Global J. Environ. Sci. Manage. 12(4): 1619-1638, Autumn 2026, Serial #48

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

Podcasts

ORIGINAL RESEARCH PAPER

Biodiversity-oriented criteria for measuring the effectiveness of mangrove ecosystem rehabilitation success

E. Yuliana[1,*], A. Winata[2], L.E. Setijorini[3], D.E. Yani[3], M.H. Fathani[4], W.A. Djatmiko[5]

[1]Department of Fisheries Management, Postgraduate School, Universitas Terbuka, Jl. Cabe Raya, Pondok Cabe, Pamulang, South Tangerang, Indonesia

[2]Department of Biology, Faculty of Science and Technology, Universitas Terbuka, Jl. Cabe Raya, Pondok Cabe, Pamulang, South Tangerang, Indonesia

[3]Department of Agribusiness, Faculty of Science and Technology, Universitas Terbuka, Jl. Cabe Raya, Pondok Cabe, Pamulang, South Tangerang, Indonesia

[4]Universitas Terbuka Malang Regional Office, Jl. Mayjen. Sungkono, Malang, Indonesia

[5]LATIN, The Indonesian Tropical Institute, Jl. Sutera, Situgede, Bogor, Indonesia

ARTICLE INFO

Article History:
Received 22 February 2026
Revised 30 April 2026
Accepted 02 June 2026

Keywords:
Biodiversity conservation
Flora and fauna
Mangroves ecosystem
Rehabilitation
Success standards

DOI:10. 22034.gjesm.2026.04.01

ABSTRACT

BACKGROUND AND OBJECTIVES: The area of Indonesia's mangrove ecosystem is approaching 3.5 million hectares. Approximately 52 percent of the area has been damaged and requires rehabilitation. The objectives of this study were to evaluate the extent of ecosystem recovery following mangrove rehabilitation by analyzing the natural occurrence and diversity of the resident biota.

METHODS: This study was conducted in Segarajaya Village, Tarumajaya District, Bekasi Regency, Indonesia, from April to November 2024. The obtained data were flora diversity data (represented by vascular plants) and fauna diversity data (represented by taxa of birds, reptiles, benthic crustaceans, mollusks, and fish). Data on flora and vegetation were collected from 5 meters x 5 meters sampled plots for seedlings and saplings (21 plots) and 10 meters x 10 meters sampled plots for trees with stem diameter ≥ 10 centimeters (17 plots), placed concentrically. Sampling plots were established systematically along a linear transect extending from land to sea, with a consistent inter-plot distance of 50 meters. Avian community data were collected using the point count method within fixed-radius circular plots (25 diameter), with a sampling duration of 20 minutes per plot. Data analysis includes Importance Value Index for vegetation, Shannon-Wiener Diversity Index, Sørensen Community Similarity Index, Chi-square Test of Independence, Mann-Whitney U Test.

FINDINGS: The results reveal that the diversity of mangroves in the rehabilitation areas is extremely low (consisting of 1–3 species; Shannon-Wiener Diversity Index of 0–0.36). No natural recruitment of associated mangrove flora was recorded within the rehabilitation areas until the stands reached ten years of age. The establishment of new habitats through this restoration planting has facilitated the colonization of both terrestrial and aquatic faunal communities. The Sørensen Community Similarity Index for terrestrial fauna in rehabilitation areas compared with natural areas only ranges between 37 percent and 58 percent, indicating a relatively low level of community similarity.

CONCLUSION: A decade of *Rhizophora stylosa* monoculture mangrove forest rehabilitation has produced structurally mature stands but has failed to restore floral and faunal to levels comparable to natural forests.

This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/)

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
47	2	10

*Corresponding Author:
Email: ernik@ecampus.ut.ac.id
Phone: +62812 1972 1445
ORCID: 0000-0002-8518-6363

Note: Discussion period for this manuscript open until December 01, 2026 on GJESM website at the “Show Article”.

INTRODUCTION

The mangrove ecosystem is crucial and unique in coastal areas (Yuliana *et al.*, 2019; Yuliana *et al.*, 2020; Hewindati *et al.*, 2023). Mangrove ecosystems function as highly effective sediment sinks, trapping terrigenous mud, organic debris, and anthropogenic litter transported by riverine and oceanic currents (Sari *et al.,* 2022). Because of its fertility, mangrove serves as a habitat for a wide range of biota (Yuliana *et al.*, 2019) as well as a nursery, feeding, and spawning ground (Hewindati *et al.,* 2023). The mangrove vegetation also serves as a critical habitat, attracting juvenile fish and small-sized teleosts (Sari *et al.,* 2022; Yuliana *et al.,* 2022). However, mangrove is also a vulnerable, extreme, and highly dynamic ecosystem. Human activities that may harm the mangrove ecosystem also pose a serious threat to its sustainability (Retnaningdyah *et al.,* 2022). Consequently, this degradation reduces the provisioning of ecosystem services to local communities (Yuliana *et al.*, 2026), particularly those derived from mangrove ecosystems (Yuliana *et al.* 2019; Rohila *et al.*, 2017). Indonesia is one of the countries with the largest area of mangrove forest in the world. With a coastline length of about 95,181 kilometers (km), Indonesia's recorded mangrove ecosystem is approximately 3,489,140.68 hectares (ha) wide, or equal to 23 percent (%) of the world's mangrove ecosystem (Metkono *et al.*, 2022; Kotijah and Ventyrina, 2019). Nevertheless, about 1,817,999.93 ha of this mangrove area (52.1% of the total area) has been damaged (Metkono *et al.,* 2022; Kotijah and Ventyrina, 2019). Given the urgency of habitat degradation, various mangrove restoration and rehabilitation efforts have become essential. In this context, targeted replanting initiatives are deployed to counteract forest loss and expedite ecosystem recuperation (Wirabuana *et al.*, 2025). The commitment of the Indonesian government to rehabilitate damaged mangrove areas has been demonstrated in the establishment of a special institution, namely the Peatland and Mangrove Restoration Agency, formed through Presidential Regulation Number 120 of 2020 (Kinasih and Harmawan, 2025). The Indonesian government has also prepared the National Mangrove Rehabilitation Roadmap 2021–2030 (Nurhati and Murdiyarso, 2023; Kinasih and Harmawan, 2025), with a target of mangrove rehabilitation of 600,000 ha (Sasmito et al., 2023). As a national level, a large-scale mangrove restoration initiative was implemented in 2020, utilizing a labor-intensive program to plant 17,641 ha across 34 provinces (Arifanti *et al.*, 2022). In 2021, the successfully planted mangrove areas increased to 80,000 ha. The successful implementation of this mangrove rehabilitation program, however, needs further monitoring, particularly in terms of whether the new plants can grow well to form mangrove forests and develop mangrove ecosystems. Current metrics for assessing the success of mangrove rehabilitation remain overly broad, often focusing on initial planting targets rather than long-term ecological functionality. As stated in Appendix VIII of the Regulation of the Minister of Environment and Forestry of the Republic of Indonesia (MEF-RI) Number 23 of 2021 on the Implementation of Forest and Land Rehabilitation, this benchmark is limited to the success of plant growth through the assessment of the area of successful growth and the percentage of plant growth and average height. Alternative indicators of successful mangrove ecosystem restoration include the natural recruitment and colonization of characteristic flora and fauna indigenous to the regional baseline. The success of the restoration is reflected in the increased diversity of the mangrove vegetation, the improved physical and chemical quality of the environment, and the diversity of macrozoobenthos—such as crustaceans and gastropods—living in the mangrove forests as bioindicators (Retnaningdyah *et al.,* 2022). The return of faunal communities, particularly fish, crustaceans, and macroinvertebrates, is an important benchmark for evaluating the functional recovery of rehabilitated mangrove ecosystems (Bosire *et al.,* 2008). Kamali and Hashim (2011) found that the

vegetation structure and species composition of replanted mangroves in Malaysia gradually recovered over time. A study conducted by Alongi (2002) in Indonesia highlights that mangrove rehabilitation success is frequently evaluated solely through the lens of seedling survival rates and canopy closure, thereby overlooking the broader dimensions of biodiversity recovery. Replanted monoculture stands of *Rhizophora* spp. have shown a limited capacity to support faunal diversity compared to naturally mixed-species mangroves. Spontaneous colonization of flora and fauna serves as a reliable bioindicator of ecosystem recovery (Damastuti *et al.,* 2022). Furthermore, biodiversity assessments are rarely integrated into official monitoring frameworks for mangrove rehabilitation (Wirabuana *et al.,* 2025). In Indonesia, the current regulatory framework, as stipulated in the Minister of Environment and Forestry Regulation No. 23 of 2021, restricts success metrics primarily to plant growth rates and canopy cover, with no provisions for biodiversity-based indicators. This disparity between empirical scientific knowledge and policy execution constitutes a major impediment to the rigorous evaluation of large-scale national rehabilitation initiatives. Biodiversity integrates the cumulative outcomes of all ecological processes into measurable indices (Magurran, 1988; Nagelkerken *et al.*, 2008). As such, biodiversity indices provide a holistic, multi-trophic signal of ecosystem recovery that single-metric, growth-based assessments fundamentally cannot capture (Bosire *et al.*, 2008; Gilman *et al.*, 2008). Moreover, chronosequence studies analyzing faunal and floral recovery across stands of varying ages within a single rehabilitation site remain exceptionally scarce in Indonesia, thereby limiting the understanding of post-intervention ecological trajectories. This study makes three novel contributions to mangrove rehabilitation assessment. First, it simultaneously evaluates flora, terrestrial fauna, and aquatic fauna diversity across a single rehabilitation chronosequence in the Segarajaya mangrove area, Bekasi Regency. Second, it applies the Sørensen Community Similarity Index to quantitatively benchmark rehabilitated against natural mangrove communities. Third, this study makes a novel contribution within the Indonesian policy context by proposing quantitative, multi-taxa biodiversity indicators designed to be integrated directly into national-level frameworks for auditing mangrove rehabilitation success. Based on this rationale, this study identified two components that most sensitively reflect rehabilitation effectiveness: 1) Mangrove diversity (Shannon-Wiener Diversity Index (H') and species richness); 2) Bird species richness and community composition, which respond rapidly to habitat structure changes and are observable without destructive sampling. Based on the objectives, this study has the following hypotheses (H):

H_1: Flora diversity in mangrove rehabilitation areas increases progressively with stand age, but remains significantly lower than that of the natural reference forest.

