JPPIPA 12(11) (2026)

Jurnal Penelitian Pendidikan IPA

http://jppipa.unram.ac.id/index.php/jppipa/index

An Integrated Species–Site Suitability, Planting Design, and Cost Assessment Framework for Mangrove Rehabilitation in Muara Sekampung, Indonesia

Dimas Hafidhin[1*], Cecep Kusmana[2], Omo Rusdiana[3]

[1] Graduate Program in Natural Resources and Environmental Management, IPB University, Bogor, Indonesia.
[2] Department of Silviculture, Faculty of Forestry and Environment, IPB University, Bogor, Indonesia.
[3] Department of Forest Management, Faculty of Forestry and Environment, IPB University, Bogor, Indonesia.

Received: June 14, 2026
Revised: October 27, 2026
Accepted: November 17, 2026
Published: November 30, 2026

Corresponding Author:
Dimas Hafidhin
dimashafidhin5@gmail.com

DOI: 10.29303/jppipa.v12i11.15691

Open Access

© 2026 The Authors. This article is distributed under a (CC-BY License)

Abstract: Mangrove rehabilitation success depends on the compatibility between selected species and site conditions, appropriate planting configurations, and the availability of adequate financial resources. This study developed an integrated framework combining species–site suitability assessment, adaptive planting design, and cost estimation to support mangrove rehabilitation planning in the Muara Sekampung Protected Forest, East Lampung, Indonesia. A descriptive quantitative approach was applied using field-derived biophysical data, literature-based ecological matching, and cost analysis. Species suitability was assessed by comparing site conditions, including water and soil salinity, substrate characteristics, and tidal inundation, with the ecological tolerance ranges and habitat preferences of candidate mangrove species. Planting configurations were then selected according to variations in substrate conditions, hydrodynamic exposure, and inundation characteristics. Initial implementation costs were estimated based on seedling requirements, seedling provision through self-managed nurseries or external procurement, labor, supporting materials, and transportation. The rehabilitation area was characterized by a muddy substrate dominated by clay texture, water salinity of 24.7 ± 0.52 ppt, soil salinity of 5.0–10.5 ppt, a diurnal tidal regime, inundation depths of 40–98 cm, and current velocities of 0.18–0.53 m/s. Seven mangrove species were identified as ecologically suitable candidates for rehabilitation: Rhizophora mucronata, R. apiculata, R. stylosa, Avicennia marina, A. alba, Sonneratia caseolaris, and S. alba. Five planting configurations, comprising cluster planting, line cluster planting, and three quadrat planting arrangements, were allocated across the 20-ha priority rehabilitation area. The estimated seedling requirement was 125,269 seedlings. Initial rehabilitation costs ranged from IDR 401.56 million under the self-managed nursery scenario to IDR 616.33 million under the ready-to-plant seedling scenario. The proposed framework provides a site-specific basis for mangrove rehabilitation planning by linking ecological suitability, planting configurations, seedling requirements, and estimated implementation costs. Its ecological effectiveness and long-term cost performance require further field validation.

Keywords: Adaptive planting design; Integrated framework; Mangrove rehabilitation; Rehabilitation cost; Species–site suitability

Introduction

Mangrove ecosystems are among the most productive and ecologically important coastal wetlands in tropical and subtropical regions. These ecosystems are characterized by vegetation adapted to saline, waterlogged, and tidally influenced environments, enabling them to occupy the dynamic interface between

How to Cite:
Hafidhin, D., Kusmana, C., & Rusdiana, O. (2026). An Integrated Species–Site Suitability, Planting Design, and Cost Assessment Framework for Mangrove Rehabilitation in Muara Sekampung, Indonesia. *Jurnal Penelitian Pendidikan IPA*, *12*(11), 64–78. https://doi.org/10.29303/jppipa.v12i11.15691

terrestrial and marine systems (Imchen et al., 2018; Ofori et al., 2023). Mangroves provide a wide range of ecosystem services, including shoreline stabilization, wave attenuation, sediment trapping, nutrient cycling, biodiversity conservation, and fisheries support (Gedan et al., 2011; Grzyb et al., 2021; Kusmana, 2014). In addition, mangrove forests are increasingly recognized for their substantial contribution to climate change mitigation through long-term carbon sequestration and storage, commonly referred to as blue carbon (Sidik et al., 2023). Consequently, the conservation and rehabilitation of mangrove ecosystems have become important priorities for enhancing coastal resilience and achieving sustainable development objectives.

Despite their ecological significance, mangrove ecosystems worldwide continue to experience extensive degradation due to land-use conversion, coastal development, aquaculture expansion, pollution, and climate-related disturbances (Lee et al., 2014; Rahadian et al., 2022). Indonesia, which contains approximately 3.36 million ha of mangroves, faces similar challenges (Yusuf et al., 2017). The degradation of mangrove habitats can result in biodiversity loss, reduced fisheries productivity, diminished coastal protection functions, and declining carbon storage capacity. These impacts have intensified efforts to rehabilitate degraded mangrove areas and restore their ecological functions.

