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Mangrove diversity and structure of Karimunjawa National Park, Indonesia: Conserving forest patches in small island ecosystem

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Abstract. *Asadi MA, Jasmine AN, Widodo AT, Isdianto A, Rafinaldo R, Rozi HF, Firdaus M. 2025. Mangrove diversity and structure of Karimunjawa National Park, Indonesia: Conserving forest patches in small island ecosystem. Biodiversitas 26: 5350-5359.* Mangrove forests are vital coastal ecosystems, and in small island settings their conservation requires more attention including continuous assessment. This study investigated the diversity and structural characteristics of mangroves in Karimunjawa National Park (KNP), Indonesia, across zones and forest patches to extend beyond previous research. Field surveys in 39 plots (10 m × 10 m) across 13 locations on Karimunjawa and Kemujan Islands recorded 1,065 individuals from 15 species in eight families. Species density ranged from 5.13 ind./ha (*Heritiera littoralis*) to 1,230.77 ind./ha (*Ceriops tagal*), while basal area varied from 0.05 m^2/ha (*Bruguiera gymnorhiza*) to 4.95 m^2/ha (*Rhizophora apiculata*). *Ceriops tagal* had the highest importance value, followed by *R. apiculata*, *Excoecaria agallocha*, and *Lumnitzera racemosa*. Ecological indices showed moderate species diversity (Shannon–Wiener *H'* = 1.73), relatively even distribution (Pielou's J = 0.64), and low dominance (Simpson's C = 0.26), indicating a mature and structurally balanced forest, although the community composition reflects dominance by a few key species with lower representation of rare taxa. The relatively high density of dominant species suggests successful regeneration yet highlights potential vulnerability if disturbances disproportionately affect these taxa. Mangroves in small islands setting in KNP are limited in area and highly sensitive to human pressures such as aquaculture and tourism. Safeguarding them is essential for ecosystem services and local livelihoods. Our findings provide baseline data to guide monitoring, zoning, and rare species protection, underscoring the need for integrated management to ensure long-term resilience.

Keywords: *Ceriops tagal*, ecological indices, forest structure, Karimunjawa National Park, species composition

INTRODUCTION

Mangrove forest is important coastal ecosystem that offer key benefits, such as protecting shorelines, storing carbon, and providing habitat for various marine and terrestrial species (Seary et al. 2021; Charoenlerkthawin et al. 2024; Islam et al. 2024). Indonesia, which harbours about 20% of the world's mangrove forests, plays a critical role in maintaining global mangrove biodiversity and carbon storage (Darmawan et al. 2020; Sasmito et al. 2023; Febrianto et al. 2025). These forests also support coastal livelihoods through timber and non-timber forest products, fisheries, ecotourism, and erosion control (Seary et al. 2021; Fan et al. 2024). They also function as natural buffers that reduce the impact of storms, waves, and saltwater intrusion, thereby safeguarding coastal infrastructure and communities.

Despite their importance, Indonesian mangroves face increasing threats from aquaculture, tourism, and infrastructure development (Ebadzadeh et al. 2024; Suhardi et al. 2024). Many mangrove forests are protected under Marine Protected Areas (MPAs), yet fragmentation and degradation are particularly concerning in several MPAs, where ecological pressures continue to intensify (Bryan-Brown et al. 2020). The effectiveness of MPAs in Indonesia is closely tied to the persistence of mangrove ecosystems, which provide nursery grounds, shoreline protection, and ecological connectivity to adjacent habitats (Charoenlerkthawin et al. 2024; Suhardi et al. 2024). Additional drivers, such as pollution from coastal settlements and climate change–induced sea-level rise, further accelerate habitat loss and decline in ecosystem services in mangrove forests. Updated assessments of mangrove diversity and structure are urgently needed to inform conservation strategies. Without such data, management actions risk being reactive rather than preventive, leading to long-term ecological deterioration.

The Karimunjawa National Park (KNP), located in the Java Sea, Indonesia, is an MPA that contains extensive mangrove habitats across various islands, including Karimunjawa and Kemujan. While earlier studies have focused on the primary mangrove forest in the Mangrove Track of Kemujan (Azzahra et al. 2023; Priandeni et al. 2025), smaller and more fragmented patches have received limited attention. These areas are particularly vulnerable to human disturbance and ecological decline, yet they are essential for maintaining species diversity and ecosystem resilience (Sabdono et al. 2024). Smaller stands may act as ecological linkages between habitat patches, supporting species dispersal and genetic flow. In KNP, mangroves are mainly threatened by aquaculture expansion, coastal development, and conversion for tourism facilities, which together drive fragmentation and habitat loss. The absence of detailed data on composition and structure in these sites constrains restoration and management planning. This gap also limits the ability to prioritize high-value conservation areas within the park. In other small island MPAs, such as the Andaman Islands and Palau, mangroves face similar pressures from tourism and development (Shankar et al. 2020; Mantiquilla et al. 2021). KNP differs in that its main mangrove area extends along the long coastline of Karimunjawa Island, posing both management challenges and opportunities for connectivity-based conservation. Evaluating species diversity and structural characteristics is crucial for assessing forest health and ecological functionality (Pototan et al. 2020; Mattone and Sheaves 2024). A high level of species richness enhances resilience, while structural attributes such as tree density and basal area relate directly to carbon storage and productivity (Andrieu et al. 2020; Sitthi et al. 2025). Ecological indices, including Shannon–Wiener diversity, Simpson's dominance, and Pielou's evenness, help identify community stability and detect shifts in species dominance. Site-specific biodiversity assessments in MPAs are increasingly recognized as essential for guiding conservation priorities (McSherry et al. 2023; Hidayah et al. 2024). They provide localized evidence to support national and international biodiversity targets.