H_2: Fauna diversity in mangrove rehabilitation areas increases with stand age.

H_3: The spontaneous presence and diversity of biotic communities across rehabilitation stands of different ages can serve as empirically valid, multi-taxa indicators for evaluating and standardizing mangrove ecosystem rehabilitation success.

The objective of the present study is to evaluate the efficacy of mangrove rehabilitation in ecosystem restoration, utilizing the natural recolonization and recruitment of resident biota as key ecological indicators of success. This study has been carried out in Segarajaya mangrove area, part of Jakarta Bay from 2024 to 2025.

MATERIALS AND METHODS

Study area

The research locations covered well-preserved mangrove rehabilitation and mangrove forest areas in Segarajaya Village, Tarumajaya District, Bekasi Regency, Indonesia (Fig. 1). To capture

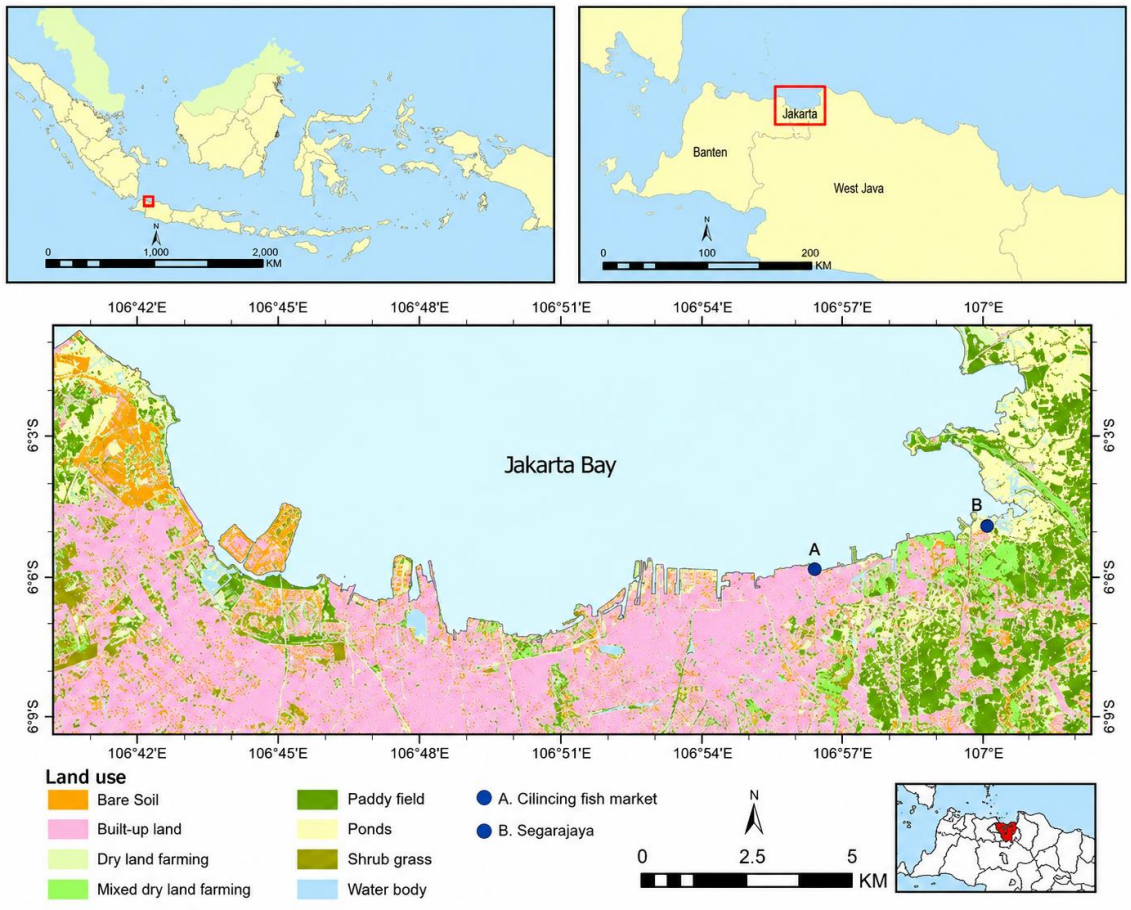

Fig. 1: Geographical location of the study area in Segarajaya Village, part of Jakarta Bay, Indonesia (Yuliana *et al.*, 2026)

post-restoration environmental dynamics, sampling was conducted across a chronosequence of mangrove rehabilitation areas characterized by distinct planting years. According to the availability in the field, the 2024 rehabilitation area (representing the 0-year-old stand), the 2019 rehabilitation area (the 5-year-old stand), and the 2014 rehabilitation area (the 10-year-old stand) were selected as the research locations. In addition, the closest remaining natural mangrove forest area was also selected for comparison.

Data collection

The collected data comprised floral diversity, represented by vascular plants, and faunal diversity, represented by five key taxonomic groups: birds, reptiles, benthic crustaceans, mollusks, and fish. Data on flora and vegetation were collected from 5 meters (m) x 5 m sampled plots (for seedlings and saplings) and 10 m x 10 m sampled plots, for trees with stem diameter ≥ 10 centimeters (cm), placed concentrically. These plots were systematically sampled in a straight line from land to sea, with a distance between plots of 50 m. Due to spatial constraints within the mangrove rehabilitation zones, the number of sampling plots allocated for floral and vegetation data collection was unevenly distributed across the different plot sizes. A total of 21 plots measuring 5 m × 5 m were established, distributed as follows: 2 plots in the 2024 area, 2 plots in the 2019 area, 8 plots in the 2014 area, and 9 plots in

the natural forest area. Additionally, 17 plots measuring 10 m × 10 m were established, comprising 8 plots in the 2014 area and 9 plots in the natural forest area. While this sampling imbalance represents a limitation of the present study, future research should implement an expanded sampling design with uniform replication across all plot sizes. Data on birds were gathered using the point count method (Ralph *et al*., 1995; Bibby *et al*., 2000), by making sampled plots in the form of a virtual circle with a diameter of 25 m and a counting time of 20 minutes in each plot. The plots were sampled systematically, with a distance between plots of 50–100 m, the placement of which was determined later in the field. With a minimum of three replicates established per rehabilitation zone, a total of 46 avian sampling sheets were compiled. Reptile data were collected using visual encounter surveys across the four designated study areas. All reptiles observed in the locations were recorded in terms of their species, numbers of individuals (ind), and microhabitats in which they were found. Data on crustaceans were acquired by setting 3 m x 3 m sampled plots. The observation was made at low tide. To maximize sampling efficiency, all benthic crustaceans within the designated plots—including both infaunal individuals in the substrate and epifaunal individuals associated with mangrove roots—were collected manually or via hand nets for subsequent recording. In a 1 m x 1 m area in the middle of the sampled plots, the mud was dug 20–30 cm deep to catch the crustaceans hiding in holes and mud sediment. The mud was then filtered using a mesh (mesh size 1 millimeters (mm)), and the crustaceans were collected, kept in plastic bags, and preserved with 70% alcohol. In permanently waterlogged zones where substrate excavation was highly constrained, crustacean sampling was supplemented by deploying crab traps and dragon traps at designated monitoring locations. This passive sampling effort yielded a total of 65 trap-nights for the crab traps and 26 trap-nights for the dragon traps. In addition to the crustacean data obtained, some data were also obtained on fish accidentally entered into the two types of traps. Other fish data were collected from fishermen's catches at the studied locations. Birds are the most reliable biological indicator for measuring the effectiveness of mangrove ecosystem rehabilitation. Birds are easily detected, highly sensitive to habitat structure, and offer extensive ecological literature for comparison. Assessments of additional faunal groups serve as complementary indicators, providing a more comprehensive evaluation of overall ecosystem recovery. A significant limitation of this study are: 1) the use of presence/absence rather than count-based data for diversity analysis; 2) the lack of seasonal consideration; 3) the absence of systematic abiotic measurements, including sediment texture, organic carbon content, redox potential, salinity, dissolved oxygen, and tidal inundation frequency. These parameters are known to exert a profound influence on both floral and faunal diversity within mangrove ecosystems (Feller *et al.*, 2010; Gilman *et al.*, 2008); consequently, their omission limits the mechanistic depth of the resulting ecological interpretations. Future studies are therefore recommended to employ count-based data collection and paired wet/dry season surveys and include all the parameters that are now limitations.

