism Park.

The lower total porosity observed in the complex agroforestry system suggests that the volume of pore spaces within the soil is relatively limited. Such conditions can restrict the movement of water and air, potentially inhibiting root growth and reducing microbial activity. Soils with low porosity often exhibit poor aeration and limited infiltration capacity, which can negatively affect plant growth and soil biological processes. In contrast, the higher total porosity recorded in the simple agroforestry system indicates the presence of a greater proportion of pore spaces. Despite still being categorized as poor, this condition is relatively more favorable for soil aeration and water movement than that observed in the complex agroforestry system. Improved porosity facilitates better root penetration and supports physiological processes essential for plant development, particularly in surface soil layers.

The difference in total porosity between the two agroforestry systems shows an inverse relationship with bulk density values. The complex agroforestry system exhibited higher bulk density, while the simple agroforestry system showed lower bulk density. This relationship is consistent with the findings of Naharuddin et al. (2020), who reported that higher soil bulk density is generally associated with lower total porosity, whereas lower bulk density indicates a greater volume of pore spaces. Total porosity is influenced not only by the amount of pore space but also by the distribution of pore sizes within the soil. Pore spaces are commonly classified into macropores and micropores, each serving different functions. Macropores facilitate gravitational water movement and soil aeration, while micropores retain water that is available for plant uptake. Therefore, pore size distribution is a key factor in determining soil hydraulic and aeration properties.

Arifin (2011) stated that soils dominated by macropores typically have low water-holding capacity because water drains rapidly through the soil profile. Conversely, soils with an adequate proportion of micropores are more capable of retaining water for plant use. In the context of this study, the low total porosity observed in the complex agroforestry system may indicate a reduction in effective pore spaces, including both macro- and micropores, due to increased soil compaction. Low total porosity in the complex agroforestry system may also be associated with mechanical pressure resulting from dense vegetation and land management activities. Accumulated biomass and repeated human activities over time can contribute to soil compaction, thereby reducing pore space volume. This suggests that although complex agroforestry systems offer ecological benefits, inappropriate management practices may adversely affect soil physical quality.

In agroforestry lands surrounding conservation areas such as Wera Nature Tourism Park, low soil porosity requires careful attention. Reduced porosity can increase surface runoff and erosion risk, particularly during periods of high rainfall. Such conditions may compromise the function of agroforestry lands as buffer zones that protect conservation areas from environmental degradation. Overall, the results of this study demonstrate that the simple agroforestry system exhibits relatively better total porosity compared to the complex agroforestry system, although both systems remain within poor porosity categories. These findings highlight the strong influence of agroforestry management practices on soil porosity. Therefore, soil management strategies aimed at improving soil structure—such as increasing organic matter inputs and minimizing soil compaction—are essential to enhance soil physical quality and sustain ecological functions around Wera Nature Tourism Park.

3.2.5 Soil Texture (USDA)

Soil texture is one of the most important soil physical properties because it reflects the relative proportions of sand, silt, and clay fractions in the soil. Soil texture is used to describe particle size distribution, which subsequently determines various physical and hydrological characteristics of the soil, such as water-holding capacity, aeration, porosity, and the soil's ability to support plant growth. Therefore, soil texture is considered a fundamental parameter in soil quality and land suitability assessments. Based on the laboratory analysis presented in Table 5, soil texture in the complex agroforestry system was classified as sandy clay loam, whereas soil texture in the simple agroforestry system was

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classified as sandy loam according to the USDA soil texture classification system. These differences indicate variations in particle-size composition influenced by land-use systems and local environmental conditions around Wera Nature Tourism Park.

The sandy clay loam texture observed in the complex agroforestry system indicates a dominance of sand fraction accompanied by a relatively higher clay content compared to silt. This texture suggests a balance between good drainage properties provided by sand particles and enhanced water and nutrient retention contributed by clay particles. When properly managed, this combination can create favorable conditions for plant growth. In contrast, the sandy loam texture identified in the simple agroforestry system reflects a more balanced proportion of sand, silt, and clay fractions, although sand remains the dominant fraction. This texture generally provides good drainage and aeration; however, its capacity to retain water and nutrients is lower than that of soils with higher clay content. As a result, sandy loam soils are more susceptible to rapid water loss, particularly during dry periods.

