Egyptian Journal of Aquatic Biology & Fisheries
Zoology Department, Faculty of Science,
Ain Shams University, Cairo, Egypt.
ISSN 1110 – 6131
Vol. 29(6): 1055 – 1073 (2025)
www.ejabf.journals.ekb.eg

A Study of the Relationship Between Mangrove Ecological Metrics and Environmental Factors in Aimas District, Southwest Papua

Ahmad Fahrizal[1*], Muhammad Kasnir[2], Abdul Rauf[2]

[1] Doctoral Study Program in Fisheries Science, Indonesian Muslim University, Jl. Urip Sumoharjo KM. 5, Makassar 90245, South Sulawesi, Indonesia
[2] Fisheries Science Study Program, Indonesian Muslim University, Jl. Urip Sumoharjo KM. 5, Makassar 90245, South Sulawesi, Indonesia

[*]Corresponding Author: 0004dip032022@student.umi.ac.id

ARTICLE INFO

Article History:
Received: Sep. 12, 2025
Accepted: Nov. 9, 2025
Online: Nov. 23, 2025

Keywords:
Aimas District,
Ecological indices,
Mangrove ecosystem,
PCA analysis,
Environmental parameter

ABSTRACT

Mangrove ecosystems are vital in coastal resilience, yet local environmental conditions strongly influence their structure. This study aims to evaluate ecological indices of mangrove communities in Aimas District, Southwest Papua, and examine their relationships with environmental parameters to inform conservation and management strategies. Aimas District was chosen as it represents a transitional mangrove area facing increasing human pressure, but still retains natural stands. Field surveys were conducted in January - February 2025 across three representative stations using systematic transect-plot sampling, where mangrove individuals were categorized into four growth classes: seedlings, saplings, poles, and mature trees. Ecological indices, including species diversity (H'), evenness (e), and dominance (D), were calculated and analyzed in relation to various environmental variables using principal component analysis (PCA). Results revealed sapling-dominated communities with limited seedling recruitment and no mature trees. PCA analysis revealed two primary gradients: water chemistry (nutrients, organic carbon, and total nitrogen) and physical parameters (salinity, transparency, and dissolved oxygen) as the primary drivers of community structure. Species diversity and evenness were higher in areas with moderate salinity and high water transparency. In contrast, low dissolved oxygen, acidic pH, and nutrient-poor substrates favored dominance by a few tolerant species. The study demonstrates strong ecological linkages between mangrove community structure and environmental conditions, providing critical insights for sustainable management and resilience of coastal mangroves.

INTRODUCTION

Mangroves are intertidal forest ecosystems that occupy the interface between land and sea in tropical and subtropical regions. Mangroves, unique woody halophytes, have long been exploited for food, timber, fuel, and medicine, now covering roughly 181,000 km² across tropical and subtropical coasts **(Alongi, 2002)**. Moreover, they provide critical ecological functions **(Anton *et al.*, 2020; Rustam *et al.*, 2020)**, including shoreline stabilization, nutrient cycling, carbon sequestration, and serving as nursery grounds for numerous aquatic organisms **(Choudhary *et al.*, 2024)**. Beyond environmental benefits, mangroves support local economies through fisheries, timber, and non-timber forest products, while they are increasingly recognized for their role in climate change mitigation **(Nyangoko *et al.*, 2022)**. The health and persistence of mangrove ecosystems are closely tied to surrounding environmental parameters such as salinity, pH, dissolved oxygen, and nutrient concentrations, which directly influence community structure and species distribution **(Dittmann *et al.*, 2022; Sraun *et al.*, 2023)**. Understanding these associations is essential for assessing mangrove resilience and sustainability.

However, mangrove ecosystems are increasingly threatened by anthropogenic activities such as aquaculture, land conversion, and pollution, leading to habitat degradation and declining biodiversity worldwide **(Yamamoto, 2023;Saoum & Sarkar, 2024)**. In Indonesia, which hosts the largest mangrove area globally, the rate of degradation remains high despite ongoing conservation efforts **(Farah, 2021; Ramadhani, 2022)**. Recent spatial analyses highlight the need for region-specific ecological assessments to support evidence-based management **(Rauf *et al.*, 2018; Rauf *et al.*, 2020)**. Studies have demonstrated that such degradation reduces mangrove cover and alters ecological indices such as species diversity, abundance, and dominance, underscoring the need for integrated ecological assessments **(Roy *et al.*, 2025)**.

Southwest Papua represents one of the vital mangrove areas in eastern Indonesia. This region is characterized by diverse mangrove stands that play an integral role in supporting fisheries and coastal livelihoods (**Sillanpää *et al.*, 2017; WRI Indonesia, 2022; Kasihiw *et al.*, 2024)**. However, like many other coastal zones, the mangroves in Aimas District are increasingly exposed to anthropogenic pressures such as aquaculture expansion, land-use conversion, and resource extraction. These pressures have caused visible degradation at some sites, while other patches remain relatively intact, creating a heterogeneous landscape that offers a unique opportunity to study ecological responses to environmental change. Aimas District was therefore selected as the study site to represent this environmental gradient, from disturbed to less disturbed mangrove stands, and to fill the lack of empirical data on how physicochemical factors influence mangrove community structure in this part of Southwest Papua. In this context, physicochemical measurements of water quality parameters such as pH, salinity, dissolved oxygen, and nutrient concentrations are essential for a comprehensive evaluation of mangrove ecosystems **(Kasnir *et al.*, 2014a, b)**. Such knowledge gaps hinder effective management and conservation strategies in a region where mangroves are vital for ecological balance and local community welfare.

Ecological indices, including species diversity, abundance, and dominance, are widely used to describe community structure and ecosystem health **(Rifadilah *et al.*, 2025)**. When analyzed in relation to environmental parameters, these indices can reveal important patterns of ecological functioning and resilience. For instance, salinity or nutrient availability shifts often correlate with changes in species composition and biomass distribution within mangrove stands **(Ahmed *et al.*, 2023)**. Previous studies in

Southeast Asia and elsewhere have shown that environmental drivers strongly influence mangrove zonation, productivity, and regeneration potential **(Sillanpää *et al.*, 2017; Mohan *et al.*, 2024)**. Therefore, assessing ecological indices with environmental parameters provides a comprehensive understanding of mangrove ecosystem dynamics.

Given the ecological significance of mangroves and the growing environmental pressures they face, there is an urgent need to conduct detailed assessments in underrepresented regions such as Southwest Papua. This study is designed to evaluate the ecological indices of mangrove communities in Aimas District and examine their relationships with various environmental parameters. This study addresses that gap by evaluating the ecological indices of mangrove communities in Aimas District and analyzing their relationships with key environmental parameters. The findings aim to clarify how physicochemical gradients shape community composition, providing novel insights for adaptive mangrove management in underrepresented regions of Papua and similar tropical coasts.

MATERIALS AND METHODS

1. Study area and period

This observational research was conducted in January - February 2025 in Aimas District, Southwest Papua, Indonesia. Warmon Village, one of the representative sites within the district, was selected due to its accessibility and relatively intact mangrove coverage. The sampled environmental parameters were assessed at the Water Quality Laboratory, Faculty of Marine Science and Fisheries, Hasanuddin University, Makassar, in February 2025. These parameters were used to examine potential linkages between mangrove community structure and the surrounding environment.

