BIODIVERSITAS
Volume 27, Number 1, January 2026
Pages: 11

ISSN: 1412-033X
E-ISSN: 2085-4722
https://doi.org/10.13057/biodiv/d270106

Mangrove ecosystem health on prograding land in Panyipatan Sub-district, South Kalimantan, Indonesia

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Manuscript received: 9 September 2025. Revision accepted: 12 January 2026.

Abstract. *Susilawati, Shiba YN, Pujawati ED, Rachmawati N, Mufidah, Prihatiningtyas E. 2026. Mangrove ecosystem health on prograding land in Panyipatan Sub-district, South Kalimantan, Indonesia Biodiversitas 27 (1): d270106. https://doi.org/10.13057/biodiv/d270106.* Mangrove forests are essential for coastal protection and climate-change mitigation. This study, conducted in the mangrove forests of Panyipatan Sub-district, South Kalimantan, Indonesia, assessed community structure, Importance Value Index (IVI), species diversity (H´), and vegetation damage across two tidal zones using 50×100 m plots and the Forest Health Monitoring (FHM). In Zone 1, *Avicennia marina* dominated with an IVI of 147.92%, followed by *Excoecaria agallocha* with an IVI of 183.08%. In Zone 2, the dominance of *E. agallocha* increased markedly, reaching IVI values of 279.49% for saplings and 226.11% for trees, accompanied by *Cerbera manghas* (IVI 19.47%). Species diversity varied between zones: sapling diversity was lower in Zone 1 (H´ = 0.69) despite more individuals, while Zone 2 showed higher sapling diversity (H´ = 0.95) with fewer individuals. Tree-level diversity was similar between zones (0.67 vs. 0.64). Vegetation damage was dominated by leaf damage (35%) and liana infestation (43%), mostly of moderate severity, with the Area Damage Index (ADI) categorized as low (5.37-5.00). These results highlight the link between species dominance and diversity, as well as the influence of growth-stage diversity on vegetation health. Management priorities include strengthening pioneer species, controlling lianas, applying adaptive rehabilitation, and enhancing collaboration between communities and government to sustain mangrove ecosystems under shifting coastlines.

Keywords: Forest health monitoring, Importance Value Index, mangrove forest, progradation, South Kalimantan

INTRODUCTION

Mangrove forests are essential coastal ecosystems that deliver critical ecological, economic, and climatic benefits. They protect coastlines from erosion, provide habitat for diverse species, and function as significant blue carbon sinks that mitigate climate change. Southeast Asia experienced an average annual mangrove loss of 0.18% between 2000 and 2012 (Richards and Friess 2015). Indonesia, as the largest mangrove extent in the world, still faces localised degradation, driven by land conversion, hydrological alteration, and socio-economic pressures (Arifanti et al. 2022; Choudhary et al. 2024). Climate-related stressors, including sea-level rise and increasing coastal hazards, further heighten the vulnerability of mangrove ecosystems (Goldberg et al. 2020). While these pressures are often framed in terms of degradation and loss, mangrove ecosystems are also shaped by dynamic coastal processes that can create opportunities for natural expansion and regeneration.

Among the coastal processes influencing mangrove dynamics, shoreline progradation plays a critical role by generating newly accreted substrates that facilitate natural colonization and successional development. Shoreline progradation generates a mosaic of substrates with differing ages and physical characteristics, creating gradients that strongly influence mangrove establishment, growth, and species composition. Newly accreted mudflats are typically colonized by salt-tolerant pioneer species, while older and more stable substrates allow the development of structurally complex communities. Despite its importance, the interaction between coastal geomorphological change and mangrove vegetation structure remains insufficiently documented, particularly in naturally expanding systems.

Beyond anthropogenic threats, geomorphological processes also shape mangrove dynamics. One such process is shoreline progradation, which creates newly accreted substrates that facilitate natural colonization by pioneer species such as *Avicennia marina*. Progradation-driven mangrove development has been documented in Bali (Hastuti et al. 2024) and the northern coast of Java (Muskananfola et al. 2020), yet its ecological implications remain underexplored in other Indonesian regions. Understanding how vegetation structure responds to prograding coastlines is increasingly important as many tropical coasts continue to shift seaward.

Panyipatan Sub-district in Tanah Laut District, South Kalimantan, Indonesia, offers a unique natural laboratory where rapid shoreline advancement coincides with community dependence on mangrove resources. However, existing studies in Indonesia tend to emphasize degradation processes, rehabilitation outcomes, or ecosystem services (Marlianingrum et al. 2021; Mahmoudi et al. 2022; Zhang et al. 2023), leaving a gap in linking coastal dynamics, vegetation structure, and forest health in naturally expanding mangrove systems. This gap limits the ability to design management strategies that respond to both ecological succession and changes in coastal geomorphology.

According to IUCN (2024), nearly half of the world's mangroves could collapse by 2050 if degradation continues. This underscores the need for integrated assessments that capture both vegetation conditions and shoreline behaviour. To address this gap, this study is the first to integrate the importance value index (IVI), species diversity (H'), Forest Health Monitoring (FHM), and NDVI-based shoreline progradation analysis to assess mangrove ecosystem health in Panyipatan. This combined approach provides a more holistic understanding of how species dominance, diversity, and vegetation health relate to coastal advancement.

Therefore, the objectives of this study are to (i) analyze species diversity and vegetation structure across progradated zones, (ii) quantify IVI and H' to evaluate species dominance and community stability, (iii) assess vegetation health using FHM indicators, (iv) relate vegetation condition to shoreline progradation to identify successional patterns and regeneration potential. This integrated assessment supports evidence-based strategies for adaptive mangrove management in prograding coastal environments.

We hypothesize that progradated lands in Panyipatan exhibit vegetation zonation patterns reflecting natural successional processes, with pioneer species such as *A. marina* dominating the seaward/front zone while species such as *Excoecaria agallocha* and *Cerbera manghas* appear in more stable, rear zones. We further hypothesize that vegetation health differs among zonations: pioneer zones are more vulnerable to abiotic stressors (salinity, tidal inundation), whereas rear zones face greater biotic pressures (liana competition, pests). Finally, we propose that shoreline change driven by progradation directly shapes community structure, making integrated monitoring of coastal dynamics and vegetation condition essential to support adaptive conservation strategies.

