Tree species distribution analysis for eco forest city development in Medan Belawan Subdistrict, North Sumatra, Indonesia

Suranto Suranto[1,6], *Rahmawaty* Rahmawaty[1,2*], *Isnen* Fitri[1,3], *Luthfi* Hakim[1,2], *Abdul* Rauf[1,4], *Delvian* Delvian[1,2], and *Mehmet* Cetin[5]

[1]Natural Resource and Environmental Management Study Program, Postgraduate School, Universitas Sumatera Utara, USU Padang Bulan Campus, Medan 20155, North Sumatra, Indonesia
[2] Faculty of Forestry, Universitas Sumatera Utara, USU Kuala Bekala Campus 2, Pancur Batu, Deli Serdang, North Sumatra, Indonesia
[3] Faculty of Engineering, Department of Architecture, Universitas Sumatera Utara, Padang Bulan Campus, Medan, North Sumatra, Indonesia
[4]Faculty of Agriculture, Department of Agrotechnology, Universitas Sumatera Utara, Medan 20155, North Sumatra, Indonesia
[5]Faculty of Architecture, Department of City and Regional Planning, Samsun, Ondokuz Mayis University, Türkiye
[6]Faculty of Engineering and Computer Science, Department of Civil Engineering, Universitas Pembinaan Masyarakat Indoneisa, Medan, North Sumatra, Indonesia

Abstract. Medan Belawan Subdistrict, a coastal area of Medan City, faces increasing urbanization pressures that threaten the sustainability of green open spaces (GOS), particularly mangrove ecosystems. This study aims to map the composition and spatial distribution of tree species in GOS, analyze community structure using the Shannon–Wiener diversity index (H′), Simpson dominance index (D), and evenness index (1−D), and propose a contextual Eco Forest City (EFC) model for coastal urban environments. Data were gathered through a comprehensive tree census (DBH ≥ 20 cm) in terrestrial GOS and plot sampling in mangrove areas, with spatial analysis used to examine species distribution, dominance, and green–blue connectivity. The results revealed that 72.02% of the 218 GOS units were mangrove areas, with *Avicennia marina* dominating at 48.17% and a density of 668 ind/ha. The community indices indicated moderate diversity (H′ = 1.65), high dominance (D = 0.232), and moderate evenness (1−D = 0.72). The proposed EFC model emphasizes the protection of mangrove ecosystems, enrichment with adaptive species, diversification of terrestrial corridors, and the creation of vegetated bioswales to enhance green–blue connectivity. These strategies provide a scientific basis for sustainable, climate-adaptive coastal urban planning in Indonesia.

* Corresponding author: rahmawaty@usu.ac.id

1 Introduction

Medan Belawan Subdistrict is a strategic coastal zone within Medan City that is undergoing rapid urbanization, land conversion, and complex environmental dynamics, including tidal fluctuations, saline intrusion, and coastal abrasion. These conditions necessitate managing green open spaces (GOS) as ecological infrastructure to maintain coastal stability, mitigate urban heat, filter pollutants, support biodiversity, and improve residents' quality of life [1–4]. However, GOS in Belawan is unevenly distributed: most units are concentrated in coastal mangroves, while terrestrial green corridors are limited and green–blue connectivity remains suboptimal. This imbalance heightens climate vulnerability and reduces the equitable distribution of ecosystem services across residential areas [2,4,5]. Globally, urban planning is shifting toward Nature-based Solutions (NbS) and integrated green–blue infrastructure to strengthen socio-ecological resilience, [2,4–7], supported by emerging frameworks and empirical evidence of benefits for climate resilience and human well-being.

Tree species distribution is a key indicator of interspecific interactions and ecosystem stability [3,8,9]. Spatial analyses of species patterns underpin biodiversity conservation and ecological balance in urban landscapes. These patterns are shaped by habitat heterogeneity and dispersal limitation, which influence community structure and natural regeneration. Accordingly, spatial analysis of tree distributions within GOS is essential for ecological urban planning and for formulating an Eco Forest City (EFC) model in coastal regions.

The EFC concept extends the traditional green-city paradigm by designing cities as ecological networks that integrate tree stands, urban forests, vegetated corridors, and green–blue systems from coast to inland [2,4,6–8]. Management is adaptive and data-driven, using species composition and ecological indicators. Recent studies show that urban forests mitigate heat and drought yet face increasing climate risks that must be mapped at city scale to guide species selection and maintenance strategies. Small green spaces and community gardens also function as ecological stepping stones that enhance biodiversity and connectivity within the urban matrix.

A notable research gap is the dominance of GOS assessments based solely on land cover or tree counts, with limited attention to community structure (diversity, dominance, evenness) and coastal–terrestrial connectivity. Recent literature highlights the value of the Shannon–Wiener index (H′) and Simpson's dominance index (D) for measuring diversity and dominance across urban land types, while supporting diversification to reduce degradation risks associated with taxonomic homogeneity [8–11]. In coastal settings, mangrove ecosystems provide critical services—shoreline protection, carbon sequestration, and water filtration—yet face urbanization pressures and varying salinity and inundation gradients [6–8,12,13]. Management strategies that integrate mangrove mosaics with urban landscapes are therefore essential to sustain coastal ecological systems.

Against this backdrop, this study evaluates GOS conditions and tree communities in Medan Belawan through spatial and ecological approaches to formulate a context-specific EFC model. We integrate species-distribution mapping, community index analysis (H′, D, 1−D), and green–blue connectivity assessment to identify priority intervention areas—such as dominance hotspots and low-connectivity nodes [2,4,6,8,9]. The findings aim to provide a scientific basis for species diversification and for enhancing green–blue networks that connect coastal and residential zones, while supporting adaptive management through risk mapping and climate-resilient species selection to establish a contextual EFC model for Belawan.

2 Materials and methods

This study was conducted in Medan Belawan Subdistrict, Medan City, North Sumatra Province, Indonesia, during the period of June to September 2025. The area was selected purposively because it represents a strategic coastal zone experiencing intense urbanization pressure, dominated by mangrove ecosystems, and exhibiting an uneven distribution of GOS between coastal and terrestrial zones [8,12,13]. These characteristics make it a relevant case for assessing coastal resilience, ecosystem service dynamics, and ecological integration potential within the EFC framework.