Mangrove rehabilitation has been widely implemented as a strategy to recover degraded coastal ecosystems; however, rehabilitation outcomes remain highly variable across sites and regions. Numerous rehabilitation projects have reported low survival rates and limited ecosystem recovery due to inappropriate species selection, inadequate consideration of hydrological conditions, and the application of generalized planting approaches that fail to account for site-specific environmental characteristics (Agaton et al., 2022; Dahdouh-Guebas et al., 2005; Lewis, 2005). Increasing evidence indicates that successful rehabilitation planning depends largely on the compatibility between selected species and local environmental conditions, including salinity gradients, substrate characteristics, hydrological regimes, and tidal inundation patterns (Hashim et al., 2010; Kusmana et al., 2017). Accordingly, species–site matching has become a fundamental principle of ecological rehabilitation by emphasizing the selection of mangrove species that are suited to the environmental conditions of the rehabilitation site.

In addition to species selection, planting design is an important component of rehabilitation planning. Planting arrangements that consider local hydrodynamic processes, sediment dynamics, and site accessibility may support seedling establishment and sediment retention. Effective rehabilitation planning also requires an understanding of implementation costs, particularly in large-scale programs where nursery development, seedling production, planting operations, and related activities constitute substantial financial investments (Damastuti et al., 2023; Kusmana et al., 2010). Cost information is therefore important for evaluating implementation requirements, optimizing resource allocation, and supporting evidence-based decision-making.

Previous studies have demonstrated the importance of ecological and hydrological conditions in mangrove rehabilitation and have examined technical and economic aspects of restoration. However, these aspects are often considered separately during rehabilitation planning. Ecological assessments may identify suitable species or environmental constraints without translating these findings into specific planting arrangements, whereas cost assessments may estimate financial requirements without explicitly considering how site conditions influence species selection and planting design. Integrating ecological suitability, planting configurations, and implementation costs is therefore important for developing rehabilitation plans that respond to site-specific environmental conditions while remaining operationally feasible.

The Muara Sekampung Protected Forest in East Lampung, Indonesia, represents a degraded mangrove landscape where rehabilitation interventions are needed to support the recovery of ecological functions and coastal resilience. Previous site-specific assessments identified sedimentation, hydrological changes, and anthropogenic pressures as important factors associated with mangrove degradation in the area (Hafidhin et al., 2026). Spatial analysis and field verification identified approximately 474.47 ha of potential rehabilitation area, dominated by areas with very low to non-vegetated conditions. Field observations in the selected rehabilitation sites also showed no living mangrove vegetation or natural regeneration, indicating limited potential for natural recovery without intervention (Hafidhin et al., 2026).

From the approximately 474.47 ha of potential rehabilitation area, 20 ha was selected as a priority area for detailed rehabilitation planning. The selected area represents part of the broader rehabilitation landscape and was identified based on vegetation cover conditions, NDVI values ranging from −1 to 0.25, substrate characteristics, tidal influence, hydrological conditions, and field accessibility (Hafidhin et al., 2026). The area is characterized by a muddy substrate dominated by clay texture, soil salinity ranging from 5.0 to 10.5 ppt, and a diurnal tidal regime. Hydrological disturbances and stagnant inundation associated with suboptimal drainage may further constrain mangrove establishment and natural regeneration, highlighting the need for

rehabilitation strategies that are adapted to local site conditions (Hafidhin et al., 2026).

Previous assessments have therefore provided important spatial and biophysical information for understanding the rehabilitation potential of the Muara Sekampung Protected Forest. However, the availability of this information alone does not directly provide guidance for implementing rehabilitation. Site conditions need to be translated into practical decisions regarding species selection, planting configurations, seedling requirements, and the financial resources required for implementation. This is particularly important in heterogeneous and degraded mangrove landscapes, where generalized rehabilitation approaches may not adequately address site-specific environmental constraints.

Building on these spatial and biophysical assessments, this study integrates species–site suitability assessment, adaptive planting design, and cost estimation to develop site-specific rehabilitation recommendations for the Muara Sekampung Protected Forest. The assessment links local environmental conditions with the selection of suitable mangrove species and planting configurations, which subsequently provide the basis for estimating seedling requirements and initial implementation costs. By considering ecological, operational, and economic aspects within a single planning framework, the study provides a practical basis for translating site information into rehabilitation planning.

Accordingly, this study aimed to (1) identify mangrove species suitable for rehabilitation based on site-specific biophysical conditions, (2) develop planting designs adapted to local environmental characteristics, and (3) estimate nursery and planting costs associated with mangrove rehabilitation in the Muara Sekampung Protected Forest, East Lampung, Indonesia. The resulting framework provides a site-specific basis for rehabilitation planning by linking ecological suitability, planting configurations, seedling requirements, and estimated initial implementation costs.

Method

Study Area

The study was conducted in the Muara Sekampung Protected Forest (Register 15), East Lampung Regency, Lampung Province, Indonesia. The location of the study area is presented in Figure 1. The study site was selected based on a previous spatial and biophysical assessment of mangrove rehabilitation potential in the area (Hafidhin et al., 2026). The assessment integrated Normalized Difference Vegetation Index (NDVI) analysis and field verification and identified approximately 474.47 ha of potential rehabilitation area.