Given the strong ecological connectivity between mangroves, seagrass beds, and coral reefs, degradation in KNP's mangroves could negatively affect broader coastal biodiversity and fisheries productivity. As part of a small island ecosystem, the condition of these mangroves is closely tied to the socio-economic well-being of local communities dependent on fisheries, ecotourism, and forest resources. Integrating ecological and socio-economic perspectives is therefore critical for sustainable management.

This study addresses the lack of recent, comprehensive data on mangrove composition and structure in KNP by documenting species composition, diversity, and structural characteristics across multiple sites. The specific objectives are to: (i) record current species composition; (ii) measure key structural parameters such as density, basal area, and importance values; and (iii) analyze diversity and dominance patterns using standard ecological indices. The findings aim to provide baseline data for monitoring programs, inform restoration and conservation strategies, and strengthen the management of mangrove resources in small island MPAs. By situating KNP within a broader small island context, this study highlights lessons that may inform adaptive conservation planning across the Indo-Pacific.

MATERIALS AND METHODS

Study area

The research was performed in Karimunjawa National Park (KNP) (5°50.386′ S-5°48.844′ S and 110°26.771′ E-110°28.925′ E) (Figure 1), a designated marine and coastal conservation zone in the Java Sea, situated roughly 125 km north of Semarang, Central Java, Indonesia. The park consists of 27 islands covering a total area of 47 km². The Karimunjawa and Kemujan islands form the primary landmass, encompassing approximately 90% of the terrestrial expanse and separated by a slender strait. These islands function as the ecological and socio-economic core of the park, supporting the majority of its mangrove forests, coral reefs, and seagrass beds. The archipelago is inhabited by roughly 9,700 residents, who predominantly participate in small-scale fishing, seaweed farming, and tourism. Recent satellite measurements estimate the overall mangrove area at 602 hectares, primarily along the beaches of Karimunjawa and Kemujan, where they are vital for habitat provision and coastal protection.

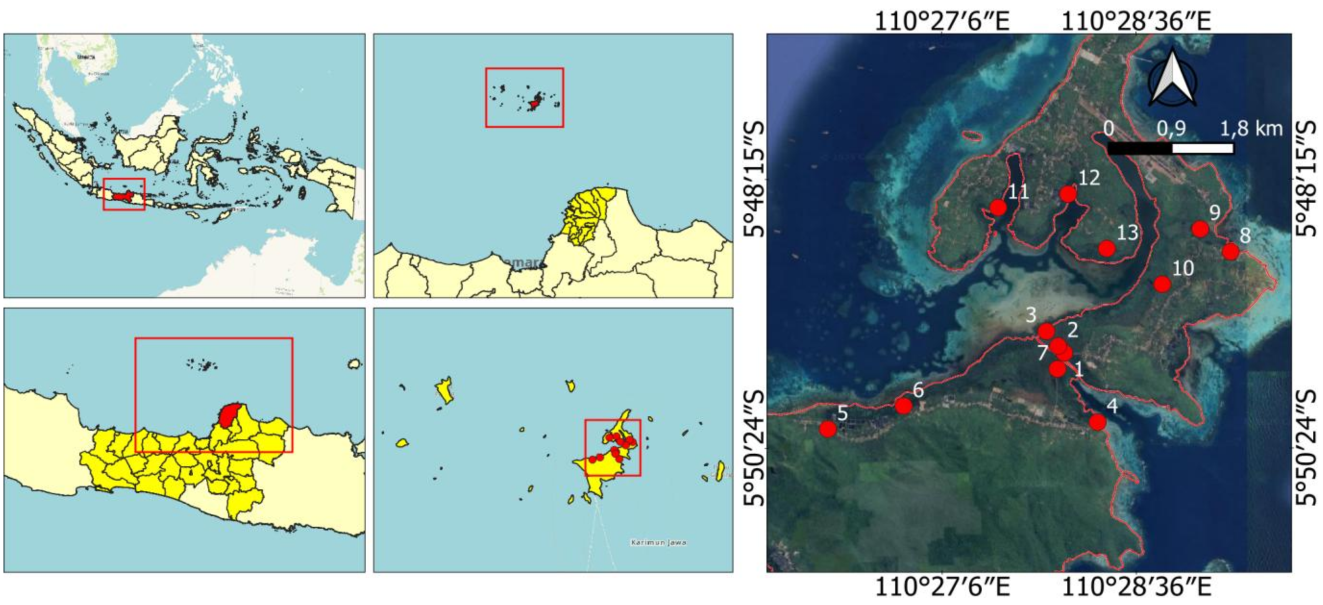

Figure 1. Map of study area showing the sampling stations in the Karimunjawa National Park (KNP), Central Java, Indonesia

KNP is situated in a humid tropical marine environment, noted for its stable temperatures and a distinct monsoonal rainfall pattern. The daily average temperatures fluctuate between 26 and 30°C, while the relative humidity levels are between 70% and 85%. The average annual precipitation is approximately 2,632 mm, featuring a marked wet season from October to March, during which monthly rainfall can reach nearly 400 mm, and a dry season from April to September, with an average of only about 60 mm per month (Prihantono et al. 2022). These climatic conditions have a significant effect on salinity, soil moisture, and nutrient dynamics, which subsequently modify the structure and composition of the local mangrove ecosystems.

