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# Soil properties of natural stands of *Diospyros celebica* in South Sulawesi, Indonesia and their management implications

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[3]Research Center for Applied Botany, National Research and Innovation Agency (BRIN). Science and Techno Park of Dr. (H.C.) Ir. Soekarno, Jl. Raya Jakarta-Bogor Km. 46, Cibinong, Bogor 16911, West Java, Indonesia

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**Abstract.** *Paembonan SA, Millang S, Allo MK, Suhartati S, Najib NN, Ura' R, Arty B, Makkasau AR. 2026. Soil properties of natural stands of Diospyros celebica in South Sulawesi, Indonesia and their management implications. Asian J For 10 (1): r100112. https://doi.org/10.13057/asianjfor/r100112.* This study aimed to characterize the variability of soil physical and chemical properties supporting *Diospyros celebica* (ebony) in three natural habitats across South Sulawesi (Maros, Barru, and Sidrap) and to interpret their implications for habitat management and species regeneration. Sampling points were determined at three representative positions within each 1×1 m observation plot. Soil samples were collected from three depth intervals: 0-30 cm (Layer I), 31-60 cm (Layer II), and 61-90 cm (Layer III). Field soil samples were collected from natural stands in each district and analyzed for texture, bulk density, porosity, permeability, pH, organic carbon, and Cation Exchange Capacity (CEC) following standard procedures. The results revealed distinct spatial variation among districts. Soils in Maros were coarse-textured (sandy clay to sandy loam) with very rapid permeability (51.25±3.17 cm $hour^{-1}$), reflecting high macroporosity and low water-holding capacity. In contrast, Barru soils were fine-textured (clay and silty clay) with slow permeability (1.80±0.42 cm $hour^{-1}$), strongly acidic pH (4.84), and low organic matter content (2.03%). Sidrap soils had intermediate textures and moderate permeability (2.30±0.38 cm $hour^{-1}$), a moderately acidic pH (5.89), and the highest CEC (18.44 cmol(+)/kg), indicating better nutrient retention. These findings demonstrate that soil texture, organic matter, and pH collectively regulate water balance and nutrient availability, key factors influencing the growth and distribution of *D. celebica*. These findings emphasize that soil texture, organic matter, and pH collectively regulate water balance and nutrient availability, key factors for the growth and establishment of *D. celebica.*

**Keywords:** Cation Exchange Capacity, *Diospyros celebica*, land management, permeability, soil texture

## INTRODUCTION

The Sulawesi ebony (*Diospyros celebica*) is an endemic tree species native to the island of Sulawesi, Indonesia, widely recognized for its distinctive dark-striped wood and high economic value for premium furniture and traditional wood crafts (Wulandari et al. 2016). These valuable aesthetic properties have driven intensive exploitation over several decades, resulting in substantial population declines across its natural range (Rukmi et al. 2017). Population recovery is further constrained by the species inherently slow growth rate, ongoing habitat conversion to agriculture, plantation areas, and persistent illegal logging (Rukmi et al. 2023; Taiyeb et al. 2025). Consequently, *D. celebica* is currently classified as "Vulnerable" on the IUCN Red List (IUCN 2023) and is legally protected under Indonesian national regulations (Ministry of Environment and Forestry 2018). Remaining natural populations are now highly fragmented, particularly in South Sulawesi, where rapid land-use changes continue to threaten the long-term persistence of the species.

Beyond its economic importance, *D. celebica* plays a significant ecological role in lowland forest ecosystems. As a locally dominant tree species, it contributes to forest structure, supports microhabitat diversity, stabilizes soil, and enhances carbon storage (Mukrimin 2023; Luo et al. 2025). The presence of ebony trees promotes ecosystem stability through interactions with soil processes, including nutrient cycling and erosion control (Indrajaya et al. 2022). Given these ecological functions, maintaining viable populations of *D. celebica* is essential not only for species conservation but also for sustaining broader forest ecosystem integrity in Sulawesi.

Effective conservation of *D. celebica* cannot rely solely on logging restrictions or the protection of remnant stands. Instead, it requires evidence-based management and restoration strategies grounded in a detailed understanding of the species' ecological requirements, particularly soil-related factors that influence growth, regeneration, and spatial distribution (Roy et al. 2021; Aldiansyah and Risna 2023; Trigunasih et al 2023). Soil properties are fundamental determinants of plant performance, as they regulate nutrient availability, root development, aeration, and water retention (Brady and Weil 2017; Giuliani et al. 2024; Sheeba et al. 2025). Physical properties such as texture, bulk density, porosity, and permeability control drainage patterns and root penetration, while chemical properties including pH, organic matter content, and Cation Exchange Capacity (CEC) govern nutrient retention and soil fertility (Havlin et al. 2014; Sharma 2022; Trigunasih et al 2023). Together, these attributes define site-specific microhabitat conditions that shape seedling establishment, tree vigor, and long-term forest sustainability.