The research employed a combination of community ecology analysis and spatial analysis using Geographic Information Systems (GIS) to establish a scientific basis for developing a contextual and applicable EFC model [9,10,14]. The integration of these approaches enabled the evaluation of species composition, community structure, and spatial relationships among GOS units in the context of climate change mitigation and sustainable spatial planning.

2.1 Vegetation data collection

2.1.1 Tree census in mainland public green open space

Vegetation data in the terrestrial area were collected using a total census method, covering all tree individuals with a diameter at breast height (DBH) ≥ 20 cm within various types of public GOS, including road and river green belts, urban parks, city forests, cemeteries, and other public vegetated spaces. For each individual tree, the following attributes were recorded: Latin name, number of individuals, DBH, tree height (when applicable), and GPS coordinates.

The total census approach was chosen because it provides a comprehensive representation of vegetation composition and structure, allowing accurate calculation of community indicators such as species proportion, dominance level, and diversity indices. This method has been widely applied in GIS-based studies of urban tree distribution and in planning green–blue corridors [2–4,10,14].

2.1.2 Plot sampling mangrove

In mangrove ecosystems, data collection was carried out using 10 × 10 m sampling plots, which were purposively placed along gradients of salinity, inundation, and substrate type. Within each plot, all trees were recorded by species, and measurements included number of individuals, DBH, height, and stand structure parameters [6–8,11–13,15].

This design was selected to capture the high spatial variability of mangrove vegetation, which tends to form clustered distributions strongly influenced by the physical and chemical characteristics of coastal waters. Species identification and interpretation of community structure followed established literature on salinity tolerance, physiological drivers, and the ecological functions of mangroves in providing environmental services.

2.2 Spatial data collection

The spatial data used in this study included administrative boundary shapefiles, public GOS inventories, land-use maps, and high-resolution satellite imagery for vegetation cover verification (Fig. 1). Road, river, canal, and drainage networks were compiled to support the analysis of potential green–blue corridors that function as ecological linkages among GOS units.

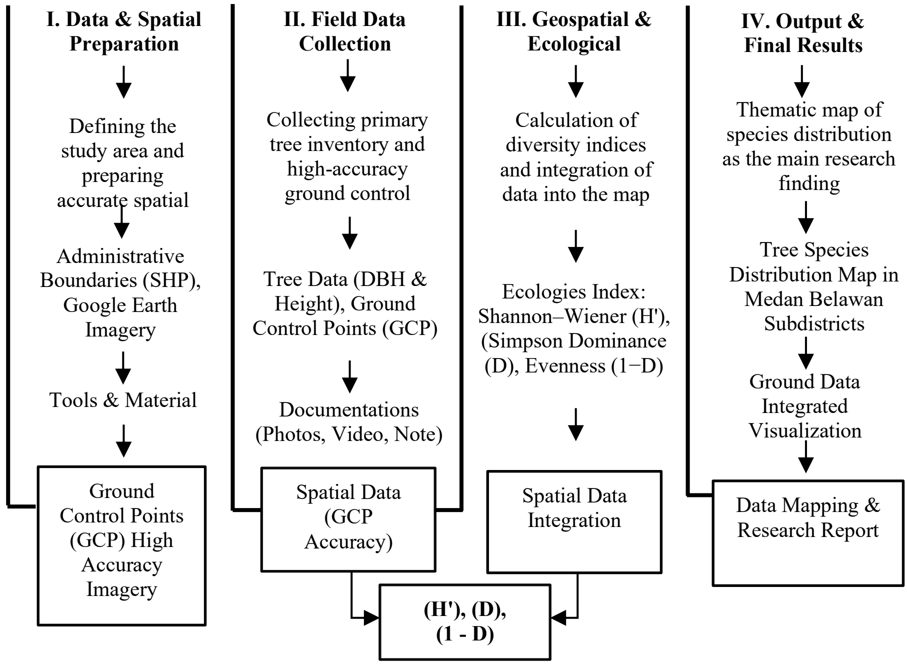


Fig. 1. Research methodology framework for tree species analysis in Medan Belawan subdistrict.

All spatial datasets were processed in ArcGIS 10.8 through stages of georeferencing, digitizing, overlaying, and spatial analysis to produce an accurate geospatial database. These analyses were used to map tree species distribution, identify dominance zones, and determine priority areas for ecological intervention within the green open space system (Fig. 1).

2.3 Spatial analysis

The initial analytical stage involved mapping the spatial distribution of tree species based on individual points within each GOS segment. This mapping process was used to identify vegetation distribution patterns—whether random, clustered, or uniform—to understand the dynamics of urban tree communities. Subsequently, species composition and dominance were mapped by calculating species proportions and dominance values at each observation site.

The resulting distribution data were processed to produce dominance hotspot maps, using spatial interpolation and heatmap analysis. Zones with high dominance levels were identified as priority areas for vegetation diversification, aiming to reduce the risk of ecological homogenization [3,4,8,9]. Based on the spatial mapping results, all GOS units were classified into three ecological position categories:

(1) Coastal zones dominated by core mangrove ecosystems;
(2) Terrestrial corridors, including roadside green belts, parks, and cemeteries; and
(3) Ecological gaps, potential spaces for developing vegetative linkages between patches.

Furthermore, green–blue connectivity analysis was performed through overlaying GOS layers with water and transportation networks. This process aimed to detect potential ecological corridors—such as bioswales, vegetated pathways, and pocket parks—and to identify low-connectivity nodes that require ecological reinforcement [4–7].

This analytical framework aligns with the risk-informed urban forestry approach widely applied in metropolitan-scale studies to assess urban forest resilience, guiding adaptive species selection and maintenance strategies under climate risk conditions.