MATERIALS AND METHODS

Study area

The research was conducted in Panyipatan Sub-district, Tanah Laut District, South Kalimantan, Indonesia, over a three-month period (May-July 2025). The study area is located at 4°3'46.04'S, 114°38'2.75' E and 4°3'31.66'S, 114°38'5.87' E. Vegetation at the sapling, pole, and tree strata was assessed. The study location is shown in Figure 1. The research location was divided into two zones based on tidal influence: (i) Zone 1 (frontal/pioneer): located at the seaward-most front, directly interacting with daily tides and characterized by high salinity. (ii) Zone 2 (mid-rear): situated farther from the sea, less frequently inundated, and exhibiting lower salinity.

Two observation plots (50×100 m each) were established on progradated land. Zone boundaries were determined using tidal data from pasanglaut.com, which show a semi-diurnal tidal pattern with two high and two low tides per day. Sediments in the frontal zone are dominated by newly deposited fine mud, while the mid-zone sediments are denser, more consolidated, and exhibit higher organic content.

Data collection

The study area was divided into two zones, with each zone covering an area of 50×100 m, subdivided into 50 plots (10×10 m for tree and pole strata, and 5×5 m for saplings. All individual mangrove species within each subplot were identified, and diameter at breast height (DBH), height, and health condition were recorded. Sampling was conducted once (single survey) during the peak of the dry season to minimize water-level variation.

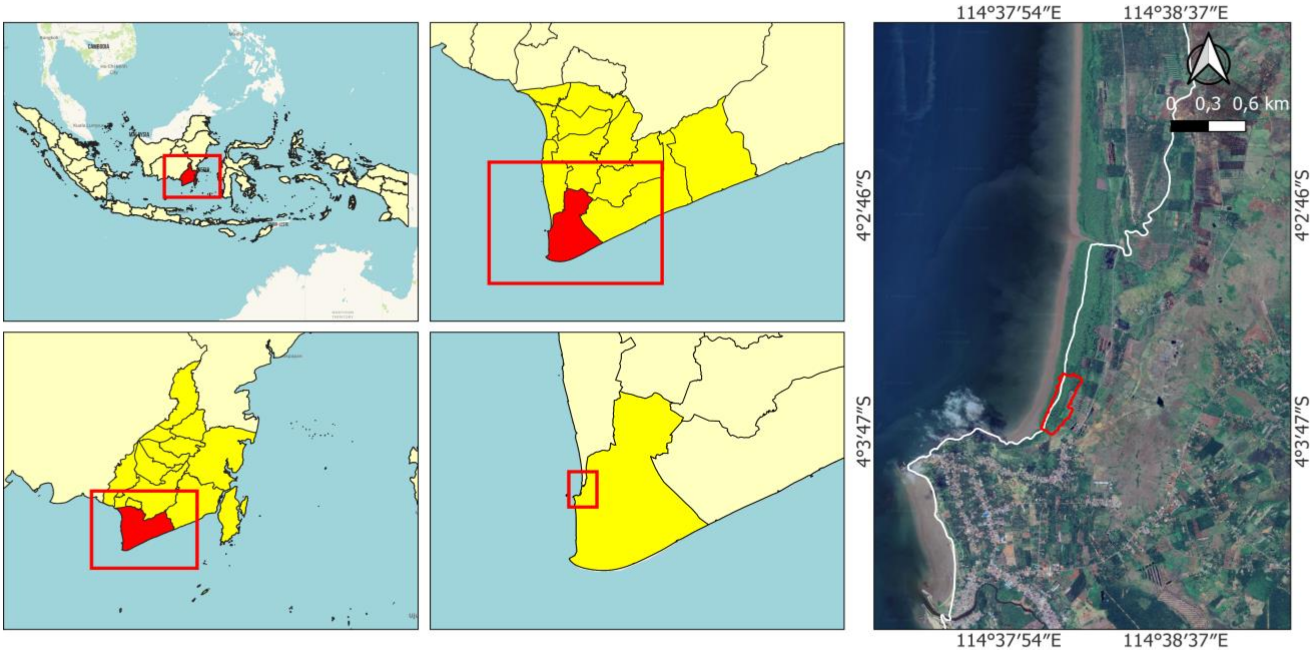

Figure 1. Map of the mangrove ecosystem study area in Panyipatan Sub-district, Tanah Laut District, South Kalimantan, Indonesia

Data analysis

Data analysis and processing in this study included calculations of the Importance Value Index (IVI), species diversity index (H'), and the mangrove health index. IVI and vegetation health data were tabulated and analyzed to determine vegetation composition and structure based on relative frequency, relative density, and relative dominance. IVI reflects species dominance and ecological roles within the community (Naidoo 1987). The calculation formulas are presented below:

$$\text{Density (D)} = \frac{\text{Number individuals of species}}{\text{Plot area}} \quad (1)$$

$$\text{Relative Density (RD)} = \frac{\text{Density of a species}}{\text{Total density of all species}} \times 100\% \quad (2)$$

$$\text{Frequency (F)} = \frac{\text{Number of plots in which a species was found}}{\text{Total number of plots}} \quad (3)$$

$$\text{Relative Frequency (RF)} = \frac{\textit{Frequency of a species}}{\text{Total frequency across all plots}} \times 100\% \quad (4)$$

$$\text{Dominance (Do)} = \frac{\text{Total basal area of a species}}{\text{Plot area}} \quad (5)$$

$$\text{Relative Dominance (RDo)} = \frac{\text{Dominance of a species}}{\text{Total dominance of all species}} \times 100\% \quad (6)$$

IVI for sapling = RD + RF (7)

IVI for poles and trees = RD + RF + RDo (8)

The species diversity index is an effective metric for comparing plant communities, assessing environmental influences, and indicating community stability or successional stage, as higher diversity typically reflects greater stability. The index is calculated as:

$$H' = -\sum pi \times Ln\ pi \quad (9)$$

$$pi = \frac{N_1}{N} \quad (10)$$

Where H' is the species diversity index; pi is the proportion of individuals of species i; N_1 is the number of individuals of species i; N is the total number of individuals; and Ln denotes the natural logarithm.