Data collection

A non-invasive technique utilizing the quadrat sampling method was implemented to evaluate the structure of mangrove forests in the primary islands of KNP, specifically the islands of Karimunjawa and Kemujan. This method was selected to reduce disruption to the ecosystem while facilitating thorough data collection. Field surveys were conducted in January 2025, coinciding with the northeast monsoon season, which is generally characterized by frequent rainfall, elevated humidity, and fluctuating wind conditions. In spite of the inclement weather, sampling took place during low tide to enhance accessibility and visibility within the mangrove stands.

A total of 13 sampling stations were established throughout representative forest regions, with each station consisting of three plots measuring 10 × 10 m, resulting in a total of 39 plots. The sampling was carried out using a stratified random method based on three ecological zones: landward, intermediate, and seaward. Alongside the documentation of spatial variation within these ecological zones, specific stations—namely Stations 6 and 8—were deliberately positioned adjacent to deserted aquaculture ponds to account for localized human influences. This approach guaranteed that the sampling design effectively reflected both the natural ecological patterns and the regions affected by prior human activities within the mangrove ecosystem. Within each plot, all mangrove trees that satisfied the minimum size criteria—at least 1.5 meters in height and a stem circumference of 5 cm or greater—were identified to the species level and measured. Diameter at Breast Height (DBH) was measured 30 cm above the highest prop root for *Rhizophora* spp., and at 1.37 m above ground for other species (Asadi and Pambudi 2020; Magarik et al. 2020). Coordinates along with the characteristics of each station, and the environmental parameters (salinity and temperature) is presented in Table 1.

Forest structure analysis

For evaluating the structural attributes of the mangrove forest, key parameters—such as individual tree basal area, stand basal area, and stem density per hectare were calculated, and basal area measurements were then used to compute relative dominance, which—together with other structural metrics—provides insights into each species' ecological roles and functional importance within the mangrove community (Asadi and Pambudi 2020; Pototan et al. 2020; Sraun et al. 2022). The equations for calculating such parameters are presented below.

$$\text{Basal area } (\text{m}^2) = 0.00007854 \text{ X DBH}^2$$

$$\text{Stand BA}\left(\frac{\text{m}^2}{ha}\right) = \frac{\sum \text{Individual tree BA (in m}^2)}{\text{Total plot area in hectare}}$$

$$\text{Density (trees/ha)} = \frac{\text{Total number of trees}}{\text{Total plot area in hectare}}$$

$$\text{Relative density (\%)} = \frac{\text{Number of individuals of a species}}{\text{Total number of individual of all species}} \text{ X } 100$$

$$\text{Relative frequency (\%)} = \frac{\text{Frequency of a species}}{\sum \text{Frequencies of all species}} \text{ X } 100$$

$$\text{Relative dominance (\%)} = \frac{\text{Total basal area of a species}}{\text{Total basal area of all species}} \text{ X } 100$$

$$\text{Importance Value Index (IVI)} = \text{RD} + \text{RF} + \text{RD}$$

Where, RD: Relative Density, RF: Relative Frequency, RD: Relative Dominance

Ecological indices and statistical analysis

Ecological indices were calculated to assess the diversity and structural composition of mangrove communities on KNP. Species richness (S) reflects the total number of species recorded. The Shannon-Wiener Index (*H′*) measures diversity based on species abundance and distribution, while Hmax represents the maximum possible diversity. Pielou's Evenness Index (J) indicates how evenly individuals are distributed. Effective Number of Species (ENS) expresses diversity as the number of equally common species. Simpson's Dominance (C) and its complement, Simpson's Diversity Index (D = 1-C), assess species dominance and overall diversity (Asadi et al. 2018; Pimple et al. 2022; Sraun et al. 2022). Here are the formulas used in the analysis:

Species Richness (S):
$S = Number\ of\ species\ observed$

Shannon-Wiener Index (H′):
$H' = -\sum_{i=1}^{s} pi \ln pi$
where $pi = \frac{\text{Ni}}{\text{N}}$

Maximum diversity (Hmax):
$Hmax = \ln(S)$

Effective Number of Species (ENS):
$ENS = Exp\ (H')$

Pielou's Index of Evenness (J):
$J = \frac{\text{H}'}{\text{Hmax}}$

Simpson's Index of Dominance (C)
$C = \sum_{i=1}^{s} Pi^2,$
where $pi = \frac{\text{Ni}}{\text{N}}$

Simpson's Index of Diversity (D):

$$D = 1 - C$$

Statistical analyses were performed using GraphPad Prism 9. Differences in biodiversity indices (Shannon Diversity, Simpson Index, and Species Richness) among landward, intermediate, and seaward zones were evaluated with two-way ANOVA, applying a significance threshold of $p < 0.05$.

Table 1. Coordinates, temperatures, salinities, and site description of research station in Karimunjawa National Park, Central Java, Indonesia