Studies into soil preferences of the genus *Diospyros* have been reported from other regions. Studies on *D. virginiana* in North America and *D. mespiliformis* in Africa indicate that these species generally perform well in slightly acidic, well-drained soils with relatively high organic matter content and moderate to high CEC (Bañares-de-Dios et al. 2022). Such conditions facilitate stable nutrient cycling and adequate aeration, which are particularly important for slow-growing tree species. However, comparable edaphic information for *D. celebica* remains scarce. Existing studies conducted in Central Sulawesi (Wulandari et al. 2016; Rukmi et al. 2017) provide only broad descriptions of habitat conditions and associated vegetation, without detailed analyses of soil physical and chemical properties. Moreover, these studies do not address South Sulawesi, a region characterized by complex topography and heterogeneous soil types (Aldiansyah and Risna 2023) that may strongly influence the distribution and performance of *D. celebica* populations.

This lack of detailed, site-specific soil data represents a critical research gap for *D. celebica* conservation in South Sulawesi. Many reforestation and enrichment planting initiatives in the region have been implemented without adequate consideration of local soil suitability, often resulting in low seedling survival and uneven growth performance (Indrajaya et al. 2022). Identifying soil properties associated with healthy natural stands is therefore essential for improving restoration success and guiding site selection for future planting efforts. Furthermore, understanding spatial variation in soil texture, permeability, organic matter content, and nutrient-holding capacity can provide key indicators of habitat suitability (Luo et al. 2025), supporting more informed land-use planning and sustainable forest management decisions (Franzluebbers 2024).

This study addresses these limitations by systematically examining the physical and chemical soil properties of natural *D. celebica* stands across three representative districts in South Sulawesi namely Maros, Barru, and Sidrap. Specifically, the objectives are to (i) characterize the physical and chemical properties of the soils that support *D. celebica* populations in these regions, and (ii) evaluate how variations in soil characteristics may affect habitat suitability and inform land management strategies. By focusing on soil factors that have received limited attention in previous research, this study advances current understanding of *D. celebica* ecology and provides a scientifically robust foundation for conservation planning and restoration programs tailored to the environmental conditions of South Sulawesi.

## MATERIALS AND METHODS

### Study area

This study was conducted in April 2024 at three sites in South Sulawesi, Indonesia: Limapocoe Village (Maros District), Coppo Village (Barru District), and Pitu Riase Village (Sidrap District). These sites werwe purposively selected based on previous reports on the distribution of *D. celebica* (ebony) and preliminary information from the South Sulawesi Natural Resources Conservation Agency, indicating the presence of actual or potential ebony habitats. All sites are located at elevations ranging from 100-600 meters above sea level, with mean air temperatures of 26-30°C and relative humidity of 80-88%. The selection of these locations also addresses the limited availability of empirical data on the soil physical and chemical characteristics of *D. celebica* (Figure 1) habitats in South Sulawesi.

### Procedures

*Sampling design*

A purposive line transect approach was applied at each study site. Three transects each 500 meter in length, were established following or intersecting the slope countours to capture topographic variability. Along each transect, 1×1 meter plots were placed at representative landscape positions including base, slope and ridge area considering elevation, habitat extent, and disturbance history.

**Figure 1.** *Diospyros celebica* (ebony)

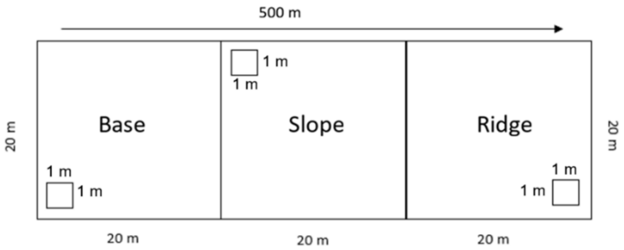


**Figure 2.** Soil sampling based on slope

*Soil sampling*

Soil sampels were collected at three topographic position lower slope (base), mid-slope, and upper slope (ridge) along each transect (Figure 2). At each position soil was sampled at three depth intervals: 0-30 cm (Layer I), 31-60 cm (Layer II), and 61-90 cm (Layer III) representing the main rooting zone of *D. celebica* stands. Both disturbed and undisturbed soil samples were collected at each depth. Undisturbed samples were obtained using soil plastic bags and georeferenced using a gps unit to ensure spatial accuracy and reproducibility.

*Soil physical and chemical analyses*

Soil physical properties including Structure, Texture, Bulk Density, Porosity, Moisture Content, and Permeability, were primarily measured from undistrubed samples at the 0-30 cm depth. Chemical analyses were performed on composite approximately 1 kg of soil was collected from each depth layer (0-30 cm, 31-60 cm, and 61-90 cm) and labeled according to sampling location and date. The observed chemical variables included soil pH, organic carbon (C) and Nitrogen content (N), phosphorus (P), exchangeable potassium (K), calsium (Ca), magnesium (Mg), Cation Exchange Capacity (CEC), Base Saturation (BS), and exchangeable acidity (Al and H) (Luo et al. 2025). Soil samples analyses were conducted at the Silviculture and Tree Physiology Laboratory faculty of Forestry and Soil Science Laboratory Faculty of agriculture Universitas Hasanuddin, South Sulawesi.