2.4 Analysis of tree community structure

Tree community structure analysis was conducted to evaluate the levels of species diversity and dominance across various ecosystem types. Three ecological indices were employed: the Shannon–Wiener Diversity Index (H′), the Simpson Dominance Index (D), and the Evenness Index (1−D). These indices are standard measures in community ecology for assessing the complexity, stability, and distribution balance of individuals among species [9,11,15].

The Shannon–Wiener Index (H′) was used to assess species diversity by considering both species richness and evenness. A high H′ value indicates a community with diverse species and evenly distributed individuals. The formula for H′ is:

$$H' = -\sum_{i=1}^{S} p_i \ln\, p_i \qquad (1)$$

where:
S = number of species; $p_i = n_i/N$; n_i= number of individuals of species i; N= total number of individuals; and ln = natural logarithm.

The Simpson Dominance Index (D) measures the degree to which a community is dominated by one or a few species—the higher the D value, the stronger the dominance. The formula for D is:

$$D = \sum_{i=1}^{S} p_i^2 \qquad (2)$$

Higher D values indicate greater dominance by one or several species. The Evenness Index (1−D) indicates how evenly individuals are distributed among species; higher values represent greater community balance. The formula for 1−D is:

$$1 - D = 1 - \sum_{i=1}^{S} p_i^2 \qquad (3)$$

Larger (1−D) values indicate more even distribution of individuals among species.

To ensure consistent interpretation across scales, Hill numbers were adopted as a conceptual framework, strengthening the comparability between sites and sampling efforts while mathematically linking entropy (H′) and effective diversity [1,9].

2.4.1 Stand structure (diameter, height, and basal area)

To complement the community analysis, tree diameter at breast height (DBH), height, and basal area (BA) were measured. The basal area per tree (in m²) was calculated using the following formula:

$$LBBD = \frac{\pi\,(DBH/100)^2}{4} \qquad (4)$$

Aggregated values were calculated per plot or per hectare to enable comparison of stand structures between locations and GOS types.

2.4.2 Environmental factor analysis

Tree community structure and composition are strongly influenced by coastal environmental conditions. Therefore, salinity, air humidity, and temperature were measured at each observation site. These parameters were analyzed to determine the relationship between environmental factors and species dominance, particularly for mangrove communities that are highly sensitive to salinity gradients, inundation duration, and coastal microclimate conditions [5,9].

2.4.3 Annual diversity change analysis

To monitor community dynamics over time, annual changes in species diversity were calculated by comparing Shannon–Wiener (H′) values between observation periods. The percentage change in diversity was determined using the following formula:

$$\Delta H^{'}(\%) \; = \; \frac{H^{'}_{t} - H^{'}_{t-1}}{H^{'}_{t-1}} \times 100\% \qquad (5)$$

This serves as an early indicator of increasing or declining diversity and supports adaptive management decision-making.

2.5 Formulation of the Eco Forest City (EFC) model

The EFC model was formulated by integrating ecological and spatial analysis results through three main stages:

(1) Ecological–spatial synthesis: combining community index results (H′, D, 1−D), species distribution and dominance maps, and green–blue connectivity layers to determine the ecological roles of each system component:
  a) Coastal mangrove ecosystems as core ecological zones,
  b) Terrestrial vegetation corridors as linkages between coastal and residential zones, and
  c) Ecological nodes such as bioswales and pocket parks to strengthen local connectivity.

(2) Implementation strategy formulation: including core mangrove protection, adaptive species enrichment, vegetation diversification to reduce species-specific dominance, and connectivity enhancement through vegetated pathways and green–blue infrastructure development.

(3) Collaborative governance strengthening: encouraging multi-stakeholder participation—including government, communities, academia, and the private sector—to ensure that EFC implementation remains applicable, climate-adaptive, and ecologically sustainable.

3 Results

3.1 Location map of Medan Belawan Subdistrict, Medan city

This map illustrates the administrative boundaries and spatial coverage of Medan Belawan Subdistrict, which served as the study area. The map highlights the coastal–urban landscape comprising GOS, mangrove ecosystems, and terrestrial vegetation corridors. The study focuses on the spatial distribution of tree species as the empirical foundation for developing a contextual EFC model for coastal urban environments in Medan City, North Sumatra, Indonesia.