Station	Coordinate	Temperature (°C)	Salinity (ppt)	Site description
1	5°49'38.35"S, 110°28'2.89"E	28.27±0.29	25.67±3.79	Station 1 is located in the landward zone within the mangrove tracking area of Kemujan. The sediment is characterized as peat, primarily composed of decomposed mangrove materials such as leaves and small branches. This station is situated more than 500 meters from the shoreline and is only inundated by seawater during the highest tides.
2	5°49'35.09"S 110°28'0.03"E	28.83±0.31	22.33±8.08	Station 2 is also located in the landward zone with similar characteristics to Station 1. The sediment is peat-like, composed mainly of decomposed mangrove materials such as leaves and twigs. This station is situated approximately 450 meters from the shoreline and is inundated by seawater only during spring tides.
3	5°49'27.96"S 110°27'54.54"E	30.00±0.56	21.00±1.73	Station 3 is located in the intermediate zone within the mangrove tracking area, approximately 170 meters from the shoreline. This station is inundated daily by tidal water The sediment consists of a mixture of sand, coral fragments, and mud.
4	5°50'11.81"S 110°28'18.47"E	30.00±0.56	29.67±2.31	Station 4 is located in the seaward zone (fringe mangroves) at Alano Beach. This station is inundated daily by tidal water. The sediment is dominated by mud with a mixture of sand.
5	5°50'5.82"S 110°26'5.73"E	28.33±0.40	23.33±0.58	Station 5 is located approximately 70 meters from the shoreline but does not have direct exposure to the sea due to its position behind Nyamplungan Beach. As it lies at a slightly higher elevation and is sheltered from direct tidal flow, this station is only inundated during spring tides, with seawater entering indirectly through adjacent mangrove areas. The sediment consists of muddy sand.
6	5°50'4.17"S 110°26'48.17"E	29.43±0.40	15.00±0.00	Station 6 is located approximately 150 meters from the shoreline, in front of an abandoned aquaculture pond, and lies within the intermediate zone. The first two plots at this station are inundated daily by tidal water, while the third plot is only inundated during above-average high tides. The substrate consists of muddy sand, with mud as the dominant component. Notably, this is the only station where *Sonneratia ovata* Backer, a near-threatened mangrove species, was recorded.
7	5°49'46.13"S 110°27'59.76"E	29.93±0.51	25.67±3.06	Station 7 is located approximately 300 meters from the shoreline and situated in front of the main road. The substrate consists of muddy sand mixed with peat. This station is only inundated by tidal water during spring tides.
8	5°48'49.67"S 110°29'20.68"E	28.20±0.20	26.17±4.25	Station 8 is located in front of an abandoned aquaculture pond. The sediment consists predominantly of mud, with some areas showing brownish mud likely influenced by former pond discharge. This station is inundated daily by tidal water.
9	5°48'37.94"S 110°29'6.32"E	29.43±0.40	15.00±1.73	Station 9 is located in Kemujan, approximately 600 meters from the shoreline. This station is only inundated during spring tides. The sediment consists of sand mixed with mud and scattered coral fragments.
10	5°49'5.31"S 110°28'48.74"E	28.27±0.15	15.50+2.18	Station 10 is located approximately 400 meters from the shoreline. This station is only inundated during spring tides. The substrate consists of muddy sand.
11	5°48'43.20"S, 110°27'26.30"E	30.67±0.57	30.33±0.57	Station 11 is located in the fringe mangrove zone and is inundated daily by tidal water. The substrate consists of muddy sand.
12	5°48'21.9"S 110°28'04.8"E	29.83±1.44	31.00±1.00	Station 12 is located in a sheltered seaward zone within a bay-like area. The substrate consists of sandy mud. This station is influenced by tidal water, but with reduced wave energy due to its protected position.
13	5°48'32.5"S 110°28'36.0"E	29.67±0.67	30.67±0.57	Station 13 shares similar characteristics with Station 12 and is located in the middle of the bay. It lies within a sheltered seaward zone. The substrate consists of sandy mud, and the station is influenced by tidal water with reduced wave energy due to its protected position.

RESULTS AND DISCUSSION

Mangrove species composition

Table 2 provides a detailed summary of the variety of mangrove species found in the study area, which includes 1,065 individuals across 15 species belonging to eight different families. The Rhizophoraceae family was the most prevalent, consisting of seven species: *Bruguiera cylindrica* (L.) Blume, *Bruguiera gymnorhiza* (L.) Lam., *Bruguiera sexangula* (Lour.) Poir., *Ceriops tagal* (Perr.) C.B.Rob., *Rhizophora apiculata* Blume, *Rhizophora mucronata* Lam., and *Rhizophora stylosa* Griff.. *Ceriops tagal* was the most dominant species, comprising 480 individuals. Species diversity extended beyond Rhizophoraceae, including *Excoecaria agallocha* L. (172 individuals, Euphorbiaceae) and *Lumnitzera racemosa* Willd. (153 individuals, Combretaceae). Other notable species include *Sonneratia alba* Sm., *Sonneratia ovata* Backer, *Xylocarpus granatum* J.Koenig, *Heritiera littoralis* Dryand. ex W.T.Aiton, *Avicennia marina* (Forssk.) Vierh., and *Scyphiphora hydrophyllacea* C.F.Gaertn.. Most species were classified as Least Concern (LC), except for *S. ovata* Backer, which was Near Threatened (NT) and recorded only at station 6 (Figure 2).

Table 2. Mangrove species identified in Karimunjawa National Park (KNP), Central Java, Indonesia

Family	Species	Number of individuals	Conservation status
Acanthaceae	*Avicennia marina* (Forssk.) Vierh	8	LC
Combretaceae	*Lumnitzera racemosa* Willd.	153	LC
Euphorbiaceae	*Excoecaria agallocha* L.	172	LC
Lythraceae	*Sonneratia alba* Sm.	21	LC
	Sonneratia ovata Backer	2	NT
Malvaceae	*Heritiera littoralis* Dryand. ex W.T.Aiton	2	LC
Meliaceae	*Xylocarpus granatum* J.Koenig	30	LC
Rhizophoraceae	*Bruguiera cylindrica* (L.) Blume	9	LC
	Bruguiera gymnorhiza (L.) Lam.	8	LC
	Bruguiera sexangula (Lour.) Poir.	4	LC
	Ceriops tagal (Perr.) C.B.Rob.	480	LC
	Rhizophora apiculata Blume	97	LC
	Rhizophora mucronata Lam.	59	LC
	Rhizophora stylosa Griff.	15	LC
Rubiaceae	*Scyphiphora hydrophyllacea* C.F.Gaertn.	5	LC
Total		1,065	

Structural characteristics of forest stands

The DBH measurements of 15 mangrove species varied from 5.40 cm for *C. tagal* to 38.53 cm for *S. ovata* (Figure 3). Most mangrove species exhibited DBH values between 8 and 15 cm, with *R. mucronata* at 13.98 cm, *A. marina* at 13.93 cm, and *B. sexangula* at 15.09 cm (Figure 4). The average DBH across species was 12.99 cm. A single *S. ovata* tree reached 68 cm in DBH, while *C. tagal* and *E. agallocha* showed smaller DBH values.