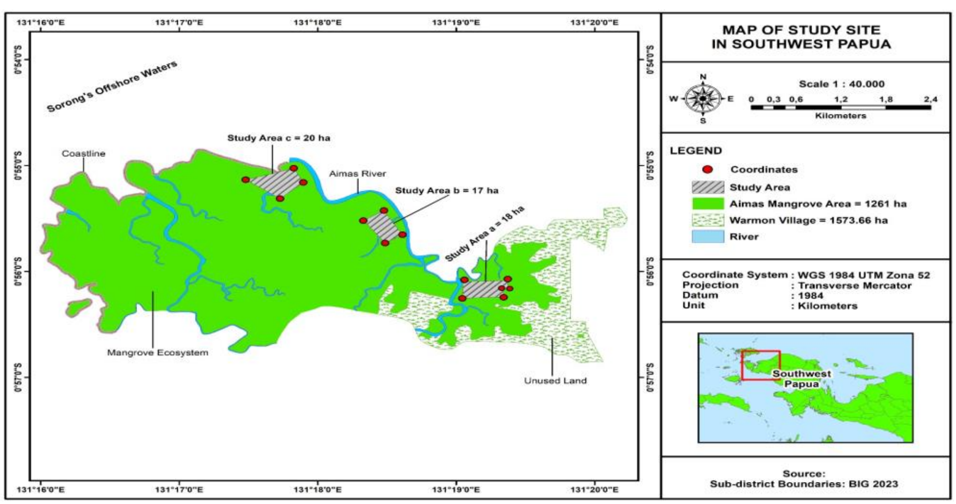

Fig. 1. Map of the research site (shaded box)

2. Research design and approach

This study employed an exploratory research design combined with a quantitative descriptive approach. The research was primarily survey-based, emphasizing the systematic collection of data from field observations to capture the current status and characteristics of mangrove ecosystems. Field sampling was conducted at three representative stations in Aimas District, selected based on differences in anthropogenic influence and habitat condition. At each station, three transects perpendicular to the shoreline were established, and within each transect, three 10 × 10m plots were systematically placed at intervals of 50m. Plot placement followed the presence and continuity of mangrove vegetation along the intertidal gradient, ensuring adequate representation of species composition and structural variation. Quantitative data were obtained through structured measurements and standardized instruments, enabling objective assessment and statistical analysis of ecological and environmental parameters. In addition, identification methods were integrated to classify mangrove species and related ecological attributes, thereby strengthening the reliability and comprehensiveness of the survey findings. This replication strategy enhanced data robustness and allowed comparative analysis among stations. This design allowed for both the numerical description of patterns and the interpretation of ecological variations within the study area.

3. Data collection

Data collection involved systematic field observations that were quantified and analyzed to characterize the prevailing conditions of mangrove ecosystems in Aimas District, Southwest Papua. Primary data were obtained directly through *in situ* observations and supporting documentation, as outlined below:

a) Mangrove community analysis

Mangrove vegetation was assessed using a systematic transect-plot method with non-continuous plots to capture the spatial variability of the ecosystem. Three transects were established perpendicular to the shoreline at each of the three sampling stations, each extending approximately 600m in length and 20m in width, covering a total sampled area of about 1.8 hectares. Within each transect, non-continuous plots were systematically placed to represent different intertidal zones and vegetation densities. All mangrove individuals were identified to species level and classified into four growth stages: seedlings, saplings, poles, and mature trees. Plot dimensions were adjusted for each growth class, such as 2 × 2m for seedlings; 5 × 5m for saplings; 10 × 10m for poles; and 20 × 20m for mature trees. For each stage, 15 plots were established (five per transect), resulting in a total of 45 plots per category. This design ensured adequate replication and representation of vegetation structure across environmental gradients.

b) Measurement of environemntal parameters

Oceanographic and environmental parameters were measured at three sampling stations. Parameters included water temperature, salinity, depth, pH, dissolved oxygen (DO), nitrate, phosphate, ammonia, nitrite, organic nitrogen, organic carbon, C/N ratio, and organic matter content. Field measurements were taken using portable instruments such as thermometers, salinometers, water level, pH, and DO meters. Nutrient concentrations were determined in the laboratory following standard procedures. Spectrophotometric methods were applied for nitrate, phosphate, ammonia, and nitrite, while titration techniques were used for organic nitrogen (Kjeldahl method) and organic carbon (Walkley–Black method). Organic matter content was quantified based on the loss-on-ignition approach. The C/N ratio was calculated by dividing the organic carbon content by the total nitrogen concentration.

a) Ecological index analysis

Ecological indices were applied to quantify species dominance, diversity, and evenness within the mangrove community. The dominance index (D) represents the degree of dominance concentration of species within the community and is computed as $D = \sum (n1/N)$. Community diversity (H') was assessed using the Shannon–Wiener diversity index (H'), which reflects the level of biological organization within the community: $H' = - \sum \{(n1/N) \log (n1/N)\}$, where n1 is the importance value of species -i and *N* reflects the total importance value of all species. Furthermore, evenness in species distribution was further determined using Pielou's evenness index (e) = H'/log S, where *e* is species evenness, H' is the Shannon–Wiener diversity index, and S denotes the total number of species.

4. Data analysis

The relationships between ecological indices (dominance, diversity, and evenness) and environmental parameters were explored using multivariate statistical techniques. Before analysis, all environmental variables were examined for normality, multicollinearity, and outliers to ensure data suitability for multivariate analysis. Variables showing high intercorrelation ($r > 0.80$) were excluded to avoid redundancy. To ensure comparability among variables with different measurement scales, all data were standardized using a z-score transformation (mean = 0, standard deviation = 1). Principal component analysis (PCA) was then applied to reduce dimensionality and to identify key environmental gradients influencing mangrove community structure. PCA was applied to reduce dimensionality and to identify the main gradients shaping community–environment interactions. The PCA was performed using SPSS version 25 with Varimax rotation to maximize the interpretability of factor loadings. Components with eigenvalues greater than 1 were retained following the Kaiser criterion, and the loading values ≥ 0.60 were considered significant for interpreting the principal components. This approach allowed visualization of associations among ecological indices and environmental factors, revealing which environmental parameters (e.g., salinity, dissolved oxygen, nutrients) most strongly influenced species composition and structural patterns within the mangrove community.

RESULTS AND DISCUSSIONS

1. Percentage distribution

Mangrove vegetation visualization is presented in Fig.(2), while Fig. (3) illustrates the percentage distribution of mangrove density across growth classes (seedlings, saplings, and poles) at the three sampling stations in Aimas District. Saplings dominated all sites, accounting for 79% at Station 1, 90% at Station 2, and 80% at Station 3. Pole individuals represented the second-largest proportion, comprising 19, 6, and 15% at Stations 1, 2, and 3, respectively. In contrast, seedlings contributed only a small fraction, with 2% at Station 1, 4% at Station 2, and 5% at Station 3. No tree-sized individuals were recorded at any site (0%), confirming the absence of mature mangrove stands within the surveyed areas. Statistical comparison (one-way ANOVA) showed no significant difference ($P > 0.05$) in the proportion of saplings among stations, suggesting similar regeneration dynamics across the study area.

