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Physical Properties, Chemical Properties, and Fertility of Soil under the Natural Stands of Ebony (*Diospyros celebica* Bakh.)

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Abstract: The soil physical and chemical properties and fertility under the natural stands of ebony were investigated from October 2022 to June 2024. The locations are the Gunung Sojol Nature Reserve and the Forest Management Unit of Sintuwu Maroso, Sulawesi. Ebony is dominant at all growth levels in Sintuwu Maroso, but only at pole level in Sintuwu Maroso as indicated by the IVI. The basal area and volume in Sintuwu Maroso are higher, indicating higher potential than Gunung Sojol. The medium texture soil with optimal moisture in Sintuwu Maroso also supports better growth than the coarse soil in Gunung Sojol. The soil in Gunung Sojol is characterized by acidic pH and high level of organic C, total P, total K, and Al-dd. Meanwhile, the soil in Sintuwu Maroso is slightly acidic with moderate levels of previous parameters. Despite high organic matter and CEC, the soil fertility of Gunung Sojol is hampered by low acidity and base saturation. While Sintuwu Maroso is challenged by low nutrient and organic matters. In general, both locations have moderate soil fertility. The results can serve as a basis for effective cultivation and conservation strategies for both in-situ and ex-situ methods.

Keywords: Ebony; Forest Management Unit; Gunung Sojol; Sintuwu Maroso; Soil Fertility

Introduction

The largest genus belonging to the Ebenaceae family, Diospyros, is composed of over 500 species (Rauf et al., 2017); (Ribeiro et al., 2023). Ninety to one hundred species of Diospyros are found in Indonesia, of which seven are called ebony, including an endemic plant on the island of Sulawesi in the Wallacea region, Diospyros celebica (Kiding Allo, 2020). Known as Sulawesi ebony, D. celebica is listed as luxurious wood with high economic value. Its aesthetic elements drive international demand (Setiawan, 2023); (Thiollay & Rahman, 2002), while its distribution is exclusively centered in Sulawesi as its natural habitat. D. celebica has an outstanding decorative value with its renowned wood's strength and durability, making it suitable for furniture, building materials, musical instruments, souvenirs, carvings, statues, manual fans, and decorative veneers. Its rich and unique color poses it as a highly marketable species. The beautifully striped ebony is highly sought after both domestically and internationally. Grows naturally in Central Sulawesi, West Sulawesi, South Sulawesi, Gorontalo, and North Sulawesi (Kinho, 2015). In 1994, approximately one million hectares of ebony stands were dispersed in Donggala (700.000 ha), Poso and Bolaang Mongondow (100,000 ha, respectively), and Luwu and Mamuju (50,000 ha, respectively). It is mostly distributed and widely cultivated for commercial purposes in Central Sulawesi, while its primary natural habitat is in Donggala and Poso. Eboni was designated as the mascot of Central Sulawesi on February 25, 1995, through Governor's Decree No. 660/78/1995. However, ebony's slow growth and limited dispersion are exacerbated by overexploitation. The International Union for Conservation of Nature classifies ebony as "vulnerable", facing a high risk of extinction in the wild in the near future due to habitat destruction and overexploitation. It is listed in Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) as it is threatened with extinction unless trade is strictly regulated.

In fact, intensive deforestation and environmental degradation pose a major threat to endemic plants and biodiversity, and affect populations in the wild (Meena & Jha, 2023); (Amos, 2025). While both ex-situ and in-situ

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conservation have been initiated, reforestation in formerly logged areas is frequently less optimal. Its success is challenged by limited knowledge of ecology and the characteristics of natural habitat. Numerous ecological factors may affect organism growth including the elements of physiography, climate, landscape, vegetation and soil. Meanwhile, continuous activities of agriculture, forestry, mining, and urbanization severely disturb the ecology, including edaphic habitats and biota (Rajakaruna & Boyd, 2019). Land degradation is one of the main global issues, particularly in tropical regions called the warehouses of valuable woods. Soil fertility is degraded by cultivation and the use of unsustainable technology. Therefore, land development for a luxury and endemic commodity should be based on the nature of species and its habitat, including land use, natural vegetation, physiography, soil properties, without disturbing the ecological balance and socio-economic conditions (Blesa-Marco et al., 2024); (Hu et al., 2024).

Adaptive capacity is influenced by genetic and environmental factors. In forest management, these factors significantly affect forest formation, growth, and productivity. While forest vegetation relies primarily on the interaction between climates and soil, the reciprocal relationship between vegetation and soil is fundamental. The dispersion pattern of a species depends on the number of individuals at the seedling and sapling stages, and is affected by biological factors, climate and soil. As the medium for growth, soil quality determines the quality and diversity of species in a region. Ebony is typically found in red-yellow podzolic, andosol, and yellowish-brown podzolic soils. However, ebony stands grow in red-yellow podzolic soils (ultisol) in their natural habitat in Mauro (Parigi) and in entisol soils in Mesua (the Western Coast of Donggala). Principally, soil types act as a guideline for improving and maintaining soil fertility. The growth and potential of trees produced in a natural stand can vary from one site to another. Different sites produce different seedlings, saplings, poles, and mature trees. The sites may vary in terms of watersheds, soil types, and climates. However, ebony generally grows in soils with moderate to high organic matter content. Soil fertility of sites can result in different stand productivity of ebony (Lodygin et al., 2023); (Menšík et al., 2019). In the modern context, soil fertility is a part of a dynamic system, significantly influenced by vegetation composition, ecology, and management practices. While soil properties are linked to the composition of the surrounding vegetation, the structure and composition of forest also greatly influence soil properties and fertility.

Soil fertility is crucial in forest management. Its maintenance determines stand growth and yield, forest productivity and timber production through the provision of essential nutrients, moisture, heat, and root support that enable trees to stand upright and sturdy (Mindawati et al., 2006); Stand composition, ecology, and management greatly affect the soil properties and fertility in forest. Additionally, soil fertility has implications on forest health, insisting on a proper carrying capacity management (Rachmadiyanto et al., 2020). The carrying capacity and land use type influence the soil fertility in terms of chemical, physical, and biological properties (Syofiani et al., 2020). As a medium for stand growth, forest soil is optimal with the support of physical, chemical, and biological properties. Soil physical and chemical properties shape the formation of forest vegetation and growth. These physical and chemical properties serve as the attributes for silvicultural practices leading the vegetation in terms of formation, growth, species composition, structure, and quality in accordance with forest functions. Relevant properties have been determined for land use analysis and ecological research in tropical forests.