**Data analysis**

Data obtained from field measurements and laboratory analysis were quantitatively processed to describe the variability of the physical and chemical properties of soil in natural stands of *D. celebica* at the three study sites. Soil characteristics such as soil color (munsell soil color chart), soil texture (Pipet method and The Texture Triangle from the United States Department of Agriculture/ USDA), bulk density, porosity, permeability, pH, organic carbon (Walkey and Black method), and Cation Exchange Capacity (CEC) were classified according to the USDA (2003) and FAO criteria (2006). Although differences in soil properties were observed among the three districts (Maros, Barru, and Sidrap), inferential statistical tests (e.g., ANOVA) were not applied due to the exploratory nature of the study and the limited replication within each habitat. Therefore, descriptive statistics were used as an appropriate approach for initial soil characterization and for identifying indicative differences among sites.

## RESULTS AND DISCUSSION

The physical and chemical properties of soil are greatly influenced by the amount of vegetation growing on it due to the interaction between vegetation, soil, and the surrounding environment. Soil properties vary depending on the type of land cover, as the properties of soil and vegetation have a mutually beneficial relationship (Leonika et al. 2021). Overall, the density at the study site is classified as high density, and high density has both significant advantages and disadvantages for the soil.

**Physical soil properties**

*Soil color*

Soil color is one of the easiest field indicators to observe, providing useful information about soil properties, particularly organic matter and oxidation levels. In this study, it was found that darker topsoil layers (dark brown) are predominant in the Maros and Sidrap Regions, whereas Barru has lighter, yellowish-brown soil layers (Figure 3 and Table 1). Darker soil on the surface usually indicates a higher amount of leaf litter and organic matter that decomposes slowly under dense canopy conditions. Studies using the Munsell Soil Color Chart show that darker colors are closely related to higher organic matter and total organic carbon content (Łachacz and Załuski 2023). The gradual change from dark to light colors with increasing soil depth reflects the natural decline of organic carbon at the surface, which is commonly observed in forest soils worldwide (Hicks Pries 2023).

Dark-colored topsoil is also commonly associated with improved soil physical and chemical characteristics, including higher Cation Exchange Capacity (CEC), enhanced nutrient and water retention, and greater soil aggregate stability. These properties are generally indicative of higher soil quality and fertility in forest ecosystems (Mattila and Rajala 2022; Łachacz and Załuski 2023). Accordingly, the variation in soil color among the study sites suggests differences in organic matter status and overall soil condition. In contrast, lighter and more oxidized soils typically reflect lower organic matter content, which may indicate less favorable soil conditions for sustaining long-term forest vegetation.

*Soil texture*

Soil texture indicates the relative percentage of sand, silt, and clay fractions present in the soil. The percentage ratio of these fractions can be determined from the results of soil texture analysis conducted in a laboratory. One of the physical properties of soil that plays an important role in plant growth is texture. Soil texture affects the size of soil pores and moisture retention (Ahmad et al. 2018; Sihombing et al. 2018).

Across the three study locations, soil texture classes varied but were dominated by textures ranging from clay dominated soils to sand dominated soils. Maros was characterized mainly by clay and sandy clay textures, with limited occurrence of clayey sand. Barru exhibited the widest range of textures, including clay, sandy clay, clayey sand, silty clay, and loamy sand, indicating greater heterogeneity in particle size composition. Sidrap also showed diverse texture classes, dominated by clay, clay loam, sandy clay, and silty clay loam (Table 1). Maros District is characterized by a narrow silt range (10-15%) and a high clay fraction (45-65%), resulting in dominant clay and clay loam classes. Barru District exhibits the broadest textural gradient, with clay contents ranging from 35% to 65% and relatively higher silt proportions (15-25%), the dominance of silty clay to loam. Sidrap District is distinguished by a consistently higher sand fraction (30-35%) combined with substantial clay content (45-65%), resulting in dominant sandy clay textures (Figures 4 and 5). Overall, Maros and Sidrap were generally more clay-rich, whereas Barru showed relatively higher proportions of sand and silt.

Differences in texture among locations imply variations in pore size distribution and soil permeability. Soils with higher sand content tend to contain more macropores, whereas clay-dominated soils are characterized by finer pores and greater water retention capacity (Sihombing et al. 2018; Franzluebbers 2024). Soils with balanced proportions of sand, silt, and clay can provide sufficient water availability while maintaining adequate aeration, which supports nutrient uptake and root activity (Salawangi et al. 2020; Sharma 2022).

*Soil structure*

The physical properties of this soil have a significant impact on air circulation, root growth, water movement, and the balance between drainage and water storage. Observations across all study sites indicate that subangular blocky and angular blocky structures are the dominant structural forms, with granular and crumb structures occurring locally (Table 1). Structure is typical of clay and sandy clay textures. Structure is typical of clay and sandy clay textures. It indicates moderate to high cohesion and good stability. These conditions allow for adequate drainage and moisture, supporting root growth in *D. celebica*.