The dominance of saplings across all stations suggests that the mangrove stands in Aimas District are currently at a regeneration or juvenile growth stage, rather than representing a fully mature forest structure. Species-level observations revealed that *Rhizophora apiculata* and *Bruguiera gymnorhiza* were most abundant in the sapling class, while *Avicennia marina* and *Sonneratia alba* were confined mainly to pole stages at less disturbed sites (Station 1 and Station 3). Station-specific conditions also explain part of this structural pattern: Station 1 showed signs of natural regeneration in semi-disturbed zones, Station 2 exhibited dense sapling clusters under moderate anthropogenic disturbance (e.g., wood cutting and aquaculture proximity), and Station 3 reflected partial recovery following past clearing activities.

The absence of mature trees is particularly striking, pointing to a disrupted stand structure that could compromise long-term ecological stability **(Asaeda *et al.*, 2016)**. Previous studies have highlighted that healthy mangrove ecosystems are generally characterized by a balanced distribution across growth stages, with mature trees playing a critical role in canopy formation, sediment stabilization, and carbon storage **(Alongi, 2020; Velázquez-Salazar *et al.*, 2025**).

Fig. 2. Mangrove vegetation in Aimas District

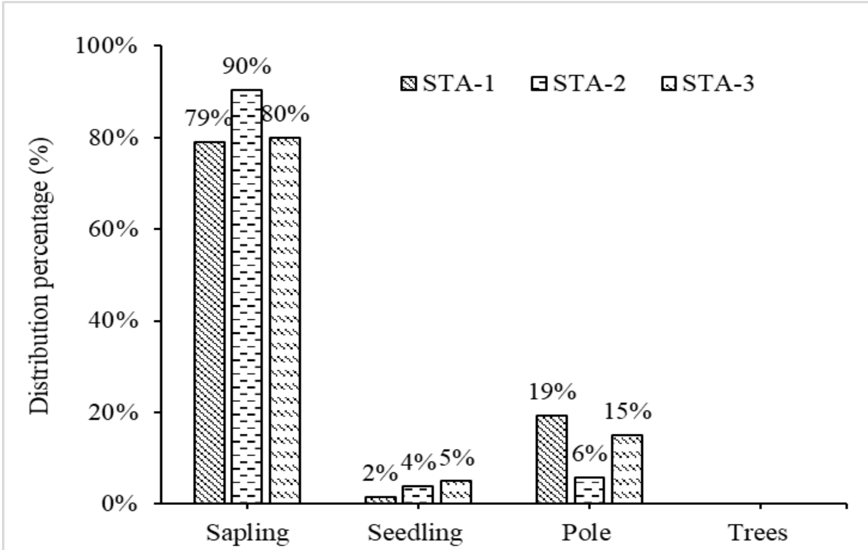

Fig. 3. Distribution of mangrove density in percent for each growth class

The relatively high proportion of poles, especially at Station 1 (19%), indicates that some progression toward maturity is occurring, although still limited. By contrast, the very low proportion of seedlings (<5% across sites) raises concern regarding the potential for continuous regeneration. In intact mangrove ecosystems, seedling recruitment is key to ensuring forest persistence and resilience against environmental stressors **(Zhang *et al.*, 2024)**. The limited seedling recruitment in Aimas may be linked to propagule predation, competition with dense saplings, or reduced substrate moisture due to periodic drying in upper intertidal zones **(Clarke & Kerrigan, 2002)**.

The structural profile of the mangrove stands in Aimas reflects a system dominated by intermediate growth classes but lacking both robust recruitment at the seedling stage and representation of mature trees. This pattern suggests that the ecosystem may be in a transitional phase, potentially recovering from disturbance but not yet stabilized into a mature forest community. The implications of such a structure are critical, as it may affect biodiversity support, carbon sequestration, and the provision of ecosystem services in the region.

2. Density of mangrove stands

Fig. (4) shows the density of mangrove growth classes expressed as individuals per square meter (ind/m²) at the three sampling stations. Pole-sized individuals exhibited the highest density at Station 1, with 33.53 ind/m², but decreased sharply to 2.89 ind/m² at Station 2 and 12.16 ind/m² at Station 3. Saplings followed with 16.14 ind/m² at Station 1, 13.78 ind/m² at Station 2, and 4.94 ind/m² at Station 3. No tree-sized individuals or seedlings were recorded at any station, confirming the absence of mature stands and early recruitment stages.

The dominance of pole-sized individuals in density, particularly at Station 1, indicates that the mangrove community in certain parts of Aimas District is transitioning into an intermediate growth stage. However, the sharp decline in pole density at Station 2 (2.89 ind/m²) suggests substantial spatial variability in stand development, likely shaped by local environmental conditions such as tidal inundation patterns, sediment fertility, or anthropogenic pressure. Station 3 demonstrates a moderate condition, where pole density is relatively higher than saplings, yet the absence of seedlings and trees limits structural balance.

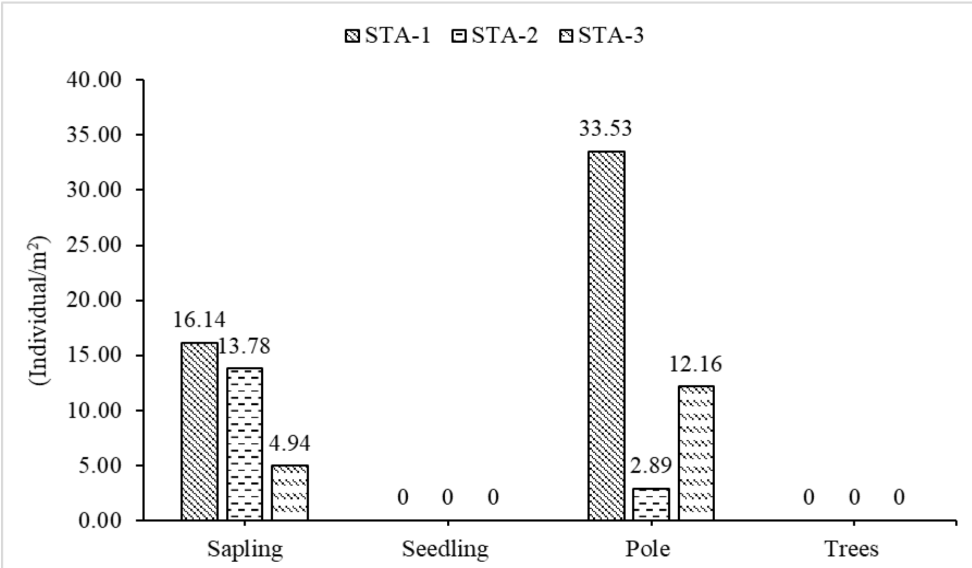

Fig. 4. Distribution of mangrove density in square meters for each growth class

The lack of mature trees across all sites indicates restricted stand development and represents a critical gap in the forest structure. In mangrove ecosystems, mature trees fulfill multiple ecological roles that extend far beyond their individual presence. Structurally, they form the upper canopy, which regulates light penetration and provides habitat for arboreal fauna such as birds, bats, and invertebrates **(Dahdouh-Guebas *et al.*, 2008)**. Their extensive root systems, particularly in genera such as *Rhizophora* and *Avicennia*, enhance sediment retention, reduce shoreline erosion, and buffer coastal communities against tidal surges and storms **(Sunkur *et al.*, 2023; Anu *et al.*, 2024)**. Regarding biogeochemical functioning, large trees represent the primary biomass reservoir, contributing disproportionately to carbon sequestration and long-term carbon storage both above and below ground **(Choudhary *et al.*, 2024; Li *et al.*, 2025)**.