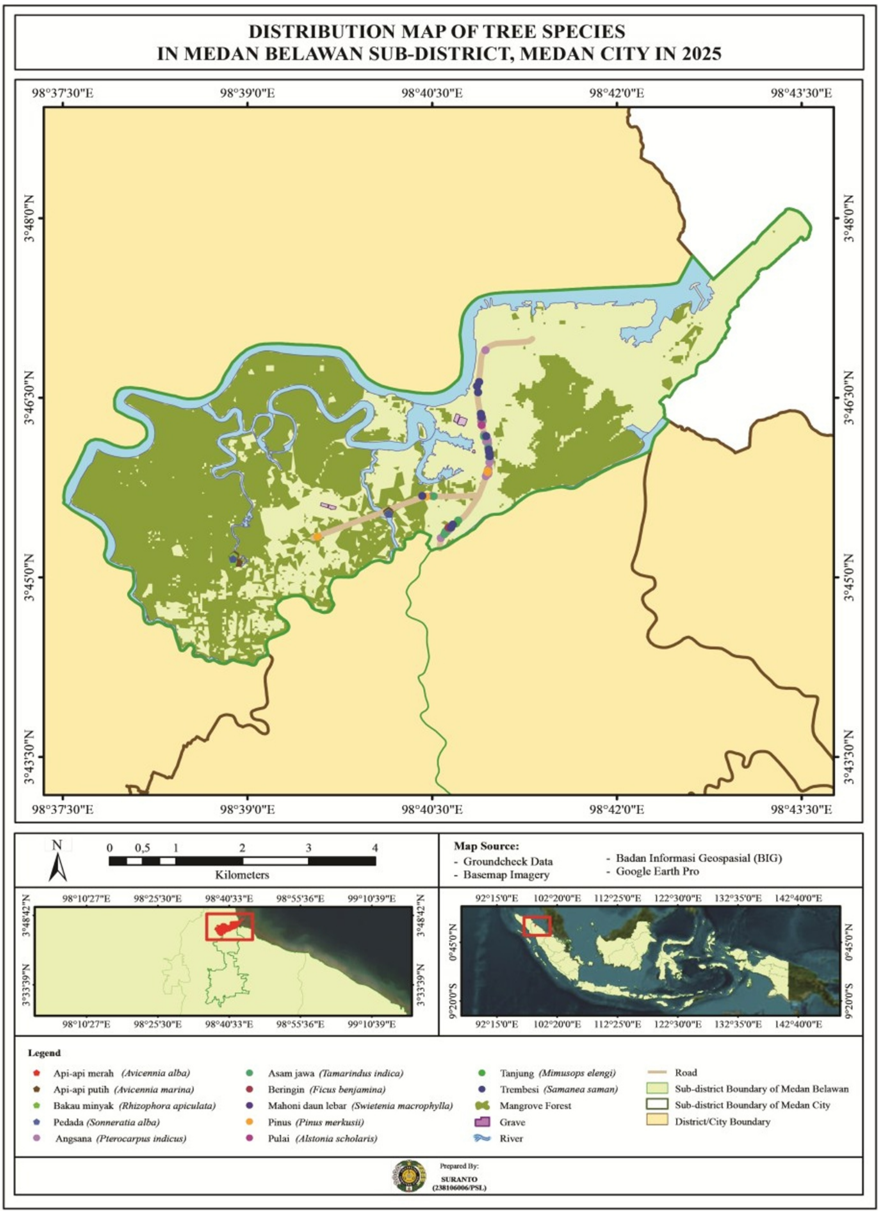


Fig. 2. Map of Medan Belawan subdistrict as a research location in Medan City in 2025.

3.2 Public green open space composition

Table 1. Composition of public green open space units in Medan Belawan Subdistrict.

Type of GOS	Number (units)	Percentage (%)
Roadside green belt	59	27.06
River green belt	0	0.00
Cemetery	2	0.92
Park/urban forest	0	0.00
Mangrove	157	72.02
Total	**218**	**100.00**

Table 1 shows that mangrove ecosystems dominate the composition of public GOS in Medan Belawan, accounting for 157 units (72.02%) of the total 218 identified units. This dominance highlights the crucial role of coastal vegetation as the primary ecological buffer maintaining environmental stability. Roadside green belts represent the second-largest share at 27.06%, functioning as linear vegetative elements along major transportation corridors. Other types of GOS, such as cemeteries, contribute only 0.92%, while river corridors and urban parks or city forests were not identified.

This composition reflects a spatial imbalance between coastal and inland green spaces, indicating a high ecological dependence on mangrove ecosystems. Therefore, non-mangrove vegetation diversification is needed to strengthen ecological connectivity and support the sustainable development of the EFC model for coastal Medan Belawan [1,2,6,7,9].

3.3 Tree species distribution & community index

The tree community in Medan Belawan consists of 218 individuals (N) and 12 species (S), with *Avicennia marina* being the dominant species, comprising 48.17% of the total individuals. As shown in Table 2, the second-most abundant species is *Pterocarpus indicus* (14.22%), followed by Avicennia alba (13.76%). *Rhizophora apiculata* makes up 8.72%, while the remaining species account for less than 5% each.

Table 2. Composition of tree species and calculation components and tree communities in Medan Belawan Subdistrict.

No	Latin Name	Family	n_i	(%)	p_i	$-p_i \ln p_i$	p_i^2
1	*Avicennia alba*	Acanthaceae	30	13.76	0.138	0.273	0.019
2	*Avicennia marina*	Acanthaceae	105	48.17	0.482	0.352	0.232
3	*Tamarindus indica*	Fabaceae	11	5.05	0.050	0.151	0.003
4	*Pterocarpus indicus*	Fabaceae	31	14.22	0.142	0.277	0.020
5	*Rhizophora apiculata*	Rhizophoraceae	19	8.72	0.087	0.213	0.008
6	*Ficus benjamina*	Moraceae	1	0.46	0.005	0.025	0.000
7	*Swietenia macrophylla*	Meliaceae	1	0.46	0.005	0.025	0.000
8	*Pinus merkusii*	Pinaceae	4	1.83	0.018	0.073	0.000
9	*Alstonia scholaris*	Apocynaceae	1	0.46	0.005	0.025	0.000
10	*Sonneratia alba*	Lythraceae	3	1.38	0.014	0.059	0.000
11	*Mimusops elengi*	Sapotaceae	1	0.46	0.005	0.025	0.000
12	*Samanea saman*	Fabaceae	11	5.05	0.050	0.151	0.003
Total			**218**	**100.00**	**1.000**	**1.647**	**0.284**

The Shannon–Wiener diversity index (H′) is 1.647, suggesting moderate diversity with a relatively balanced species richness, though still somewhat uneven due to the dominance of a few species. The Simpson dominance index (D) of 0.284 indicates strong dominance by *A.*

marina. Additionally, the evenness index (1−D) is 0.716, showing a moderate distribution of individuals among the species. These findings highlight the role of *A. marina* as a keystone species that stabilizes the coastal ecosystem.

However, with p_i^2 nearing the threshold of 0.25, it is recommended to introduce 2-3 non-dominant, adaptive species to reduce dominance and improve overall community balance. This strategy is critical for maintaining optimal H′ and 1−D values, supporting the principles of adaptive ecosystem management within the EFC model.