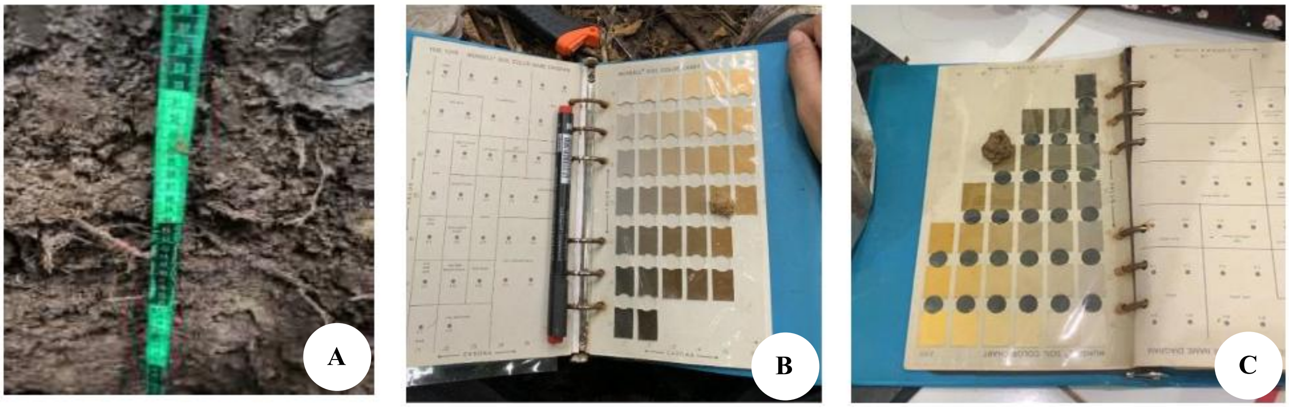


**Figure 3.** Observation of soil color in South Sulawesi, Indonesia. A. Maros District, B. Barru District, C. Sidrap District

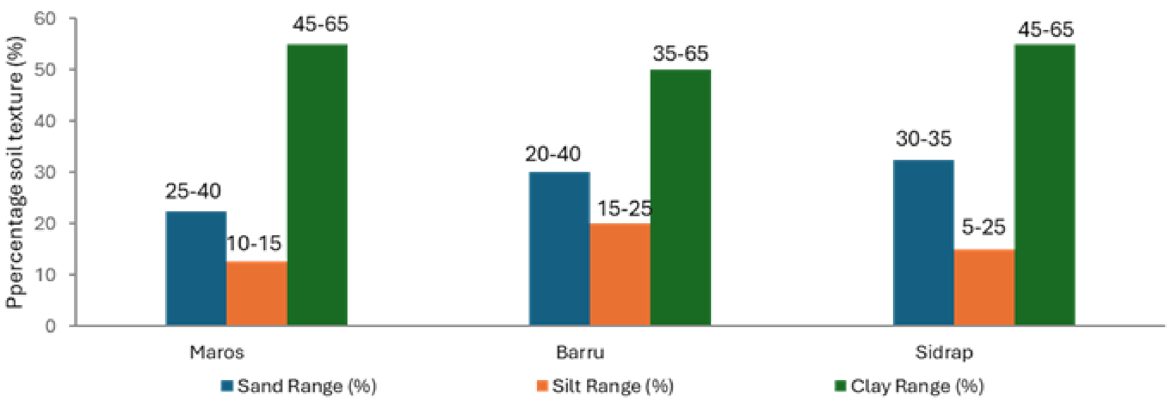


**Figure 4.** Percentage data of the soil texture in Maros District, Barru District, and Sidrap District in South Sulawesi, Indonesia