Figures 4 and 5 depict the basal area and density of mangrove stands at the research stations. The total stand density was 2,730.77 ind./ha, with a cumulative basal area of 22.91 m²/ha. *Ceriops tagal* demonstrated the highest density at 1,230.77 ind./ha, followed by *E. agallocha* (441.03 ind./ha) and *L. racemosa* (392.31 ind./ha). *Rhizophora apiculata* had the largest basal area at 4.95 m²/ha, despite having fewer individuals. Several species, including *B. gymnorhiza* and *H. littoralis*, showed low densities and small sizes.

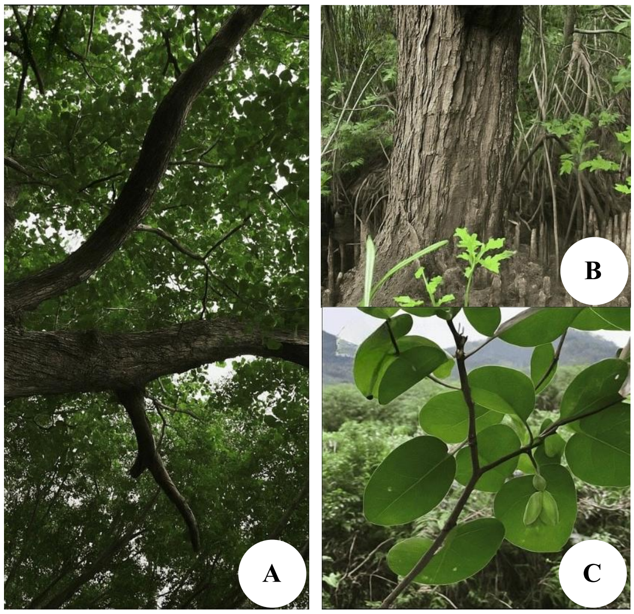

Figure 2. The near-threatened mangrove species *Sonneratia ovata* Backer found in the research area. A. Standing tree, B. Base of the trunk with visible roots and surrounding sediment, C. Flower and leaves of the tree

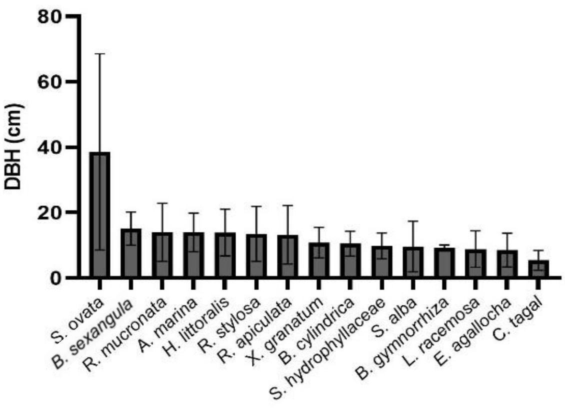

Figure 3. Mean DBH of 15 mangrove species recorded on Karimunjawa National Park (KNP), Central Java, Indonesia

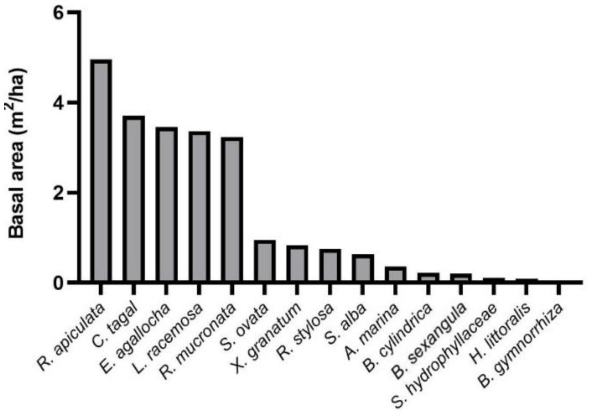

Figure 4. Basal area (m²/ha) of mangrove species in Karimunjawa National Park, Central Java, Indonesia, arranged from highest to lowest

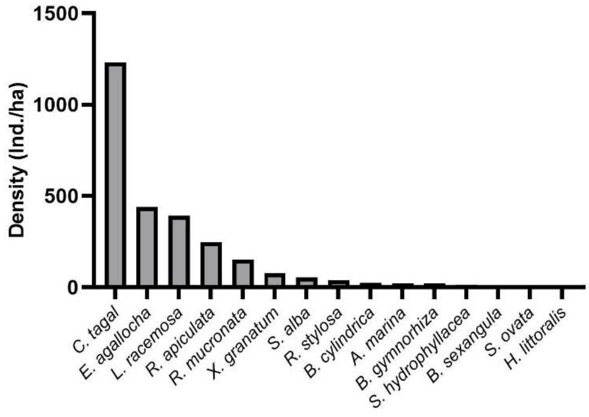

Figure 5. Density (ind./ha) of mangrove species in Karimunjawa National Park, Central Java, Indonesia, arranged from highest to lowest

The Importance Value Index (IVI) of mangrove stands

Ceriops tagal was the predominant mangrove species in KNP, with the highest IVI (82.47%) driven by its high relative density (45.07%) (Table 3). *Rhizophora apiculata*, although less abundant, contributed most to basal area, indicating the presence of larger stems. Other species with relatively high IVI values included *E. agallocha*, *L. racemosa*, and *R. mucronata*. Mid-IVI species such as *X. granatum*, *S. alba*, and *B. cylindrica* were also present, while species with low IVI values included *H. littoralis* and *S. hydrophyllacea*.