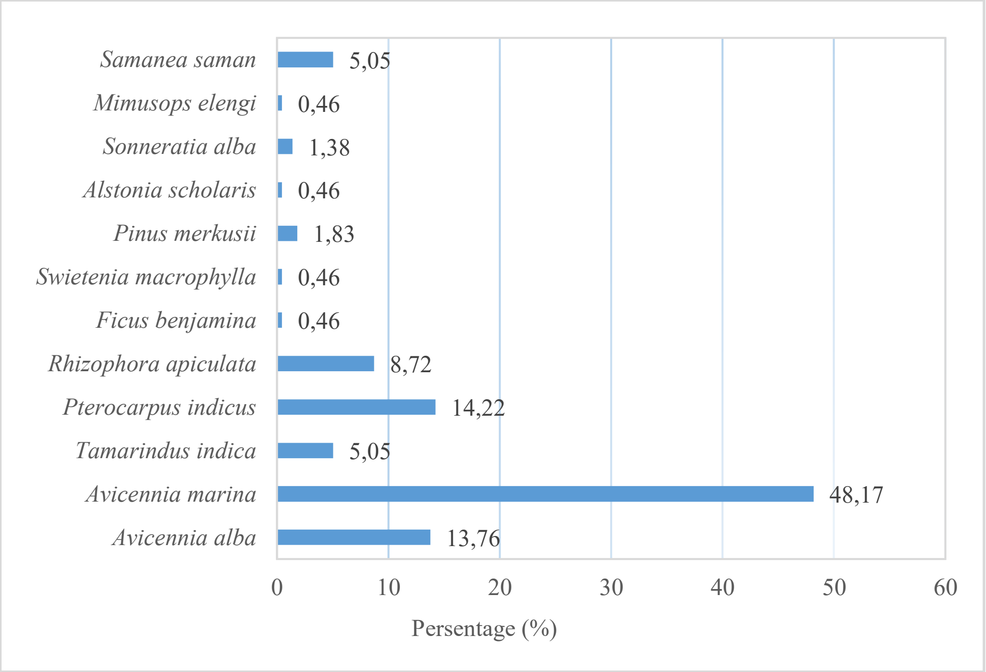
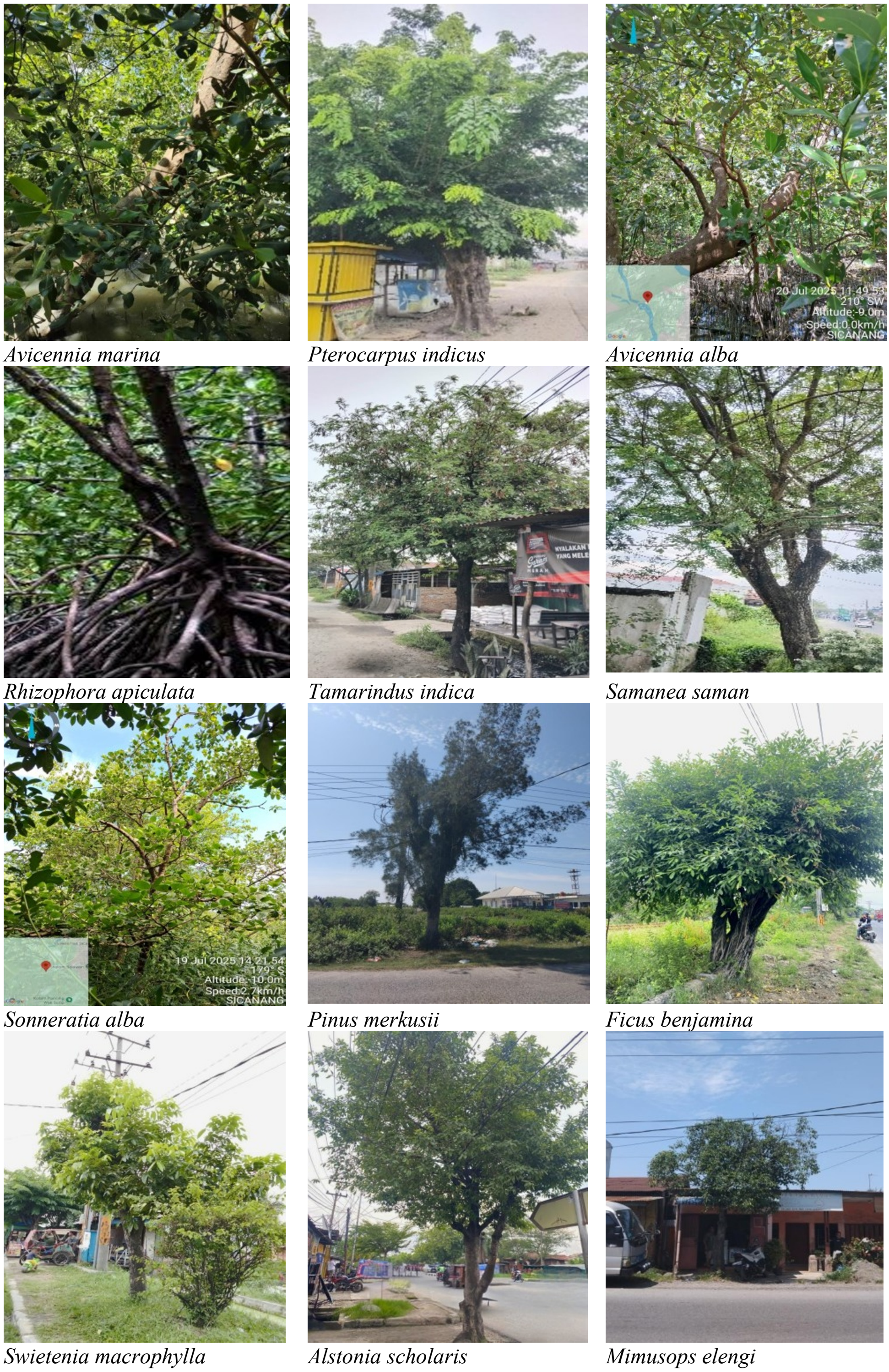


Fig. 3. Percentage distribution of tree species in Medan Belawan Subdstrict.

The gradient from coastal to inland zones shows that mangrove species (*A. marina, A. alba, R. apiculata, and S. alba*) dominate nearshore areas. These halophytic taxa play vital roles in shoreline protection, sediment stabilization, and nursery habitat provision for coastal fauna. In transition zones toward residential areas, broad-canopy trees from the *Fabaceae* family, including *Pterocarpus indicus*, *Tamarindus indica*, and *Samanea saman*, provide shade, fix soil nitrogen, and help regulate the microclimate.