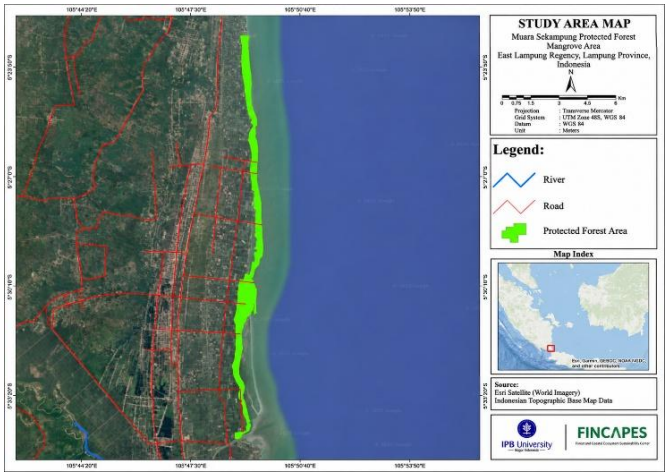

Figure 1. Location of the study area in the Muara Sekampung Protected Forest, East Lampung Regency, Lampung Province, Indonesia

From this broader area, 20 ha was purposively selected as the priority rehabilitation area for detailed planning. The selection considered vegetation conditions, NDVI values ranging from −1 to 0.25, substrate characteristics, tidal influence, hydrological conditions, and field accessibility. The spatial boundary of the 20-ha priority rehabilitation area is presented in Figure 2.

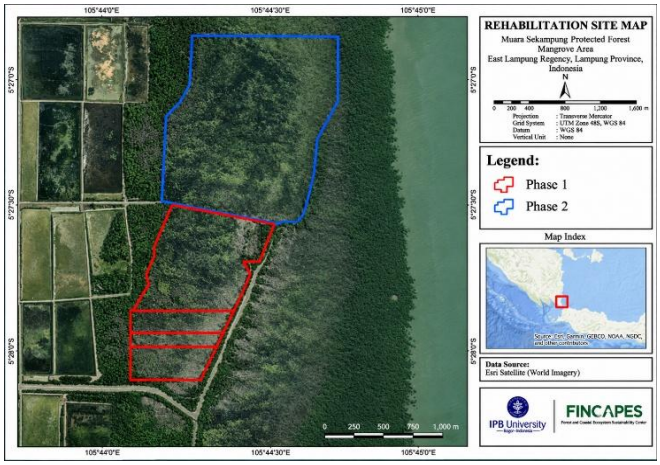

Figure 2. Location and delineation of the mangrove rehabilitation area in the Muara Sekampung Protected Forest, East Lampung Regency, Lampung Province, Indonesia

Site-specific biophysical data, including substrate characteristics, salinity, tidal inundation, and hydrodynamic conditions, were subsequently used as the basis for the species–site matching assessment and the development of planting configurations.

Species–Site Matching Assessment

Suitable mangrove species were identified using a species–site matching approach based on the principle that rehabilitation success depends on the compatibility

between species ecological requirements and site environmental conditions (Hashim et al., 2010; Lewis, 2005). Inappropriate species selection may increase seedling mortality and reduce rehabilitation success, particularly in severely degraded mangrove areas (Lewis, 2005; Kusmana et al., 2010).

The assessment was conducted by comparing the biophysical conditions of the priority rehabilitation area with the ecological requirements and habitat preferences of candidate mangrove species. Salinity, substrate characteristics, and tidal inundation and hydrological conditions were used as the principal environmental parameters, following the mangrove site suitability concept that relates species distribution to tidal conditions, salinity, substrate characteristics, and site physiography (Kusmana et al., 2005).

The biophysical data used in the assessment were derived from previous field-based studies conducted in the Muara Sekampung rehabilitation area. Water salinity data were obtained from Amanta (2026), while soil salinity, substrate characteristics, tidal conditions, inundation depth, current velocity, and vegetation condition were obtained from Hafidhin et al. (2026). The environmental conditions used in the assessment are summarized in Table 1.

Table 1. Biophysical Conditions Used for the Species–Site Matching Assessment in the Muara Sekampung Rehabilitation Area

Environmental parameter	Site condition	Data source	Role in the assessment
Water salinity	24.7 ± 0.52 ppt	Amanta (2026)	Primary indicator of salinity conditions
Soil salinity	5.0–10.5 ppt	Hafidhin et al. (2026)	Supporting information on soil conditions
Substrate	Muddy, dominated by clay texture	Hafidhin et al. (2026)	Assessment of substrate compatibility
Tidal regime	Diurnal	Hafidhin et al. (2026)	Characterization of hydrological conditions
Inundation depth	40–98 cm	Hafidhin et al. (2026)	Assessment of flooding conditions
Current velocity	0.18–0.53 m/s	Hafidhin et al. (2026)	Supporting information on hydrodynamic conditions
Vegetation condition	No living mangrove vegetation or natural regeneration observed	Hafidhin et al. (2026)	Supporting evidence of limited natural recovery

Note: Water salinity data were obtained from Amanta (2026), while the remaining biophysical characteristics were derived from Hafidhin et al. (2026).

The observed site conditions were compared with species-specific ecological tolerance and habitat preferences. The interpretation of inundation conditions referred to the classifications of Watson (1928) and de Haan (1931), as summarized by Kusmana et al. (2005). Information on species tolerance to salinity, substrate conditions, and inundation frequency was obtained from Kusmana et al. (1998), while species-specific habitat preferences were used as supporting information based on Kusmana et al. (2008).