The complete absence of seedlings in density records is equally concerning, consistent with percentage distribution findings (Fig. 3). Seedling recruitment is a vital process in sustaining mangrove forests, and its failure suggests potential barriers such as predation, propagule dispersal limitations, or unsuitable microhabitats for establishment **(Clarke & Kerrigan, 2002; Kibler *et al.*, 2022)**. The comparatively higher sapling densities at stations 1 and 2 indicate localized microenvironments that support regeneration, but their imbalance with poles and the lack of new seedlings signal an unstable regeneration trajectory. The density structure observed in Aimas District reflects a mangrove community in partial recovery, dominated by intermediate growth forms but constrained by the absence of seedlings and mature trees. Without interventions that enhance propagule establishment and promote growth to maturity, the long-term sustainability of these mangrove stands may be at risk.

3. Environmental parameters

Table (1) presents the average values of environmental parameters measured across the three sampling stations. The water temperature averaged 29.20°C, reflecting warm tropical conditions typical of mangrove ecosystems. Salinity was relatively low, averaging 16.25ppt, suggesting freshwater influence likely from rainfall or nearby riverine input. Water depth was measured at 27.00cm, with a relatively high clarity of 91.67cm, indicating low suspended sediment. The mean pH value was 5.56, indicating acidic conditions. Dissolved oxygen (DO) was notably low, averaging 2.427mg/ L, which falls below the threshold for well-oxygenated waters. Nutrient concentrations were also low: nitrate (0.077ppm), phosphate (0.01mg/ L), ammonia (0.01ppm), and nitrite (0.002ppm). Soil chemical properties revealed total nitrogen (0.002%), organic carbon (0.77%), C/N ratio (12.51%), and organic matter content (1.55%), reflecting nutrient-poor substrate conditions.

The measured environmental parameters reveal a distinctive coastal condition in Aimas. Surface water temperature was warm (29.2°C), salinity was brackish (16.3ppt), pH was acidic (5.56), and dissolved oxygen was very low (2.43mg L^{-1}). Nutrient concentrations were minimal, with nitrate (0.077ppm), phosphate (0.01mg L^{-1}), ammonia (0.01ppm), and nitrite (0.002ppm) all near detection limits. Soil organic carbon (0.77%) and total nitrogen (0.002%) were also low, yielding a moderate C/N ratio (12.5). These gradients jointly reflect freshwater influence, low nutrient availability, and hypoxic stress, key drivers determining species dominance and regeneration success across the three sampling stations. Such conditions indicate a mangrove system influenced by freshwater input, restricted nutrient availability, and poor oxygenation, which shape community composition and regeneration dynamics **(Ahmed *et al.*, 2022; Haseeba *et al.*, 2025)**.

Table 1. Environmental parameters

Parameter	Average value
Temperature (T, °C)	29.20
Salinity (S, ppt)	16.25
Depth, (D, cm)	27.00
Clarity (C, cm)	91.67
pH	5.56
Dissolved Oxygen (DO, mg/L)	2.427
Nitrate (NO_3 or Na, ppm)	0.077
Phosphate (PO_4 or P, mg/L)	0.01
Ammonia (NH_3 or N, ppm)	0.01
Nitrite (NO_2or Ni, ppm)	0.002
Total N (TN, %)	0.002
Organic Carbon (OC, %)	0.77
C/N Ratio (C/N R%)	12.51
Organic Matter (OM, %)	1.55

The average temperature (29°C) falls within the optimal range for tropical mangroves, supporting photosynthesis and seedling establishment. However, temperature interacts with salinity and hydrodynamics to influence mangrove zonation. Moderate salinity (16ppt) reflects brackish water conditions, which are favorable for some species but suboptimal for halophilic taxa. In Aimas, this moderate salinity combined with freshwater influx likely favors the dominance of *Bruguiera* and *Sonneratia* species observed in sapling stages, rather than *Rhizophora* taxa that prefer higher salinity. This may partly explain the uneven recruitment observed in the study area, where only certain growth classes were dominant. Previous studies emphasize that salinity gradients and hydrological regimes are among the strongest drivers of mangrove distribution patterns **(Ahmed *et al.*, 2023; Kimera *et al.*, 2024)**.

The acidic pH (5.56) combined with low dissolved oxygen indicates reducing soil and water conditions. Mangrove soils are often waterlogged, leading to hypoxia and the accumulation of reduced compounds such as sulfides. These conditions restrict root respiration and microbial nutrient cycling, limiting seedling survival and tree growth. Short-term hypoxia during tidal cycles has also been shown to suppress early recruitment stages, creating a bottleneck for regeneration **(Gillis *et al.*, 2019; Yang *et al.*, 2025)**. The results are consistent with such stressors, as few seedlings and no mature trees were recorded. Nutrient levels were strikingly low, suggesting oligotrophic conditions. Nitrogen and phosphorus are key regulators of mangrove productivity and litter decomposition. Although the C/N ratio (12.5) indicates a balanced substrate for microbial activity, the absolute carbon and nitrogen stocks are too small to sustain high productivity. Consequently, the ecosystem's potential for long-term carbon sequestration is reduced compared with mature mangrove stands in more nutrient-rich environments **(Kang *et al.*, 2025)**.

Overall, these environmental conditions, such as low salinity, acidic pH, and nutrient-poor soils, directly constrain regeneration processes and explain the dominance of intermediate growth classes (saplings and poles) observed in the vegetation structure. Integrating these parameters with the structural data shows a coherent ecological picture: intermediate stages of mangrove regeneration (saplings and poles) dominate, while both seedlings and mature trees are suppressed. This reflects an environment where brackish salinity supports mid-stage growth, but acidic, hypoxic, and nutrient-poor conditions limit recruitment and prevent stands from reaching maturity. In addition to natural stressors, anthropogenic disturbance, such as wood harvesting or land-use change, may further constrain regeneration. From a management perspective, these findings highlight the need for continuous monitoring of sediment and water quality, rehabilitation of organic matter inputs, and assisted planting programs to accelerate the transition toward mature, self-sustaining mangrove forests.