Non-mangrove species such as *Pinus merkusii, Ficus benjamina*, *Swietenia macrophylla, Alstonia scholaris*, and *Mimusops elengi* primarily serve landscape, shade, and cultural ecosystem functions within built environments. This composition demonstrates strong coastal–inland ecological linkages, where mangrove dominance along the shoreline is complemented by shade and ornamental species inland. These elements form the structural basis for designing green corridors and ecological nodes within the EFC framework [1,2,6,7].



Avicennia marina | *Pterocarpus indicus* | *Avicennia alba*

Rhizophora apiculata | *Tamarindus indica* | *Samanea saman*

Sonneratia alba | *Pinus merkusii* | *Ficus benjamina*

Swietenia macrophylla | *Alstonia scholaris* | *Mimusops elengi*

Fig. 4. Tree species in Medan Belawan Subdstrict.

3.4 Mangrove Stands and the Environment

Field observations identified four true mangrove species in Belawan's mangrove forests: *Avicennia alba*, *Avicennia marina*, *Rhizophora apiculata*, and *Sonneratia alba*. Among them, *A. marina* was the most dominant, with 668 individuals per hectare, reflecting its high adaptability to muddy substrates and variable salinity [8,12,13].

Table 3. Number of individual tree categories in mangrove forests in Medan Belawan Subdistrict.

No	Species	Family	Density	Individuals (ha^{-1})
1	*Avicennia alba*	Avicennioideae	54	174
2	*Avicennia marina*	Avicennioideae	207	668
3	*Rhizophora apiculata*	Rhizophoraceae	25	81
4	*Sonneratia alba*	Lythraceae	3	10
	Total		**289**	**932**

As shown in Table 3, *A. marina* accounts for more than 70% of all individuals, functioning as the main stabilizer of the ecosystem and showing strong regeneration capacity under moderate salinity. In contrast, *R. apiculata* and *S. alba* exhibited lower densities, possibly indicating limited natural regeneration due to unstable substrates, inundation frequency, or anthropogenic pressure [6,7].

Table 4 provides data on the average diameter, height, and basal area (LBBD) of the mangrove tree categories. The mean diameter (17.69 cm) and height (4.44 m) indicate that Belawan's mangrove stands are in early to mid-growth phases. The relatively uniform basal area (~0.03 m²) suggests balanced biomass distribution across species despite variations in canopy and root structures. These conditions characterize a secondary regeneration stage, still influenced by tidal dynamics and human activity [8,14,15].

Table 4. Average diameter, height and LBBD of tree categories in mangrove forests in Medan Belawan Subdistrict.

No	Species	Family	Avg. Diameter (cm)	Avg. Diameter (m)	Avg. Height (m)	Avg. LBBD (m²)
1	*Avicennia alba*	Avicennioideae	18.52	0.19	5.51	0.03
2	*Avicennia marina*	Avicennioideae	16.46	0.16	4.47	0.03
3	*Rhizophora apiculata*	Rhizophoraceae	17.77	0.18	4.17	0.03
4	*Sonneratia alba*	Lythraceae	18.00	0.18	3.63	0.03
Average			**17.69**	**0.18**	**4.44**	**0.03**

Salinity levels, as shown in Table 5, ranged from 15.5‰ to 24.0‰, classified as brackish to slightly saline. This range is typical for estuarine ecosystems affected by tidal and freshwater inflows. *A. marina* tolerates salinity exceeding 30‰, which explains its dominance in the study area area [12,13].

Table 5. Salinity, air humidity, and temperature data in mangrove forests in Medan Belawan Subdistrict.

Test	Salinity (‰)	Air Humidity (%)	Air Temperature (°C)
1	15.5	53.5	34.0
2	24.0	41.5	32.1
3	17.8	43.3	34.2

Air humidity, as shown in Table 5, varied between 41.5% and 53.5%, indicating moderately humid conditions but below the optimal threshold (>60%) for healthy mangrove growth. Low humidity can increase transpiration rates and reduce leaf water retention, particularly during midday sampling under high temperatures. Air temperature ranged from 32.1°C to 34.2°C, typical of tropical heat and within the tolerance range for mangroves (28–35°C). While temperatures above the optimal 28–30°C accelerate metabolism, extreme heat (>40°C) can inhibit growth. These findings align with previous studies emphasizing the role of temperature, salinity, and soil moisture as key determinants of mangrove regeneration success [6–8,11,15].

The variability of environmental parameters indicates a dynamic estuarine system, where high salinity and fluctuating humidity reflect strong tidal influence and freshwater mixing. The dominance of *A. marina* demonstrates adaptive composition under salinity and inundation pressures, whereas the lower density of *R. apiculata* and *S. alba* suggests limited regeneration due to substrate instability or anthropogenic disturbance [6,7].

To maintain ecosystem resilience, species enrichment and vegetation diversification are recommended to reduce dependence on a single species. Continuous environmental monitoring of salinity, humidity, and temperature is also necessary to ensure the long-term adaptive capacity of mangrove ecosystems against climate change and human activities. Such measures will reinforce coastal–inland ecological connectivity and provide a scientific foundation for implementing the EFC model in coastal Medan.

4 Discussion

This study explored tree community structure, species distribution, and green–blue connectivity in Medan Belawan Subdistrict, a strategic coastal area that relies heavily on GOS, particularly mangrove ecosystems.

The results show that *Avicennia marina* dominates the mangrove stands. While this species plays a pivotal role in coastal protection, its dominance is associated with reduced functional diversity. Accordingly, species diversification and green–blue connectivity enhancement are required to improve overall ecosystem resilience.

4.1 The dominance of *Avicennia marina* and its implications for biodiversity

Avicennia marina is the most dominant species in Medan Belawan, contributing 48.17% of all recorded tree individuals. This dominance is attributable to its ecological adaptations to high salinity and fluctuating inundation. Such traits allow *A. marina* to act as a pioneer species in conditions where other taxa struggle to establish.