Ecological indices

The ecological indices displayed in Table 4 provide information regarding the mangrove community structure of Karimunjawa Island. The mangrove forest exhibits moderate variety, with a species richness of 15. The Shannon-Wiener Index (*H'*) was 1.73, and the Effective Number of Species (ENS) was 5.65. Pielou's Evenness Index (J) was 0.64. Simpson's Index of Dominance (C) was 0.26, while the Simpson's Diversity Index (D) was 0.74.

Mangrove habitat zonation

The distribution of mangrove species across the sampling stations is summarized in Table 5, while the results of the two-way ANOVA analysis of ecological indices among zones are presented in Figure 6. *Ceriops tagal* was dominant in several landward stations (1, 2, 7, 9, 10), where the mean salinity was approximately 20.9 ppt. In contrast, *R. apiculata* and *R. mucronata* were the main species recorded in seaward stations such as 4 and 11. Intermediate zones (Stations 3, 6, and 8) showed higher species richness, with species such as *L. racemosa, R. stylosa*, and *E. agallocha*. Notably, Station 6, located in front of abandoned aquaculture ponds, also contained *S. ovata*, a species of conservation concern. The sheltered seaward stations (12 and 13) exhibited the highest species richness, with the presence of *X. granatum, B. cylindrica, H. littoralis*, and other species.

Table 3. Relative density, frequency, dominance, and Importance Value Index (IVI) of mangrove species observed in Karimunjawa National Park (KNP), Central Java, Indonesia

Species	Relative density (%)	Relative frequency (%)	Relative dominance (%)	Importance value (%)
Ceriops tagal (Perr.) C.B.Rob.	45.07	21.21	16.19	82.47
Rhizophora apiculata Blume	9.11	15.15	21.61	45.87
Excoecaria agallocha L.	16.15	12.12	15.08	43.35
Lumnitzera racemosa Willd.	14.37	12.12	14.67	41.16
Rhizophora mucronata Lam.	5.54	11.36	14.13	31.03
Xylocarpus granatum J.Koenig	2.82	6.82	3.64	13.27
Sonneratia alba Sm.	1.97	4.55	2.76	9.28
Rhizophora stylosa Griff.	1.41	3.79	3.27	8.47
Bruguiera cylindrica (L.) Blume	0.85	4.55	0.97	6.36
Sonneratia ovata Backer	0.19	0.76	4.15	5.10
Scyphiphora hydrophyllacea C.F.Gaertn.	0.47	3.03	0.48	3.98
Avicennia marina (Forssk.) Vierh.	0.75	1.52	1.58	3.85
Bruguiera sexangula (Lour.) Poir.	0.38	1.52	0.87	2.76
Bruguiera gymnorhiza (L.) Lam.	0.75	0.76	0.22	1.73
Heritiera littoralis Dryand. ex W.T.Aiton	0.19	0.76	0.39	1.33
	100	100	100	300

Table 4. Ecological indices analysis of mangrove forest in Karimunjawa National Park (KNP)

Diversity indices	Value
Species Richness	15
Shannon-Weiner Diversity Index (H')	1.73
Hmax	2.71
Effective Number of Species (ENS)	5.65
Pielou's Index of Evenness (J)	0.64
Simpson's Index of Dominance (C)	0.26
Simpson's Index of Diversity (D)	0.74

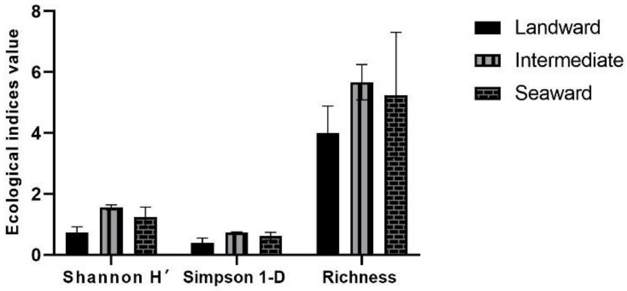

Figure 6. Diversity indices (Shannon *H′*, Simpson 1–d, and Species Richness) across mangrove zonation

Table 5. Mangrove species composition and zonation across sampling stations in Karimunjawa National Park (KNP), Central Java, Indonesia