4. Ecological implications based on their relationship

The ecological indices of mangrove stands were analyzed in relation to environmental parameters using correlation matrices (Tables 2–4) and multivariate principal component analysis (PCA) (Figs. 5, 6). Although the correlation tables provide extensive numerical relationships, the PCA allowed the identification of significant gradients and patterns of influence among environmental variables. Sapling-dominated plots of *Bruguiera gymnorhiza* and *Sonneratia alba* showed positive associations with moderate salinity and water transparency, whereas pole-dominated plots of *Rhizophora apiculata* corresponded to zones with higher acidity and low dissolved oxygen. These findings suggest that specific growth stages respond differently to environmental stressors, reflecting species-level adaptation and regeneration dynamics.

Table 2. Correlation of species diversity index (*H'*) with environmental parameters

	H'	T	S	D	C	pH	DO	Na	P	A	Ni	TN	OC	C/N R	OM
H'	1														
T	-0.740	1													
S	-0.981	0.856	1												
D	0.998	-0.779	-0.990	1											
C	-0.907	0.954	0.971	-0.930	1										
pH	0.830	-0.989	-0.922	0.862	-0.987	1									
DO	-0.718	0.064	0.570	-0.675	0.359	-0.209	1								
Na	-0.315	0.871	0.492	-0.371	0.684	-0.789	-0.434	1							
P	-0.190	0.800	0.376	-0.248	0.585	-0.704	-0.546	0.991	1						
A	0.936	-0.928	-0.986	0.956	-0.997	0.972	-0.429	-0.626	-0.521	1					
Ni	0.741	-0.999	-0.857	0.780	-0.954	0.989	-0.065	-0.870	-0.799	0.929	1				
TN	-0.694	0.030	0.541	-0.649	0.327	-0.176	0.999	-0.464	-0.574	-0.398	-0.032	1			
OC	-0.299	0.862	0.478	-0.356	0.672	-0.779	-0.448	0.999	0.993	-0.614	-0.862	-0.478	1		
C/N R	-0.667	0.994	0.798	-0.710	0.918	-0.968	-0.039	0.917	0.858	-0.885	-0.994	-0.073	0.910	1	
OM	-0.301	0.864	0.480	-0.358	0.674	-0.781	-0.446	0.999	0.993	-0.615	-0.863	-0.476	0.999	0.911	1

Table 3. Correlation of species evenness index (*e*) with environmental parameters

	E	T	S	D	C	pH	DO	Na	P	A	Ni	TN	OC	C/N R	OM
e	1														
T	0.022	1													
S	-0.498	0.856	1												
D	0.609	-0.780	-0.991	1											
C	-0.278	0.954	0.971	-0.931	1										
pH	0.125	-0.989	-0.923	0.863	-0.988	1									
DO	-0.996	0.064	0.570	-0.675	0.359	-0.210	1								
Na	0.510	0.871	0.493	-0.372	0.685	-0.790	-0.434	1							
P	0.616	0.801	0.376	-0.249	0.585	-0.704	-0.547	0.992	1						
A	0.351	-0.929	-0.987	0.956	-0.997	0.973	-0.430	-0.627	-0.521	1					
Ni	-0.020	-1.000	-0.857	0.781	-0.955	0.989	-0.066	-0.870	-0.800	0.929	1				
TN	-0.999	0.030	0.542	-0.650	0.327	-0.176	0.999	-0.464	-0.575	-0.399	-0.032	1			
OC	0.524	0.863	0.478	-0.356	0.673	-0.780	-0.449	1.000	0.994	-0.614	-0.862	-0.479	1		
C/N R	0.125	0.995	0.799	-0.711	0.918	-0.969	-0.039	0.917	0.858	-0.885	-0.994	-0.073	0.911	1	
OM	0.522	0.864	0.480	-0.358	0.674	-0.781	-0.447	1.000	0.993	-0.616	-0.863	-0.477	1.000	0.911	1

Table 4. Correlation of dominance index (*D*) with environmental parameters

	D	T	S	D	C	pH	DO	Na	P	A	Ni	TN	OC	C/N R	OM
D	1														
T	0.377	1													
S	0.801	0.856	1												
D	-0.874	-0.780	-0.991	1											
C	0.637	0.954	0.971	-0.931	1										
pH	-0.509	-0.989	-0.923	0.863	-0.988	1									
DO	0.948	0.064	0.570	-0.675	0.359	-0.210	1								
Na	-0.126	0.871	0.493	-0.372	0.685	-0.790	-0.434	1							
P	-0.253	0.801	0.376	-0.249	0.585	-0.704	-0.547	0.992	1						
A	-0.694	-0.929	-0.987	0.956	-0.997	0.973	-0.430	-0.627	-0.521	1					
Ni	-0.379	-1.000	-0.857	0.781	-0.955	0.989	-0.066	-0.870	-0.800	0.929	1				
TN	0.937	0.030	0.542	-0.650	0.327	-0.176	0.999	-0.464	-0.575	-0.399	-0.032	1			
OC	-0.142	0.863	0.478	-0.356	0.673	-0.780	-0.449	1.000	0.994	-0.614	-0.862	-0.479	1		
C/N R	0.280	0.995	0.799	-0.711	0.918	-0.969	-0.039	0.917	0.858	-0.885	-0.994	-0.073	0.911	1	
OM	-0.140	0.864	0.480	-0.358	0.674	-0.781	-0.447	1.000	0.993	-0.616	-0.863	-0.477	1.000	0.911	1

The PCA results (Fig. 5) highlight two principal components explaining the majority of variance in ecological indices relative to environmental variables. Component 1 primarily reflects the influence of water chemistry parameters, such as nitrate, phosphate, organic carbon, and total nitrogen. In contrast, Component 2 is strongly associated with physical parameters, including salinity, transparency, and dissolved oxygen. The rotated component plot demonstrates that sapling-dominated stands and limited recruitment of seedlings are related to low dissolved oxygen, acidic pH, and low nutrient availability. Conversely, areas with higher transparency and moderate salinity favor greater species diversity and evenness, indicating that light penetration and brackish conditions contribute positively to community balance. These multivariate patterns further imply that early-stage regeneration is more constrained by soil and water chemistry, while mid-growth stages (poles and saplings) are primarily shaped by physical gradients such as light and salinity. This supports the ecological hypothesis that abiotic stress filters determine community assembly by favoring stress-tolerant taxa and excluding less adaptive seedlings under hypoxic, acidic, and oligotrophic conditions.

The relationship patterns between indices and environmental factors (Fig. 6) reveal that species diversity and evenness negatively correlate with extreme nutrient limitations, hypoxia, and low pH. In contrast, dominance is positively associated with environmental stressors, particularly low oxygen and acidic conditions, suggesting that a few tolerant species dominate under suboptimal conditions. This pattern indicates that environmental constraints act as selective filters, shaping species composition and preventing the establishment of late-successional, mature trees **(Eddy *et al.*, 2019; Gue *et al.*, 2025)**. The observed relationships corroborate findings from other tropical mangrove ecosystems, where oligotrophic and hypoxic conditions favor sapling- and pole-dominated stands while reducing community complexity **(Lee *et al.*, 2014; Medina-Calderón *et al.*, 2021)**. However, while the correlation and PCA results reveal strong associations, statistical validation of these ecological hypotheses, such as testing specific response models between growth stages and environmental variables, remains a subject for further investigation. Future analyses should incorporate generalized linear or redundancy-based models to confirm the strength and direction of these interactions.