Differences in particle-size composition between the two agroforestry systems directly influence other soil physical properties. Soils with higher sand content, such as those found in the complex agroforestry system, tend to contain a greater proportion of macropores, allowing water to move more rapidly through the soil profile. This condition is consistent with the higher saturated hydraulic conductivity observed in the complex agroforestry system. Hanafiah (2005) stated that increasing sand fraction in soil texture facilitates faster water movement through the soil. However, soils dominated by sand fractions generally exhibit lower water-holding capacity because water drains quickly through large pores. Therefore, sandy-textured soils require appropriate management strategies to maintain sufficient water availability for plants.

The presence of clay particles plays a critical role in enhancing soil water retention and nutrient-holding capacity. Clay particles have large specific surface areas and carry negative charges, enabling them to adsorb water and essential nutrients effectively. In the complex agroforestry system, the relatively higher clay content compared to the simple agroforestry system may contribute to improved water retention and soil fertility. Nevertheless, soil water movement and storage are not determined solely by soil texture. Other factors, including soil porosity, organic matter content, soil structure, and pore continuity, also significantly influence soil hydraulic behavior. Soils with similar textures may exhibit different physical properties depending on differences in aggregation and organic matter levels.

In agroforestry systems, well-developed root networks and continuous organic matter inputs can improve soil structure by promoting aggregate stability and pore connectivity. In the complex agroforestry system, higher vegetation diversity and more intensive root activity likely enhance soil aggregation, thereby improving the functional effectiveness of soil pores despite the relatively high sand content. Overall, the results of this study demonstrate that differences in soil texture between complex and simple agroforestry systems reflect the influence of land-use practices on soil physical properties. The sandy clay loam texture in the complex agroforestry system provides a balance between drainage and water retention, while the sandy loam texture in the simple agroforestry system is more porous but has a lower capacity to retain water. These findings highlight the importance of agroforestry management practices that consider soil texture characteristics to support sustainable land use around Wera Nature Tourism Park.

The integration of soil physical parameters namely soil texture, bulk density, total porosity, saturated hydraulic conductivity (Ksat), and soil color provides a comprehensive understanding of soil physical quality under different agroforestry systems around Wera Nature Tourism Park. These parameters are interrelated and collectively determine soil structure, water movement, aeration, and the overall capacity of soil to support plant growth and ecological functions. Soil texture forms the fundamental framework influencing other soil physical properties. In this study, the complex agroforestry system exhibited a sandy clay loam texture, while the simple agroforestry system was characterized by a sandy loam texture. The higher clay fraction in the complex agroforestry system contributes to greater water and nutrient retention potential, whereas the dominance of sand fraction promotes higher permeability. Conversely, the sandy loam texture in the simple agroforestry system favors drainage and aeration but limits water-holding capacity, making soil moisture more susceptible to rapid loss.

Bulk density reflects the degree of soil compaction and is closely linked to soil texture and land management practices. The higher bulk density observed in the complex agroforestry system indicates greater soil compaction, which is often associated with reduced pore space. Despite having a more developed vegetation structure, the accumulation of biomass and prolonged land-use pressure may have contributed to increased compaction in surface soil layers. In contrast, the lower bulk density in the simple agroforestry system suggests relatively looser soil conditions that are more conducive to root penetration. The inverse relationship between bulk density and total porosity was clearly evident in this study. The complex agroforestry system, which exhibited higher bulk density, showed lower total porosity, whereas the simple agroforestry system had higher porosity values. Reduced porosity limits soil aeration and water storage capacity, while higher porosity enhances gas exchange and root growth. However, porosity alone does not fully describe soil hydraulic behavior, as pore size distribution and continuity are equally important.