Table 2. Species–Site Suitability Matrix for Mangrove Rehabilitation in the Muara Sekampung Protected Forest

Species	Salinity preference (ppt)	Substrate and habitat preference	Hydrological compatibility	Assessment
Rhizophora mucronata	10–30	Muddy substrates; river margins and coastal to middle zones	Compatible with site conditions	Suitable
Rhizophora apiculata	10–13	Deep mud and estuarine substrates	Compatible with site conditions	Suitable
Rhizophora stylosa	10–30	Sandy mud and seaward habitats	Compatible with site conditions	Suitable
Avicennia marina	10–30*	Deep mud and coastal or river-margin habitats	Compatible with site conditions	Suitable
Avicennia alba	10–30*	Deep mud, river margins, and coastal habitats	Compatible with site conditions	Suitable
Sonneratia caseolaris	10–13	Clay and sandy mud; river and estuarine environments	Suitable for appropriate microsites	Suitable
Sonneratia alba	10–13	Clay, sandy mud, and coastal or estuarine habitats	Compatible with site conditions	Suitable

Note: Salinity tolerance and environmental suitability were interpreted from Kusmana et al. (1998), habitat preferences were supported by Kusmana et al. (2008), and the interpretation of species distribution in relation to inundation conditions referred to Kusmana et al. (2005). *The salinity range for* Avicennia *species represents the general tolerance range reported for the genus*

The assessment used a descriptive and comparative approach without a quantitative weighting or scoring system. A species was considered suitable when its ecological tolerance and habitat preferences were compatible with the prevailing salinity, substrate, inundation, and hydrological conditions of the rehabilitation area. Species showing incompatibility with a major environmental limitation were excluded from the final recommendation.

Based on this assessment, seven mangrove species were identified as ecologically suitable candidates for rehabilitation: Rhizophora mucronata, R. apiculata, R. stylosa, Avicennia marina, A. alba, Sonneratia caseolaris, and S. alba. The species–site suitability matrix is presented in Table 2.

No numerical ranking was applied; therefore, the recommended species represent ecologically compatible candidates rather than species ranked according to a quantitative suitability score. The results of the species–site matching assessment subsequently provided the ecological basis for developing the planting design. The inclusion of a species in Table 2 does not imply that all recommended species were assigned equal proportions, as species composition and planting arrangements were subsequently determined according to local environmental and hydrological conditions.

Development of Planting Design

Planting designs were developed based on the results of the species–site matching assessment and the environmental characteristics of the priority rehabilitation area. Substrate conditions, hydrodynamic exposure, tidal inundation, water depth, and current velocity were considered because these factors influence seedling establishment and the suitability of planting arrangements.

Table 3. Decision Matrix for Selecting Planting Configurations in the Muara Sekampung Rehabilitation Area

Site condition	Recommended planting design	Rationale
Higher hydrodynamic exposure and unstable substrate	Cluster planting	Groups of seedlings provide greater protection from water movement and promote sediment retention
Moderate hydrodynamic exposure or elongated site conditions	Line cluster planting	Clustered rows facilitate sediment trapping and substrate stabilization
Relatively stable substrate and favorable hydrological conditions	Quadrat planting	Regular spacing supports uniform establishment and facilitates maintenance and monitoring

The selection of planting configurations was based on a descriptive site assessment rather than a quantitative scoring system. Hydrological conditions, substrate characteristics, current velocity, and inundation depth were considered jointly to determine the most appropriate planting pattern for each part of the rehabilitation area. The site is characterized by a diurnal tidal regime, inundation depths of 40–98 cm, and current velocities of 0.18–0.53 m s^{-1} (Hafidhin et al., 2026). These conditions were used to distinguish areas requiring greater protection from hydrodynamic exposure from relatively stable areas suitable for regular planting arrangements. The decision criteria used to select planting configurations are presented in Table 3.

Five planting configurations were applied across the 20-ha priority rehabilitation area, comprising cluster planting, line cluster planting, and three quadrat planting arrangements. The spatial allocation of these configurations reflected differences in local environmental and hydrological conditions.

Cluster Planting

Cluster planting was applied to 16 ha of the priority rehabilitation area, particularly in areas requiring greater protection from hydrodynamic forces and substrate instability. Each planting cluster measured 5 m × 2 m, with seedlings spaced at 0.5 m × 0.5 m within the cluster. Clusters were separated by approximately 6 m to provide space for water movement and sediment deposition. Each cluster contained 55 seedlings, with approximately 117 clusters established per hectare, resulting in an estimated planting density of 6,435 seedlings ha^{-1}.

Line Cluster Planting

Line cluster planting was allocated to 1 ha of the rehabilitation area characterized by moderate hydrodynamic exposure and site conditions suitable for planting along elongated features. Seedlings were arranged in clustered rows to facilitate sediment trapping and support substrate stabilization. The orientation and arrangement of the planting rows were adapted to local site conditions, particularly the prevailing tidal flow and field accessibility.