The physical properties as the parameters of soil fertility are effective depth, soil texture and soil permeability (Batu et al., 2019). Meanwhile, the assessment of soil fertility to maintain soil productivity is done using a quantitative approach through soil chemical analysis that involves Cation Exchange Capacity/CEC (Achmad & Hadi, 2015) pH, available phosphorus, nitrogen, potassium, calcium, magnesium, organic matter, and base saturation (Lukina et al., 2019); (Panawong et al., 2021). The parameters of chemical properties for soil fertility are based on the criteria from the Center for Soil and Agroclimate Research for evaluating soil fertility in natural stands. Based on the criteria for soil fertility the soil fertility under the natural stands of ebony in the Sausu Watershed, Maleali, Parigi Moutong Regency is relatively low on the ridge and middle slopes, but higher on the lower slopes.

Geographically, the natural habitats of ebony in Mount Sojol and Sintuwu Maroso are located at different latitudes. The former is north of the Equator while the latter is south of the Equator, making distinctive patterns of the ebony heartwood. These differences influence the quality of ebony. However, the fertility levels of soil under the ebony natural stands in Sulawesi, particularly the Gunung Sojol Nature Reserve and the FMU Sintuwu Maroso have not been identified. Therefore, this study aimed at investigating the soil fertility, including the soil chemical and physical properties in both locations, to provide a basis for soil fertility management. The results can serve as a basis for effective cultivation and robust conservation strategies for both in-situ and ex-situ methods.

Method

Site observations were conducted in two locations, namely the administrative area of Donggala Regency and Poso Regency, Central Sulawesi Province. The sites are situated in the Gunung Sojol Nature Reserve and the FMU Sintuwu Maroso. The site observation was followed by laboratory research at the Soil Science Laboratory, Faculty of Agriculture, Tadulako University, Palu, Central Sulawesi. The activities were conducted from October 2022 to June 2024, including plot establishment and measurement, observation of soil morphology, and physical and chemical soil sampling. Descriptive approach was used with purposive sampling method to determine sample plots. Site orientation was carried out to observe the soil conditions and to determine the research plots representatively. Fertility assessment used a survey method. Plots of size 100 m x 100 m were allocated throughout the selected study area.

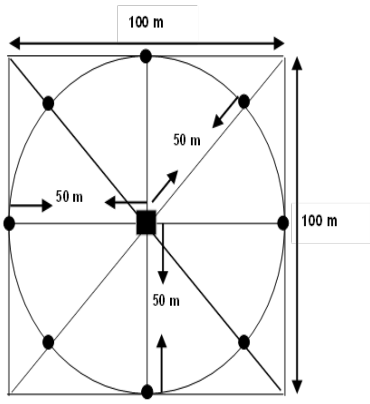

Figure 1. Research Plot Design for Soil Analysis

Subsequently, for the purposes of physical and chemical analysis, nine points (eight peripheral points in a circular plot and one central point) were established at each plot. The soil samples, both undisturbed and disturbed (repacked), were collected from each point. For the purposes of chemical properties and soil texture analysis, the disturbed samples were composited into one or two soil depth classes. The classes were 0-30 cm, and 30-60 cm. The sample of each depth class was composited into one. The soil samples represent a relatively similar area in terms of soil type, topography, slope, and parent material. The location of sampling in each plot is presented in Figure 1. Mineral soil samples should be composited for assessing the fertility status of forest land. Soil chemical analysis through composites is common for estimating soil fertility, also suggests the method of eight sample points in a circular plot with specific distance and one central point as the coordinate of the research area (Saleha & Ngakan, 2016).

Site Observation

Data collection was carried out through measurement, observation, and literature study. The primary data consists of physical and chemical soil properties, soil profiles, soil horizons, effective depth, slope, and vegetation. Plot establishment is aimed at obtaining the specified vegetation data. The parameters for soil analysis include: soil pH (H2O and KCl), organic matters (C, N), cation composition (Ca, Mg, K, Na), CEC, Al, H, P2O5 and K2O content (total and available). The parameters for physical soil properties are soil texture, permeability, bulk density, porosity, and soil moisture. Vegetation data were retrieved from plots of 100 m x 100 m located at the same location as the soil collection. Each plot was divided into 16 quadrats (25 m x 25 m) (Figure 2). Each quadrat consisted of three circular subplots, each consisting of: seedling data for measuring the seedling stage with a radius of 1 meter (0–1 m), sapling data with a radius of 2 meters (0–2 m), and pole data with a radius of 5 meters (0–5 m).

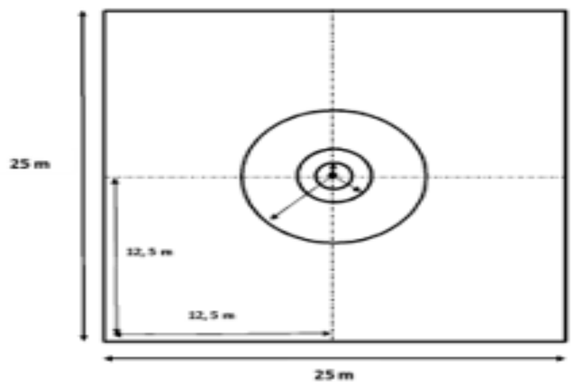

Figure 2. Quadrat layout for vegetation data

All the trees within the plots with a DBH of 10 cm or higher were evaluated. Measurement at 1.30 m above the ground was conducted using diameter tape. Tree height was measured from the base at the ground to the top of crown or peak, using a clinometer. The common names and the recognized scientific genus and species names of trees were identified during site observation. The specimens of unknown species were identified and verified at the Herbarium of Tadulako University with the Herbarium Celebence Profile Book and Checklist of Woody Plants of Sulawesi as the references.

Data Analysis

Data analysis includes physical and morphological analysis of the soil, chemical analysis of the soil, evaluation of soil fertility, vegetation and volume analysis of ebony.

Physical and Morphological Properties

Soil morphology analysis is based on the results of the soil profile description of each research plot for each site, referring to the Soil Survey Guideline. The parameters include: soil color, soil structure, consistency, and roots. The observed variables included: soil horizon thickness, soil color, structure, and soil physiography. The physical variables of the soil were examined through the disturbed and undisturbed samples, including soil texture, soil permeability, bulk density, soil porosity, and soil moisture. Soil texture is measured in the laboratory using the Stokes' law pipette method. Soil permeability is measured using the constant head permeameter method. The gravimetric method is used to calculate the bulk density. The undisturbed soil sample was oven-dried for 2 days at a temperature of 105 ^{o}C. The total weight (oven-dried soil + ring) was then subtracted by the weight of the ring to obtain the dry soil weight. Soil porosity is estimated based on the total porosity that is derived from the density of soil particles with constant value of 2.65 Mg m^{-3}. The soil moisture followed the method in.

Chemical Properties and Soil Fertility

The methods for soil chemical analysis include: The for organic carbon, for total nitrogen, the Bray method for the soil available phosphorus, total P, and total K using 25% HCl extraction, and the available potassium using 1 mol/L NH4OAc extraction followed by flame photometry, and a glass electrode for the soil pH measured in H2O and KCl at 1: 2.5 soil-to-solution ratio (Guo et al., 2022). The 1M Ammonium acetate buffered at pH 7.0 for CEC, and (f) The 1M Ammonium acetate with parameters of Ca, Mg, Na, and K for base saturation. The criteria for chemical properties and soil fertility are based on the guidelines of the Center for Soil and Agroclimate Research.