Station	Mangrove species	Habitat zones
Station 1	*Ceriops tagal* (75.44%), *Rhizophora apiculata* (0.88%), *Lumnitzera racemosa* (16.67%), *Rhizophora stylosa* (0.88%), *Rhizophora mucronata* (6.14%)	Landward zone
Station 2	*Ceriops tagal* (72.81%), *Lumnitzera racemosa* (24.56%), *Excoecaria agallocha* (2.63%)	Landward zone
Station 3	*Lumnitzera racemosa* (7.94%), *Rhizophora stylosa* (19.05%), *Rhizophora apiculata* (26.98%), *Rhizophora mucronata* (36.51%), *Sonneratia alba* (4.76%), *Excoecaria agallocha* (4.76%)	Intermediate zone
Station 4	*Rhizophora apiculata* (54.54%), *Ceriops tagal* (38.64%), *Rhizophora mucronata* (6,82%)	Seaward/fringe zone
Station 5	*Lumnitzera racemosa* (77.08%), *Sonneratia alba* (17.71%), *Excoecaria agallocha* (5,21%)	Landward zone
Station 6	*Excoecaria agallocha* (9.09%), *Sonneratia ovata* (6.06%), *Ceriops tagal* (21.21%), *Rhizophora apiculata* (39.39%), *Rhizophora stylosa* (6.06%), *Rhizophora mucronata* (18.18%)	Intermediate zone
Station 7	*Ceriops tagal* (94.56%), *Xylocarpus granatum* (3.40%), *Rhizophora mucronata* (1.36%), *Rhizophora apiculata* (6.80%)	Landward zone
Station 8	*Ceriops tagal* (36.96%), *Lumnitzera racemosa* (8.70%), *Excoecaria agallocha* (30.43%), *Avicennia marina* (17.39%), *Rhizophora apiculata* (6.52%)	Intermediate zone
Station 9	*Rhizophora apiculata* (19.23%), *Excoecaria agallocha* (5.13%), *Lumnitzera racemosa* (0.40%), *Xylocarpus granatum* (3.85%), *Ceriops tagal* (69.23%)	Landward zone
Station 10	*Excoecaria agallocha* (49.72%), *Ceriops tagal* (38.67%), *Sonneratia alba* (0.55%), *Lumnitzera racemosa* (11.05%)	Landward zone
Station 11	*Rhizophora apiculata* (66%), *Rhizophora mucronata* (12.5%), *Bruguiera gymnorhiza* (12.5%), *Ceriops tagal* (9%)	Seaward/fringe zone
Station 12	*Rhizophora apiculata* (17.5%), *Rhizophora mucronata* (32.5%), *Bruguiera cylindrica* (12.5%), *Ceriops tagal* (3%), *Xylocarpus granatum* (22.5%), *Scyphiphora hydrophyllacea* (2.5%), *Heritiera littoralis* (5%)	(Sheltered) seaward zone
Station 13	*Rhizophora apiculata* (2.5%), *Rhizophora mucronata* (2.5%), *Bruguiera cylindrica* (5%) *Xylocarpus granatum* (16.25%), *Lumnitzera racemosa* (12.5%), *Scyphiphora hydrophyllacea* (5%), *Excoecaria agallocha* (62.5%)	(Sheltered) seaward zone

Based on two-way ANOVA, there were significant differences among zones in all diversity indices measured (Shannon, Simpson, and species richness). The intermediate zone had the highest biodiversity values (Shannon index = 1.56, Simpson index = 0.74, richness = 5.67). The seaward zone also showed relatively high diversity (H′ = 1.24, 1–D = 0.61), while the landward zone presented the lowest diversity (H′ = 0.73, 1–D = 0.39, richness = 4).

Discussion

The Rhizophoraceae family includes the largest number of true mangrove species, represented by four genera—*Rhizophora*, *Bruguiera*, *Ceriops*, and *Kandelia*—accounting for approximately 18 obligate mangrove species worldwide (Ngernsaengsaruay et al. 2024). These four genera constitute the tribe Rhizophoreae, which is predominant in mangrove ecosystems, especially in the Indo-West Pacific, owing to a distinctive array of evolutionary adaptations such as vivipary, aerial root structures, and mechanisms for salt exclusion (Ankure et al. 2023). Their ecological success is further enhanced by whole-genome duplications and positive selection on genes associated with stress tolerance, enabling them to surpass other mangrove lineages in challenging intertidal environments and to establish themselves as the structural and functional foundation of numerous mangrove forests globally (Chen et al. 2025).

Other families, beyond Rhizophoraceae, also significantly contribute to the structure of mangrove communities. The differences in abundance among species highlight complex ecological dynamics, shaped by varying environmental tolerances, reproductive strategies, and microhabitat heterogeneity (Vorsatz et al. 2021; Pimple et al. 2022; Torres et al. 2022). Moreover, the conservation status of certain species underscores the need for attention to localized ecological conditions. The occurrence of Near Threatened species such as *S. ovata*, as well as the very small populations of *H. littoralis*, emphasizes the importance of site-specific factors and habitat protection in sustaining mangrove biodiversity.

The DBH values indicate a prevalence of medium-aged trees in the region. The forest structure appears mature, as suggested by the mean DBH of 12.99 cm, which included both canopy and sub-canopy species. The exceptional size of *S. ovata* (68 cm) distinguishes it from other species and suggests unique environmental conditions. By contrast, smaller DBH values in *C. tagal* and *E. agallocha* may reflect younger individuals, shade-tolerant characteristics, or inherently smaller growth forms. These variations in DBH enhance the ecological functions and resilience of the mangrove forest.

Ceriops tagal often develops dense thickets of small trees, usually 1.8-7.5 m in height with DBH around 5-6 cm, producing high density but low per-tree basal area, which results in a reduced total basal area (Salum et al. 2021). In mixed stands, *C. tagal* can reach densities similar to main species (~2,300 ind./ha) but contributes much less to biomass (25.7 Mg/ha compared to >120 Mg/ha for *R. apiculata*) (Tun et al. 2025). Although *C. tagal* is numerically dominant, its lesser contribution to basal area indicates smaller average diameters (Seiwa et al. 2023). Conversely, *E. agallocha* and *L. racemosa* are structurally significant due to their combination of abundance and moderate to high basal area. *Rhizophora apiculata*, despite lower density, plays a key role by contributing the greatest basal area.