Data analysis

The obtained data were analyzed using the following formulas.

a. Density (D) (ind/ha or ind/m²)

D = Number of a species / Total area sampled (1)

b. Relative density (RD)

RD = Density of a species / Total density of all species × 100% (2)

c. Frequency (F)

F = Number of plots in which a species is found / Total area sampled (3)

d. Relative frequency (RF)

RF = Frequency of a species / Total frequency of all species × 100% (4)

e. Importance Value Index (IVI)

IVI = RD + RF (5)

For the mangrove trees, the processed data were added to those of tree dominance:

f. Dominance of a species (Do) (m^2/ha)

Do = Basal area (BA) of a species / Total area sampled (6)

g. Relative dominance (RDo)

RDo = Dominance of a species / Total dominance of all species × 100% (7)

h. Importance Value Index (IVI)

IVI = RD + RF + RDo (8)

Data were processed to obtain the Shannon-Wiener Diversity Index (H'), Sørensen Community Similarity Index (S_s), Chi-square Test of Independence (χ^2), and Mann-Whitney U Test (U), using some equation on Table 1. The use of H' as a standalone metric introduces key interpretive constraints. (1) it conflates species richness and evenness, meaning that a community containing five evenly distributed species can yield an identical H' value to a community of ten species dominated heavily by a single taxon; (2) It requires abundance data, not just presence/absence, so H' there reflects only species richness; (3) It does not capture functional diversity, trophic structure, or community composition similarity with natural reference forests. H' was complemented with species richness, and S_s to produce a more robust multi-metric assessment.

RESULTS AND DISCUSSION

Flora and vegetation

The selected study locations represent a chronosequence of mangrove rehabilitation areas, spanning different planting cohorts to capture post-restoration ecological dynamics. Each block was planted as part of a mangrove planting project carried out by certain institutions, either private or public. The seedlings and planting areas were prepared by the locals through a mangrove conservation community. Therefore, the diversity of mangroves in the rehabilitation areas is determined primarily by the species planted (Bosire *et al.*, 2008). Mangrove species planted in the locations is mainly the spotted mangrove (*Rhizophora stylosa*). According to local accounts, this species is selected due to the high availability of wild seedlings, which develop directly from its viviparous propagules. In addition, the size of its seedling is big, and it is easy to handle until planting time. Ecologically, *R. stylosa* is well-adapted to muddy substrates and high salinity, making it a preferred species for mangrove rehabilitation programs across the Indo-Pacific region (Primavera and Esteban, 2008; Tomlinson, 1986). Besides *R. stylosa*, there are various other species of mangrove flora around Segarajaya Village. Despite dense human settlement and extensive land conversion for residential use, aquaculture, and industrial infrastructure including factories, a crematorium, and a combined-cycle power plant (PLTGU), diverse mangrove species persist within interstitial spaces between households, fish farms, and marginal abandoned lands (Table 2). A total of 16 mangrove flora species were recorded, comprising 10 tree species, 5 herbs, and 1 shrub. The most abundant species in these locations are grey mangrove (*Avicennia marina*), white mangrove

Table 1: Equations used to calculate the parameters of flora and fauna communities

Equation	Note
Shannon-Wiener Diversity Index (Magurran, 1988):	
$H' = -\sum_{i=1}^{s} \left(\frac{n_i}{N}\right) ln \left(\frac{n_i}{N}\right)$	H' = Shannon-Wiener Diversity Index n_i = number of ind per species N = total number of all ind
Sørensen Community Similarity Index (Sørensen, 1948):	
$S_s = \frac{2a}{2a+b+c}$	S_s = Sørensen Community Similarity Index a = total species in both communities b = number of species in community A c = number of species in community B
Chi-square Test of Independence (Zar, 2010): $\chi^2 = \Sigma [(O - E)^2 / E]$	χ^2 = Chi-square Test of Independence O = frequency of species presences or absences E = expected frequency under the null hypothesis of independence
Mann-Whitney U Test (Zar, 2010): $U = n_1 \times n_2 + n_1(n_1+1)/2 - R_1$	n_1 = group 1 observation n_2 = group 2 observation R_1 = sum of ranks assigned to Group 1

Table 2: Diversity of mangrove flora recorded in the research locations

Scientific name	English name	Habits
Avicennia alba	White mangrove	tree
Avicennia marina	Grey mangrove	tree
Cerbera manghas	Sea mango	tree
Hibiscus tiliaceus	Sea hibiscus	tree
Lumnitzera racemosa	White-flowered black mangrove	tree
Rhizophora stylosa	Spotted mangrove	tree
Rhizophora mucronata	Red mangrove	tree
Sonneratia alba	Mangrove apple	tree
Sonneratia caseolaris	Crabapple mangrove	tree
Sonneratia ovata	-	tree
Acanthus ilicifolius	Sea holly	herbs
Acrostichum aureum	Golden leather fern	herbs
Cyperus javanicus	Javanese flat sedge	herbs
Pluchea indica	Marsh fleabane	shrubs
Schoenoplectus subulatus	Coast club-rush	herbs
Typha angustifolia	Narrowleaf cattail	herbs

(*A. alba*), and mangrove apple (*Sonneratia alba*). Adjacent to the village, in former rice fields or reed swamps, the two dominating flora species are narrowleaf cattail (*Typha angustifolia*) and coast club-rush (*Schoenoplectus subulatus*). The presence of herbaceous species such as *Acrostichum aureum* and *Acanthus ilicifolius* underscores localized habitat degradation, reflecting their well-documented role as opportunistic pioneers in disturbed or open mangrove ecotones (Feller *et al.*, 2010). At the 2024 area, the species of mangrove selected as the main rehabilitation plant is the spotted mangrove (*R. stylosa*) (Table 3), strongly dominates the rehabilitation area (RD 0.99; IVI 149.43%), while the only other species in this area, i.e., *A. alba*, is found in very small quantities. The impoverished floral diversity within this rehabilitation area is further underscored by an exceptionally low Shannon-Wiener Diversity Index (H'), value of 0.04. The dominance of *R. stylosa* reflects the deliberate planting strategy rather than natural successional dynamics (Primavera and Esteban, 2008). The Shannon-Wiener Diversity Index value of H' = 0.04 indicates an extremely low species richness, approaching the theoretical minimum of zero for single-species stands (Magurran, 2021). While monoculture plantations facilitate rapid initial establishment, extensive ecological literature demonstrates that

Table 3: Mangrove plant species in the study areas

Scientific name	D	F	BA	RD	RF	RDo	IVI	H'
2024 rehabilitation area								
Rhizophora stylosa	69,400	2	-	0.9943	0.50	-	149.43	0.04
Avicennia alba	400	2	-	0.0057	0.50	-	50.57	
	69,800	4						
2019 rehabilitation area								
Rhizophora stylosa	24,200	2	-	0.90977	0.40	-	130.98	0.36
Sonneratia alba	1,600	2	-	0.06015	0.40	-	46.02	
Avicennia alba	800	1	-	0.03008	0.20	-	23.01	
	26,600	5						
2014 rehabilitation area								
Tree level:								
Rhizophora stylosa	500.0	8	7.38	1.00	1.00	1.00	300.00	0
Sapling level:								
Rhizophora stylosa	337.5	8	-	1.00	1.00	-	200.00	0
	837.5							
'Peil' secondary natural forest								
Tree level:								
Avicennia marina	388.9	0.78	10.31	0.67	0.54	0.76	197.12	0.84
Avicennia alba	122.2	0.56	1.69	0.21	0.38	0.12	72.06	
Rhizophora stylosa	66.7	0.11	1.57	0.12	0.08	0.12	30.82	
	577.8	1.44	13.58				300.00	
Sapling level:								
Avicennia marina	266.7	0.78	-	0.51	0.39	-	89.95	1.10
Rhizophora sp.	122.2	0.78	-	0.23	0.39	-	62.29	
Avicennia alba	122.2	0.33	-	0.23	0.17	-	40.07	
Sonneratia alba	11.1	0.11	-	0.02	0.06	-	7.68	
	522.2	2.00					200.00	

Notes: D (density) in stems/ha; F = frequency; BA (basal area) in m^2/ha; RD = relative density; RF = relative frequency; RDo = relative dominance; IVI (Importance Value Index) in percentage; H' = Shannon-Wiener Diversity Index

these low-diversity stands exhibit heightened vulnerability to pathogens, pest outbreaks, and environmental stressors compared to their species-rich counterparts (Bosire *et al.*, 2008; Field, 1998). *A. alba* was planted in this location as part of the rehabilitation process. However, its seedling is only incidentally available in the location; it is obtained naturally, not as a result of mangrove nursery efforts, hence its limited quantity. The 2024 rehabilitation site consists of a decommissioned aquaculture pond that was deliberately reforested, resulting in a highly waterlogged substrate. Notably, no natural regeneration or recruitment of non-planted mangrove seedlings was observed within this location. The average height of the existing *R. stylosa* seedlings is 60–70 cm. The incidental occurrence of *A. alba* through natural recruitment, rather than systematic nursery production, is noteworthy. Natural recruitment of mangroves into degraded coastal areas depends heavily on propagule availability, tidal connectivity, and suitable substrate conditions (Tomlinson, 1986; Giesen *et al.*, 2006). Given the continuous inundation regime of the decommissioned pond substrate within the 2024 area, natural recruitment is heavily constrained, particularly for target taxa that lack specialized adaptations to prolonged inundation. Incorporation of *A. alba* into future nursery programs would help diversify the stand composition and improve long-term resilience of the rehabilitation site (Bosire *et al.*, 2008). The 2019 stand has reached a canopy height of 6–7 m, and its canopy cover has been intertwined. Nonetheless, its flora diversity is still dominated by *R. stylosa* (Table 3). The species dominates this area since it has the greatest quantity, with a density reaching 24,200 stems/ha, despite its rather small trunk circumference of 9–26 cm. Notably, *S.alba* appeared to establish spontaneously prior to formal rehabilitation efforts; several individuals exhibited trunk