Quadrat Planting

Quadrat planting was allocated to relatively sheltered areas with more stable substrates and favorable hydrological conditions. Three quadrat arrangements were applied, each covering 1 ha: Quadrat 1 × 1 m, Quadrat 1 × 2 m, and Quadrat 2 × 2 m. The corresponding theoretical planting densities were 10,000 seedlings ha^{-1}, 5,000 seedlings ha^{-1}, and 2,500 seedlings ha^{-1}, respectively. Overall, the 20-ha priority

rehabilitation area was allocated among the five planting configurations: 16 ha for cluster planting and 1 ha each for line cluster planting, Quadrat 1 × 1 m, Quadrat 1 × 2 m, and Quadrat 2 × 2 m.

Seedling requirements were calculated based on the effective planting area and planting density associated with each configuration. For quadrat planting, the theoretical number of seedlings was calculated as:

$$N = A / (S_1 \times S_2) \quad (1)$$

Where:
N = number of seedlings
A = effective planting area (m²)
S_1 and S_2 = the planting distances (m)

For cluster planting, seedling requirements were calculated by multiplying the number of clusters by the number of seedlings per cluster. The effective planting area excluded portions of the site that could not be planted because of physical or environmental constraints. The resulting planting designs provided an operational basis for determining seedling requirements and estimating the initial costs of rehabilitation. By adapting planting density and spatial arrangements to local hydrodynamic and substrate conditions, the approach avoided the application of a single planting pattern across the entire rehabilitation area.

Rehabilitation Cost Estimation

A descriptive cost analysis was conducted to estimate the financial requirements for the initial implementation of mangrove rehabilitation in the 20-ha priority rehabilitation area. The analysis covered seedling provision and initial planting activities (P-0). Therefore, the estimated costs represent initial rehabilitation costs and do not include long-term maintenance, monitoring, or other post-establishment activities.

Seedling requirements were determined based on the planting designs developed for the 20-ha rehabilitation area, resulting in a total requirement of 125,269 seedlings. Two alternative seedling provision scenarios were evaluated: (1) independent seedling production through a nursery and (2) procurement of ready-to-plant seedlings.

Cost information was obtained through interviews with the head of the Mutiara Hijau 1 Forest Farmer Group (KTH), surveys of prevailing prices for materials and services in Pasir Sakti District, and supporting rehabilitation documents, including the 2022 Mangrove Forest and Land Rehabilitation Technical Plan prepared by the Way Seputih–Way Sekampung Watershed Management Agency. The unit prices used in the analysis were based on the prevailing prices during the study period and are expressed in Indonesian Rupiah (IDR). The cost of each component was calculated by multiplying the required quantity or volume by its corresponding unit price:

$$C_i = Q_i \times P_i \quad (2)$$

Where:
C_i = Cost of component i
Q_i= Quantity or volume
P_i = Unit price

Nursery and Seedling Provision Costs

Under the independent nursery scenario, cost components included propagule procurement, polybags and planting media, nursery labor, nursery bed and shading construction, propagule transportation, preventive pesticide application, and nursery equipment. The estimated seedling provision cost under this scenario was Rp184,295,900, equivalent to approximately Rp1,472 per seedling.

Under the ready-to-plant seedling procurement scenario, cost components included the purchase of seedlings, seedling transportation, preventive pesticide application, and nursery equipment. The estimated seedling provision cost under this scenario was Rp399,057,000, equivalent to approximately Rp3,185 per seedling.

Initial Planting Costs

Initial planting costs included labor for planting operations, bamboo stakes, and transportation of seedlings to the rehabilitation site. Planting activities were estimated to require 900 person-days (HOK), with a labor cost of Rp80,000 per person-day. Bamboo stakes were provided for 125,269 seedlings at a unit cost of Rp1,000 per stake, while transportation to the rehabilitation site was estimated at 20 transportation packages at Rp1,000,000 per package.

The total initial planting cost was Rp217,269,000, comprising Rp72,000,000 for planting labor, Rp125,269,000 for bamboo stakes, and Rp20,000,000 for seedling transportation. The initial rehabilitation cost was calculated as the sum of seedling provision and initial planting costs:

$$IRC = SC + PC \quad (3)$$

Where:
IRC = initial rehabilitation cost (IDR)
SC = seedling provision cost, including either independent nursery production or ready-to-plant seedling procurement (IDR)
PC = initial planting cost (IDR)

Based on the two scenarios, the estimated initial rehabilitation cost was Rp401,564,900 for the independent nursery scenario and Rp616,326,000 for the ready-to-plant seedling procurement scenario. These values were equivalent to Rp20,078,245 ha^{-1} and Rp30,816,300 ha^{-1}, respectively, based on the 20-ha rehabilitation area.

To facilitate comparison with rehabilitation programs using a standard planting density, the estimated costs were also normalized to 5,000 seedlings ha^{-1}. The normalized costs were Rp16,025,000 ha^{-1} for the independent nursery scenario and Rp24,600,000 ha^{-1} for the ready-to-plant seedling procurement scenario.

The estimates represent baseline costs for the initial implementation stage and should not be interpreted as the total long-term cost of mangrove rehabilitation. Changes in seedling prices, labor costs, transportation requirements, and seedling mortality may affect the total financial requirements. A separate sensitivity analysis was not conducted because the estimates were based on the seedling requirements and prevailing unit prices used during the study. Additional costs associated with maintenance, replacement planting, and long-term monitoring would need to be considered in a comprehensive life-cycle cost assessment.