Taken together, the ecological implications are that environmental parameters strongly govern the structure and stability of mangrove stands in the Aimas District. Low nutrient concentrations, acidic pH, and hypoxia limit regeneration and succession, resulting in communities dominated by saplings and poles rather than mature trees. The PCA results confirm that physical and chemical factors interact to determine the spatial variation in diversity, evenness, and dominance. Such relationships are consistent with findings on aquatic fauna associations, where relatively high diversity indicates that environmental parameters likewise shape the composition and stability of faunal communities linked to mangrove habitats **(Hairil *et al.*, 2024)**. These insights are critical for informing conservation and management strategies, including restoration efforts, nutrient management, and protection of recruitment zones as revealed by **Goni *et al.* (2018)**, to maintain a resilient mangrove ecosystem.

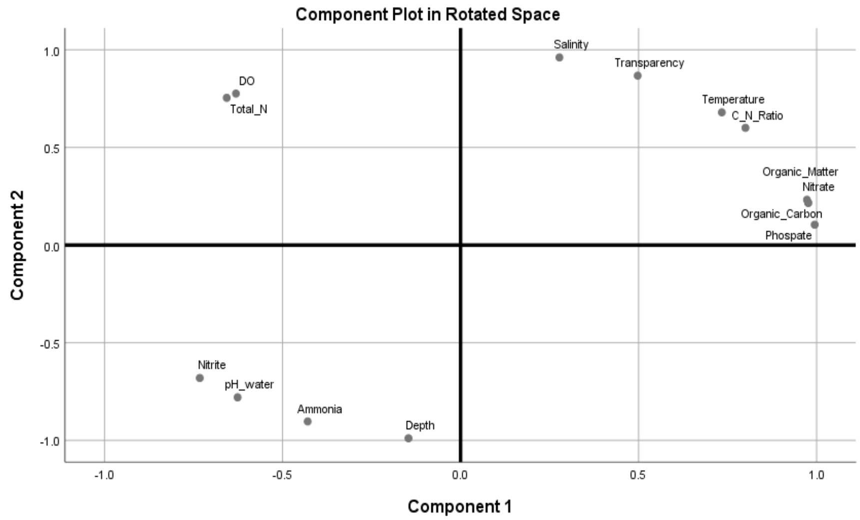

Fig. 5. Component plot in rotated space between variables in PCA analysis

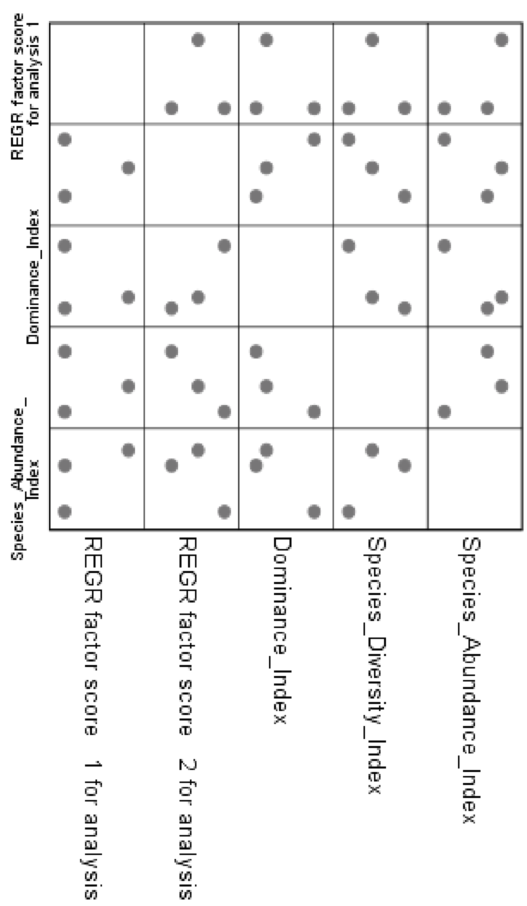

Fig. 6. Relationship patterns between environmental variables in PCA analysis

The combined analysis of ecological indices and environmental gradients underscores the fundamental role of both abiotic and biotic interactions in shaping mangrove community structure **(Granek & Ruttenberg, 2008)**. Diversity metrics, including species richness, evenness, and the Shannon-Wiener index, offer detailed insights into species composition and distribution patterns **(Ihwan *et al.*, 2025; Punong *et al.*, 2025)**. In contrast, dominance indices highlight the relative influence of key species within the ecosystem. Tables (2– 4) provide comprehensive quantitative correlations between these ecological indices and environmental parameters, enabling a nuanced understanding of how factors such as salinity, pH, and sediment characteristics affect community organization. Figs. (5, 6) further synthesize these complex relationships into interpretable ecological patterns, revealing the primary environmental and biological drivers that shape diversity, dominance, and evenness in brackish mangrove habitats. This integrative approach clarifies the mechanisms underlying community structure and provides a scientific foundation for effective management and conservation strategies to maintain ecosystem function and resilience.

CONCLUSION

This study concludes that mangrove communities in Aimas District are dominated by saplings, with limited seedling recruitment and no mature trees, reflecting early to intermediate successional stages. The findings contribute to understanding how physicochemical conditions, particularly dissolved oxygen, pH, and nutrient availability, govern mangrove structure and regeneration. From a management perspective, the study highlights the need to enhance seedling recruitment, control water quality degradation, and protect sites with moderate salinity and high transparency that support community balance. These insights provide a scientific basis for targeted restoration planning and adaptive management to strengthen mangrove resilience and long-term sustainability.

REFERENCES

Ahmed, S.; Sarker, S. K.; Friess, D. A.; Kamruzzaman, M.; Jacobs, M.; Sillanpää, M.; Sullibie, C.; Naabeh, S. C. and Pretzsch, H. (2023). Mangrove tree growth is size-dependent across a large-scale salinity gradient. Forest Ecology and Management, 537: 120954. https://doi.org/10.1016/j.foreco.2023.120954

Ahmed, S.; Sarker, S. K.; Friess, D. A.; Kamruzzaman, M.; Jacobs, M.; Islam, M. A.; Alam, M. A.; Suvo, M. J.; Sani, M. N. H.; Dey, T.; Naabeh, C. S. S. and Pretzsch, H. (2022). Salinity reduces site quality and mangrove forest functions. From monitoring to understanding. Science of The Total Environment, 853: 158662. https://doi.org/10.1016/j.scitotenv.2022.158662

Alongi, D. M. (2002). Present state and future of the world's mangrove forests. Environmental Conservation, 29(3): 331–349. https://doi.org/10.1017/S0376892902000231

Alongi, D. M. (2020). Carbon balance in salt marsh and mangrove ecosystems: A global synthesis. Journal of Marine Science and Engineering, 8(10): 767. https://doi.org/10.3390/jmse8100767