To complement field data, mangrove land cover was mapped using Sentinel-2 multispectral imagery (2020-2025). Image preprocessing (atmospheric correction, georeferencing, and cloud masking) was performed in ArcGIS Enterprise 11.4. Vegetation condition was evaluated using the Normalized Difference Vegetation Index (NDVI), focusing on threshold-based classification of vegetation density (water <0.0; very barren land 0.0-0.1; very sparse vegetation 0.1-0.2; moderate vegetation 0.2-0.5; dense/ healthy vegetation 0.5-0.8; and very dense vegetation ≥0.8) (Rouse et al. 1973). Field verification followed a purposive sampling approach to validate classification results.

Vegetation patterns were analyzed using the NDVI, calculated as:

NDVI = (NIR – RED) / (NIR + RED) (11)

Where: NIR: Near Infrared, RED: Red Band

Forest health was assessed following the Forest Health Monitoring (FHM) framework (Mangold 1997; Susilawati et al. 2024). Forest vitality is measured through field observations and data collection on tree damage, characterized by the location, type, and severity of damage (Alongi 2014; Nur et al. 2021).

The formula for the tree/pole damage index combines these three parameters—location (X), type (Y), and damage level (Z)—using a weighted sum of all observed damage types on each tree:

$$\text{Tree/pole damage index} = (X_1 \times Y_1 \times Z_1) + (X_2 \times Y_2 \times Z_2) + (X_n \times Y_n \times Z_n) \quad (12)$$

This index quantifies the extent and impact of individual damages, reflecting the overall stress experienced by each tree. Table 1 displays the weighting values for each location code, type, and level of tree damage in accordance with Mangold (1997) and Safe'i et al. (2020).

Next, the Area Damage Index (ADI) averages the damage scores across all trees within a plot, offering a summary measure of vegetation health over the area:

Area damage index (ADI) = Average damage score of trees within the area (13)

This aggregation translates individual-level damage into a broader ecosystem-level health status, where the tree damage index quantitatively reflects the severity and extent of damage within individual mangrove trees. Higher index values indicate more severe or extensive damage, while lower values correspond to healthier trees with minimal or no visible damage. According to Safe'i et al. (2021) and Azizah et al. (2023), these damage values are categorized into tree health classes as shown in Table 2, providing a clear framework to interpret the condition of mangrove vegetation and guide forest management decisions.

This integrated approach enabled spatial and ecological evaluation of mangrove vegetation, linking community structure, remote-sensing indicators, and observed field health.

Table 1. Weighting values for each location code, type, and level of tree damage

Tree damage location code	Weighting value (X)	Tree damage type code	Weighting value (Y)	Tree damage level code	Weighting value (Z)
0	0	01, 26	1.9	0	1.5
1	2.0	02	1.7	1	1.1
2	2.0	03, 04	1.5	2	1.2
3	1.8	05	2.0	3	1.3
4	1.8	06	1.5	4	1.4
5	1.6	11	2.0	5	1.5
6	1.2	12	1.6	6	1..6
7	1.0	13, 20	1.5	7	1.7
8	1.0	21, 22, 23, 24	1.3	8	1.8
9	1.0	25, 31	1.0	9	1.9

Table 2. Tree health classes and corresponding tree damage index values

Tree health category	Tree damage index value
Healthy	0-5
Light damage	6-10
Moderate damage	11-15
Severe damage	≥16

RESULTS AND DISCUSSION

Importance Value Index (IVI) of mangrove forest at Panyipatan Sub-district

The results of the IVI calculations conducted at the two study locations are presented in Table 3 below. Values correspond to the summed relative contributions of density, frequency, and dominance for each life stage (sapling, pole, tree).

Table 3 presents the IVI values of several mangrove species, which serve as an ecological indicator to quantify species dominance and their relative ecological roles within the community. The results show that both Zone 1 and Zone 2 were dominated by *E. agallocha*. In Zone 1, *E. agallocha* recorded the highest IVI at the tree stage (183.08%), while in Zone 2, it exhibited the highest IVI at the pole stage (279.49%). The dominance of *E. agallocha* at these growth stages suggests the development of a more stable stand, reflecting a structural transition from the pioneer-dominated phase toward a more mature mangrove assemblage.

In addition to *E. agallocha*, *A. marina* was also found in both Zone 1 and Zone 2. In Zone 1, *A. marina* showed the highest IVI at the pole stage (147.92%), while in Zone 2, its highest IVI occurred at the tree stage (54.42%). This pattern indicates that *A. marina* maintains a notable presence across growth stages and zones, reflecting its broad ecological tolerance within the mangrove stand.

Cerbera manghas appeared only in Zone 2, with IVI values of 40% at the sapling stage and 19.47% at the tree stage. Compared to *E. agallocha* and *A. marina*, the IVI of *C. manghas* was lower, indicating a more limited dominance within the community. Nevertheless, its occurrence in Zone 2 adds to the overall structural complexity of the mangrove stand.

The dominance of *E. agallocha* at both pole and tree stages indicates that this species has successfully occupied later growth phases within the stand. The high IVI of *E. agallocha*, especially in Zone 2, demonstrates its strong competitive advantage and ecological plasticity in increasingly sheltered sites, allowing it to maintain structural control over the community during mid- to late-growth phases. Several regional studies have also reported that *E. agallocha* can become a leading dominant in Southeast Asian mangrove communities when local conditions favor it, including recent findings from the Philippines, where it recorded the highest IVI at certain sites (Lillo et al. 2024).

The substantial IVI values of *A. marina* across zones and growth stages complement the dominance pattern of *E. agallocha* and reflect the dynamic nature of the mangrove community. The distribution of *A. marina* observed in this study aligns with previous reports describing its role as a pioneer species tolerant of high salinity and tidal inundation (Triest et al. 2021; Aljahdali et al. 2021; Zimmer et al. 2022). Progradation-driven accretion opens new "successional windows" in which newly formed muddy flats are first colonized by *Avicennia* (and sometimes *Sonneratia*), before later being joined or partially supplanted by other species as the substrate stabilizes and the stand develops (Muskananfola et al. 2020; Hastuti et al. 2024).