Tree Volume

The measurement of tree height is done using a clinometer from the ground to the top of the first living branch, while tree diameter using a measuring tape at 1.30 m above the ground. The volumes of *D. celebica* trees in Gunung Sojol Nature Reserve (v *NR*) and the FMU Sintuwu Maroso (v FMU) are represented by those in Mesua and Mauro, respectively. The equations are expressed as follow:

$$v\ (NR) = 0.3848.\, d_{1,3}^2.\, h + \ 0.0035\ d_{1,3}.\, h + \ 0.0001.\, h \quad (1)$$

$$v\ (FMU) = 0.2925.\, d_{1,3}^2.\, h + \ 0.0203\ d_{1,3}.\, h + \ 0.0005.\, h \quad (2)$$

Where:
v = volume (m^3)
$d_{1,3}$ = diameter at breast height (cm)
h = tree height (m).

Meanwhile, stand volume is estimated by summing the volumes of all the trees that make up the stand.

Vegetation Analysis

Since the soil fertility is greatly affected by vegetation, the Importance Value Index (IVI) must be determined prior to the analysis. The equations for calculating the IVI are as follows:

$$\text{Density} = \frac{\text{Total number of individuals}}{\text{Total area sampled}} \quad (3)$$

$$\text{Relative density} = \frac{\text{Frequency value of the species}}{\text{Total density of all species}}\ x\ 100\% \quad (4)$$

$$\text{Frequency} = \frac{\text{Number of quadrats in which the species occurred}}{\text{Total number of quadrats sampled}} \quad (5)$$

$$\text{Relative frequency} = \frac{\text{Frequency value of the species}}{\text{Sum of frequency of all species studied}}\ x\ 100\% \quad (6)$$

$$\text{Dominance} = \frac{\text{Total basal area (cover)of a species}}{\text{Total area of quadrat sampled}} \quad (7)$$

$$\text{Relative dominance} = \frac{\text{Dominance of a species}}{\text{Sum of the dominance of all species}}\ x\ 100\% \quad (8)$$

Result and Discussion

Vegetation Analysis and Ebony Stand Potential

As presented in Table 1–4, the vegetation analysis of the natural stands of ebony reveals differences in species composition, density, and dominance between Gunung Sojol and Sintuwu Maroso. Based on the Important Value Index (IVI) calculations at four growth stages in Gunung Sojol, the pole stage was dominated by ebony (IVI of 52.86%) while the seedling, sapling, and mature stages were dominated by Mangifera foetida, Neonauclea calycina, Calophyllum soulattri, and Dracontomelon dao. However, in Sintuwu Maroso, ebony dominated at almost all growth stages with very high IVI values, namely the seedling (143.06%), sapling (96.05%), pole (146.63%), and mature tree (70.65%).

Table 1. The IVI of Several Species at the Seedling Stage

Local name	Scientific name	Family	IVI
	Location: Gunung Sojol Nature Reserve		
Mangga	*Mangifera foetida*	Anacardiaceae	69.14
Eboni	*Diospyros celebica*	Ebenaceae	25.14
Nantu	*Palaquium obtosifolium*	Sapotaceae	16.78
Besusu	*Garcinia sp.*	Guttiferae	10.23
Laru	*Myristica*	Myristicaceae	5.11
Lebanu	*Neonauclea calycina*	Rubiaceae	5.11
Palili	*Lithocarpus sp.*	Fagaceae	5.11
Rao	*Dracontomelon dao*	Anacardiaceae	5.11
Suka	*Gentum gnemon*	Gnetaceae	5.11
Tapi-tapi	*Sondorium kucape*	Meliaceae	5.11
	Location: NFU Sintuwu Maroso		
Eboni	*Diospyros celebica*	Ebenaceae	143.06
Raja	*Cassia fistula*	Fabaceae	16.44
Wuli	*Eugenia sp.*	Myrtaceae	11.81
Damar ayam	*Agathis dammara*	Araucariaceae	7.18
Nantu	*Palaquium obtosifoliu*	Sapotceae	7.18
Kayu kambing	*Garuga floribunda*	Bureseraceae	7.18
Bayur	*Pterospermum celebicu*	Sterculiaceae	7.18
Bintangor	*Calophylum soulatri*	Guttiferae	7.18
Poli	*Bischefia javanica*	Euphorbiaceae	7.18
Pangi	*Pangium edule*	Flacourtiaceae	7.18

Table 2. The IVI of Several Species at the Sapling Stage

Local name	Scientific name	Family	IVI
Location: Gunung Sojol Nature Reserve			
Mangga hutan	*Mangifera foetida*	Anacardiaceae	20.81
Eboni	*Diospyros celebica*	Ebenaceae	15.61
Lebanu	*Neonauclea calycina*	Rubiaceae	15.61
Jongi	*Dillenia serata*	Dillineacea	15.61
Binuang	*Octomeles sumatrana*	Datisaceae	15.61
Laru	*Myristica sp*	Myristicaceae	12.91
Langsat	*Lansium humile*	Melaiceae	10.41
Palapi	*Terrietia javanica*	Sterculiaceae	10.41
Besusu	*Garcinia sp*	Guttiferae	10.41
Rao	*Dracontomelon dao*	Anacardiaceae	7.70
Location: NFU Sintuwu Maroso			
Eboni	*Diospyros celebica*	Ebenaceae	96.05
Damar ayam	*Agathis dammara*	Araucariaceae	12.98
Nantu	*Palaquium obtusifolium*	Sapotaceae	12.98
Tawafa	*Duabanga moluccana*	Sonneratiaceae	8.66
Kadundung	*Spondias pinnata*	Anacardiaceae	8.66
Poli	*Bischefia jacvanica*	Euphorbiaceae	7.27
Raja	*Cassia fistula*	Fabaceae	4.33
Lengaru	*Alstonia scholaris*	Apocynanceae	4.33