Anton, S. W.; Anton, A.; Jarir, D. V.; Fatmah, F.; Usman, H. and Kuruseng, I. (2020). Function of mangrove as a biofilter of vaname shrimp culture waste in the intensive pond SUPM Negeri Bone. Journal of Indonesian Tropical Fisheries (JOINT-FISH): Jurnal Akuakultur, Teknologi dan Manajemen Perikanan Tangkap, Ilmu Kelautan, 3(1): 14–27. https://doi.org/10.33096/joint-fish.v3i1.61

Anu, K.; Parveen K. H.; Sneha, V. K.; Busheera, P.; Muhammed, J. and Augustine, A. (2024). Mangroves in environmental engineering: Harnessing the multifunctional potential of nature's coastal architects for sustainable ecosystem management. Results in Engineering, 21: 101765. https://doi.org/10.1016/j.rineng.2024.101765

Asaeda, T.; Barnuevo, A.; Sanjaya, K.; Fortes, M.; Kanesaka, Y. and Wolanski, E. (2016). Mangrove plantation over a limestone reef - Good for the ecology? Estuarine, Coastal and Shelf Science, 173: 1–10. https://doi.org/10.1016/j.ecss.2016.02.017

Choudhary, B.; Dhar, V. and Pawase, A. S. (2024). Blue carbon and the role of mangroves in carbon sequestration: Its mechanisms, estimation, human impacts and conservation strategies for economic incentives. Journal of Sea Research, 199: 102504. https://doi.org/10.1016/j.seares.2024.102504

Clarke, P. J. and Kerrigan, R. A. (2002). The effects of seed predators on the recruitment of mangroves. Journal of Ecology, 90(4): 728–736. https://doi.org/10.1046/j.1365-2745.2002.00705.x

Dahdouh-Guebas, F.; Cannicci, S.; Fratini, S.; Smith III, T. J.; Offenberg, J. and Koedam, N. (2008). Faunal impact on vegetation structure and ecosystem function in mangrove forests: A review. Aquatic Botany, 89(2): 186–200. https://doi.org/10.1016/j.aquabot.2008.01.009

Dittmann, S.; Mosley, L.; Stangoulis, J.; Nguyen, V. L.; Beaumont, K.; Dang, T.; Guan, H. and McGrath, A. (2022). Effects of Extreme Salinity Stress on a Temperate Mangrove Ecosystem. Frontiers in Forests and Global Change, 5: 859283. https://doi.org/10.3389/ffgc.2022.859283

Eddy, S.; Ridho, M. R.; Iskandar, I. and Mulyana, A. (2019). Species composition and structure of degraded mangrove vegetation in the Air Telang Protected Forest, South Sumatra, Indonesia. Biodiversitas, 20(8): 2119–2127. https://doi.org/10.13057/biodiv/d200804

Farah, N. (2021, November 5). Econusa. Nature. Culture. Conservation. From EcoNusa: https://econusa.id/id/ecodefender/mengenal-wanamina/

Gillis, L. G.; Hortua, D. A.; Zimmer, M. and Jennerjahn, T. C. (2019). Interactive effects of temperature and nutrients on mangrove seedling growth and implications for establishment. Marine Environmental Research, 151: 104750. https://doi.org/10.1016/j.marenvres.2019.104750

Goni, A.; Rauf, A. and Asbar, A. (2018). Analysis of coastline changes and management strategies on the West Coast of South Sulawesi. JOINT-FISH: Journal of Aquatic Resources, Management, and Conservation, 1(1): 89–99. https://doi.org/10.33096/joint-fish.v1i1.24

Granek, E. F. and Ruttenberg, B. I. (2008). Changes in biotic and abiotic processes following mangrove clearing. Estuarine, Coastal and Shelf Science, 80(4): 555–562. https://doi.org/10.1016/j.ecss.2008.09.012

Guo, P.; Lin, Y.; Du, L.; Gu, X.; Deng, Y.; Wang, W. and Wang, M. (2025). Long-term vegetation succession increases aquatic animal structural stability and functional vulnerability following pond-to-mangrove restoration. Global Ecology and Conservation, 62: e03838. https://doi.org/10.1016/j.gecco.2025.e03838

Hairil, M.; Asbar, A. and Hamsiah. (2024). Association of aquatic fauna in the mangrove ecosystem in the Coastal Village of Laliko Campalagian District Polewali Mandar Regency. Jurnal Ilmiah Wahana Laut Lestari, 1(2): 108–119.

Haseeba, K. P.; Aboobacker, V. M.; Vethamony, P. and Al-Khayat, J. A. (2025). Water and sediment characteristics in the *Avicennia marina* environment of the Arabian Gulf: A review. Marine Pollution Bulletin, 216: 117963. https://doi.org/10.1016/j.marpolbul.2025.117963

Ihwan, M.; Mulyana, A.; Ridho, M. R. and Iskandar, I. (2025). Mangrove diversity and community structure in Savu Sea Marine National Park – East Nusa Tenggara, Indonesia. Egyptian Journal of Aquatic Biology and Fisheries, 29(1): 333–354. https://doi.org/10.21608/ejabf.2025.404348

Kang, L.; Huamei, H.; Ran, Y.; Shengpeng, Z.; Di, D. and Bo, P. (2025). Carbon storage potential and influencing factors of mangrove plantation in Kaozhouyang, Guangdong Province, South China. Frontiers in Marine Science, 11: 1439266. https://doi.org/10.3389/fmars.2024.1439266

Kasihiw, P.; Bawole, R.; Marwa, J.; Murdjoko, A.; Wihyawari, A.; Heipon, Y.; Cabuy, R. L.; Benu, N. M. H.; Hematang, F. and Leftungun, N. Y. (2024). Mangrove distribution to support biodiversity management in Teluk Bintuni District, West Papua, Indonesia. Biodiversitas, 25: 644–653. https://doi.org/10.13057/biodiv/d250223

Kasnir, M.; Harlina. and Jayadi. (2014a). Soil quality analysis of brackishwater shrimp farming in Coastal Areas of Takalar Regency – Indonesia. Journal of Environment and Ecology, 5(2): 307–320. https://doi.org/10.5296/jee.v5i2.7043

Kasnir, M.; Harlina. and Rosmiati. (2014b). Water quality parameter analysis for the feasibility of shrimp culture in Takalar Regency, Indonesia. Modern Applied Science, 8(6): 321–325. https://doi.org/10.5539/mas.v8n6p321

Kibler, K. M.; Pilato, C.; Walters, L. J.; Donnelly, M. and Taye, J. (2022). Hydrodynamic Limitations to Mangrove Seedling Retention in Subtropical Estuaries. Sustainability, 14(14): 8605. https://doi.org/10.3390/su14148605

Kimera, F.; Sobhi, B.; Omara, M. and Sewilam, H. (2024). Impact of salinity gradients on seed germination, establishment, and growth of two dominant mangrove species along the Red Sea Coastline. Plants, 13(24): 3471. https://doi.org/10.3390/plants13243471

Lee, S. Y.; Primavera, J. H.; Dahdouh-Guebas, F.; McKee, K.; Bosire, J. O.; Cannicci, S.; Diele, K.; Fromard, F.; Koedam, N.; Marchand, C.; Mendelssohn, I.; Mukherjee, N. and Record, S. (2014). Ecological role and services of tropical mangrove ecosystems: A reassessment. Global Ecology and Biogeography, 23(7): 726–743. https://doi.org/10.1111/geb.12155