The occurrence of *C. manghas* only in Zone 2, where it contributes to the sapling and tree layers, further supports the interpretation that parts of the habitat represent a more advanced stage of development. As a species typically associated with more backshore or landward positions under lower salinity and more stable substrates, the presence of *C. manghas* is an ecological indicator that the habitat has become more stable (Tomlinson 2016; Ma et al. 2022). Indonesian vegetation studies linking stand structure and IVI to abiotic gradients such as salinity, mud depth, and sediment dynamics describe similar patterns, with strong pioneer dominance at the seaward edge followed by compositional shifts as physical conditions change and sediments thicken (Eddy et al. 2022). In this context, the marked differences between Zone 1 and Zone 2 not only reflect an underlying environmental gradient, but also reveal the influence of specific drivers—progradation dynamics, salinity regimes, and interspecific competition—that promote ecological succession and determine species dominance patterns; the high IVI of *E. agallocha* at the tree level in Zone 1 and at the pole level in Zone 2 can therefore be viewed as a key indicator of its ecological flexibility under these interacting processes.

Diversity Index (H') of mangrove forest at Panyipatan Sub-district

The IVI serves as the basis for calculating the Shannon-Wiener diversity index (H'). Diversity index values for the three growth stages are presented in Table 4 and Figure 2.

The data in Table 4 illustrate ecological dynamics and clear differences in community structure between the two mangrove zones driven by environmental conditions and successional processes. In sapling stage, Zone 1 had high individual density (126) but lower diversity (H' = 0.69), while Zone 2 had fewer individuals (10) but higher diversity (H' = 0.95). In pole stage, Zone 1 maintained stable diversity (H' = 0.69) with 212 individuals, while Zone 2 showed sharply lower diversity (H' = 0.24) with 94 individuals. In tree stage, both zones coverged to similar diversity values (H' = 0.67 vs. 0.64), but Zone 2 supported substantially more trees (30 vs. 156).

Table 3. Importance Value Index (IVI) for each life stage in each zone

Scientific name	Local name	IVI (%)		
		Sapling	Pole	Tree
Zone 1				
Avicennia marina (Forssk.) Vierh.	*Api-api*	97.38	147.92	116.92
Excoecaria agallocha L.	*Buta-buta*	102.62	152.08	183.08
Zone 2				
Avicennia marina (Forssk.) Vierh.	*Api-api*	40	20.51	54.42
Excoecaria agallocha L.	*Buta-buta*	120	279.49	226.11
Cerbera manghas L.	*Bintaro*	40	0	19.47

Table 4. Species diversity index (H´) for mangrove vegetation at different growth stages in two zones

Growth stage	Number of individuals		H'	
	Zone 1	Zone 2	Zone 1	Zone 2
Sapling	126	10	0.69	0.95
Pole	212	94	0.69	0.24
Tree	30	156	0.67	0.64

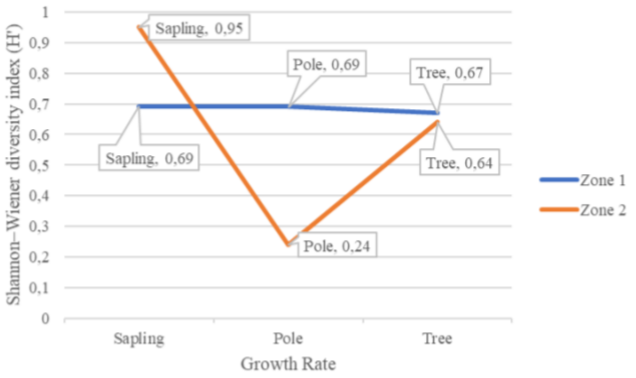

Figure 2. Shannon-Wiener diversity index (H') for two mangrove zones in Panyipatan

The sapling stage in Zone 2 has fewer saplings (10 individuals) but higher diversity (H' = 0.95), suggests constrained early recruitment, potentially due to disturbance (e.g., trampling or selective cutting), propagule predation (e.g., by crabs or gastropods), or suboptimal hydrological conditions (e.g., prolonged inundation or poor drainage) that limit seedling establishment (Liu et al. 2024). These observations highlight the role of salinity, inundation frequency, and substrate type as primary limiting factors during early mangrove regeneration

At the pole stage, diversity in Zone 2 declined sharply (H´ = 0.24) as one or two species became dominant, reflecting strong environmental filtering and interspecific competition. Conversely, Zone 1 maintained stable diversity (H' = 0.69) with high abundance (212 individuals), indicating a well-established community structure. Although there were still significant disparities in abundance, diversity values by the tree stage converged between zones (0.67 in Zone 1 and 0.64 in Zone 2). More mature trees (156) were found in Zone 2 than in Zone 1 (30), suggesting either a higher carrying capacity for the ecosystem or better long-term regeneration conditions. Zone 1's reduced tree abundance may reflect stand dynamics, including background mortality and the cumulative effects of environmental stressors (Ohtsuka et al. 2019).

Taken together, these findings demonstrate that IVI and H´ provide complementary insights into successional trajectories rather than static community states. Interactions among shoreline dynamics, tidal inundation, sediment availability, and species competition appear to shape the observed patterns. Integration of shoreline monitoring (e.g., DSAS/PlanetScope) with field-based indicators (IVI, H´, density, canopy cover, and health metrics) is therefore recommended to improve zone-specific diagnosis and inform management interventions (Winterwerp et al. 2020; Roslinda et al. 2021).

Ecological analysis of two mangrove zones in Panyipatan Sub-district

Building on Table 3, Zone 1 shows pioneer co-dominance by *A. marina* and *E. agallocha* across all growth stages. In contrast, Zone 2 exhibits later-stage dominance by *E. agallocha*, reaching its peak IVI (279.49%) at the pole stage. The presence of *C. manghas* in Zone 2 further supports its classification as an intermediate or landward zone characterized by less frequent tidal flooding, lower salinity, and finer substrate. These environmental conditions allow for the establishment of semi-mangrove species or those with lower salt tolerance (Wang et al. 2011; Ma et al. 2020).