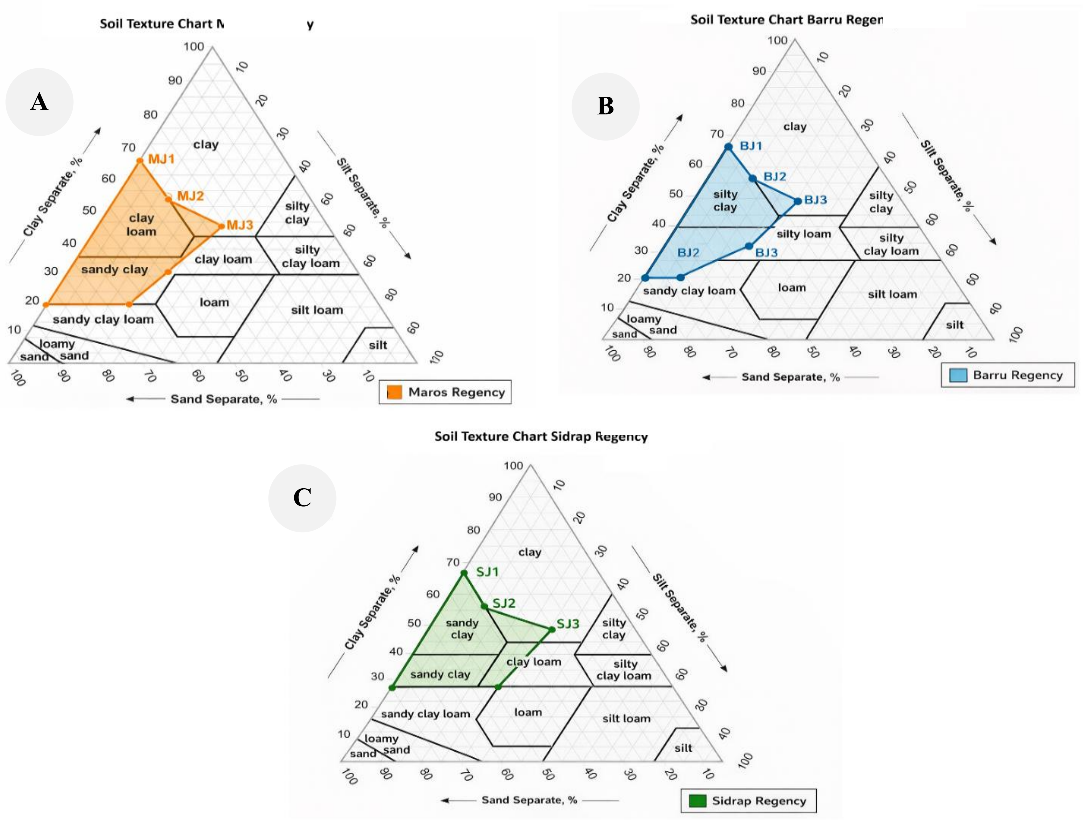


**Figure 5.** Soil texture chart in South Sulawesi, Indonesia. A. Maros District, B. Barru District, C. Sidrap District

Comparatively, soils in Maros are predominantly subangular to angular blocky, consistent with their clay dominated textures and indicating moderate permeability with good structural stability. Barru soils, while still largely subangular blocky, show more frequent granular structures, reflecting higher sand and silt contents and looser aggregate arrangements. Sidrap exhibits the greatest structural variability, including blocky and crumb structures, indicating differences in aggregation processes likely influenced by both texture and organic matter inputs (Meurer et al. 2020). These variations illustrate how texture and structure jointly regulate soil permeability and moisture dynamics across locations.

Stable soil structure is an important indicator of long-term soil functionality and resistance to degradation. Well-formed aggregates help maintain porosity, reduce erosion, and protect soil organic matter from rapid decomposition (Keller et al. 2021; Dor et al. 2023). The presence of blocky and crumb structures in Maros and Sidrap suggests relatively stable aggregation, whereas the more granular and less cohesive structures observed in parts of Barru indicate faster drainage but potentially lower moisture retention. Understanding these integrated texture–structure patterns provide a basis for evaluating soil condition and for informing site-specific soil management and restoration strategies.

*Soil permeability*

Soil permeability describes the ability of soil to transmit water through its pore system and is influenced by soil texture, structure, and organic matter content. The measured permeability values (Figure 6) show clear variation among the three districts. Maros exhibits the highest average permeability (51.25 cm hour$^{-1}$), classified as very rapid, while Barru shows slow permeability (1.80 cm hour$^{-1}$) and Sidrap moderate permeability (2.30 cm hour$^{-1}$). Based on the USDA classification (2003), permeability values below 0.5 cm hour$^{-1}$ are categorized as very slow, 0.5-2.0 as slow, 2-6 as moderate, 6-20 as rapid, and values above 20 as very rapid. These results indicate that soils in Maros allow much faster water movement compared to Barru and Sidrap, consistent with differences in soil physical characteristics. Similar patterns have been reported in tropical forest soils, where higher sand content and lower compaction are associated with increased hydraulic conductivity (Asdak 2018).

Differences in permeability among sites reflect contrasting soil water transmission conditions that are ecologically relevant. Very rapid permeability, as observed in Maros, indicates efficient drainage and high aeration but also faster water loss from the soil profile. In contrast, slow permeability in Barru suggests greater water retention and reduced air exchange, while the moderate permeability recorded in Sidrap represents an intermediate condition between drainage and moisture storage. Therefore, understanding this permeability pattern is crucial for reforestation and ensuring that groundwater conditions are suitable for the ecological needs of the *D. celebica* species.

**Table 1.** Average physical properties of soil at the research site for ebony habitat characterization

| Sample | Soil color | Soil structure | Soil texture |
|---|---|---|---|
| Maros District | | | |
| MJ1 | Brown, Dark Brown, Very Dark Grayish Brown | Subangular Blocky, Angular Blocky | Clay, Sandy Clay |
| MJ2 | Brown, Dark Brown | Subangular Blocky, Angular Blocky | Clay, Sandy Clay |
| MJ3 | Brown, Dark Brown, Dark Reddish Brown, Very Dark Brown, Very Dark Grayish Brown | Granular, Subangular Blocky, Angular Blocky | Clay, Sandy Clay, Sandy Loam |
| Barru District | | | |
| BJ1 | Brown, Grayish Brown, Yellowish brown, Light Yellowish Brown, Brownish Yellow, Strong Brown, Brownish Yellow | Granular, Subangular Blocky | Silty Clay, Clay, Sandy Loam, Sandy Clay |
| BJ2 | Yellowish Brown, Light Yellowish Brown, Yellowish Brown, Brown, Pale Yellow Orange | Subangular Blocky | Silty Clay Loam, Sandy Clay, Clay, Sandy Loam |
| BJ3 | Brown, Yellowish Brown, Light Yellowish Brown, Yellowish Brown, Light Gray, Yellowish Brown | Subangular Blocky | Clay, Sandy Clay, Sandy Loam |
| Sidrap District | | | |
| SJ1 | Brown, Yellowish Brown, Light Yellowish Brown, Olive Brown, Very Dark Grayish Brown, Dark Yellowish Brown, Dark Brown | Subangular Blocky, Angular Blocky, Crumb | Clay, Sandy Clay, Silty Clay |
| SJ2 | Strong Brown, Light Yellowish Brown, Yellowish Brown, Grayish Brown, Pale Yellow Orange, Dark Brown, Brown, Dark Yellowwish Brown, Olive Brown, Very Dark Grey, Very Dark Grayish Brown | Subangular Blocky, Angular Blocky | Sandy Clay, Sandy Loam, Clay |
| SJ3 | Grayish Yellow Brown, Yellowish Brown, Light Yellowish Brown, Brownish Yellow, Strong Brown, Dark Reddish Brown, Reddish Brown, Yellowish Red, Dark Brown. | Subangular Blocky, Angular Blocky | Sandy Loam, Clay, Sandy Loam, Silty Clay, Silty Clay Loam |