Table 3. The IVI of Several Species at the Pole Stage

Local name	Scientific name	Family	IVI
Location: Gunung Sojol Nature Reserve			
Eboni	*Diospyros celebica*	Ebenaceae	52.86
Besusu	*Garcinia sp*	Guttifere	32.26
Lengaru	*Altsonia scholaris*	Apocynaneae	27.24
Mangga hutan	*Mangifera foetida*	Anacardiaceae	21.96
Nantu	*Palaquium obtusifolium*	Sapotaceae	21.09
Laru	*Myristica sp.*	Myristicaceae	20.76
Palili	*Lithocarpus sp.*	Fagaceae	10.47
Tapi-tapi	*Sondorium kucape*	Meliaceae	10.47
Baloli	*Macaranga tanarius*	Euphorbiaceae	10.35
Rao	*Dracontomelon dao*	Anacardiaceae	9.94
Location: NFU Sintuwu Maroso			
Eboni	*Diospyros celebica*	Ebenaceae	146.63
Lengaru	*Alstonia scholaris*	Apocynaceae	21.15
Bayur	*Pterospermum celebicum*	Sterculiaceae	19.69
Kayu kambing	*Garuga floribunda*	Burseraceae	17.68
Benuang	*Octomeles sumatrana*	Datiscaceae	17.68
Damar ayam	*Agathis dammara*	Araucariaceae	11.55
Poli	*Bischefia javanica*	Euphorbiaceae	13.93
Nantu	*Palaquium obtusifolium*	Sapotaceae	8.68
Tawafa	*Duabanga moluccana*	Sonneratiaceae	8.60
Pangi	*Pangium edule*	Flacourtiaceae	8.60

Table 4. The IVI of Several Species at the Tree Stage

Local name	Scientific name	Family	IVI
Location: Gunung Sojol Nature Reserve			
Lebanu	*Neonauclea calycina*	Rubiaceae	31.85
Bintangor	*Calophylum soulatri*	Guttiferae	29.54
Bayur	*Pterospermu celebicu*	Sterculiaceae	29.53
Rao	*Dracontomelon dao*	Anacardiaceae	26.08
Mangga hutan	*Mangifera foetida*	Anacardiaceae	22.83
Palili	*Lihocarpus sp.*	Fagaceae	20.91
Lita-lita	*Litsea firma*	Lauraceae	12.34
Eboni	*Diospyros celebica*	Ebenaceae	9.42
Lengaru	*Alstonia scholaris*	Apocynaceae	8.06
Nantu	*Palaqium obtusifoliu*	Sapotaceae	7.35
Location: FNU Sintuwu Maroso			
Eboni	*Diospyros celebica*	Ebenaceae	70.56
Kayu kambin	*Garuga floribunda*	Burseraceae	38.56
Raja	*Cassia fistula*	Fabaceae	39.29
Damar ayam	*Agathis dammara*	Araucariaceae	21.41
Dao	*Drcontomelon dao*	Anacardiaceae	16.63
Nantu	*Palaquium obtusifolum*	Sapotaceae	15.45
Bayur	*Pterospermum celebicum*	Sterculiaceae	13.46
Tawafa	*Duabalanga moluccana*	Sonneratiaceae	9.06
Bintangor	*Calophylum soulatri*	Guttiferae	6.22
Lengaru	*Altsonia scholaris*	Apocynaceae	4.51

In Gunung Sojol, the most dominant species at the seedling stage were M. foetida, D. celebica, and P. obtusifolium with the IVI values of 69.14%, 25.46%, and 16.78%, respectively. At the sapling stage, M. foetida also obtained the highest IVI (20.81%), followed by D. celebica (15.61%), N. calycina, and Dillenia serrata. At the pole stage, ebony was dominant (IVI of 52.86%) along with Garcinia sp. (32.26%) and Alstonia scholaris (27.24%). At the tree stage, dominance shifted to N. calycina (31.85%), C. soulattri (29.54%), and Pterospermum celebicum (29.53%) with ebony only 9.42%. Overall, there were 19 to 23 species from 14 to 18 families with the number of individuals varying from 29 to 115 per growth stage in Mount Sojol. In Sintuwu Maroso, ebony dominates all stages with the highest density at the seedling level and 52.94% at the pole level. Other species, including Cassia fistula, Garuga floribunda, P. celebicum, Agathis dammara, and P. obtusifolium, obtained lower IVI values (7–39%). The number of species and families in Sintuwu Maroso is relatively low (7 to 19 species and 7 to 18 families), indicating a vegetation composition strongly dominated by ebony.

The main species in Barru Regency, Sulawesi, are ebony, sugar palm, intsia, Shorea spp., and Pandanaceae. In Babul Maros National Park, the main species consist of Arenga pinnata, Pandanus sp., Ficus spp., Vitex cofassus,

D. dao (dao), and dispersed ebony. In Kalaena Nature Reserve, East Luwu Regency, Sulawesi, ebony coexists with Octomeles sumatrana, Duabanga moluccana, and Pterospermum celebicum and dominates at the first two stages of growth in Tambarana. At the mature tree level, the number decreases, replaced by other species. In the present study, species diversity was quantified using the Shannon-Wiener Index (H') and the Margalef Index (Dmg) as presented in Table 6.

Table 5. Vegetation Level, Species, Families, and Number of Individuals

Location	Vegetation level	Species	Family	Number of individuals
Gunung Sojol Nature Reserve	Seedling	19	15	60
	Sapling	22	18	40
	Pole	16	14	29
	Mature tree	23	18	115
FMU Sintuwu Maroso	Seedling	7	7	108
	Sapling	18	17	68
	Pole	13	13	34
	Mature tree	19	18	68

Table 6. Shannon-Wiener Index and Margalef Index

Vegetation level	Gunung Sojol Nature Reserve		FMU Sintuwu Maroso	
Seedling	2.06	0.74	4.40	1.00
Sapling	2.96	1.70	5.69	4.03
Pole	2.62	1.83	4.45	3.40
Mature tree	2.97	2.35	4.64	4.27

The Shannon-Wiener Index (H') values show significant differences between the two locations. The species diversity in Mount Sojol ranged from moderate to high category (2.06–2.97), while the value was lower in Sintuwu Maroso (0.74–2.35). Similarly, the Margalef Index (Dmg) also showed that the species diversity in Gunung Sojol (4.40–5.69) was higher than that in Sintuwu Maroso (1.28–4.27). The number of individuals in Gunung Sojol (115) was higher than those in Sintuwu Maroso, yet the number of ebony in Sintuwu Maros outnumbered Gunung Sojol. The significantly higher number of ebony seedlings in Sintuwu Maroso (87 of 108) compared to Gunung Sojol (7 of 60) also indicates the potential for natural regeneration in the area. High density of ebony at the seedling, sapling, pole, and mature tree levels (17.30, 2.08, 143, and 24 individuals/ha, respectively) in Sintuwu Maroso was significantly higher than those in Gunung Sojol (1.39, 149, 40, and 4 individuals/ha, respectively) (Figure 3). It forms an inverse J-shaped curve, indicating a continuous natural regeneration and stable stand structure, similar to the pattern of population in Palanro Forest, Maros, Kalaena Nature Reserve, and Ponda-Ponda Nature Reserve.