circumferences slightly exceeding 30 cm yet remained classified within the sapling cohort. Similarly, multiple *A. alba* saplings within this zone displayed large circumferences approaching 30 cm. Nonetheless, since the numbers of individuals are limited, the IVI value of these two species combined does not reach 10%. The 2019 area demonstrates a modest improvement in species diversity compared to the 2024 area (H' = 0.36 vs. 0.04), reflecting the early stages of natural species recruitment over a five-year period. The spontaneous establishment of *S. alba* is ecologically significant, as this pioneer species plays an important role in sediment stabilization and the facilitation of secondary species colonization in mangrove ecosystems (Tomlinson, 1986). However, the IVI values confirm that *R. stylosa* continues to overwhelmingly structure the stand (IVI = 130.98%), suggesting that natural diversity recovery in planted monocultures is a slow process that may require active intervention to accelerate successional dynamics (Bosire *et al.*, 2008; Alongi, 2009). Established in 2014, this stand represents the oldest mangrove rehabilitation cohort within the study area. Situated along the estuarine margin roughly 10 m from the riverbank, the site is subject to continuous tidal inundation. Unlike the other two areas (2024 and 2019), the 2014 stand only consists of one species of mangrove, namely *R. stylosa* (Table 3). The 10-year-old *R. stylosa* stands just reached tree level, where the largest trunk circumference has not reached 40 cm. Typically, *R. stylosa* trees are multi-stemmed, with branches emerging slightly above their prop roots. The total density of this stands is 837.5 ind/ha, with individuals at the tree level amounting to 500 stems/ha and those at the sapling level reaching 337.5 stems/ha. The total basal area for the tree level alone is 7.38 m²/ha. The forest canopy height within the 2014 stand reaches approximately 9–10 m, reflecting advanced structural development. Since this 2014 area only consists of one species, its IVI value is 100% (or 300%, as it is measured through three parameters), belonging entirely to *R. stylosa*. Meanwhile, its Shannon-Wiener Diversity Index (H') is 0 because the stands are uniform. The structural maturity of the 2014 stand, characterized by a canopy height of 9–10 m, a basal area of 7.38 m²/ha, and the presence of both tree-and sapling-level cohorts—indicates that the rehabilitation has been structurally successful in terms of biomass accumulation. However, the persistence of a monospecific composition (H' = 0) after a decade highlights a critical limitation of single-species planting approaches: structural recovery does not necessarily translate to biodiversity recovery (Feller *et al.*, 2010). The sapling cohort (337.5 stems/ha) suggests adequate natural regeneration of *R. stylosa* within the stand, the complete absence of alternative colonizing taxa suggests that dense canopy closure may severely attenuate light availability at the forest floor, thereby precluding recruitment opportunities for less shade-tolerant mangrove species. The natural mangrove forest near the research location is a quite old secondary forest, although the area is getting narrower due to land clearing for fish farming. Only about two ha of forest area remain, and it is almost always waterlogged, albeit shallow (about 10–20 cm on the south, towards the land). Some of the biggest trees, located outside the measurement plot, have trunk circumferences reaching 171 cm (*A. alba*) and 139 cm (*A. marina*). The residents of Segarajaya call this area the '*Peil* forest', possibly because it is located near the *peilschaal*, a water level measuring scale installed on the water drainage channel of Muara Tawar Power Plant (PLTGU Muara Tawar). This stand is classified as depauperate, comprising only five mangrove tree species, four of which were explicitly recorded within the sampling plots (Table 3). This is most likely due to its isolated location, far from other natural mangrove forests, with almost no dry land area. Another species found in the *Peil* forest, but not within the plot, is the red mangrove (*R. mucronata*). In terms of stem abundance, this forest exhibits a slightly higher density than the 2014 stand, supporting approximately 578

stems/ha. Conversely, its basal area (13.58 m^2/ha) is nearly twofold that of the 2014 cohort, indicating a substantially greater wood volume and structural maturity. This implies that the natural forest is likely more fertile than the rehabilitation area. Another possibility is that the *Peil* forest is older, thus having a greater amount of accumulated biomass than that in the rehabilitation area. The greater basal area of the *Peil* forest (13.58 m^2/ha) compared to the 2014 rehabilitation area (7.38 m^2/ha) reflects the superior structural complexity and accumulated biomass of the natural stand. This structural progression aligns with the expected trajectory of mangrove forest development and temporal succession. The multi-species composition of the *Peil* forest—including *A. marina, A. alba, R. stylosa*, and *S. alba*-supports a higher Shannon-Wiener Diversity Index (H' = 0.84 at tree level; H' = 1.10 at sapling level) relative to all rehabilitation areas, underscoring the ecological value of conserving remnant natural forests alongside ongoing rehabilitation efforts (Murdiyarso *et al.*, 2015; Feller *et al.*, 2010). The dominance of *A. marina* (IVI = 197.12%) in the *Peil* forest is characteristic of mature secondary mangrove forests in Java, where this species is often a late-successional dominant on muddy substrates (Duke, 2006; Giesen *et al.*, 2006). The ecological isolation of the *Peil forest* from adjacent natural mangrove stands likely severely restricts autochthonous propagule supply and constrains the recovery of species richness, highlighting the urgent priority for in situ conservation of this critical remnant patch (Bosire *et al.*, 2008). To analyze the differences in flora between the 2024 area, 2019 area, 2014 area, and natural forest, a Chi-Square Test of Independence was conducted (Table 4), with H_o: mangrove species richness is equally distributed across all four locations (no significant difference); H_1: Species richness differs significantly among locations. The result of Chi-square test indicates that the distribution of mangrove species richness did not differ significantly among the four study areas, thereby failing to reject the null hypothesis (H_0). But, ecologically, the number of flora species in each region shows differences (Table 3). Pairwise Mann-Whitney U tests were also conducted on per-species density values (D, stems/ha). Stand density (D) provides an alternative and complementary dimension of structural differentiation among the study sites, proving particularly instrumental when contrasting high-density, pioneer-stage monocultures against low-density, structurally mature stands. H_o: density distributions are equal between paired areas. Pairwise Mann-Whitney U tests (Table 5) show that mangrove diversity in all rehabilitation and natural forest areas was not significantly different. The lowest p-value (0.10) for the 2019 area and natural forest reflects the large density contrast: a mean of 8,866.7 stems/ha (2019 area) and 192.6 stems/ha (natural forest). To enhance the robustness and generalizability of future findings, expanding the sampling intensity by incorporating a greater number of replications stands across diverse age cohorts is strongly recommended to ensure improved statistical reliability, broader ecological representation, and comprehensive comparative analysis outcomes across varying environmental and management conditions. The dominance of *Rhizophora stylosa* as a near-absolute monoculture in all three rehabilitation areas—with a time span of 0 to 10 years—is likely not solely attributable to early planting decisions; it reflects a convergence of ecological mechanisms that collectively suppress spontaneous floristic diversification. Canopy closure observed in the 2014 stands generated significant shade that selectively inhibited the recruitment of intolerant pioneer species such as *Avicennia* spp. and *Sonneratia* spp. These species' seedlings necessitate high levels of solar irradiance for germination and and early vegetative growth (Tomlinson, 1986; Krauss *et al.*, 2008). Simultaneously, the former pond substrate in the 2024 area—characterized by persistent waterlogging and dense, anoxic sediments—limited colonizing species to the most resilient

Table 4: Results of the Chi-Square statistical test on the number of mangrove species per rehabilitation area

Statistic	Value
Chi-square statistic (χ^2)	3.18
Degrees of freedom (df)	3
p-value	0.36
Critical value χ^2 (α = 0.05, df = 3)	7.82
Decision	Failed to reject H_o— NS (p = 0.3644 > 0.05)

Table 5: Pairwise Mann-Whitney U tests on the number of mangrove species

Area pair	n_1	n_2	Mean D area 1	Mean D area 2	U Statistic	p-value	Decision
2024 area and 2019 area	2	3	34,900.0	8,866.7	3.00	1.00	NS
2024 area and 2014 area	2	2	34,900.0	418.8	3.00	0.67	NS
2024 area and natural forest	2	3	34,900.0	192.6	6.00	0.20	NS
2019 area and 2014 area	3	2	8,866.7	418.8	6.00	0.20	NS
2019 area and natural forest	3	3	8,866.7	192.6	9.00	0.10	NS
2014 area and natural forest	2	3	418.8	192.6	5.00	0.40	NS
Final decision	Failed to reject H_o— NS (all p-value > 0.05)						

Notes: n_1 = group 1 observation; n_2 = group 2 observation; D = density; U = Mann-Whitney test; p-value = probability value; NS = Not significant.

taxa to environmental stress, namely *Rhizophora* itself (Youssef and Saenger, 1998; Kitaya *et al.*, 2002; Friess *et al.*, 2019). The presence of these abiotic barriers explains why floral recovery in this chronosequence stalled well below levels observed in natural forests (H' = 0.84–1.10), despite a decade of growth in vegetation structure.