Data Analysis

Data were analyzed using a descriptive and integrated approach to establish the relationship between site conditions, species suitability, planting design, seedling requirements, and initial rehabilitation costs. The analysis was conducted sequentially, with the results of each stage providing the basis for the subsequent decision-making process, as illustrated in Figure 3.

First, the biophysical conditions of the rehabilitation area, including salinity, substrate characteristics, tidal inundation, and hydrological conditions, were used to characterize site conditions. These characteristics were subsequently compared with the ecological requirements and habitat preferences of candidate mangrove species through a species–site matching assessment. Species were considered suitable when their ecological characteristics were compatible with the major environmental conditions of the rehabilitation site. This assessment was based on descriptive ecological evaluation and did not apply a numerical weighting or quantitative ranking system.

The results of the site assessment and species–site matching were then used to develop planting configurations appropriate to local environmental conditions. The selected planting configurations and spacing arrangements were subsequently used to calculate seedling requirements for the 20-ha priority rehabilitation area. The total seedling requirement was then used as the basis for estimating initial rehabilitation costs under two seedling provision scenarios: independent nursery production and procurement of ready-to-plant seedlings.

This integrated analysis links ecological suitability with operational and economic considerations to provide a site-specific basis for mangrove rehabilitation planning. The cost estimates represent the initial implementation stage and do not include long-term maintenance, replacement planting, or monitoring costs.



Figure 3. Integrated analytical framework for site-specific mangrove rehabilitation planning in the Muara Sekampung Protected Forest

Result and Discussion

Species–Site Matching Assessment

The biophysical conditions of the Muara Sekampung Protected Forest provided the basis for assessing the suitability of mangrove species for rehabilitation. Mangrove establishment is strongly influenced by the compatibility between species ecological requirements and local environmental conditions, particularly salinity, substrate characteristics, and tidal inundation (Gnanappazham et al., 2014; Haan, 1931; Kusmana et al., 2005; Watson, 1928). The observed biophysical conditions of the rehabilitation site are presented in Table 4.

Table 4. Biophysical Conditions of the Rehabilitation Site in the Muara Sekampung Protected Forest

Environmental parameter	Site condition	Data source
Water salinity	24.7 ± 0.52 ppt	Amanta (2026)
Soil salinity	5.0–10.5 ppt	Hafidhin et al. (2026)
Substrate	Muddy, dominated by clay textur	Hafidhin et al. (2026)
Tidal regime	Diurnal	Hafidhin et al. (2026)
Inundation depth	40–98 cm	Hafidhin et al. (2026)
Current velocity	0.18–0.53 m/s	Hafidhin et al. (2026)
Vegetation condition	No living mangrove vegetation or natural regeneration observed	Hafidhin et al. (2026)

The rehabilitation site was characterized by a muddy substrate dominated by clay texture and a diurnal tidal regime, with inundation depths ranging from 40 to 98 cm and current velocities of 0.18–0.53 m/s (Table 4). Water salinity was 24.7 ± 0.52 ppt (Amanta, 2026), whereas soil salinity ranged from 5.0 to 10.5 ppt (Hafidhin et al., 2026). In addition, no living mangrove vegetation or natural regeneration was observed within the rehabilitation area (Hafidhin et al., 2026).

These conditions indicate that species selection should consider the combined influence of salinity, substrate, and hydrological conditions rather than relying on a single environmental parameter. The absence of living mangrove vegetation and natural regeneration further indicates limited natural recovery at the selected rehabilitation site. Consequently, the selection of species was based on the compatibility between the measured site conditions and the documented ecological characteristics of candidate mangrove species.

The comparison between site conditions and species-specific ecological requirements identified seven mangrove species as ecologically suitable candidates for rehabilitation: Rhizophora mucronata, R. apiculata, R. stylosa, Avicennia marina, A. alba, Sonneratia caseolaris, and S. alba. The results of the species–site matching assessment are presented in Table 5.

Table 5. Species–Site Suitability Matrix for Mangrove Rehabilitation in the Muara Sekampung Protected Forest

Species	Salinity (ppt)	Substrate	Site compatibility	Assessment
Rhizophora mucronata	10–30	Muddy	Compatible with salinity and substrate conditions	Suitable
Rhizophora apiculata	10–13	Deep mud	Compatible with substrate and tidal conditions	Suitable
Rhizophora stylosa	10–30	Sandy mud	Compatible with salinity and tidal conditions	Suitable
Avicennia marina	10–30*	Deep mud	Compatible with site conditions	Suitable
Avicennia alba	10–30*	Deep mud	Compatible with site conditions	Suitable
Sonneratia caseolaris	10–13	Clay and sandy mud	Suitable for appropriate microsites	Suitable
Sonneratia alba	10–13	Clay and sandy mud	Compatible with substrate and tidal conditions	Suitable

The results presented in Table 5 represent a descriptive ecological assessment and should not be interpreted as a quantitative ranking of species performance. No numerical weighting or composite suitability index was applied. Therefore, the identification of the seven species as suitable indicates their ecological compatibility with the prevailing site conditions, while their allocation within the rehabilitation area should consider local variation in hydrological and substrate conditions.

The muddy substrate dominated by clay is an important consideration for mangrove establishment. Fine-textured substrates generally retain water and organic materials but may experience limited soil aeration under prolonged inundation. Mangrove species possess specialized morphological and physiological adaptations that enable them to survive and establish under waterlogged and oxygen-limited conditions (Ayu et al., 2023; Dookie et al., 2024; Nguyen et al., 2023). Therefore, substrate compatibility was considered together with salinity and hydrological conditions in the species–site assessment.