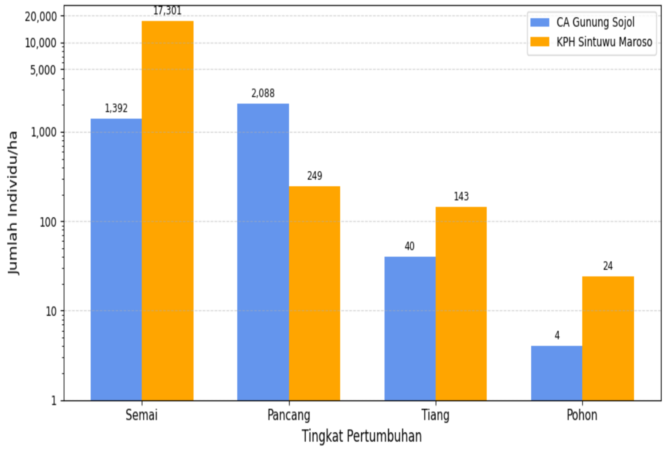

Figure 3. The number of *D. celebica* stands per hectare

In Mount Sojol, the mean diameter and height of ebony stands at the pole level was 11.25 cm and 11.64 m, respectively. Meanwhile, in Sintuwu Maroso, it was 12.21 cm and 11.78 m, respectively. At the mature tree level, the mean diameter reached 35.20 cm with a height of 18.60 m in Gunung Sojol, and 28.47 cm with a height of 20.22 m in Sintuwu Maroso. The maximum diameter was recorded at 41.1 cm in Gunung Sojol and 74 cm in Sintuwu Maroso, relatively similar to the findings of in the Forest Concession area of PT Inhutani I (55 cm). Meanwhile, in the Palanro Forest, Maros, the mean diameters at the pole level were 11 to 12 cm with heights of 5.5 to 6.5 m, respectively.

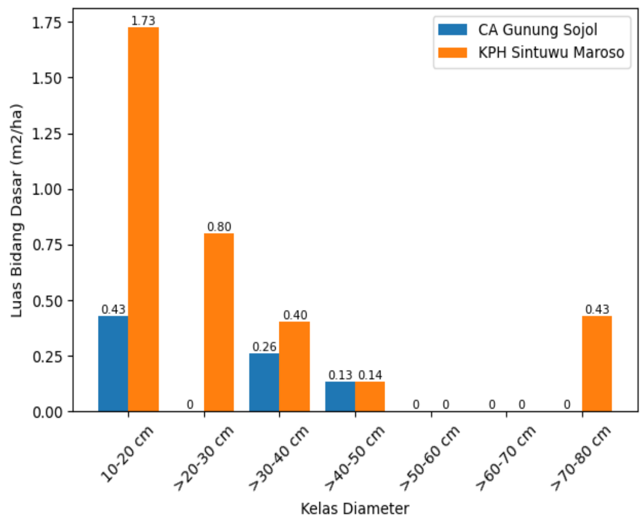

Figure 4. Basal area of ebony (*D. celebica*) based on diameter classes

The basal area of ebony in Mount Sojol was 0.82m²/ha (pole of 0.43 m²/ha and mature tree of 0.39 m²/ha). Meanwhile, it reached 3.49 m²/ha (pole of 1.72 m²/ha and mature tree of 1.77 m²/ha) in Sintuwu Maroso (Figure 4). The larger basal area in Sintuwu Maroso indicates that the site is more fertile and supportive for stem growth, confirming that soil fertility directly influences basal area. The basal area of ebony has been recorded of 0.81 m²/ha in Mamuju, 1.09–1.20 m²/ha in Mauro, and 0.47–0.59 m²/ha in Mesua. Nevertheless, the basal area of D. celebica in both Gunung Sojol and Sintuwu Maroso is relatively lower compared to previous reports in Mamuju, Mauro, and Mesua. The basal area of ebony is 0.81 m²/ha in Mamuju, 1.09–1.20 m²/ha in Mauro, and 0.47–0.59 m²/ha in Mesua. The basal area of tree in Mauro (1.20 m²/ha) consists of poles (0.11 m²/ha) with the area of 0.31, 0.35, 0.34, 0.09 and 1.09 m²/ha, respectively, for the tree diameter of 20-30, 30-40, 40-50, 50-60, and 60-70 cm. In Mesua, the basal area is 0.59 m²/ha consisting of poles (0.12 m²/ha) with the areas of 0.28, 0.14, 0.03, 0.02, and 0.47 m²/ha, respectively, for the tree diameter of 20-30, 30-40, 40-50, 50-60, 60-70 cm. Areas with high basal areas, such as the FMU Sintuwu Maroso, have the potential for greater stand volume. Conversely, areas with low basal areas, such as Gunung Sojol Nature Reserve, tend to have lower stock as reported by similar study commentators that the tree at the top of the tree list has the highest volume and IVI value. The stand volume in Sintuwu Maroso is presented in Figure 5. Figure 5 illustrates that the total tree volume in Sintuwu Maroso is 17.63 m³/ha, consisting of 16.49 m³/ha (24 mature trees) and 1.14 m³/ha (18 poles). This volume is higher than that of Gunung Sojol with a total volume of 6.35 m³/ha, consisting of 3.64 m³/ha (4 mature trees) and 2.71 m³/ha (5 poles).

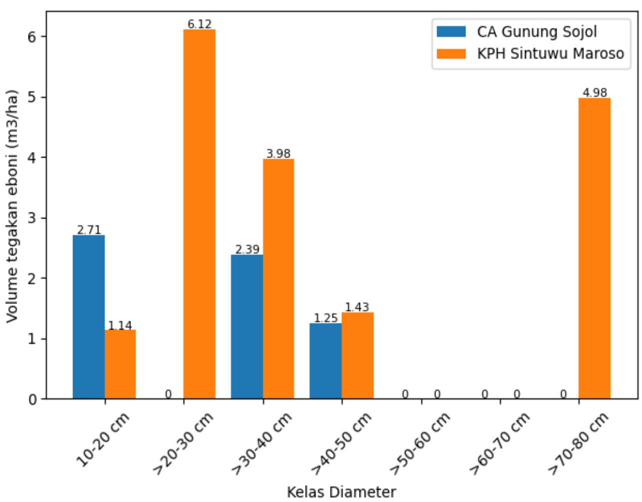

Figure 5. Natural stand volume of ebony (*D. celebica*)