Terrestrial fauna diversity

Terrestrial wildlife encounters within the study area were dominated by avian species, with secondary anecdotal records documenting the presence of specific mammal and reptile assemblages. This study recorded two species of mammals, 17 species of birds, and three species of reptiles (Table 6). This clear taxonomic skew toward birds is consistent with the constraints of rapid ecological inventories in mangrove habitats. Avian species are more readily detectable during daytime surveys, whereas the cryptic and often elusive nature of local mammals and reptiles inherently limits their capture in short-term assessment (MacKinnon and Phillipps, 1993; Bibby *et al.*, 2000). The relatively low overall species richness recorded across the study sites reflects the broader pattern of reduced faunal diversity in fragmented and rehabilitated mangrove landscapes, where habitat heterogeneity and structural complexity are still developing (Feller *et al.*, 2010; Alongi, 2009). The presence of birds across the research location is widely spread according to the available habitat and its conditions. Of the 17 species of birds recorded (Table 6), 16 species were observed in the secondary natural forest, while only 10 species were recorded in the rehabilitation areas. Among the rehabilitation areas, the 2014 area has the greatest number of species, with eight species recorded - half the total found in the secondary natural forest. Notably, the 2024 area and the 2019 area supported fewer species, consistent with the lower structural complexity of younger stands. This finding indicates that the mangrove rehabilitation areas exhibit low avian species richness, a trend potentially driven by the depauperate nature of the restoration stands themselves, which similarly lack structural and taxonomic mangrove diversity. The greater bird diversity recorded in the 2014 area is most likely attributable to its more mature and closed canopy cover reaching 9–10 m in height, which provides shelter, nesting opportunities, and invertebrate prey resources largely absent in younger, open-canopy rehabilitation stands (Sodhi *et al.*, 2004; Nagelkerken *et al.*, 2008). The low taxonomic diversity of mangrove plant species in the rehabilitation areas likely constrains

Table 6: Diversity of terrestrial fauna recorded in the research locations

Scientific name	English name	Location			
		2024 Area (0 y)	2019 Area (5 y)	2014 Area (10 y)	Natural forest
Mammals:					
Aonyx cinerea	Asian small-clawed otter				✓
Rattus sp.	unidentified tree rat				✓
No. of mammal species	-				2
Birds:					
Actitis hypoleucos	Common sandpiper				✓
Alcedo coerulescens	Cerulean kingfisher	✓		✓	✓
Ardeola speciosa	Javan pond heron				✓
Butorides atricapilla	Little heron	✓		✓	✓
Chlidonias leucopterus	White-winged tern				✓
Cinnyris ornatus	Ornate sunbird		✓		✓
Collocalia linchi	Linchi swiftlet				✓
Egretta garzetta	Little egret				✓
Gerygone sulphurea	Golden-bellied gerygone	✓	✓	✓	✓
Hirundo javanica	Pacific swallow	✓			✓
Orthotomus ruficeps	Ashy tailorbird		✓	✓	✓
Passer montanus	Eurasian tree sparrow		✓	✓	
Pycnonotus aurigaster	Sooty-headed bulbul			✓	✓
Rhipidura javanica	Sunda pied fantail		✓	✓	✓
Spilopelia chinensis	Spotted dove			✓	✓
Streptopelia bitorquata	Sunda collared dove				✓
Todiramphus chloris	Collared kingfisher	✓			✓
No. of bird species	-	5	5	8	16
Reptiles:					
Cerberus schneideri	Schneider's bockadam	✓		✓	✓
Hemidactylus platyurus	Flat-tailed house gecko				✓
Varanus salvator	Asian water monitor	✓	✓	✓	✓
No. of reptile species	-	2	1	2	3
Total species richness	-	7	6	10	21

avifaunal richness by limiting the variety of trophic resources and architectural vegetation structures available to local bird communities (Feller *et al.*, 2010; MacKinnon and Phillipps, 1993). In contrast, the multi-species composition and greater structural heterogeneity of the *Peil* forest underpin its superior capacity to accommodate a more diverse and species-rich avian assemblage. No mammals were directly observed in the mangrove rehabilitation areas during this study. The absence of mammal detections is most likely attributable to the timing of surveys, which were conducted during daylight hours when human activity around the rehabilitation areas was considerable. This condition is consistent with documented trends in alternative mangrove ecosystems, where ongoing human encroachment and a lack of understory structural complexity act as primary barriers to mammal recruitment within restored stand (Alongi, 2009; Nagelkerken *et al.*, 2008). Future surveys employing camera traps and nocturnal transects would provide a more comprehensive picture of mammal presence and activity patterns across the rehabilitation gradient. Anthropogenic activities—specifically intensive aquaculture, recreational angling, and the routine transit of fishers through these habitats—likely induce disturbance-mediated avoidance behaviors among local mammalian assemblages. Of the three reptile species recorded in the research locations, two species namely the Schneider's bockadam (*Cerberus schneideri*) and the Asian water monitor (*Varanus salvator*) are also pond pests as they prey on fish and other biotas. The two species of land reptiles, both living in these waters, are found in both the natural forest area and the mangrove rehabilitation areas. Furthermore, both reptilian species exhibited

opportunistic foraging behavior, preying directly upon teleost fish captured within the study's sampling traps. The confinement of *Hemidactylus platyurus* to the natural forest underscores the dependence of certain reptile species on mature, structurally complex vegetation, as well as the limited capacity of young rehabilitation stands to support the full complement of herpetofauna characteristic of natural mangrove ecosystems (Feller *et al*., 2010; Giesen *et al.*, 2006). To analyze the differences in fauna in each rehabilitation area, the Sørensen Community Similarity Index test was carried out (Table 7). A chi-square test of independence was applied to evaluate whether the distribution of species presence/absence differed significantly across the three rehabilitation areas (Table 8). The H_o states that species presence is independent of rehabilitation age. The association was evaluated using a 2×3 contingency table (presence/absence × three study areas), utilizing the 22 documented species as the primary unit of analysis. Furthermore, the values of S_s were converted to (1-S_s) to obtain the dissimilarity between fauna communities in the research locations (Table 9). As shown in Tables 7 and 9 and Fig. 2, the community similarity of terrestrial fauna between the 2014 area and the natural forest has the highest value. However, the similarity value between the two fauna communities only reaches 58%, still far from the expected value. The faunal community similarity between the natural forest and the 2019 rehabilitation area exhibited a comparatively low value of approximately 37%. The similarity of fauna communities between rehabilitation areas is even lower, ranging from 26.67% to 52.63%. This indicates that fauna communities in rehabilitation areas remain highly variable due to ongoing ecological succession, species turnover, and habitat recovery processes.

Aquatic biota diversity

The diversity of aquatic fauna recorded in the research locations consists of two taxa: fish and crustaceans (Table 10). The documented aquatic biota was primarily captured using stationary fish traps deployed systematically across the designated sampling locations. Some decapod crustaceans (crabs) were caught directly by hand. The use of fish traps and direct hand-catching as collection methods is consistent with standard aquatic biodiversity survey protocols in mangrove and coastal wetland environments (Welcomme *et al.*, 2010). The dual-taxa approach - simultaneously monitoring fish and crustacean assemblages—provides a comprehensive assessment of aquatic community structure across different successional stages of mangrove restoration (Nagelkerken *et al.*, 2008). The study area designated in 2024 consists primarily of open, waterlogged terrain that remains submerged. Conversely, certain elevated margins along the pond embankments exhibit drier characteristics, experiencing inundation exclusively during high-tide events. The habitat partitioning observed here reflects well-documented patterns in decapod ecology. Former fish ponds undergoing restoration exhibit hydrological variability that creates microhabitat heterogeneity, supporting distinct assemblages of intertidal and semi-terrestrial crustaceans (Wolff *et al.*, 2000). The perennially waterlogged, open nature of early-stage restoration sites such as the 2024 study area characteristically favors opportunistic and euryhaline taxa that are ecologically adapted to disturbed, fluctuating environmental conditions and stressors. (Duke *et al.*, 2007). The species of decapods found in the 2024 area are Thai vinegar crabs (*Episesarma mederi*), orange signaller crabs (*Metaplax elegans*), marsh crabs (*Parasesarma* sp.), fiddler crabs (*Uca* sp.), and broad-fronted mangrove crabs (*Metopograpsus latifrons*). All of the crabs are mudflat crabs whose habitat is in slightly dense soil and exposed to outside air. The dominance of mudflat crabs (*Episesarma*, *Metaplax*, *Parasesarma*, and *Uca* spp.) in the 2024 area is ecologically significant. These semi-terrestrial sesarmid and varunid crabs are known pioneer colonisers of disturbed intertidal mudflats (Cannicci *et al.*, 2008). Their occurrence within early-successional zones signifies the nascent establishment of a detritivore guild, which serves

Table 7: Sørensen community similarity index of terrestrial fauna in the locations

Compared habitat	a	b	c	a+b+c	S_s
Natural forest and 2014 area	9	12	1	21	0.58
Natural forest and 2019 area	5	16	1	22	0.37
Natural forest and 2024 area	7	14	0	21	0.50
2014 area and 2019 area	5	5	1	11	0.63
2014 area and 2024 area	5	5	2	12	0.59
2019 area and 2024 area	2	4	5	11	0.31

Notes: a = total number of shared species (found in both communities); b = number of species found only in first community; c = number of species found only in second community; S_s = Sørensen Community Similarity Index

Table 8: Chi-Square test of independence for diversity of terrestrial fauna at three mangrove rehabilitation area

Indicators	Locations		
	2024 area	2019 area	2014 area
No. of species present	7	6	10
No. of species absent	15	16	12
Total species tested	22	22	22
Chi-square statistic (χ^2)	1.74		
Degrees of freedom (df)	2		
p-value	0.42		
Decision	H_0 is therefore not rejected. Not significant (p = 0.4200 > 0.05): species presence distribution does not differ significantly among the three rehabilitation areas		

Table 9: Distance of community dissimilarity between habitats

Natural forest	Natural forest	2014 area	2019 area	2024 area
2014 Area	0.4194	-		
2019 Area	0.6296	0.4737	-	
2024 Area	0.5172	0.4737	0.7333	-