Note: Primary data (2024)

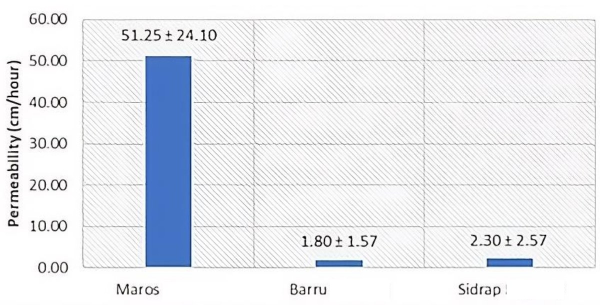


**Figure 6.** Average values of soil permeability in natural *Diospyros celebica* stand in Maros District, Barru District, and Sidrap District in South Sulawesi, Indonesia

## Chemical soil properties

*Soil pH*

Soil acidity (soil pH) is a soil reaction that indicates the acidity or alkalinity of the soil, which plays a role in determining how easily nutrients are absorbed by plants. The level of acidity or alkalinity of an object is measured on a scale of 0 to 14. Soil pH is a standard measurement of the level of acidity or alkalinity of a piece of land. Based on laboratory analysis, the soil pH (acidity) values for Maros District are 5.29-5.53, categorized as acidic, with an average of 5.40 per plot, also categorized as acidic. Barru District has values of 4.60-4.98, categorized as acidic, with an average of 4.84 per plot, also categorized as acidic. Sidrap District has a pH range of 5.70-5.97, classified as slightly acidic, with an average pH of 5.89, also classified as slightly acidic. Among the three study locations, Sidrap District has the highest soil pH, indicating less acidic conditions compared to Maros and Barru (Table 2). The relatively higher pH in Sidrap, which is closer to neutral, suggests more favorable chemical conditions for general plant growth, although liming may still be required if crops with neutral pH preferences are introduced. Nutrient availability in soil is optimal at a neutral pH level. Optimal availability of macro and micro nutrients occurs at a pH of 6-7 and is still sufficient at a pH of 5.5-6 or 7-7.5. Low soil pH in forest soils is caused by high organic matter content, which makes the soil more acidic (Rukmi et al. 2023).

**Table 2.** Soil acidity (soil pH)

| Location | soil pH | Category |
|---|---|---|
| Maros District | | |
| MJ1 | 5.29 | Acidic |
| MJ2 | 5.39 | Acidic |
| MJ3 | 5.53 | Acidic |
| Average | 5.40 | Acidic |
| Barru District | | |
| BJ1 | 4.6 | Acidic |
| BJ2 | 4.98 | Acidic |
| BJ3 | 4.93 | Acidic |
| Average | 4.84 | Acidic |
| Sidrap District | | |
| SJ1 | 5.97 | Slightly acidic |
| SJ2 | 5.91 | Slightly acidic |
| SJ3 | 5.7 | Slightly acidic |
| Average | 5.86 | Slightly acidic |

Note: Primary data (2024)

Based on the analysis results, the deeper the soil, the lower the soil pH value tends to be, indicating that the soil falls into the acidic category. This decrease in pH is also influenced by the use of acidic fertilizers. To increase soil pH, lime materials such as $CaCO_3$ or $CaSO_4$ can be added. However, in some soil samples, there is a pattern of increasing pH with increasing soil depth. This is due to the minimal decomposition process at that depth. The cause of acidic reactions (low pH) in soil is due to a lack of calcium (CaO) and magnesium (MgO) content in the soil, resulting from excessive rainfall in humid climates. Naturally, high rainfall causes soil to become acidic due to nutrient leaching, poor drainage, and continuous waterlogging. Soil in such conditions is always acidic (Palupi 2015).

*Organic matter*

Organic matter is a collection of organic compounds present in soil that originates from plant and animal residues at various stages of decomposition. Based on laboratory analysis, the organic matter content in Maros District for C% values range from 1.97-2.36%, with organic matter values of 3.39-4.07%, categorized as low to moderate, with an average C% value of 2.18% and organic matter of 3.76%, categorized as moderate. Barru District has a C% value of 1.14-1.25% and an organic matter value of 1.95-2.03%, categorized as low, with an average C% of 1.17% and organic matter of 2.03%, categorized as low. Sidrap District has a C% value of 1.59-2.05% and an organic matter value of 2.74-3.53, categorized as low-moderate, with an average C% value of 1.89% and an organic matter value of 3.26, categorized as moderate. Among the three study locations, Maros District has the highest organic matter content with a C% value of 2.18% and organic matter content of 3.76% in the moderate category.