Tidal inundation is another important factor influencing mangrove distribution and establishment. Differences in tidal frequency, inundation depth, and hydrodynamic conditions affect sediment deposition, propagule retention, salinity gradients, and soil aeration, which collectively influence the distribution of mangrove species (Watson, 1928; de Haan, 1931; Kusmana et al., 2005; Gnanappazham & Selvam, 2014). The diurnal tidal regime and inundation depths of 40–98 cm observed at the study site therefore provided an important ecological context for interpreting species compatibility and their potential allocation under different local site conditions.

Among the recommended species, *Rhizophora apiculata* and *R. mucronata* showed strong ecological compatibility with the muddy substrate and tidal conditions of the rehabilitation area. *R. apiculata*, in particular, is commonly associated with muddy environments and tidal conditions. Its stilt-root system

provides mechanical support in soft substrates and can contribute to sediment retention during the early stages of establishment. However, this interpretation does not represent a quantitative ranking of *R. apiculata* over the other recommended species.

Previous studies have also emphasized the importance of matching mangrove species with local environmental conditions to support successful establishment. Basyuni et al. (2019) reported successful establishment of mangrove seedlings under suitable environmental conditions, while Usman et al. (2022) highlighted the importance of matching planted species with local site characteristics to support rehabilitation success. Seedling quality is also an important consideration because successful establishment depends on the capacity of seedlings to adapt to field conditions following planting (Basyuni et al., 2019).

Overall, the species–site matching assessment identified seven mangrove species that are ecologically compatible with the prevailing environmental conditions of the Muara Sekampung rehabilitation area. These findings provide the ecological basis for the subsequent development of the proposed planting design. The recommended species should not be interpreted as requiring uniform planting across the entire 20-ha rehabilitation area; instead, species composition and planting arrangements should remain responsive to local variation in substrate and hydrological conditions.

Planting Design

The planting design was developed based on the results of the species–site matching assessment and the biophysical characteristics of the rehabilitation area. The proposed design considered substrate conditions, tidal inundation, and hydrodynamic exposure to translate the ecological assessment into an operational rehabilitation strategy. This approach is important because planting techniques that are not adapted to local site conditions may reduce seedling survival and limit the effectiveness of mangrove rehabilitation efforts (Gorman et al., 2022).