These findings underscore an environmental gradient driven by coastal progradation. Progradation creates newly accreted land initially colonized by pioneers such as *A. marina*, followed progressively by species better adapted to stable substrate and reduced salinity, such as *E. agallocha* and *C. manghas*. This sequence is consistent with the successional patterns commonly reported for mangroves in Southeast Asia (Muskananfola et al. 2020; Hastuti et al. 2024).

Results in Table 4 reveal clear diversity differences between the two zones. In Zone 1 (frontal zone), the number of sapling individuals is very high (126) but the diversity index (H') is low (0.69), indicating massive colonization by pioneer species that reduce community evenness—consistent with successional theory indicating that early colonization stages are often characterized by strong dominance of pioneer species and reduced community evenness (Ahmed et al. 2022; Djamaluddin and Djabar 2022). Conversely, Zone 2 (intermediate/inner zone) has fewer saplings (10) but a higher H' (0.95), reflecting more diverse recruitment despite limited numbers. At the pole stage, diversity declines markedly (H' = 0.24) due to strong dominance by *E. agallocha*, consistent with interspecific competition mechanisms in which one species outcompetes others during mid-growth stages (Hutchings and Saenger 1987). At the tree stage, H' values are nearly similar between Zone 1 (0.67) and Zone 2 (0.64), yet Zone 2 supports many more trees (156) than Zone 1 (30), indicating greater habitat carrying capacity or a longer period of substrate stabilization that allows more optimal stand development.

Differences in mangrove community structure between Zones 1 and 2 reflect ecological dynamics driven by progradation. Zone 1 functions as a pioneer area where salt-tolerant species such as *A. marina* play a key role in stabilizing new sediments. Over time, prograding zones develop into more complex habitats (Zone 2), allowing the establishment of other species such as *C. manghas*. The shift in dominance from *A. marina* to *E. agallocha* and the presence of *C. manghas* indicate a rapid successional process at the study site. This phenomenon aligns with findings by Hastuti et al. (2024) in Bali and Muskananfola et al. (2020) on the northern coast of Java, which show that shoreline changes due to progradation produce habitat mosaics that accelerate vegetation dynamics.

A clear understanding of community dynamics is best supported by visualizing changes in diversity across zones and growth stages. The following figure illustrates Shannon-Wiener diversity index (H´) variations between the frontal and intermediate mangrove zones in Panyipatan, highlighting how diversity shifts from initial colonization to mature stand development. This graphical representation helps to clarify recruitment patterns, species turnover, and ecosystem stability within the context of ongoing coastal progradation and environmental filtering.

The line graph (Figure 2) illustrates differences in diversity dynamics between zones at each growth stage. The sapling stage in Zone 2 has higher diversity (H' = 0.95) despite lower individual counts, reflecting more diverse species recruitment even when numbers are limited. Zone 1 is dominated by a few pioneer species, resulting in a lower H' (0.69). At the pole stage, Zone 2 undergoes a marked decline in diversity (H' = 0.24) due to the strong dominance of *E. agallocha*, whereas Zone 1 remains relatively stable (H' = 0.69), indicating a more even community composition. At the tree stage, H' values are similar between the zones (Z1 = 0.67; Z2 = 0.64), although Zone 2 supports a much greater number of trees; this suggests that greater abundance is accompanied by dominance of a single species, thereby reducing evenness. Overall, the graph indicates that Zone 1 is more homogeneous with pioneer-species dominance, while Zone 2 is more structurally complex but strongly influenced by the dominance of *E. agallocha*.

The ecological implications of these results are: (i) coastal progradation plays a critical role in shaping mangrove community dynamics, as newly accreted land is rapidly colonized by pioneer species such as *A. marina* that tolerate extreme conditions; (ii) over time, substrate stabilization produces zones with environmental conditions that favor the establishment of other species, such as *C. manghas*, and facilitates long-term dominance by *E. agallocha*; (iii) this shift indicates a transition from a simple, pioneer-dominated community toward a more complex community structure with increasingly intense interspecific competition. These dynamics not only reflect the natural successional trajectory of mangrove ecosystems but also underscore the importance of maintaining ecological balance to preserve coastal ecosystem functions. The successional stages are illustrated in Figure 3.

The illustration in Figure 3 describes three stages of mangrove community development: (i) Early Progradation Zone dominated by the pioneer *A. marina* on exposed substrates with high salinity; (ii) Middle Zone with more stable substrate dominated by *E. agallocha* at the pole and tree stages; (iii) Stable/Rear Zone characterised by more complex environmental conditions and the presence of *C. manghas* and other semi-mangrove species. The diagram synthesizes field observations and the interpreted successional processes at the study site. A spatial visualization of mangrove progradation at the study location, showing newly accreted land and vegetation colonization from 2020 to 2025, is presented in Figure 4.

Figure 4 shows annual mangrove land-cover maps for Panyipatan Sub-district, 2020-2025, derived from Sentinel-2 MSI Level-2A (10 m) imagery using dry-season median composites after cloud masking (QA60/SCL). Land cover was classified with the Normalized Difference Vegetation Index (NDVI) into five classes—Water, Very Barren Land, Very Sparse Vegetation, Moderate Vegetation, and Dense/Healthy Vegetation—using NDVI threshold ranges calibrated from reference samples and visual checks (see methods). Each panel represents one year, enabling a consistent multi-year temporal comparison. Based on Figure 4, the dynamics of mangrove area in the study site are summarized in Table 5.

Table 5 presents changes in mangrove area from 2020 to 2025 based on the NDVI analysis presented in Figure 4. NDVI-based vegetation index analysis reveals a substantial increase in mangrove cover in Panyipatan throughout the period 2020-2025. The extent of mangrove cover expanded from 7.62 ha in 2020 to 10.5 ha in 2025, or an increase of 2.88 ha over the past five years. This growth was not entirely linear, with annual fluctuations attributable to climatic factors and anthropogenic activities. The expansion of vegetated area was generally dominated by the Dense/Healthy Vegetation and Moderate Vegetation categories, while the Very Sparse Vegetation category appeared only intermittently and was subsequently restored in the following year.