The total basal area of 22.91 m^2/ha is typical for mid-aged or relatively undisturbed mangrove forests, indicating overall forest health (Sraun et al. 2022; Aye et al. 2023). Similar values have been reported in the Lower Padsan River basin (~20 m^2/ha; Along et al. 2024) and the pristine mangroves of Bhitarkanika National Park, India (25 m^2/ha; Panda et al. 2024). The irregular distribution of basal area and density across species likely reflects ecological succession, species-specific growth patterns, and localized environmental conditions. Such variability strengthens resilience by providing redundancy in ecological functions (Pimple et al. 2022; Calipayan et al. 2024).

The structural dominance of *C. tagal* in KNP, as indicated by its high IVI, is consistent with reports from both Southeast Asia and East Africa, where the species is known for its adaptability to salinity gradients and its ability to form dense stands in challenging intertidal zones (Tangah et al. 2018; Njana 2020; Sukmarani et al. 2023). Compared to mainland mangrove forests—where large *Rhizophora* species typically dominate both in density and basal area—the prevalence of *C. tagal* in KNP suggests ecological adaptation to low-energy, nutrient-limited island environments (Moity et al. 2019; Tun et al. 2025).

Other dominant species such as *E. agallocha*, *L. racemosa*, and *R. mucronata* reflect a typical Indo-Pacific assemblage (Sari et al. 2023). Mid-IVI species like *X. granatum*, *S. alba*, and *B. cylindrica* contribute to vertical stratification and microhabitat diversity (Shearman et al. 2022; Suhardi et al. 2024). Low-IVI species, including *H. littoralis* and *S. hydrophyllacea*, though rare, tend to occupy peripheral or transitional zones and contribute to habitat heterogeneity (Veettil et al. 2023; Islam et al. 2024) and long-term resilience—roles similarly reported in small island mangrove systems in the Galápagos and Pacific Islands (Moity et al. 2019).

In line with this species composition, the ecological indices highlight the structural balance of the mangrove forest. The evenness value suggests that individuals are relatively well distributed, although certain species remain dominant. The low dominance index and high diversity index indicate a community that maintains structural stability, where the presence of dominant species such as *C. tagal* does not substantially reduce overall diversity (Singh 2020; Roswell et al. 2021).

When compared to mainland mangrove systems, Karimunjawa demonstrates reduced diversity. Studies in Southeast Asia reported higher values, such as Davao del Norte in the Philippines with H' between 1.91 and 2.07 and evenness of approximately 0.66 (Pototan et al. 2020), and the Setiu Wetlands in Malaysia with H' values exceeding 2.0 (Rahman et al. 2023). However, the indices from Karimunjawa are comparable to other island mangroves, including a protected river-fringe mangrove stand on Panay Island (H' = 1.76; Barrientos and Apolonio 2017) and the Klang Islands Mangrove Forest in Peninsular Malaysia (H' = 1.5-1.8; Rozainah et al. 2018). These parallels indicate that geographic isolation, restricted land area, and environmental limitations typically result in lower species richness on small islands. Nevertheless, the indices from Karimunjawa confirm that its mangrove forest remains structurally balanced and ecologically significant.

The zonation patterns observed in Karimunjawa are consistent with ecological gradients commonly reported in tropical Southeast Asia and the Indo-West Pacific, where salinity, elevation, and hydrological conditions determine mangrove distribution (Mantiquilla et al. 2021; Suhardi et al. 2024). *Ceriops tagal* dominated the landward sites, reflecting its adaptation to elevated, less frequently inundated areas with moderate salinity (Sukmarani et al. 2023; Lamani and Murthy 2025). The mean salinity of ~20.9 ppt measured in these zones aligns with previous findings that *C. tagal* thrives in mesohaline environments (de Silva and Amarasinghe 2021; Pootakham et al. 2022). In contrast, seaward stations were dominated by *R. apiculata* and *R. mucronata*, species that are well suited to tidal inundation and soft substrates due to their stilt-root morphology (Singh 2020; Yunasfi et al. 2024).

Intermediate zones supported higher species richness and structural complexity, with the coexistence of *L. racemosa, R. stylosa*, and *E. agallocha*. Notably, Station 6, located in front of abandoned aquaculture ponds, also contained *S. ovata*, a Near Threatened species. The occurrence of this species in regenerating sites highlights the ecological role of transitional habitats in both successional dynamics and conservation value (Shankar et al. 2020; Shearman et al. 2022). These findings emphasize how disturbed but recovering areas can contribute significantly to mangrove biodiversity, adding resilience and ecological functionality to the overall forest mosaic.

The sheltered seaward stations exhibited the highest richness, including less common species such as *X. granatum,* *B. cylindrica*, and *H. littoralis.* These species are often associated with more stable substrates and reduced wave energy, which create conditions favorable for their persistence (Pimple et al. 2022). Such sites are ecologically significant as they enhance structural diversity and ecosystem stability, yet they are increasingly vulnerable to pressures from tourism and climate change (Azzahra et al. 2023). The significant statistical differences among landward, intermediate, and seaward zones confirm that each habitat contributes uniquely to mangrove diversity. Conservation strategies in Karimunjawa National Park should therefore adopt a zonal perspective, recognizing the complementary roles of all habitats in sustaining ecosystem resilience and biodiversity.

In conclusion, this study provides a quantitative assessment of mangrove diversity and structure in Karimunjawa National Park, highlighting the ecological roles of dominant species such as *C. tagal* and *R. apiculata* and the conservation importance of vulnerable taxa like *S. ovata*. Species-specific data can guide restoration and zoning under pressures from aquaculture and tourism. The findings reinforce broader conservation frameworks, including SDG 14 (Life Below Water), SDG 15 (Life on Land), and Indonesia's coastal management policies, while supporting the integration of scientific evidence into MPA management plans to enhance resilience and climate adaptation.

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