Li, M.; Ishfaq, M.; González Quintero, V. A.; Peng, D.; Lang, T.; Gao, C.; Tam, N. F. and Zhou, H. (2025). Impact of elevated environmental pollutants on carbon storage in mangrove wetlands: A comprehensive review. Ecological Indicators, 178: 113830. https://doi.org/10.1016/j.ecolind.2025.113830

Medina-Calderón, J. H.; Mancera-Pineda, J. E.; Castañeda-Moya, E. and Rivera-Monroy, V. H. (2021). Hydroperiod and salinity interactions control mangrove root dynamics in a Karstic Oceanic Island in the Caribbean Sea (San Andres, Colombia). Frontiers in Marine Science, 7: 598132. https://doi.org/10.3389/fmars.2020.598132

Mohan, M.; Dutta Roy, A.; Montenegro, J. F.; Watt, M. S.; Burt, J. A.; Shapiro, A.; Ouerfelli, D.; Daniel, R.; De-Miguel, S.; Ali, T.; Ortega Pardo, M.; Al Sayah, M.; Aboobacker, V. M.; El Beyrouthy, N. and Reef, R. (2024). Mangrove forest regeneration age map and drivers of restoration success in Gulf Cooperation Council countries from satellite imagery. Remote Sensing Applications: Society and Environment, 36: 101345. https://doi.org/10.1016/j.rsase.2024.101345

Nyangoko, B. P.; Berg, H;, Mangora, M. M.; Shalli, M. S. and Gullström, M. (2022). Local perceptions of changes in mangrove ecosystem services and their implications for livelihoods and management in the Rufiji Delta, Tanzania. Ocean & Coastal Management, 219: 106065. https://doi.org/10.1016/j.ocecoaman.2022.106065

Punong, A.; Pentason, J. and Amores, A. (2025). Diversity and morphometry of mangrove species and it's relation to environmental factors in Tagum City, Davao del Norte, Philippines. International Journal of Bonorowo Wetlands, 15: 20–27. DOI: 10.13057/bonorowo/w150103

Ramdhani, I. (2022). Indonesia doubles down on efforts to restore endangered mangrove ecosystem. Maritime Fairtrade. https://maritimefairtrade.org/indonesia-doubles-down-on-efforts-to-restore-endangered-mangrove-ecosystem/ (Accessed on September 15, 2025, at 09.00 AM)

Rauf, A.; Wamnebo, M. I. and Yusuf, K. (2020). Application of satellite remote sensing technology in monitoring sediment distribution in the coastal waters of Pangkep Regency, South Sulawesi, Indonesia. AACL Bioflux, 13(5): 3182–3187.

Rauf, A.; Yusuf, K.; Asmidar, A.; Kasnir, M. and Tajuddin, M. (2018). Application of remote sensing technology and geographic information systems in monitoring coastal and marine resource potential in Pangkep Regency. Journal of Indonesian Tropical Fishes (JOINT-FISH), 1(1): 11–16.

Rifadilah, B.; Rachmad, B.; Rahardjo, P.; Maulid Al Wirai, R.; Triyono, H.; Abdul Rahman, A.; Steward Samusamu, A.; Sugianti, Y. and Mujiyanto. (2025). Ecological status and community structure of mangroves in East Siantan, Anambas Marine Tourism Park: A baseline study for sustainable management. Egyptian Journal of Aquatic Biology & Fisheries, 29(4): 1495–1519. https://doi.org/10.21608/ejabf.2025.443513

Roy, S. K.; Mojumder, P.; Chowdhury, M. A. A. and Hasan, M. M. (2025). Evaluating mangrove forest dynamics and fragmentation in Sundarbans, Bangladesh using high-resolution Sentinel-2 satellite images. Global Ecology and Conservation, 58: e03493. https://doi.org/10.1016/j.gecco.2025.e03493

Rustam, R.; Hamsiah, H. and Hartinah, H. (2020). Development of crab aquaculture business in mangrove forest areas through a community-based silvofishery system. Jurnal Balireso: Jurnal Pengabdian pada Masyarakat, 5(2): 133–140. https://doi.org/10.33096/balireso.v5i1.139

Saoum, M. R. and Sarkar, S. K. (2024). Monitoring mangrove forest change and its impacts on the environment. Ecological Indicators, 159: 111666. https://doi.org/10.1016/j.ecolind.2024.111666

Sillanpää, M.; Vantellingen, J. and Friess, D. A. (2017). Vegetation regeneration in a sustainably harvested mangrove forest in West Papua, Indonesia. Forest Ecology and Management, 390: 137–146. https://doi.org/10.1016/j.foreco.2017.01.022

Sraun, M.; Bawole, R.; Marwa, J.; Sinery, A. S. and Cabuy, R. L. (2023). Assessing environmental factors on the growth and distribution of mangrove seedlings along the Bintuni Riverbank Area, Bintuni Bay, West Papua, Indonesia. Journal of Ecological Engineering, 24(8): 1–11. https://doi.org/10.12911/22998993/162776

Sunkur, R.; Kantamaneni, K.; Bokhoree, C. and Ravan, S. (2023). Mangroves' role in supporting ecosystem-based techniques to reduce disaster risk and adapt to climate change: A review. Journal of Sea Research, 196: 102449. https://doi.org/10.1016/j.seares.2023.102449

Velázquez-Salazar, S.; Valderrama-Landeros, L.; Villeda-Chávez, E.; Cervantes-Rodríguez, C. G.; Troche-Souza, C.; Alcántara-Maya, J. A.; Vázquez-Balderas, B.; Rodríguez-Zúñiga, M. T.; Cruz-López, M. I. and Flores-de-Santiago, F. (2025). Mangrove damage and early-stage canopy recovery following hurricane Roslyn in Marismas Nacionales, Mexico. Forests, 16(8): 1207. https://doi.org/10.3390/f16081207

WRI Indonesia. (2022). Protecting the landscape of Papua land. WRI Indonesia. Retrieved September 18, 2025, from https://wri-indonesia.org/en/initiatives/protecting-landscape-tanah-papua

Yamamoto, Y. (2023). Living under ecosystem degradation: Evidence from the mangrove–fishery linkage in Indonesia. Journal of Environmental Economics and Management, 118: 102788. https://doi.org/10.1016/j.jeem.2023.102788

Yang, H.; Zheng, B.; Li, J.; Chen, X.; Lv, X.; Zhong, C. and Bai, H. (2025). Environmental drivers of regeneration in *Scyphiphora hydrophyllacea*: Thresholds for Seed germination and seedling establishment in Hainan's intertidal zones. Forests, 16(8): 1346. https://doi.org/10.3390/f16081346

Zhang, B.; Zhang, L.; Chen, B.; Deng, L.; Fu, B.; Yan, M. and Ji, C. (2024). Assessment of mangrove health based on pressure–state–response framework in Guangxi Beibu Gulf, China. Ecological Indicators, 167: 112685. https://doi.org/10.1016/j.ecolind.2024.112685