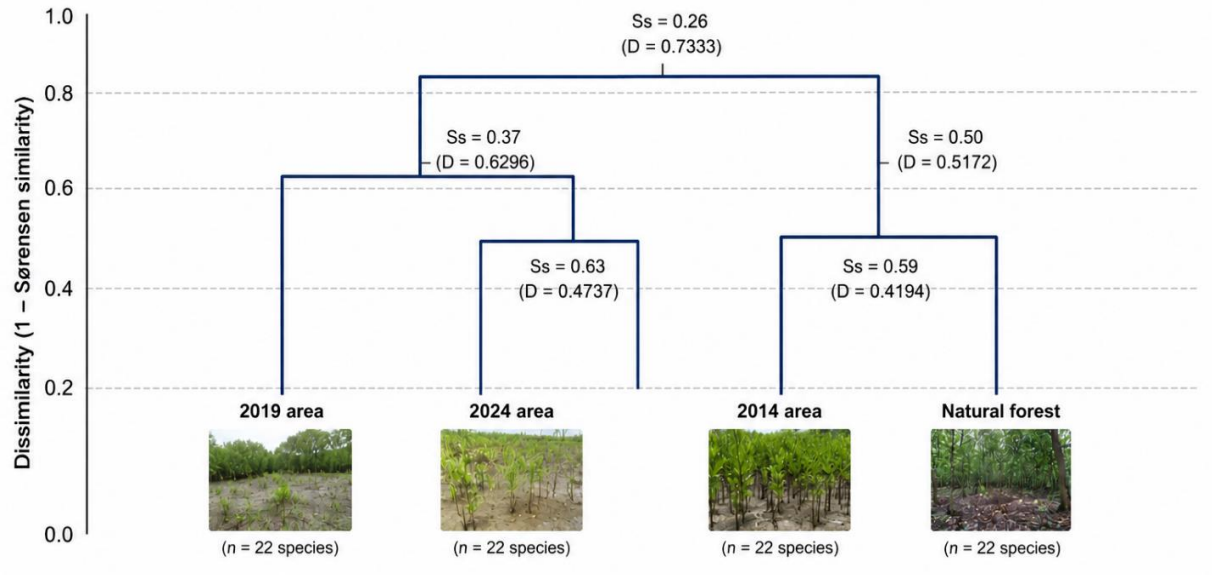

Fig. 2: Tree diagram of the community similarity between terrestrial fauna in rehabilitation areas and those in secondary natural mangrove forest

Table 10: Diversity of aquatic biota recorded in the research locations

Scientific name	English name	Location			
		2024 area (0 y)	2019 area (5 y)	2014 area (10 y)	Natural forest
Fishes:					
Ambassis cf. *vachelli*	Vachelli's glass perchlet			✓	
Chanos chanos	Milkfish	✓			
Psammogobius cf. *biocellatus*	Sleepy goby			✓	
Hexanematichthys sagor	Sagor catfish			✓	
Mayaheros urophthalmus	Mayan cichlid	✓		✓	
Monopterus javanensis	Sunda swamp eel	✓	✓		
Planiliza subviridis	Greenback mullet	✓	✓	✓	✓
Mystus cf. *gulio*	Long whiskers catfish	✓	✓		
Oreochromis mossambicus	Mozambique tilapia	✓	✓	✓	✓
Periophthalmus sp.	Mudskipper		✓	✓	✓
Plotosus canius	Gray eel-catfish			✓	
Poecilia latipinna	Sailfin molly	✓	✓	✓	
Scatophagus argus	Spotted scat			✓	✓
Terapon jarbua	Crescent grunter		✓		
Trichopodus trichopterus	Three-spot gourami		✓		
No. of fish species	-	7	8	10	4
Crustaceans:					
Metapenaeus ensis	Greasyback shrimp	✓			
Penaeus merguiensis	Banana prawn	✓	✓		✓
Episesarma mederi	Thai vinegar crab	✓			✓
Metaplax elegans	Orange signaller crab	✓			
Metopograpsus latifrons	Broad-fronted Mangrove Crab	✓		✓	✓
Parasesarma sp.	Sesarmid marsh crab	✓			
Scylla paramamosain	Green mud crab			✓	
Thranita crenata	Crenate swimming crab			✓	
Uca sp.	Fiddler crab		✓		
Varuna litterata	River swimming crab			✓	
Carcinoscorpius rotundicauda	Mangrove horseshoe crab			✓	✓
No. of crustaceans species	-	6	2	5	4
Total species richness	-	13	10	15	8

a pivotal role in mediating nutrient cycling and accelerating organic matter decomposition within mangrove sediments (Lee, 1998). The 2019 and the 2014 areas are land covered by vegetation, almost always completely submerged, even at low tide. The persistent inundation of the 2019 and 2014 areas, reflecting progressively mature mangrove canopy cover, creates conditions more suitable for fully aquatic and semi-aquatic crustaceans. Characterizing established mangrove stands requires accounting for complex microhabitats; thus, employing a combination of trapping and hand-collecting in vegetated strata serves to mitigate sampling bias against cryptic and arboreal crustacean assemblages (Kathiresan and Bingham, 2001). The species of crustaceans found in these areas include: green mud crabs (*Scylla paramamosain*), crenate swimming crabs (*Thranita crenata*), broad-fronted mangrove crabs (*Metopograpsus latifrons*), river swimming crabs (*Varuna litterata*), and mangrove horseshoe crabs (*Carcinoscorpius rotundicauda*). All of these are swimming crustaceans, while broad-fronted mangrove crabs is a species of crab that climbs on mangrove tree roots. The functional divergence between swimming crustaceans (*Scylla*, *Thranita*, *Varuna*, and *Carcinoscorpius*) and *Metopograpsus latifrons* in the older areas is consistent with increasing structural complexity in maturing mangrove habitats. As mangrove structural complexity advances, the developing root architecture provides critical attachment substrates and refugia for climbing or cryptic macrofauna, whereas the adjacent deeper channels accommodate mobile, pelagic taxa (Gilman *et al.*, 2008). This trophic and functional

diversification is an indicator of ecosystem recovery and habitat maturation over the observed 10-year restoration timeline through progressive ecological succession and stabilization across rehabilitated mangrove habitats and ecosystems.

CONCLUSION

This study provides compelling evidence that structural maturity and biodiversity recovery are fundamentally decoupled processes - and that the conventional growth-based metrics currently prescribed by Indonesian national policy are insufficient to capture the full ecological trajectory of mangrove rehabilitation. By simultaneously evaluating flora, terrestrial fauna, and aquatic fauna diversity across a chronosequence of rehabilitation stands aged 0, 5, and 10 years in the Segarajaya mangrove area, Bekasi Regency, this study demonstrates that these distinct biotic components exhibit decoupled recovery trajectories and must be assessed independently. The 2024 stand was virtually a monoculture of *R. stylosa* (IVI = 149.43%; H' = 0.04), and this dominance persisted through the 2019 stand (IVI = 130.98%; H' = 0.36) and the 2014 stand, where *R. stylosa* remained the sole species with H' = 0. Monoculture planting of *R. stylosa* produced structurally mature stands after a decade - yet failed to support floristic diversity. Despite a canopy height of 9–10 m and a basal area of 7.38 m^2/ha, the 2014 area failed to recruit additional mangrove species. This lack of diversification suggests that dense canopy closure suppressed light availability at the forest floor and thereby constrained natural colonization. This trajectory suggests that without deliberate floristic enrichment, monoculture rehabilitation stands are prone to remaining arrested in a low-diversity state indefinitely. In these systems, intense competitive exclusion exerted by the dominant canopy species effectively impedes the recruitment and establishment of incoming propagules from adjacent natural forests. In contrast, the reference secondary natural forest supported five tree species with a Shannon-Wiener Diversity Index of H' = 0.84 at the tree level and H' = 1.10 at the sapling level, underscoring the superior ecological complexity of naturally structured stands. The significantly greater basal area of the natural forest (13.58 m^2/ha) relative to the 10-year rehabilitation stand (7.38 m^2/ha) further highlights the long developmental lag inherent in monoculture restoration approaches. Terrestrial fauna diversity exhibited a consistent, age-related progression across the rehabilitation gradient, yet remained markedly impoverished relative to the natural forest. The secondary natural forest supported 21 species of mammals, birds, and reptiles, whereas the 2024, 2019, and 2014 areas hosted only 7, 6, and 10 species, respectively. The Sørensen Community Similarity Index (S_s) revealed that even the most structurally mature rehabilitation area (2014) achieved a biotic similarity of only 58% with the natural forest - a value that falls substantially below any ecologically meaningful threshold for functional recovery. The 2019 area attained the lowest community similarity index of 37.04%. This pronounced divergence underscores that early-stage successional stands support highly distinct faunal configurations compared to mature, intact mangrove forests. The absence of mammal detections in all rehabilitation areas, as well as the restriction of *Hemidactylus platyurus* to the natural forest, underscores the limited capacity of young monoculture rehabilitation stands to support the full complement of vertebrate fauna characteristic of intact mangrove ecosystems. The progressive but incomplete faunal recovery observed across the chronosequence reinforces the view that habitat structural complexity, rather than stand age alone, is the primary driver of vertebrate community assembly in restored mangroves. The surveyed aquatic biota, comprising 15 fish species and 11 crustacean species across all locations, revealed ecologically meaningful patterns of community succession. The 2024 site harbored opportunistic and semi-terrestrial mudflat crabs that serve as pioneer

detritivores, playing a critical role in driving organic matter cycling in restored sediments. Older, vegetated areas supported a shift toward swimming crustaceans reflecting progressively maturing root architecture and tidal channel development. Ichthyofaunal assemblages similarly exhibited distinct successional dynamics; notably, the 2014 rehabilitation stand supported the highest species richness among all restored sites and shared four fish species with the natural forest. Notably, the presence of commercially important species such as *Scylla paramamosain* and *Penaeus merguiensis* in older and natural forest indicates that rehabilitated mangroves can progressively recover their role as nursery habitats for coastal fisheries — a provisioning ecosystem service of direct socioeconomic relevance to local communities in Bekasi Regency. These findings expose a critical deficiency in MEF-RI Regulation No. 23/2021, which evaluates rehabilitation success solely on plant growth and canopy cover — metrics the 2014 area would pass despite near-zero biodiversity. To establish a more holistic standard for ecosystem evaluation, this study demonstrates the necessity of embedding quantitative, multi-taxa indicators within national monitoring protocols. Utilizing trajectories from spontaneously recruited flora, vertebrate fauna (specifically birds), and macroinvertebrates (specifically crustaceans) provides a highly sensitive, cross-taxonomic baseline for assessing genuine restoration success. Achieving these benchmarks will require mixed-species nursery programs, that for instance in Segarajaya case, incorporating *A. marina*, *A. alba*, and *S. alba* alongside *R. stylosa*, and active restoration of tidal connectivity to facilitate propagule dispersal and faunal recolonization. Extended monitoring beyond the 10-year horizon examined in this study is imperative to ascertain whether mixed-species stands ultimately converge toward the biodiversity levels observed in the reference natural forest, and to establish scientifically grounded recovery targets for inclusion in future revisions of national rehabilitation policy.