According to Surya et al. (2017), the organic matter content decreases with depth due to the accumulation of concentrated organic matter in the upper layers. Sari et al. (2023) similarly report that organic carbon concentrations tend to decline with increasing depth, as topsoil layers receive continuous organic inputs, while subsurface layers contain lower carbon concentrations (Warren et al. 2021). The organic matter content affects the increase in soil fertility and productivity (Zhao et al. 2024). The observed variation in organic matter content among locations reflects differences in measured organic carbon levels within surface soils, which are commonly used indicators of soil chemical condition (Franzluebbers 2024).

*Cation Exchange Capacity (CEC)*

The Cation Exchange Capacity (CEC) of soil is the ability of soil colloids to absorb and exchange cations (Putri et al. 2019). Based on laboratory analysis results, the CEC content for Maros District ranges from 17.46-18.11 cmol/kg, classified as moderate, with an average per plot of 17.74 cmol/kg. Barru District shows CEC values of 14.22-17.81 cmol/kg, ranging from low to moderate, with an average per plot of 16.58 cmol/kg, classified as moderate. Sidrap District has CEC values ranging from 18.19-18.63 cmol/kg, also classified as moderate, with an average per plot of 18.44 cmol/kg. According to commonly used soil fertility classifications, CEC values below 16 cmol/kg are categorized as low, 16-24 cmol/kg as moderate, and above 24 cmol/kg as high (Mukhlis 2007). Based on this classification, all study sites fall within the moderate CEC category, with Sidrap District exhibiting the highest average value among the three locations.

The magnitude of CEC values depends on soil texture and organic matter content. This is in line with Mukhlis' (2007) opinion, who stated that the higher the organic matter content and the finer the soil texture, the higher the CEC value of the soil. Conversely, the lower the organic matter content and the coarser the soil texture, the lower the CEC value of the soil. Additionally, it is also caused by low pH levels. This aligns with Syachroni's (2020) research, which found that pH levels in the acidic category have relatively low fertility, resulting in low nutrient availability for plants. Based on the research results, in route 1, the CEC value is relatively low, while in routes 2 and 3, it is moderate, but the difference in values between these categories is not significant. High Cation Exchange Capacity (CEC) values are influenced by clay content, as soils dominated by clay fractions have high ion exchange capacity and water-holding ability (Bin et al. 2025). Therefore, soils dominated by clay fractions have high aggregate stability due to interparticle soil bonds (Widyantari et al. 2015). High CEC indicates a soil's ability to retain and supply cations to plants, which is vital for soil fertility and nutrient retention (Sheeba et al. 2025).

The physical differences among the three study sites namely Maros, Barru, and Sidrap, reflect variations in parent material, topography, and land-use intensity that influence soil formation processes (Table 3). Soils in Maros are characterized by coarser textures dominated by sandy clay and sandy loam, subangular blocky to granular structures, and very rapid permeability (51.25 cm $hour^{-1}$), indicating high infiltration capacity but limited water retention. In contrast, soils in Barru exhibit finer textures (clay and silty clay) with slow permeability (1.80 cm $hour^{-1}$), reflecting restricted water movement. Sidrap soils display intermediate textures (clay-sandy clay) and moderate permeability (2.30 cm hour$^{-1}$), indicating a more balanced soil physical condition.

In addition to physical properties, chemical soil characteristics also vary among locations. Maros soils have moderate organic matter content (3.76%) and acidic pH (5.40). Barru soils show the lowest organic matter content (2.03%) and the most acidic pH (4.84). Sidrap soils exhibit slightly acidic pH (5.89), moderate organic matter content (3.26%), and the highest Cation Exchange Capacity (CEC) at 18.44 cmol(+)/kg, indicating greater nutrient retention potential compared to the other sites.

These combined physical and chemical differences highlight the role of soil texture and structure in regulating both hydraulic behavior and nutrient dynamics. Coarse-textured soils, such as those in Maros, promote rapid drainage and aeration but limit moisture and nutrient retention. Conversely, fine-textured soils in Barru tend to retain water but may experience reduced aeration. Sidrap's intermediate texture offers a more favorable balance between aeration and water storage, creating suitable conditions for *D. celebica* seedling establishment and sustained growth. This trend is consistent with the observations of Widyantari et al. (2015) and Asdak (2018), who emphasized the importance of soil structure and pore connectivity in regulating both permeability and cation exchange efficiency.

The spatial variability observed in the physical and chemical properties of soil in the Maros, Barru, and Sidrap regions has important implications for the conservation, restoration, and sustainable management of *D. celebica*. Differences in soil texture, permeability, organic matter content, and pH directly affect soil water balance, aeration, and nutrient availability, which together determine the suitability of the habitat for ebony cultivation and its long-term survival (Luo et al. 2025).