The volume of ebony stands in Sintuwu Maroso was 17.63 m³/ha, consisting of 16.49 m³/ha (24 mature trees) and 1.14 m³/ha (18 poles), and only 6.35 m³/ha in Gunung Sojol, namely 3.64 m³/ha (4 mature trees) and 2.71 m³/ha (5 poles). The largest contributing diameter classes in Gunung Sojol were tree diameters of 30–39 cm (2.39 m³/ha) and 40–49 cm (1.25 m³/ha), while in Sintuwu Maroso, they were 10–19 cm (6.11 m³/ha) and larger than 60 cm (4.98 m³/ha). The potential volumes of stands in Sintuwu Maroso and Gunung Sonjol are higher than those in PT Inhutani I Mamuju of 5.01 m³/ha and Pangi Binangga Nature Reserve of 2.35 m³/ha. However, they are still below the maximum potential range of 30–60 m³/ha in the natural forest of Central Sulawesi. The volume of ebony in PT Inhutani I Mamuju is 5.01 m³/ha, while claims a potential of 2.35 m³/ha in Pangi Binangga Nature Reserve. The maximum potential volume of ebony in Maros, Barru, Sidrap, and Malili are 4.35, 6.75, 5.76, and 6.86 m³/ha, respectively, with the minimum potential from 2.25 to 3.16 m³/ha. Nevertheless, claims that the natural stands of ebony can reach 20 to 60 m³/ha in the natural forests in Central Sulawesi. The recorded volume of undisturbed stands is 30-60 m³/ha. The difference in the volume between Gunung Sojol and Sintuwu Maroso is not solely influenced by soil fertility, although both are categorized as moderate. Ebony can grow appropriately in soils with moderate to high soil fertility, as demonstrated by the volume of 5.83–8.46 m³/ha in moderate soil fertility and 4.85–6.39 m³/ha in high soil fertility in the Sausu Watershed area. A study in the FMU Dampelas Tinombo, Tonggolobibi Village, revealed a low potential volume of ebony stands, namely 0.23 and 0.06 m3/ha for mature tree and pole level, respectively. It is lower than the value namely 5.01 m³/ha with an estimated minimum mean volume of 3.16 and a maximum of 6.86 m³/ha.

Soil Physical Properties

The physical properties of soil under the natural stands of ebony in Gunung Sojol and Sintuwu Maroso show variations based on soil depth. The soil depth in Gunung Sojol and Sintuwu Maroso is, respectively, 100 and 110 cm. The average soil depth in ebony natural stands is greater than 100 cm in Palanro Forest, Maros, 120 cm in Kalaena Nature Reserve and 29.19 in Bantimurung National Park (Sari et al., 2021); (Tang et al., 2023); (Maeght et al., 2013). The effective root depths of ebony habitat in Mangkutana, Mamuju, Maros, and Poso are 45, 55, 55, and 60 cm, respectively. Meanwhile, in Amaro Forest, Barru Regency, the average depth is between 57 and 77 cm with remnants of stands at 25 cm soil depth. Shallow root system can affect ebony growth. Soil color was observed through the soil profile of Gunung Sojol, namely: layer 1 is very dark (10 YR 2/2), layer 2 is yellowish brown (10 YR 5/4), layers 3 and 4 are brown (10 YR 5/3), layer 5 is yellowish brown (10 YR 5/6), indicating high organic matter accumulation. The soil profile of Sintuwu Maroso consists of: layer 1 is very dark gray (10 YR 3/1), layer 2 is dark yellowish brown (10 YR 3/4), layer 3 is dark yellowish brown (10 YR 3/6), layer 4 is dark yellowish brown (10 YR 4/6), layer 5 is yellowish brown (10 YR 5/6), layer 6 is brownish yellow

(10 YR 6/8), and layer 7 is brown (10 YR 5/3). The soil in Gunung Sojol is darker than that in Sintuwu Maroso. Meanwhile, the latter is lighter with a looser structure, reflecting better aeration.

The soil in Gunung Sojol is relatively dense with a bulk density of 1.31–1.24 g/cm³, soil porosity of 50.59–51.35%, and soil permeability of 10.96–32.51 cm/hour. Meanwhile, the soil in Sintuwu Maroso has a lower bulk density (1.29–1.24 g/cm³), higher porosity (53.23–54.61%), and faster permeability (28.23–36.01 cm/hour). In Kalaena Nature Reserve, the bulk density values at soil depths of 0–30, 30–60, 60–90, and 90-120 cm are 1.29, 1.42, 1.44, and 1.38 g/cm³, respectively. The bulk density of the natural stands of ebony is 1.65 g/cm³ and 1.34 g/cm³ in the sandy loam soil of the Sausu Watershed. The examination of soil porosity under the natural stands of ebony in Gunung Sojol and Sintuwu Maroso showed the value of 50.59 % and 53.23%, respectively at soil depth of 0–30. It increased to 51.35% and 54.61%, respectively, at a depth of 30-60 cm. The values are classified as good and relatively similar to the values of soil porosity at ebony habitat in Pangi Binangga Nature Reserve of 51.84-54.30%.

Meanwhile, soil permeability in Pangi Binangga Nature Reserve ranged from 13.27 cm/hour (fast) to 32.51 cm/hour (very fast). The soils in Gunung Sojol and Sintuwu Maroso have crumbly and granular structure in the upper layers, and angular blocky structure in the lower layers. The crumbly and granular soil is also found at depth of 0-60 cm in the Pangi Binangga Nature Reserve. The soil moisture in Gunung Sojol at a depth of 0-30 cm (40.27%) is significantly higher ($p < 0.05$) than that in Sintuwu Maroso (27.20% (Figure 6).

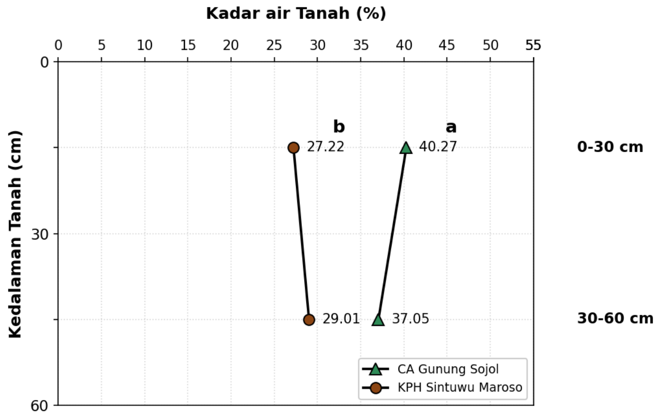

Figure 6. Soil moisture in Gunung Sojol Nature Reserve and the FMU Sintuwu Maroso

Soil Chemical Properties

The results of the chemical properties analysis of soil under ebony stands in Gunung Sojol and Sintuwu Maroso at depths of 0-30 and 30-60 cm are presented in Table 7. The properties include soil pH, organic carbon (*C*), exchangeable aluminum (*Al*) and hydrogen (*H*). Table 7 shows that the soil pH in the ebony habitat of Gunung Sojol is acidic (5.25 and 5.45 at depth of 0–30 and 30–60 cm, respectively), and slightly acidic in Sintuwu Maroso (6.10 and 6.09 at depth of 0–30 and 30–60 cm, respectively). This finding confirms previous studies carried out in the Western Coast of Donggala, namely: acidic soil (4.78) in Mesua, slightly acidic soil (5.92) in Dampelas Tinombo and Mauro (6.49), and neutral soil (6.62) in Sintuwu Maroso. Meanwhile, the soil in the Sausu Watershed varies from 4.69 (acidic) to 6.39 (slightly acidic). A study on ebony growth in Cikampek, West Java (acidic soil of 4.59) shows slower development than those in the natural habitat Malili (pH of 5.89). This species grows well at a pH of 4.8-6.9 and is considered well-suited at 5.60-7.50.