AUTHOR CONTRIBUTIONS

E. Yuliana, the corresponding author, conceived, designed, and conducted research, as well as data analysis, preparing the manuscript draft, and finalizing the manuscript draft. A. Winata contributed to data sampling, especially for flora sampling, and data analysis. L.E. Setijorini conducted observation of vegetation, data analysis, and also reviewed the paper draft. D. E. Yani developed research instruments and conducted flora sampling. M.H. Fathani contributed to data processing, flora and terrestrial fauna sampling, and data analysis. W.A. Djatmiko made contributions to flora, fauna, and fish identification, sampling activities, data processing, and writing the manuscript draft.

ACKNOWLEDGEMENT

The authors are grateful to the Indonesia Endowment Fund for Education Agency (Lembaga Pengelola Dana Pendidikan/LPDP) for supporting the funding for the writing of this article and its publication through the Universitas Terbuka EQUITY Program. The authors also acknowledge Universitas Terbuka through Research and community service institutions (Lembaga Penelitian dan Pengabdian kepada Masyarakat/LPPM) for providing research funding for the Applied Research Scheme under grant number [B/123/UN31.LPPM/PT.01.03/2024]. The authors would like to thank the fishermen and other local community in Segarajaya, Bekasi Regency. Finally, the authors sincerely thank the anonymous reviewers for the insightful comments and constructive feedback, which have significantly enhanced the quality of this study.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and

redundancy have been completely observed by the authors.

OPEN ACCESS

©2026 The author(s). This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and the intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit: http://creativecommons.org/licenses/by/4.0/

PUBLISHER'S NOTE

GJESM Publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

☑ Positive AI Statement

During the preparation of this work the author(s) have used Artificial Intelligence (AI) [Claude AI] in order to [to improve language clarity and check typographical errors in the manuscript]. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

ABBREVIATIONS

%	Percent
χ^2	Chi-square Test of Independence
a	Total species in both communities
b	Number of species in community A
c	Number of species in community B
BA	Basal area
cm	Centimeter
df	Degrees of freedom
D	Density
Do	Dominance of a species
F	Frequency
H	Hypothesis
H_0	Null hypothesis
H1	Hypothesis 1
H2	Hypothesis 2
H3	Hypothesis 3
ha	Hectare
H'	Shannon-Wiener Diversity Index
ind	Individuals
IVI	Importance Value Index
km	Kilometer
km^2	Square kilometers
m	Meter
m^2	Meter square
mm	Millimeters
m^2/ha	Square meter per hectare
MEF-RI	Ministry of Environment and Forestry of the Republic of Indonesia
MMAF	Ministry of Maritime Affairs and Fisheries
n_i	Number of individuals per species
N	Total number of all individuals
No	Number
p	Probability
RD	Relative density
RDo	Relative dominance
RF	Relative frequency
sp	Species
S_s	Sørensen Community Similarity Index
U	Mann-Whitney U Test
y	year

REFERENCES

Alongi, D. M., (2002). Present state and future of the world's mangrove forests. Environ. Conserv., 29(3): 331–349 **(19 pages)**.

Alongi, D.M., (2009). The energetics of mangrove forests. Springer Science & Business Media, Dordrecht. **(216 pages)**.

Arifanti, V.B.; Kauffman, J.B.; Subarno; Ilman, M.; Tosiani, A.; Novita, N., (2022). Contributions of mangrove conservation and restoration to climate change mitigation in Indonesia. Global Change Biol., 28(15): 4523–4538 **(16 pages)**.

Bibby, C.J.; Burgess, N.D.; Hill, D.A.; Mustoe, S., (2000). Bird Census Techniques (2nd ed.). London: Academic Press **(302 pages)**.

Bosire, J.O.; Dahdouh-Guebas, F.; Walton, M.; Crona, B.I.; Lewis, R.R.; Field, C.; Kairo, J.G.; Koedam, N., (2008). Functionality of restored mangroves: A review. Aquat. Bot., 89(2): 251–259 **(9 pages).**

Cannicci, S.; Burrows, D.; Fratini, S.; Smith III, T.J.; Offenberg, J.; Dahdouh-Guebas, F., (2008). Faunal impact on vegetation structure and ecosystem function in mangrove forests: A review. Aquat. Bot., 89(2): 186–200 **(15 pages).**

Damastuti, E.; Groot, R.d.; Debrot, A.O.; Silvius, M.J., (2022). Effectiveness of community-based mangrove management for biodiversity conservation: A case study from Central Java, Indonesia. Trees For. People. 7(2022): 100202 **(13 pages).**

Duke, N.C., (2006). Australia's Mangroves: The Authoritative Guide to Australia's Mangrove Plants. Brisbane: University of Queensland.

Duke, N.C.; Meynecke, J.O.; Dittmann, S.; Ellison, A.M.; Anger, K.; Berger, U.; Cannicci, S.; Diele, K.; Ewel, K.C.; Field, C.D.; Koedam, N.; Lee, S.Y.; Marchand, C.; Nordhaus, I.; Dahdouh-Guebas, F., (2007). A world without mangroves? Science, 317(5834): 41–42 **(2 pages).**

Feller, I.C.; Lovelock, C.E.; Berger, U.; McKee, K.L.; Joye, S.B.; Ball, M.C., (2010). Biocomplexity in mangrove ecosystems. Ann. Rev. Mar. Sci., 2(1): 395–417 **(23 pages)**.

Field, C.D., (1998). Rehabilitation of mangrove ecosystems: An overview. Mar. Pollut. Bull., 37(8–12): 383–392 **(10 pages)**.

Friess, D.A.; Rogers, K.; Lovelock, C.E.; Krauss, K.W.; Hamilton, S.E.; Lee, S.Y.; Lucas, R.; Primavera, J.; Rajkaran, A.; Shi, S., (2019). The state of the world's mangrove forests: past, present, and future. Annu. Rev. Environ. Resour., 44: 89-115 **(27 pages)**.

Giesen, W.; Wulffraat, S.; Zieren, M.; Scholten, L., (2006). Mangrove Guidebook for Southeast Asia. Bangkok: FAO and Dharmasarn Co. Ltd.

Gilman, E.L.; Ellison, J.; Duke, N.C.; Field, C., (2008). Threats to mangroves from climate change and adaptation options: A review. Aquat. Bot., 89(2): 237–250 **(14 pages)**.

Hewindati, Y.T.; Yuliana, E.; Winata, A.; Adimu, H.E.; Djatmiko, W.A., (2023). Mangrove vegetation and fish diversity in Kaledupa Island, Wakatobi National Park, Southeast Sulawesi, Indonesia. Biodiversitas, 24(3): 1766-1772 **(7 pages)**.

Kamali, B.; Hashim, R., (2011). Mangrove restoration without planting. Ecol. Eng., 37(2): 340–348 **(5 pages)**.

Kathiresan, K.; Bingham, B.L., (2001). Biology of mangroves and mangrove ecosystems. Adv. Mar. Biol., 40: 81–251 **(171 pages)**.

Kinasih, N.A.; Harmawan, B.N., (2025). Analysis of the co-managing process in the management of the Mangrove Botanical Gardens conservation area in Surabaya City. Sosio Edukasi: Jurnal Ilmu Sosial dan Ilmu Pendidikan, 14(4): 3741–3750 **(10 pages)**.

Kitaya, Y.; Jintana, V.; Piriyayotha, S.; Jaijing, D.; Yabuki, K.; Izutani, S.; Nishimiya, A.; Iwasaki, M., (2002). Early growth of seven mangrove species planted at different elevations in a Thai estuary. Trees, 16: 150–154 **(5 pages)**.

Kotijah, S.; Ventyrina, I., (2019). Preventive regulations to remove environmental damage to mangrove ecosystem in East Kalimantan, Indonesia. INJURILESS, 1(1): 9–19 **(11 pages)**.

Krauss, K.W.; Lovelock, C.E.; McKee, K.L.; Lopez-Hoffman, L.; Ewe, S.M.L.; Sousa, W.P., (2008). Environmental drivers in mangrove establishment and early development: A review. Aquat. Bot., 89: 105–127 **(23 pages)**.

Lee, S.Y., (1998). Ecological role of grapsid crabs in mangrove ecosystems: A review. Mar. Freshwater Res., 49(4): 335–343 **(9 pages)**.

MacKinnon, J.; Phillipps, K., (1993). A Field Guide to the Birds of Borneo, Sumatra, Java, and Bali. Oxford: Oxford University Press.