However, a relatively high Simpson dominance ($D = 0.28$) alongside a moderate Shannon–Wiener diversity ($H' = 1.65$) indicates constrained functional diversity. Community structure remains uneven ($1-D = 0.72$), reflecting a strong single-species dominance and heightened vulnerability to disturbances such as pests, disease, and climate anomalies [1,3,4,8,9]. To counterbalance this, planned species diversification is recommended, especially along terrestrial corridors linking coasts to residential areas. Introducing 5–7 tree species per 100 m segment is proposed to reduce D and increase evenness ($1-D$), consistent with the principle of ecological redundancy whereby higher diversity underpins stability and resilience.

4.2 The influence of dominance on ecosystem resilience

Single-species dominance by *A. marina* has a dual effect: it protects shorelines from abrasion and saline intrusion, yet overreliance on one species diminishes ecosystem resilience to external stressors [1,8,12].

Communities with higher diversity are generally more robust because species differ in their adaptive strategies. Incorporating complementary, stress-tolerant species (heat, inundation, salinity) will help balance *A. marina*'s dominance and sustain key ecosystem services—habitat provision, carbon uptake, water filtration, and microclimate regulation—over the long term.

4.3 The green-blue connectivity gap

A notable finding is the connectivity gap, indicated by the absence of river green belts and urban parks. Green–blue connectivity is essential for linking fragmented ecosystem elements and distributing ecosystem services—clean air, passive cooling, and hydrologic balance—across the urban fabric [2,4–7].

To address this gap, vegetated bioswales along canals and drainage lines are proposed to connect mangrove belts with terrestrial corridors, enhancing infiltration, reducing runoff, filtering pollutants, and providing microhabitats. These measures can also facilitate the advection of cooler, vegetation-driven air into residential zones.

4.4 Conceptual model of the Eco Forest City (EFC)

The findings inform a coastal EFC model for Medan Belawan aimed at reducing single-species dominance, strengthening green–blue connectivity, and rebalancing coastal–inland ecological functions [9,11,12,15]. The design is guided by three principles: Protect – Diversify – Rehab.

4.4.1 EFC design principles

In coastal zones, mangroves are designated as core protected areas, with enrichment planting of *Rhizophora apiculata* in more inundated sites and *Sonneratia alba* in sandier, more dynamic zones to improve functional diversity and ecosystem stability.

In terrestrial corridors, species diversification is applied to curb *A. marina* dominance, with species selected to fit local utilities (sidewalks, overhead lines, drainage). Each 100 m corridor segment should include 5–7 distinct species to diversify canopy structure, rooting, and phenology.

Along canal and drainage margins, vegetated bioswales form linkages between the coast and settlements, filtering pollutants, improving infiltration, and maintaining microclimatic moisture—thus enhancing connectivity and public co-benefits.

4.4.2 EFC implementation strategy

Implementation integrates three strategies: (1) protecting coastal zones, (2) diversifying terrestrial corridors, and (3) reinforcing green–blue connectivity via bioswales. Coastal protection focuses on existing mangrove belts, particularly *A. marina*, supplemented by enrichment with *R. apiculata* (inundated/energetic wave areas) and *S. alba* (sandy/dynamic areas) to bolster shoreline stability and functional diversity [1,2,8,12].

Terrestrial corridors adopt multi-species planting (5–7 species per 100 m) aligned with infrastructure constraints, plus understory/bioretention plantings along drains to increase infiltration, reduce surface temperatures, and filter runoff.

Canal/drainage setbacks host vegetated bioswales to slow runoff, filter pollutants, and provide microhabitats—thereby knitting together coastal and residential ecosystems and expanding ecosystem service delivery.

Collectively, these actions create an adaptive coastal-to-inland ecological network, reinforcing resilience and operationalizing nature-based solutions in Indonesian coastal cities [6,7,9].

4.5 Index-based adaptive monitoring

To ensure effective EFC operation, an index-based adaptive monitoring scheme is applied, with thresholds triggering corrective actions (Table 6).

Table 6. Index thresholds & adaptive management actions.

Indicator	Trigger (Threshold)	Management Action
Dominance (D)	D > 0.25 at corridor level (community baseline ≈ 0.28)	Enrichment (infill planting) with ≥2–3 non-dominant species; revise palette until (p_i^2) declines and 1−D ≥ 0.75 in core corridors.
Diversity (H′)	(ΔH′ < −10%) year^{-1} vs. baseline	Audit mortality/site conflicts; adjust species/placement; add understory or bioretention to restore evenness.
Seedling survival	<70% at 12 months	Strengthen protection (stakes, fencing, mulch), improve watering/drainage; replace species or relocate to suitable microsites.

This data-driven framework keeps dominance in check, raises diversity, and improves plant survival rates over time [4,9,11,15].

4.6 Index-based adaptive monitoring

Phase 1 (0–12 months). Protect core mangroves—especially stands dominated by *A. marina* (high p_i^2)—and pilot diversification in 2–3 corridors exceeding the dominance threshold ($p_i^2 > 0.25$). Construct one priority bioswale to link terrestrial corridors to mangrove belts. Establish per-segment (~100 m) baselines for H′, D (p_i^2), 1−D, and 12-month seedling survival [6–8].

Phase 2 (1–3 years). Scale up infill planting in terrestrial corridors and mangrove-edge enrichment at erosion-prone sites. Expand bioswale networks and pocket parks to extend green–blue connectivity into residential pockets. Conduct annual evaluations of $\Delta H'$and adjust palettes/designs if evenness targets are unmet [1,9].

Phase 3 (3–5 years). Standardize species palettes by road class (arterial, collector, local) and implement maintenance/replacement programs guided by monitoring data. Core-corridor ecological targets: 1−D ≥ 0.75, steadily declining D relative to baseline, and stable or increasing H′ [8,12].

5 Conclusion

This study aimed to assess the structure and composition of GOS in Medan Belawan, with a particular focus on mangrove ecosystems and tree species distribution. The findings show that *Avicennia marina* is the dominant species, accounting for 48.17% of all recorded individuals. Its dominance reflects strong adaptability to salinity and inundation but also limits functional diversity, thereby increasing the ecosystem's vulnerability to external disturbances and environmental change.