Table 7. Chemical Properties of Soil Based on Soil Depths

	Gunung Sojol Nature Reserve		FMU Sintuwu Maroso	
Chemical Properties	0-30 cm	30-60 cm	0-30 cm	30-60 cm
pH H_2O	5.25	5.45 (M)	6.10	6.09
KCl pH	4.55	3.94	4.81	4.51
Organic C (%)	6.29	4.55	2.85	2.45
Total N (%)	0.22	0.16	0.11	0.09
C/N	28.59	28.44	32.25	14.80
Total K (mg/100 g)	39.44	45.75	29.64	28.33
Total P (mg/100 g)	47.94	48.08	19.37	24.58
Available P (ppm)	19.38	24.51	10.02	12.86
CEC (cmol (+) kg^{-1})	32.39	40.82	27.12	27.83
Ca (cmol (+) kg^{-1})	11.24	4.88	10.46	10.97
Na (cmol(+) kg^{-1})	0.62	0.28	0.15	0.22
K (cmol(+) kg^{-1})	0.56	0.46	0.10	0.05
Mg (cmol(+) kg^{-1})	1.19	1.53	1.47	0.78
Base saturation (%)	42.02	17.52	44.91	43.19
Al-dd (cmol(+) kg^{-1})	0.80	1.99	0.38	0.50
H-dd (cmol (+) kg^{-1})	0.20	0.20	0.09	0.10

At 0–30 cm, the soil in Gunung Sojol has very high organic C (6.29%), moderate total N (0.22%), high total P (47.94 mg/100 g), moderate available P (19.38 ppm), and moderate total K (39.44 mg/100 g). These values are higher than in Sintuwu Maroso, which has moderate organic C (2.85%), low total N (0.11%), moderate total P (19.37 mg/100 g), low available P (10.02 ppm), and moderate total K (29.64 mg/100 g). Similarly, at 30-60 cm, Mount Sojol also obtains higher values (namely, high organic C (4.55%, moderate total N (0.16%), high total P (48.08 mg/100), high available P (24.51 ppm), moderate total K (45.75 mg/100 g)) than those in Sintuwu Maroso (namely, moderate organic C (2.45%, low total N (0.09%), moderate total P (24.58 mg/100 g), moderate available P (12.86 ppm) and low total K (28.33 mg/100 g). Those areas dominated by ebony have relatively low organic C levels. verifies the finding, claiming the organic C level decreases from 2.64% at soil depth of 0–30 cm to 1.49% at 30–60 cm. Furthermore, despite the relatively high density of ebony in Sintuwu Maroso, the organic matter content is lower, consistent with the findings in other locations such as Poso, Maros, Mangkutana, and Mamuju. Elevation also plays a significant role in the higher organic matter in Mount Sojol, as lower temperatures at higher altitudes slow decomposition and increase surface organic C. In Amaro Forest, organic C reaches 4.31 to 5.45%. The C/N ratio in Gunung Sojol at soil depth of 0–30 cm (28.58) and 30–60 cm (28.44) is very high.

In Sintuwu Maroso, the C/N value is lower, namely 22.82 at the upper and 15.11 at the lower layer. The mean C/N ratio in Gunung Sojol is high (28.53), while in Sintuwu Maroso it is moderate (18.96). (Rukmi et al., 2023) affirms that the ideal C/N ratio for a balance of mineralization and immobilization ranges from 15 to 25. Meanwhile, the C/N ratio of soil in Maleali varies between 14.30 to 32.25. N, P, and K are essential for plant metabolism. Nitrogen (N) is required in the formation of proteins, amino acids, and chlorophyll. P is vital in the formation of ATP, DNA, and RNA. Meanwhile, K supports plant physiological processes, including enzyme activation, stomatal regulation, and resistance to biotic and abiotic stresses (Yani Kamsurya & Botanri, 2022). At acidic pH soil, P solubility frequently decreases due to fixation by Al^{3+}, but mycorrhizal symbiosis increases phosphorus absorption by ebony roots. The levels of CEC in Gunung Sojol, namely 32.39 and 40.82 cmol(+) kg^{-1} at soil depth of 0–30 cm and 30–60 cm, respectively, are higher than those in Sintuwu Maroso of 27.12 and 27.83 cmol(+) kg^{-1}. The higher CEC level in Gunung Sonjol indicates the larger soil capacity to store nutrients, which is directly correlated with the availability of macro and micro nutrients, than in Sintuwu Maroso. The higher organic matter accumulation in Mount Sojol also contributes to the CEC level. Furthermore, differences in CEC levels between locations are highly affected by the condition of organic matter and precipitation. Higher precipitation in Gunung Sojol (2,872 mm/year) than Sintuwu Maroso (2,429 mm/year) surely supports organic matter accumulation through improved vegetation productivity and soil biological activities. (Autufuga et al., 2023) suggest that high precipitation is followed up by high amounts of organic matter as the indirect source of CEC.

Compared to the CEC level in Amaro Forest, namely 13.93 cmol(+) kg^{-1} with 5.45% organic carbon that is higher than in site 1 (a CEC of 8.76 cmol(+) kg^{-1} and 4.31% organic carbon), the CEC levels of both Gunung Sojol and Sintuwu Maroso are higher. It confirms that the presence of organic matter has a major influence on increasing the CEC of soil under ebony stands. Exchangeable base analysis showed that the Ca content at the upper layer soil (11.24 cmol(+) kg^{-1}, high category) of the natural stands in Gunung Sojol was higher than that at the lower layer (4.88 cmol(+) kg^{-1}, low category). In contrast, in the Sintuwu Maroso, the Ca content was relatively stable, namely 10.46 cmol(+) kg^{-1} at the 0–30 cm layer and slightly increased to 10.97 cmol(+) kg^{-1} at the 30–60 cm layer. The Mg content in Gunung Sojol was moderate, namely 1.19 cmol(+) kg^{-1} at the upper layer and 1.53 cmol(+) kg^{-1} at the lower layer. In Sintuwu Maroso, the Mg content decreases from 1.47 cmol(+) kg^{-1} to 0.78 cmol(+) kg^{-1} with increasing depth. The Na content in Gunung Sojol decreases with increasing depth, namely 0.62 cmol(+) kg^{-1} (moderate) at a depth of 0–30 cm and 0.28 cmol(+) kg^{-1} (low) at 30–60 cm. Meanwhile, in Sintuwu Maroso, the levels were low at both depths, 0.15 and 0.22 cmol(+) kg^{-1}, respectively. The K content in Gunung Sojol was moderate (0.56 cmol(+) kg^{-1} at the upper layer) and slightly decreased at the lower layer (0.46 cmol(+) kg^{-1}).