This interaction is further illustrated by the results of saturated hydraulic conductivity. The complex agroforestry system exhibited higher Ksat values despite having higher bulk density and lower total porosity. This apparent contradiction highlights the importance of macropore continuity, largely formed by root channels and biological activity, which facilitates rapid water movement through the soil profile. In contrast, the lower Ksat values in the simple agroforestry system indicate more restricted water transmission, likely due to less developed macropore networks. Soil color provides additional insight into soil development and organic matter status, which influence and are influenced by other physical properties. The darker soil color (7.5 YR 2.5/3, Very Dark Brown) observed in the complex agroforestry system indicates higher organic matter accumulation, resulting from dense vegetation cover and continuous litter input. Organic matter plays a critical role in improving soil aggregation, stabilizing soil structure, and enhancing pore connectivity, thereby indirectly affecting bulk density, porosity, and hydraulic conductivity.

In contrast, the lighter soil color (10 YR 7/4, Dark Yellowish Brown) in the simple agroforestry system reflects relatively lower

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organic matter content. Lower organic inputs reduce aggregate stability and biological pore formation, which may explain the lower saturated hydraulic conductivity despite higher total porosity. This demonstrates that effective soil water movement depends not only on the quantity of pore space but also on pore structure and connectivity. Overall, the integrated analysis of soil physical parameters reveals that the complex agroforestry system exhibits mixed soil physical conditions: higher bulk density and lower total porosity are offset by improved macropore development and organic matter accumulation, resulting in higher saturated hydraulic conductivity and darker soil color. Meanwhile, the simple agroforestry system shows lower bulk density and higher porosity but limited pore connectivity, leading to lower Ksat values and lighter soil color. These findings emphasize that soil physical quality is governed by the interaction of multiple parameters rather than individual properties alone. From a land management perspective, this synthesis underscores the importance of conservation-oriented agroforestry practices that enhance organic matter input while minimizing soil compaction. Maintaining balanced soil texture utilization, improving organic matter management, and preserving biological pore networks are essential strategies for sustaining soil physical quality and hydrological functions in agroforestry systems surrounding Wera Nature Tourism Park.

4. CONCLUSION

The soil physical properties differed between agroforestry systems around Wera Nature Tourism Park. The complex agroforestry system had a sandy clay loam texture, higher bulk density (1.27 g cm^{-3}), lower total porosity (39.49%), higher saturated hydraulic conductivity (9.85 cm h^{-1}), and darker soil color (7.5 YR 2.5/3, very dark brown). The simple agroforestry system showed a sandy loam texture, lower bulk density (1.18 g cm^{-3}), higher total porosity (47.69%), lower saturated hydraulic conductivity (2.66 cm h^{-1}), and lighter soil color (10 YR 7/4, dark yellowish brown). These results indicate clear differences in soil physical conditions between complex and simple agroforestry systems on agroforestry lands surrounding Wera Nature Tourism Park, Central Sulawesi, Indonesia.