Magurran, A.E., (1988). Ecological Diversity and Its Measurement. Cambridge, New York: Cambridge University Press **(179 pages)**.

Magurran, A.E., (2021). Measuring Biological Diversity. Curr. Biol., 31(19): R1174-R1177 **(4 pages)**.

Metkono, E.; Salampessy, M.L.; Lidiawati, I., (2022). Potential of local institutions in mangrove forest management in Pantai Bahagia Village Bekasi. Jurnal Nusa Sylva, 22(1): 17–26 **(10 pages)**.

Murdiyarso, D.; Purbopuspito, J.; Kauffman, J.B.; Warren, M.W.; Sasmito, S.D.; Donato, D.C.; Manuri, S.; Krisnawati, H.; Taberima, S.; Kurnianto, S., (2015). The potential of Indonesian mangrove forests for global climate change mitigation. Nat. Clim. Change., 5(12): 1089–1092 **(4 pages)**.

Nagelkerken, I.; Blaber, S.J.M.; Bouillon, S.; Green, P.; Haywood, M.; Kirton, L.G.; Meynecke, J.O.; Pawlik, J.; Penrose, H.M.; Sasekumar, A.; Somerfield, P.J., (2008). The habitat function of mangroves for offshore fish and shellfish populations: A review. Aquat. Bot., 89(2): 155–185 **(31 pages)**.

Nurhati, I.S.; Murdiyarso, D., (2023). National strategy for mangrove ecosystem management: A reference for the conservation and rehabilitation of coastal areas to achieve Sustainable Development Goals and Low Carbon Development (Working Paper No. 14). Center for International Forestry Research and World Agroforestry (CIFOR-ICRAF).

Primavera, J.H.; Esteban, J.M.A., (2008). A review of mangrove rehabilitation in the Philippines: Successes, failures and future prospects. Wetlands Ecol. Manage., 16(5): 345–358 **(14 pages)**.

Ralph, C.J.; Sauer, J.R.; Droege, S., (eds). (1995). Monitoring bird populations by point counts. Gen. Tech. Rep. PSW-GTR-149. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station **(187 pages)**.

Retnaningdyah, C.; Febriansyah, S.C.; Hakim, L., (2022). Evaluation of the quality of mangrove ecosystems using macrozoobenthos as bioindicators in the Southern Coast of East Java, Indonesia. Biodiversitas, 23(12): 6480-6491 **(12 pages)**.

Rohila, A. K.; Ansul; Maan, D.; Kumar, A.; Kumar, K., (2017). Impact of agricultural practices on environment. Asian Jr. of Microbiol. Biotech. Env. Sc., 19(2): 145-148 **(4 pages)**.

Sasmito, S.D.; Basyuni, M.; Kridalaksana, A.; Saragi-Sasmito, M.F.; Lovelock, C.E.; Murdiyarso, D., (2023). Challenges and opportunities for achieving Sustainable Development Goals through restoration of Indonesia's mangroves. Nat. Ecol. Evol., 7(1): 62–70 **(9 pages)**.

Sari, A.; Tuwo, A.; Saru, A.; Rani, C., (2022). Diversity of fauna species in the mangrove ecosystem of Youtefa Bay Tourism Park, Papua, Indonesia. Biodiversitas, 23(9): 4490-4500 **(12 pages)**.

Sodhi, N.S.; Koh, L.P.; Brook, B.W.; Ng, P.K.L., (2004). Southeast Asian biodiversity: An impending disaster. Trends Ecol. Evolution. 19(12): 654–660 **(7 pages)**.

Sørensen, T., (1948). A Method of establishing groups of equal amplitudes in plant sociology based on similarity of species content and its application to analyses of the vegetation on Danish Commons. Kongelige Danske Videnskabernes Selskab, Biologiske Skrifter, 5: 1-34 **(30 pages)**.

Tomlinson, P. B., (1986). The Botany of Mangroves. Cambridge: Cambridge University Press.

Welcomme, R.L.; Cowx, I. G.; Coates, D.; Bene, C.; Funge-Smith, S.; Halls, A.; Lorenzen, K., (2010). Inland capture fisheries. Philosophical Transactions of the Royal Society B: Biol. Sci., 365(1554): 2881–2896 **(16 pages)**.

Wirabuana, P.Y.A.P.; Baskorowati, L.; Pamungkas, B.; Mulyana, B.; South, J.; Purnobasuki, H.; Andriyono, S., (2025). Mangroves, fauna compositions and carbon sequestration after ten years restoration on Flores Island, Indonesia. Sci. Rep., 15: 4866 **(11 pages)**.

Wolff, M.; Koch, V.; Isaac, V., (2000). A trophic flow model of the Caeté Mangrove Estuary (North Brazil) with considerations for the sustainable use of its resources. Estuarine Coastal Shelf Sci., 50(6): 789–803 **(15 pages)**.

Youssef, T.; Saenger, P., (1998). Photosynthetic gas exchange and accumulation of phytotoxins in mangrove seedlings in response to soil physico-chemical characteristics associated with waterlogging. Tree Physiol., 18: 317–324 **(8 pages)**.

Yuliana, E.; Hewindati, Y.T., Winata, A., Djatmiko, W.A., Rahadiati, A., (2019). Diversity and characteristics of mangrove vegetation in Pulau Rimau Protection Forest, Banyuasin District, South Sumatra, Indonesia. Biodiversitas. 20(4): 1215-1221 **(7 pages)**.

Yuliana, E.; Winata, A.; Rahadiati, A.; Hewindati, Y.T., (2020). Mangrove Ecosystem Services Mapping in The Protected Forest Area of Rimau island, Banyuasin District, Sumatera Selatan Province. Majalah Ilmiah Globe, 22(2): 83-92 **(10 pages)**.

Yuliana, E.; Winata, A.; Adimu, H.E.; Hewindati, Y.T.; Djatmiko, W.A., (2022). Reef fish in the mudflats of Kaledupa Island in Wakatobi National Park, Indonesia. Hayati. 29(2): 245-254 **(10 pages)**.

Yuliana, E.; Nurilmala, M.; Rahadiati, A.; Farida, I.; Kurniawati, H.; Agustina, S.; Difah, D.A.; Pertiwi, P.R.; Wicaksana, B.E.; Ramilo, R.V.; Djatmiko, W.A., (2026). Provisioning ecosystem services through the sustainable management of fish resources extracted by small-scale fishers. Global J. Environ. Sci. Manage., 12(3): 1311-1332 **(22 pages)**.

Zar, J.H., (2010). Biostatistical Analysis (5th ed.). Upper Saddle River, NJ: Prentice Hall.

AUTHOR (S) BIOSKETCHES

Yuliana, E., Doctor, Professor, Department of Fisheries Management, Postgraduate School Universitas Terbuka, Jl. Cabe Raya, Pondok Cabe, Pamulang, South Tangerang, Indonesia.
- Email: *ernik@ecampus.ut.ac.id*
- ORCID: 0000-0002-8518-6363
- Web of Science ResearcherID: A-9453-2018
- Scopus Author ID: 57189384374
- Homepage: https://www.ut.ac.id/

Winata, A., Master, Associate Professor, Department of Biology, Faculty of Science and Technology, Universitas Terbuka, Jl. Cabe Raya, Pondok Cabe, Pamulang, South Tangerang, Indonesia.
- Email: *adit@ecampus.ut.ac.id*
- ORCID: 0009-0007-4127-6088
- Web of Science ResearcherID: NA
- Scopus Author ID: 57225987001
- Homepage: https://www.ut.ac.id/

Setijorini, L.E., Master, Associate Professor, Department of Agribusiness, Faculty of Science and Technology, Universitas Terbuka, Jl. Cabe Raya, Pondok Cabe, Pamulang, South Tangerang, Indonesia.
- Email: *vica@ecampus.ut.ac.id*
- ORCID: 0009-0005-5430-1970
- Web of Science ResearcherID: GPK-6471-2022
- Scopus Author ID: 57214672698
- Homepage: https://www.ut.ac.id/

Yani, D.E., Master, Associate Professor, Department of Agribusiness, Faculty of Science and Technology, Universitas Terbuka, Jl. Cabe Raya, Pondok Cabe, Pamulang, South Tangerang, Indonesia.
- Email: diarsi*@ecampus.ut.ac.id*
- ORCID: 0000-0002-2784-9587
- Web of Science ResearcherID: A-9485-2018
- Scopus Author ID: 57214664258
- Homepage: https://www.ut.ac.id/

Fathani, M.H., Master, Instructor, Universitas Terbuka Malang Regional Office, Jl. Mayjen. Sungkono No. 9, Malang, Indonesia.
- Email: *hamas.fathani@gmail.com*
- ORCID: 0009-0002-9823-2354
- Web of Science ResearcherID: NA
- Scopus Author ID: 59551657100
- Homepage: https://www.ut.ac.id/

Djatmiko, W.A., Master, Instructor, LATIN The Indonesian Tropical Institute, Jl. Sutera No. 1 Situgede, Bogor, Indonesia.
- Email: *bowie146@gmail.com*
- ORCID: 0000-0002-7537-4782
- Web of Science ResearcherID: NA
- Scopus Author ID: 57208246546
- Homepage: https://latin.or.id/

HOW TO CITE THIS ARTICLE:
Yuliana, E.; Winata, A.; Setijorini, L.E.; Yani, D.E.; Fathani, M.H.; Djatmiko, W.A., (2026). Biodiversity-oriented criteria for measuring the effectiveness of mangrove ecosystem rehabilitation success. Global J. Environ. Sci. Manage., 12(4): 1619-1638.

DOI: 10.22034/gjesm.2026.04.01
URL: https://www.gjesm.net/article_735281.html