In response to the study's objective of proposing a contextual EFC model, this research recommends three key strategies: (1) protecting mangrove ecosystems as core areas, (2) diversifying species along terrestrial corridors, and (3) enhancing green–blue connectivity through vegetated bioswales. These strategies are designed to improve functional diversity, strengthen coastal ecological resilience, and create continuous ecological linkages from coastal to inland areas, ultimately fostering a more adaptable and diverse ecosystem.

The successful implementation of the EFC model requires multi-stakeholder collaboration, involving local governments, communities, academia, and the private sector, to ensure the sustainability and effectiveness of the model. Furthermore, continuous monitoring of environmental parameters such as salinity, air humidity, and temperature is crucial to support the long-term adaptive capacity of mangrove ecosystems in the face of climate change and human activities.

Overall, this study provides a scientific foundation for sustainable, climate-adaptive urban planning in coastal cities, with the proposed EFC model offering a replicable framework for other Indonesian coastal cities seeking to enhance ecosystem resilience and sustainability.

Acknowledgements

The authors gratefully acknowledge funding support from the Directorate General of Research and Community Service, Directorate General of Research and Development, Ministry of Higher Education, Science, and Technology, Fiscal Year 2025, Contract No. 7/UN5.4.10.K/PT.01.03/DPPM/2025, dated 28 May 2025, under the Doctoral Dissertation Research Scheme.

References

1. I. Kowarik, L. K. Fischer, and D. Kendal, Biodiversity Conservation and Sustainable Urban Development. Sustainability. **12**, 12 (2020). https://doi.org/10.3390/su12124964
2. S. Pauleit, E. Andersson, B. Anton, A. Buijs, D. Haase, R. Hansen, I. Kowarik, A. Stahl Olafsson, and S. Van der Jagt, Urban green infrastructure – connecting people and nature for sustainable cities. Urban Forestry & Urban Greening. **40**, (2019). https://doi.org/10.1016/j.ufug.2019.04.007
3. G. M. Locosselli and M. S. Buckeridge, The science of urban trees to promote well-being. Trees. **37**, 1 (2023). https://doi.org/10.1007/s00468-023-02389-2
4. T. Semeraro, A. Scarano, R. Buccolieri, A. Santino, and E. Aarrevaara, Planning of Urban Green Spaces: An Ecological Perspective on Human Benefits. Land. **10**, 2 (2021). https://doi.org/10.3390/land10020105
5. M. H. E. M. Browning, A. Rigolon, O. McAnirlin, and H. (Violet) Yoon, Where greenspace matters most: A systematic review of urbanicity, greenspace, and physical health. Landscape and Urban Planning. **217**, (2022). https://doi.org/10.1016/j.landurbplan.2021.104233
6. P. Menéndez, I. J. Losada, S. Torres-Ortega, S. Narayan, and M. W. Beck, The Global Flood Protection Benefits of Mangroves. Scientific Reports. **10**, 1 (2020). https://doi.org/10.1038/s41598-020-61136-6
7. M. W. Beck, N. Heck, S. Narayan, P. Menéndez, B. G. Reguero, S. Bitterwolf, S. Torres-Ortega, G.-M. Lange, K. Pfliegner, V. Pietsch McNulty, and I. J. Losada, Return on investment for mangrove and reef flood protection. Ecosystem Services. **56**, (2022). https://doi.org/10.1016/j.ecoser.2022.101440
8. B. B. Hanggara, D. Murdiyarso, Y. R. Ginting, Y. L. Widha, G. Y. Panjaitan, and A. A. Lubis, Effects of diverse mangrove management practices on forest structure, carbon dynamics and sedimentation in North Sumatra, Indonesia. Estuarine, Coastal and Shelf Science. **259**, (2021). https://doi.org/10.1016/j.ecss.2021.107467

9. E. K. Morris, T. Caruso, F. Buscot, M. Fischer, C. Hancock, T. S. Maier, T. Meiners, C. Müller, E. Obermaier, D. Prati, S. A. Socher, I. Sonnemann, N. Wäschke, T. Wubet, S. Wurst, and M. C. Rillig, Choosing and using diversity indices: insights for ecological applications from the German Biodiversity Exploratories. Ecology and Evolution. **4**, 18 (2014). https://doi.org/10.1002/ece3.1155
10. M. Cetin, The effect of urban planning on urban formations determining bioclimatic comfort area's effect using satellitia imagines on air quality: a case study of Bursa city. Air Quality, Atmosphere & Health. **12**, 10 (2019). https://doi.org/10.1007/s11869-019-00742-4
11. S. Sumani, K. Komariah, S. Suntoro, M. Mujiyo, and H. Ullah, Rainfall, drought, and irrigation in relation to crop patterns in the volcanic topo sequence of Central Java, Indonesia. SAINS TANAH - Journal of Soil Science and Agroclimatology. **22**, 1 (2025). https://doi.org/10.20961/stjssa.v22i1.87786
12. S. D. Ginting, A. Rauf, and Rahmawaty, The Analysis of Land Use Change of Mangrove Ecosystem in Langkat, North Sumatera, Indonesia. Journal of Environmental and Development Studies. **4**, 2 (2023). https://doi.org/10.32734/jeds.v4i2.12559
13. Rahmawaty, M. M. Harahap, H. Kurniawan, and A. Rauf, Land use changes monitoring over a period of ten years in Panjang Island, Pangkalan Susu, Langkat, North Sumatra. IOP Conference Series: Earth and Environmental Science. **782**, 3 (2021). https://doi.org/10.1088/1755-1315/782/3/032008
14. H. Şevik, M. Çetin, A. Türkyılmaz, and K. Işınkaralar, Using Abies's Needles as Biomonitors of Recent Heavy Metal Accumulation. Kastamonu University Journal of Engineering and Sciences. **7**, 1 (2021)
15. M. Sembiring, J. M. Hutahuruk, D. N. Susilowati, E. Yuniarti, T. Sabrina, and L. A. M. Siregar, Functional diversity of bacteria in various saline soil plant vegetations around Sialang Buah Coast, North Sumatra, Indonesia. SAINS TANAH - Journal of Soil Science and Agroclimatology. **21**, 2 (2024). https://doi.org/10.20961/stjssa.v21i2.80075