The findings of this study provide important implications for the mamagement and conservation of *D. celebica* in South Sulawesi. From an ecological perspective, the variation in soil physical and chemical properties across sites reflects fundamental differences in habitat suitability for *D. celebica*. Ecologically, this species is associated with moderately acidic soils, sufficient nutrient availability, and relatively stable soil moisture conditions. Sidrap District soils most closely approximate these requirements, suggesting a higher ecological compatibility for establishment and long-term persistence. In contrast, the extremely rapid drainage observed in Maros District many lead frequent moisture deficits, management interventions should prioritize improving soil water retention. Practices including the enrichment of organic matter, application mulching, and maintenance of canopy cover are recommended to reduce moisture loss and evapotranspiration. While the slow permeability in Barru District may periodically limit soil aeration, both of which can impose physiological stress for *D. celebica.*

These site-specific soil constraints indicate that the balance between soil texture, permeability, and chemical fertility plays a central role in regulating water availability and nutrient cycling within *D. celebica* habitats. Coarse textured soils whit high permeability such as those in Maros District, may reduce water retention and nutrient residence time, potentially limiting seedling survival and early growth. Conversely, fine textured soils with poor drainage as found in Barru District may increase the risk of hypoxic conditions in the root zone, which can negatively affect root function and overall plant performance. The more intermediate physical conditions and balanced chemical properties observed in Sidrap District suggest that such environments provide a more favorable ecological niche for *D. celebica.* Higher organic matter content, moderate pH, and greater cation exchange capacity contribute to improved soil structure, sustained nutrient availability, and enhanced moisture regulation. These conditions support key ecological processes, including microbial activity, root development, and nutrient uptake, which collectively underpin successful regeneration and population stability.

From a management perspective these findings highlight the importance of site specific (Figure 7). Ecologically informed management strategies rather than uniform conservation approaches. Results indicate that Sidrap District has the most balanced conditions (intermediate texture, moderate pH, more stable CEC and organic matter). Therefore, management implementation can be designated as a priority conservation zone and seed source area. Maros District can be managed as a restoration zone focused on improving groundwater retention, and Barru District can be managed as a rehabilitation zone aimed at improving soil aeration. Management interventions should ain to maintain or restore soil physical and chemical balance in accordance with the autecological requirements of *D. celebica*. Enhancing organic matter inputs, protecting forest floor integrity, and minimizing soil disturbance are particularly important for promoting natural regeneration and sustaining soil conditions.

**Table 3.** Summary of dominant soil characteristics

| **Parameter** | **Maros** | **Barru** | **Sidrap** |
|---|---|---|---|
| Texture class | Clay-clay loam | Silty clay-loam | Sandy clay |
| Permeability (cm h$^{-1}$) | 51.25 (Very rapid) | 1.80 (Slow) | 2.30 (Moderate) |
| pH | 5.40 | 4.84 | 5.89 |
| Organic matter (%) | 3.76 | 2.03 | 3.26 |
| CEC (cmol(+)/kg) | 17.74 | 16.58 | 18.44 |

Note: Primary data (2024)

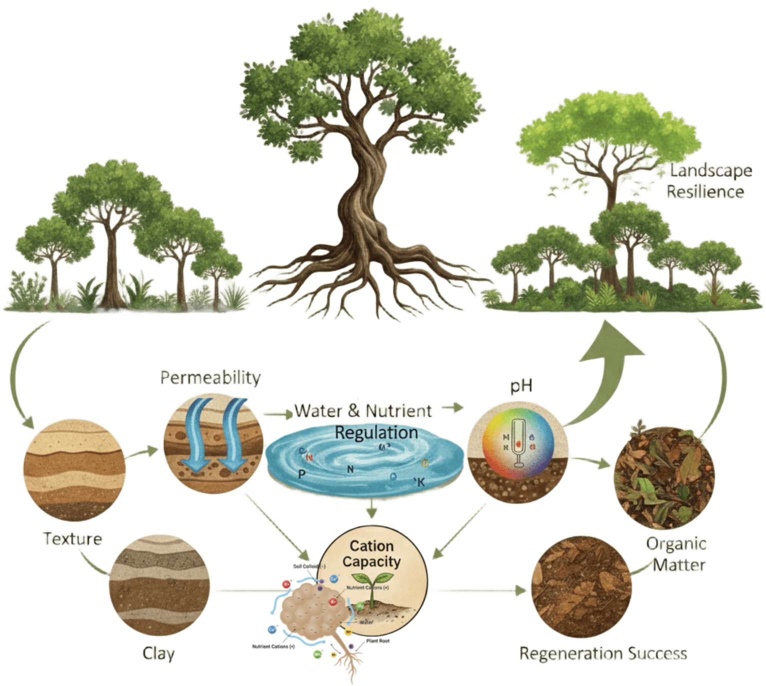


**Figure 7.** Model of soil ecology management for *Diospyros celebica* conservation

In conclusion, this integrated ecological understanding of soil and plant interactions provides a robust scientific basis for evaluating habitat quality and guiding conservation and restoration planning for *D. celebica*. Aligning management practices with the ecological conditions of the species enables regeneration, supports the long-term viability of *D. celebica* populations, and enhances the resilience of lowland forest ecosystems in South Sulawesi.

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