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REFERENCES

1. Archer, J. R., & Smith, P. D. (1972). The Relation Between Bulk Density, Available Water Capacity, and Air Capacity Of Soils. Journal of Soil Science, 23(4). https://doi.org/10.1111/j.1365-2389.1972.tb01678.x
2. Asase, A., & Tetteh, D. A. (2010). The role of complex agroforestry systems in the conservation of forest tree diversity and structure in southeastern Ghana. Agroforestry Systems, 79(3). https://doi.org/10.1007/s10457-010-9311-1
3. Asdak, C. (2002). Hidrologi dan daerah aliran sungai. Gadjah Mada University Press, Yogyakarta.
4. Awazi, N. P., Njamnjubo, N. A., & Ambebe, T. F. (2025). Agroforestry for Ecosystem Services: Assessing the Role of Agroforestry for Water Regulation. Forestist, Vol. 75. https://doi.org/10.5152/forestist.2024.24032
5. Delgado, A., & Gómez, J. A. (2024). The soil: Physical, chemical, and biological properties. In Principles of agronomy for sustainable agriculture (pp. 15–30). Springer.
6. Dexter, A. R. (2004). Soil physical quality: Part I. Theory, effects of soil texture, density, and organic matter, and effects on root growth. Geoderma, 120(3–4), 201–214.
7. Dreschel, T. W., & Sager, J. C. (1989). Control of water and nutrients using a porous tube: A method for growing plants in space. HortScience, 24(6), 944–947.
8. Fahad, S., Chavan, S. B., Chichaghare, A. R., Uthappa, A. R., Kumar, M., Kakade, V., … Poczai, P. (2022). Agroforestry Systems for Soil Health Improvement and Maintenance. Sustainability (Switzerland), Vol. 14. https://doi.org/10.3390/su142214877
9. Houlbrooke, D. J., Thom, E. R., Chapman, R., & McLay, C. D. A. (1997). A study of the effects of soil bulk density on root and shoot growth of different ryegrass lines. New Zealand Journal of Agricultural Research, 40(4). https://doi.org/10.1080/00288233.1997.9513265
10. Jose, S., Malla, M. A., Renuka, N., Bux, F., & Kumari, S. (2024). Cyanobacteria-green microalgae consortia enhance soil fertility and plant growth by shaping the native soil microbiome of Capsicum annuum. Rhizosphere, 30. https://doi.org/10.1016/j.rhisph.2024.100892
11. Lestari, K. W., & Dewi, N. (2023). Potensi Simpanan Karbon pada Beberapa Tipe Agroforestri Berbasis Kopi Robusta di Desa Rowosari, Jember. Journal of Tropical Silviculture, 14(02). https://doi.org/10.29244/j-siltrop.14.02.150-157
12. Li, S., Gong, S., Hou, Y., Li, X., & Wang, C. (2022). The impacts of agroforestry on soil multi-functionality depending on practices and duration. Science of the Total Environment, Vol. 847. https://doi.org/10.1016/j.scitotenv.2022.157438
13. Li, Y., Shi, Z., Wu, H.-X., Li, F., & Li, H.-Y. (2013). Definition of management zones for enhancing cultivated land conservation using combined spatial data. Environmental Management, 52(4), 792–806.
14. Octavia, D., Murniati, Suharti, S., Hani, A., Mindawati, N., Suratman, … Faubiany, V. (2023). Smart agroforestry for sustaining soil fertility and community livelihood. Forest Science and Technology, Vol. 19. https://doi.org/10.1080/21580103.2023.2269970
15. Ollinaho, O. I., & Kröger, M. (2021). Agroforestry transitions: The good, the bad and the ugly. Journal of Rural Studies, 82. https://doi.org/10.1016/j.jrurstud.2021.01.016
16. Pachepsky, Y., & Park, Y. (2015). Saturated Hydraulic Conductivity of US Soils Grouped According to Textural Class and Bulk Density. Soil Science Society of America Journal, 79(4). https://doi.org/10.2136/sssaj2015.02.0067
17. Rerkasem, K., Yimyam, N., & Rerkasem, B. (2009). Land use transformation in the mountainous mainland Southeast Asia region and the role of indigenous knowledge and skills in forest management. Forest Ecology and Management, 257(10), 2035–2043.

DOI: 10.5281/zenodo.18522339

18. Unger, P. W., & Kaspar, T. C. (1994). Soil Compaction and Root Growth: A Review. Agronomy Journal, 86(5). https://doi.org/10.2134/agronj1994.00021962008600050004x
19. Yu, C., Mawodza, T., Atkinson, B. S., Atkinson, J. A., Sturrock, C. J., Whalley, R., … Zhou, H. (2024). The effects of soil compaction on wheat seedling root growth are specific to soil texture and soil moisture status. Rhizosphere, 29, 100838.
20. Zulkaidhah, Z., Hapid, A., Ariyanti, A., & Fadilah, D. R. (2025). Altitudinal Variation in Termite Species Diversity and Distribution in Agroforestry Systems of Lore Lindu National Park, Indonesia. International Journal of Design and Nature and Ecodynamics, 20(1). https://doi.org/10.18280/ijdne.200106
21. Zulkaidhah, Z., Malik, A., Hapid, A., Hamka, H., Ariyanti, A., & Rahman, N. (2021). The diversity of termite species on natural forest and agroforestry land in Sulawesi tropical forests in Indonesia. Annals of Silvicultural Research, 46(2). https://doi.org/10.12899/asr-2228

DOI: 10.5281/zenodo.18522339