This positive growth trend is influenced by two main factors: (i) natural progradation, in the form of coastal sediment accumulation that provides new substrate for mangrove growth, and (ii) the strong natural regenerative capacity of mangrove vegetation, which is effective in recovering affected areas even after environmental or anthropogenic stress. Fluctuations in vegetated cover in certain years, such as in 2022, were mainly triggered by variations in the dry season and rainfall intensity. Nevertheless, the mangrove ecosystem in Panyipatan exhibited high ecological resilience and effective adaptation.

Table 5. Dynamics of mangrove area from 2020 to 2025

Vegetation classification	2020	2021	2022	2023	2024	2025
Water	0	0	0	0	0	0.01
Very barren land	0	0	0	0	0	0.07
Very sparse vegetation	0	0	0	0.02	0	0.07
Moderate vegetation	0.4	0	0.05	2.91	0.38	1.63
Densehealthy vegetation	3.74	0.59	8.6	6.01	9.16	8.72
Very dense vegetation	3.48	7.46	0	0	0	0
Total	7.62	8.05	8.65	8.94	9.54	10.5

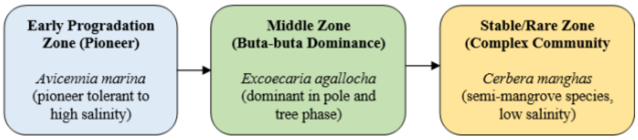

Figure 3. Conceptual diagram of mangrove ecosystem succession driven by coastal progradation

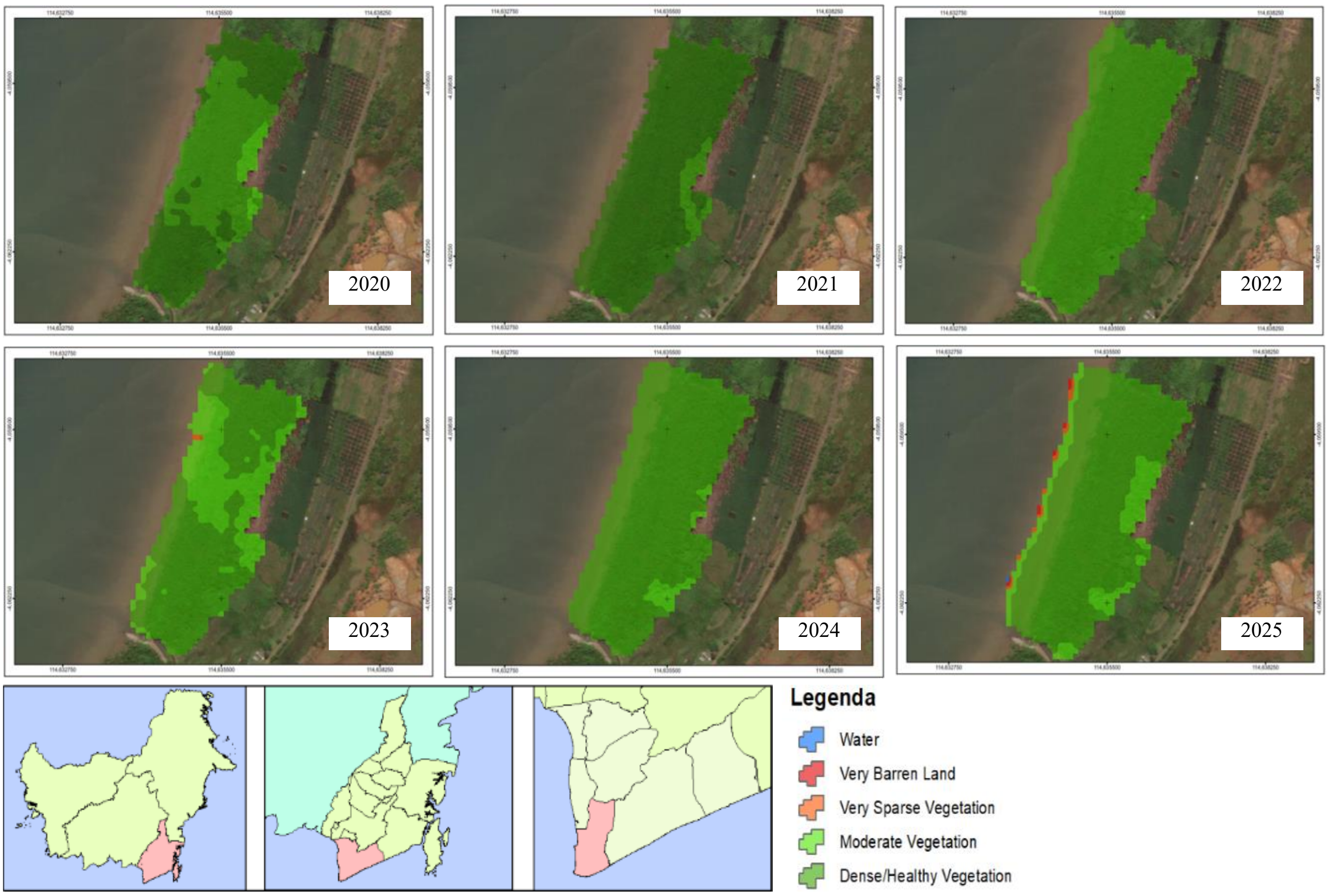

Figure 4. Map of mangrove land-cover change in Panyipatan Sub-district, 2020-2025

Mangrove vegetation health in Panyipatan Sub-district

Observation of vegetation health identified seven damage locations, summarized in Table 6. These findings provide insight into the spatial distribution and types of plant injury observed across the study area.

The identification results in Table 6 indicate that leaves were the most vulnerable organ, accounting for 648 damage cases (35%). Leaves play a central role in photosynthesis and are directly exposed to environmental stressors; therefore, foliar damage is widely recognized as an early indicator of declining ecosystem health. Symptoms such as chlorosis, desiccation, and obscission may result from salinity stress, hydrological fluctuations (flooding or prolonged dryness), herbivory, foliar pathogens, and nutrient limitation or soil compaction (Kathiresan and Bingham 2001; Alongi 2020). Alongi (2020) reports that salinity stress is among the principal constraints on mangrove leaf physiology.