In Sintuwu Maroso, the levels were low (0.10 cmol(+) kg^{-1}) at soil depth of 0–30 cm and very low (0.05 cmol(+) kg^{-1}) at 30–60 cm. Exchangeable bases in soil consist of essential cations, such as calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), and potassium (K^{+}), which determine the base saturation level. In Gunung Sojol, the base saturation was high (42.02%) at soil depth of 0–30 cm and low (17.17%) at 30–60 cm. Meanwhile, in Sintuwu Maroso, the levels at both depths were high, 44.91% and 43.19%, respectively.Base saturation is strongly linked to soil pH and precipitation. The acidic pH soil with lower base saturation due to higher precipitation in Mount Sojol influences the exchangeable base. In Sintuwu Maroso, the lower C/N ratio and slightly acidic pH lead to the more adaptive ebony due to higher base saturation. The exchangeable aluminum content (Al-dd) in the ebony habitat in Mount Sojol is 0.80 and 1.99 me/100 g, respectively, at soil depth of 0–30 and 30–60 cm. The values are higher than those in Sintuwu Maroso, namely 0.38 and 0.50 me/100 g. The higher acidic level of soil in Gunung Sojol than in Sintuwu Maroso causes the higher Al-dd content since the Al^{3+} ions are more active in solution and toxic to vegetation in acidic conditions (pH < 5.5). The higher Al-dd content is allegedly caused by the acidic soil pH and higher precipitation. Conversely, the lower Al-dd content indicates a slightly acidic soil reaction with slower alkaline leaching and lower potential aluminum toxicity to ebony growth (Liu et al., 2025); (Cornelissen et al., 2018). Higher precipitation has the potential to accelerate leaching (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) and elevate the dominance of Al^{3+} ions in the soil.

Soil Fertility

Based on the soil fertility assessment criteria, the soil fertility status can be determined using the parameters of CEC, base saturation, total P, total K, and organic C as presented in Table 8.

Table 8. Soil Fertility under the Natural Stands of D. celebica

Parameter	Gunung Sojol Nature Reserve	FMU Sintuwu Maroso
CEC (me/100 gr)	36.61 (H)	27.48 (M)
Base saturation (%)	29.77 (L)	44.05 (M)
Total P (mg/100 gr)	48.01(H)	21.98 (M)
Total K (mg/100 gr)	42.59 (H)	28.98 (M)
Organic C (%)	5.42(VH)	2.15 (M)
Soil fertility	Moderate	Moderate

*VL= extremely low, M= moderate, H= high, VH= very high

The fertility status of soils under the natural stands of ebony in the study area is classified as moderate (Table 8). In Gunung Sojol, soil fertility is limited by base saturation, despite the high levels of Total P, Total K, and Total C. Meanwhile, the soil fertility in Sintuwu Maroso is limited by moderate levels of all parameters. Site observations reveal that the differences in CEC and base saturation levels at the two locations reflect variations in soil chemistry as well as indicating a unique environmental response to vegetation cover (Mustafa et al., 2024). Soil fertility is determined by several chemical parameters, such as CEC, base saturation organic C and macronutrients such as phosphorus and potassium (Onyegbule et al., 2023); (Usman & Jayeoba, 2025). The volume of ebony stands in Sintuwu Maroso is greater than that in Gunung Sojol. Despite similar soil fertility status (moderate), the characteristics of the elements are different. The former location has a lower organic C content and C/N ratio less than 20, indicating a dominant mineralization process that supports the availability of nitrogen. Meanwhile, in Gunung Sojol, a higher C/N ratio decelerates the decomposition rate, causing some nitrogen to remain in unavailable forms. Low CEC and high CEC in soils potentially limit the effectiveness of cation exchange (Hansson et al., 2020); (Purnamasari et al., 2021); (Fang et al., 2017). The soil fertility status determines the land management system that relates to the CEC and base saturation level (Ma et al., 2024); (Nadalia et al., 2025) The higher the CEC, the more fertile the soil, supported by base cations as essential nutrients for tree growth. The higher the base saturation, the higher the pH is. Soil with a base saturation of less than 50% is classified moderate to low fertile, while a level greater than 50% is highly fertile soil (Kasno et al., 2021); (Zhang et al., 2023).

Conclusion

The natural stands of ebony (*Diospyros celebica* Bakh.) in the Gunung Sojol Nature Reserve and the Forest Management Unit of Sintuwu Maroso have been studied in terms of chemical properties, physical properties, and soil fertility. The results reveal the strong dominance of ebony at all growth levels in Sintuwu Maroso with the IVI values of 143.06%, 96.05%, 143.63%, and 70.65% at seedling, sapling, pole, and mature tree level, respectively. Meanwhile, in Gunung Sojol, ebony is only dominant at pole level (an IVI of 52.86%). The total volume of ebony ranges from 2.71 to 6.35 m^3/ha in Gunung Sojol, and 4.98 to 13.65 m^3/ha in Sintuwu Maroso, indicating a higher stand potential of the latter. The volume difference is primarily affected by soil physical properties, particularly the ideal soil moisture at soil depth of 0-30 cm in Sintuwu Maroso. The medium texture with optimal soil moisture in Sintuwu Maroso supports better growth and larger volume than the coarse soil in Gunung Sojol. The soil in Gunung Sojol is characterized by acidic pH (pH 5.25–5.45), very high organic C (5.42%), high total P (48.01 mg/100 g), high total K (42.59 mg/100 g), and Al-dd (0.8–1.99 me/100 g). Meanwhile, the soil in Sintuwu Maroso is slightly acidic (6.09–6.10) with moderate organic C (2.15%), moderate total P (21.98 mg/100 g), moderate total K (28.98 mg/100 g), and base saturation (0.38–0.50%). Despite the high organic matter content and CEC (36.61 cmol(+)/kg), the soil fertility of Gunung Sojol is hampered by low acidity and base saturation (29.77%). Meanwhile, Sintuwu Maroso has a slightly acidic soil with a moderate CEC (27.48 cmol(+)/kg) and moderate base saturation (44.05%), but low nutrient and organic matters. In general, both locations have moderate soil fertility. The findings of the present study contribute scientifically to the determination of ex-situ conservation of ebony in accordance with the soil physical properties, chemical properties, and fertility in its natural habitat in the Gunung Sojol Nature Reserve and the FMU Sintuwu Maroso. The findings are expected to enhance the understanding of the ecology and conservation needs of ebony through soil characterization based on physical, chemical, and fertility aspects. The findings can be a basis for conservation planning in the ebony natural habitat in the Gunung Sojol Nature Reserve and the FMU Sintuwu Maroso, Sulawesi.

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Author Contributions

Conceptualization, A.T.; methodology, A.T., M.H; formal analysis, A.T., A.M., I.R.; investigation, A.T., A.M., I.R; resources, A.T., A.M., I.R.; data curation, A.T., A.M., I.R; writing—original draft preparation, A.T.; writing—review and editing, A.T., M.H. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest.

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