Subsequent major damage was also recorded on the lower and upper stems (458 cases, 25%) and branches (428 cases, 23%), largely attributable to mechanical forces, including strong winds, tidal currents, anthropogenic disturbance, and loading from liana infestation. Lianas were particularly prominent (43% of total damage cases) because they compete for light and nutrients and increase structural fragility; similar findings have been reported globally (Estrada-Villegas et al. 2021). Roots and lower stems exhibited very low damage frequencies (0%), suggesting relative protection from direct exposure. Overall, the level of vegetation damage fell within the moderate category (20-29%), indicating potential for natural recovery where stressors are reduced (Djamaluddin and Djabar 2022). Results for the identification of damage types are presented in Table 7.

The damage-type identification in Table 7 reinforces the predominance of leaf-related injuries. As discussed above, leaves are both physiologically critical and highly exposed, meaning that foliar symptoms often provide an early warning of environmental stress. Subsequent categories include cracking/dieback and open wounds, while liana infestation forms the largest single damage class (43%), reflecting competitive pressure from climbing vegetation (Estrada-Villegas et al. 2021).

This pattern corresponds to a clear ecological gradient. In the front (pioneer) zone, newly formed substrates are dominated by species such as *A. marina* and are primarily affected by abiotic stressors, especially salinity and tidal inundation, which are expressed mainly as foliar damage. As the substrates stabilize and communities mature toward the back zone (Zone 2), stands become more structurally complex and biotic interactions - including liana infestation, branch breakage, and herbivory - increasingly shape damage outcomes. This progressive shift from abiotic to biotic drivers along the successional sequence has been reported in other tropical mangrove systems (Friess et al. 2020). Representative examples are shown in Figure 5.

Field photographs in Figure 5 document the main types of damage to mangrove vegetation, including: (i) signs of animal activity; (ii) open wounds on stems; (iii) dead branches; (iv) fractured stems or roots; (v) liana infestation; (vi) leaf discoloration; (vii) fruiting bodies/pathogenic fungi; (viii) traces of wildlife activity; and (ix) brooming (abnormal branching). Data were obtained from 10 observation subunits within two plots. The results indicate that leaves were the most vulnerable organ (35% of observed damage), while lianas constituted the principal biotic damage factor (43%). Based on the observations shown in Figure 5, the identified levels of mangrove damage are summarized in Table 8.

The highest severity category from Table 8 data is 20-29%, with 958 occurrences, representing 52% of the total observed damage. This severity indicates that most damage is moderate: parts of the tree or mangrove organs still have the potential to recover if environmental conditions improve and causative factors are mitigated. The next most frequent category is 30-39% (494 occurrences, 27%), indicating moderate-to-severe damage that generally requires a longer recovery period and appropriate interventions to prevent further deterioration. The 10-19% category (364 occurrences, 20%) corresponds to mild damage that is relatively less disruptive to physiological functions but still warrants monitoring. The least frequent categories are 40-49% (40 occurrences, 2%) and 1-9% (2 occurrences, 0%), showing that extreme or very low-level damage was rare at the study sites. Distribution of mangrove health classes in Panyipatan can be seen in Figure 6.

Classification based on damage classes in Figure 6 showed that the largest percentage fell in the light-damage category (51%). This indicates that most mangrove vegetation can still function adequately despite signs of disturbance and generally can recover naturally if the causative factors are controlled. The proportion of healthy trees was 48%, indicating a relatively good condition that still comprises nearly half of all observations. The moderate-damage category was found only at 1%, meaning that moderate severity damage was rare in the study area. Index instance of severe damage was recorded (0%), indicating that environmental conditions at the sites were not conducive to extreme mangrove degradation. Overall, these data suggest that the mangrove ecosystem at the study sites is in fairly good condition, with most vegetation classified as healthy to lightly damaged. Area Damage Index in this research can be seen in Figure 7.

The ADI analysis (Figure 7) values (Zone 1 = 5.37; Zone 2 = 5.00) classify both zones as lightly damaged (Mangold 1997), although their dominant stress drivers differ. Zone 1 shows mostly abiotic leaf stress associated with salinity and tidal variability (Tomlinson 2016; Alongi 2020; Ahmed et al. 2023), whereas Zone 2 is characterized by biotic damage, particularly lianas and branch injuries. In other words, the pioneer zone is more vulnerable to abiotic stressors, whereas the back zone is more affected by biotic interactions. These patterns are consistent with broader evidence that mangrove community trajectories are jointly regulated by shoreline dynamics, environmental gradients, and biotic interactions (Friess et al. 2020). These contrasting patterns illustrate how shoreline dynamics and community development jointly regulate mangrove health, emphasizing that vegetation damage should be interpreted within its ecological context.

Ecological analysis of these findings indicates: (i) the predominance of leaf damage underscores the leaf's vital role as an early indicator of mangrove ecosystem health, given its photosynthetic function and vulnerability to abiotic stress; (ii) the dominance of liana-induced damage in Zone 2 signals an increasing influence of biotic factors as community complexity rises, intensifying competition for light and nutrients; and (iii) the contrasting damage patterns between Zone 1 (more abiotic-driven) and Zone 2 (more biotic-driven) reflect an ecological transition consistent with coastal progradation processes. Together, these dynamics highlight the linkage between environmental pressures and community structure and emphasize the necessity of understanding vegetation damage mechanisms as a basis for management and conservation strategies for coastal mangrove ecosystems.

Table 6. Identification of mangrove vegetation damage locations

Damage location	Damage percentage (%)	Number of damage cases
Roots and lower stem	0	6
Lower stem	0	4
Lower and upper stem	25	458
Upper stem	9	172
Crown stem	8	142
Branches	23	428
Leaves	35	648

Table 7. Identification of mangrove forest damage types

Damage type	Damage percentage (%)	Number of damage cases
Cancer	0	2
Open wounds	24	440
Cracking or dieback	17	314
Leaf discoloration	17	310
Others - liana	43	792

Table 8. Results of mangrove forest damage level identification

Severity level (%)	Percentage of severity (%)	Number of occurrences
1-9	0	2
10-19	20	364
20-29	52	958
30-39	27	494
40-49	2	40

Figure 5. Types of mangrove vegetation damage identified in Tanjung Dewa Village, Panyipatan

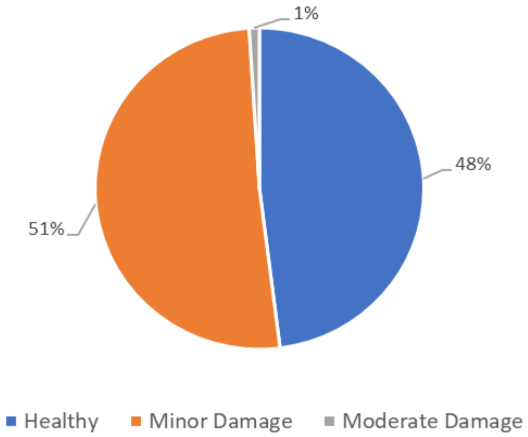

Figure 6. Percentage of distribution of mangrove vegetation health classes in Panyipatan

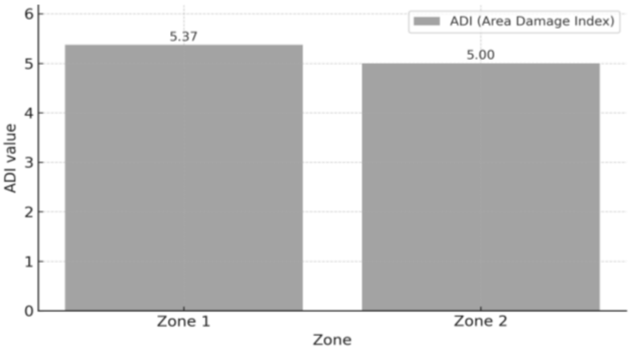

Figure 7. Area Damage Index (ADI) of mangroves in the two study zones

Management implications of mangrove forest in Panyipatan Sub-district

Management of the prograding coastlines in Panyipatan should consider zone-specific strategies informed by the observed structure, diversity, and vegetation-health indicators. In the frontal, accreting zone dominated by *A. marina*, maintaining open substrates and allowing natural colonization appears appropriate, as recruitment is active but foliage remains vulnerable to abiotic stress. Targeted planting should only be considered when the IVI or natural recruitment declines below the observed threshold, consistent with evidence that assisted regeneration is most effective when natural recruitment fails (Triest et al. 2021; Djamaluddin and Djabar 2022). In the landward zone, where *C. manghas* indicates increasing stability and terrestrial influence, managers should consider maintaining hydrological connectivity to prevent excessive drying and salinity buildup. Overall, strategies that integrate mangrove health indicators (canopy metrics, damage classes, ADI) with structural attributes (IVI, diversity) provide an early-warning basis for management and align with the generally light-damage status observed, suggesting that maintaining ecosystem functions should be prioritized over large-scale planting (Friess et al. 2020; Roslinda et al. 2021). In the mid-zone, shifts in the relative dominance of *E. agallocha* together with the high proportion of liana-related damage (43% of total cases) indicate the need for regular monitoring of species composition and microhabitat heterogeneity. Selective liana control may be considered where infestation is substantial; the indicative trigger of liana damage ≥40% or ADI approaching >6 serves as a precautionary benchmark, representing the point at which "light damage" may begin to transition toward moderate categories, while still reflecting current site values (Zone 1 = 5.37; Zone 2 = 5.00) (Mangold 1997; Estrada-Villegas et al. 2021; Shaduw et al. 2024). These zone-specific considerations support a management approach that is adaptive, evidence-based, and closely linked to the successional dynamics of prograding mangrove systems.

These recommendations should be interpreted within the ecological context of coastal progradation and the temporal scope of the present study, which may not fully capture seasonal or interannual variability. Remote-sensing products and DSAS-derived shoreline metrics inherently contain spatial and algorithmic uncertainties, and proxy indicators (IVI, Mangrove Health Index) do not directly resolve demographic processes or physiological stress pathways. The threshold values proposed here are therefore heuristic benchmarks grounded in the observed distribution of ADI and damage classes, complemented by published frameworks, rather than fixed management rules. Future research should consider multi-season and multi-year monitoring to evaluate persistence of trends, experimental evaluation of liana control and pioneer reinforcement, coupling of hydrology-sediment models to assess connectivity scenarios, genetic assessment of *Avicennia* planting stocks, and socio-ecological analyses of co-management effectiveness and long-term maintenance costs.

In conclusion, this study demonstrates that mangrove ecosystem condition in Panyipatan is strongly shaped by shoreline progradation and the associated successional gradient. Pioneer stands of *A. marina* stabilize newly accreted substrates, while *E. agallocha* increasingly dominates as habitats mature, with the presence of *C. manghas* indicating more stable landward environments. By integrating community structure, diversity metrics, and vegetation-health indicators, the results reveal that pioneer zones are mainly constrained by abiotic stress, whereas biotic pressures, especially liana competition, become more influential in rear zones; yet overall, the predominance of light damage suggests a resilient system. These findings underline that mangrove patterns represent ecological trajectories rather than fixed states, supporting management approaches that encourage natural regeneration, maintain hydrological connectivity, and selectively address biotic pressures. Future efforts should prioritize multi-season monitoring, targeted experiments on liana control and pioneer reinforcement, and coupling hydrology-sediment modeling with community-based governance to strengthen adaptive management on prograding coasts.

ACKNOWLEDGEMENTS

The authors wish to express their sincere gratitude to the Rector of Universitas Lambung Mangkurat, Indonesia, for the continued support provided throughout this research. Special thanks are extended to the Head of the Research and Community Service Institute for funding support through the Basic Competitive Grant Scheme (fiscal year 2025). We greatly appreciate the cooperation and assistance of the local communities in Tanjung Dewa and Batakan Villages, Panyipatan Sub-district, Tanah Laut District, South Kalimantan, Indonesia, whose participation and local knowledge substantially enriched our fieldwork. Finally, the authors thank the dedicated field team for their invaluable efforts in data collection and field observations.

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