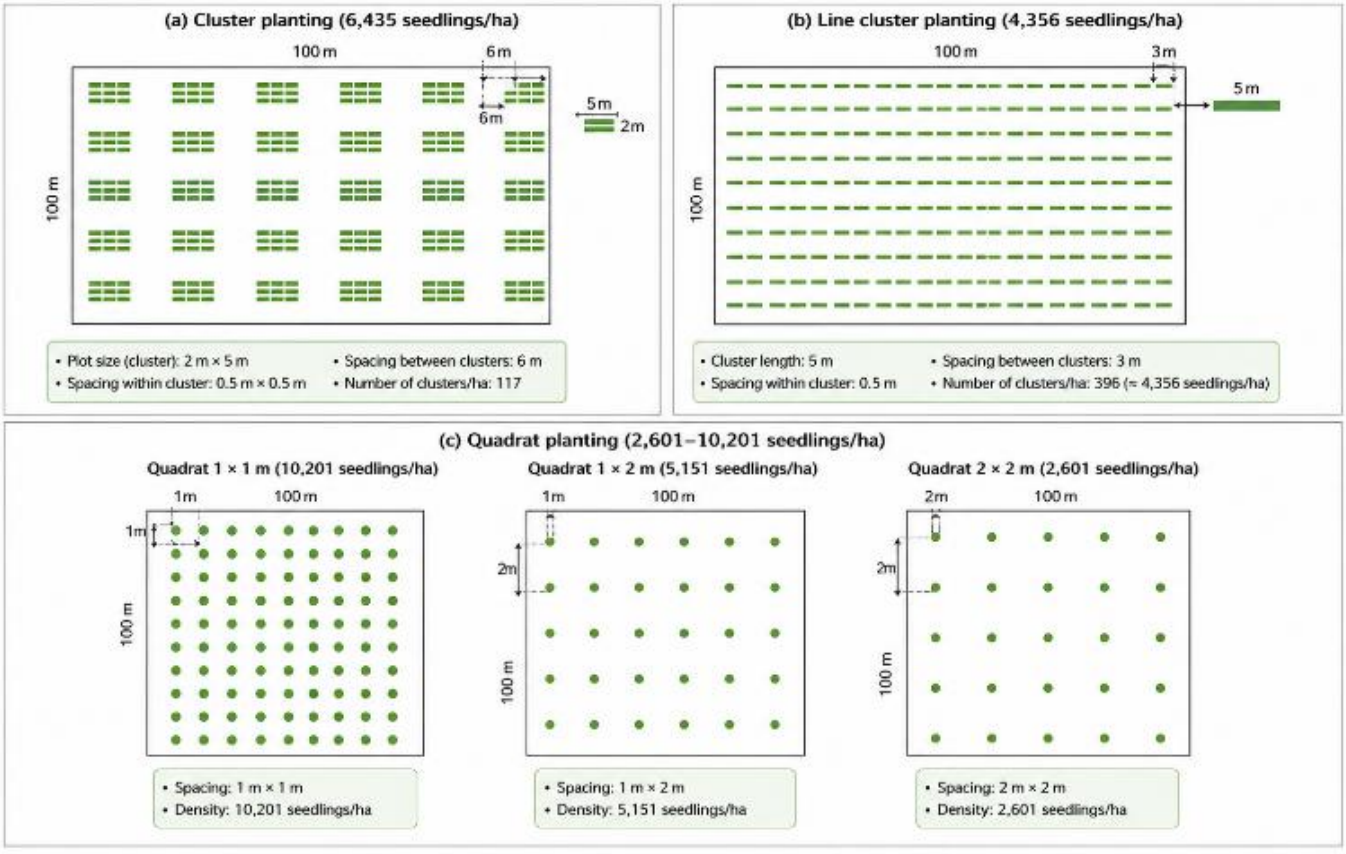

Figure 4. Mangrove planting design patterns

The rehabilitation area was characterized by a muddy substrate dominated by clay texture, a diurnal tidal regime, inundation depths ranging from 40 to 98 cm, and current velocities of 0.18–0.53 m/s (Hafidhin et al., 2026). These conditions indicate environmental variation within the 20-ha priority rehabilitation area, suggesting that a single planting configuration may not be appropriate for the entire site.

Based on these site characteristics, five planting configurations were proposed, comprising cluster

planting, line cluster planting, and three quadrat planting arrangements with different spacing. Cluster planting was allocated to 16 ha, whereas line cluster planting, quadrat planting with 1 × 1 m spacing, quadrat planting with 1 × 2 m spacing, and quadrat planting with 2 × 2 m spacing were each allocated to 1 ha. The proposed planting layouts are presented in Figure 4.

Cluster planting was the dominant configuration, covering 16 ha of the priority rehabilitation area. Each cluster measured 2 m × 5 m, with seedlings planted at 0.5 m × 0.5 m within the cluster and approximately 6 m between clusters. Each cluster contained 55 seedlings, with approximately 117 clusters per hectare, resulting in an estimated planting density of 6,435 seedlings ha^{-1}.

This configuration was proposed for areas requiring greater protection during the early establishment stage, particularly where soft and muddy substrates and water movement may affect seedling stability. Grouped vegetation can modify local hydrodynamic conditions, promote sediment deposition, and create more favorable microsite conditions for seedling establishment (Willemsen et al., 2016; Yang et al., 2025). Clustered planting may therefore provide a practical spatial arrangement for environmentally challenging rehabilitation sites (Peny et al., 2025).

Line cluster planting was proposed for 1 ha of the rehabilitation area, particularly in areas where local water movement or site morphology favored an elongated planting arrangement. The arrangement of planting clusters in lines was intended to maintain water exchange while providing localized protection and supporting sediment retention. Discontinuous vegetation arrangements can create sheltered areas that promote sediment accumulation and substrate stabilization (Willemsen et al., 2016; Yang et al., 2025).

Quadrat planting was proposed for three separate 1-ha areas using spacing arrangements of 1 × 1 m, 1 × 2 m, and 2 × 2 m. These arrangements resulted in theoretical planting densities of 10,000, 5,000, and 2,500 seedlings ha^{-1}, respectively. The different spacing arrangements were included to accommodate variation in local site conditions and operational requirements. Denser arrangements provide greater initial vegetation coverage, whereas wider spacing provides greater growing space for individual seedlings (Kusmana, 2015; Amanta, 2025).

To clarify the relationship between site conditions and the proposed planting configurations, the main decision considerations are summarized in Table 6. The matrix does not establish fixed quantitative thresholds but presents the environmental and operational considerations used to guide the selection of each planting approach.

Table 6. Decision Matrix Linking Site Conditions with Proposed Planting Configurations for Mangrove Rehabilitation

Site condition	Main consideration	Proposed planting configuration
Soft, muddy substrate and areas requiring greater protection during seedling establishment	Substrate stability and early seedling protection	Cluster planting
Areas influenced by concentrated water movement or elongated site features	Hydrodynamic exposure and sediment retention	Line cluster planting
Relatively stable areas suitable for regular planting arrangements	Uniform establishment and site accessibility	Quadrat planting
Areas requiring high initial planting density	Greater initial vegetation coverage	Quadrat planting (1 × 1 m)
Areas requiring moderate planting density	Balance between site coverage and growing space	Quadrat planting (1 × 2 m)
Areas with greater available growing space	Wider spacing and lower planting density	Quadrat planting (2 × 2 m)

The proposed planting configurations were subsequently used to determine planting density and seedling requirements, thereby linking the ecological assessment with the cost estimation. The species–site matching assessment provided the basis for identifying ecologically suitable species, while the planting configurations determined the spatial arrangement and number of seedlings required for the 20-ha rehabilitation area.

Overall, the proposed planting design represents a site-adapted planning approach rather than a uniform planting prescription. By incorporating variation in substrate conditions, inundation, and hydrodynamic exposure, the design provides an operational basis for calculating seedling requirements and estimating the initial costs of rehabilitation. As the proposed configurations have not yet been implemented or evaluated in the field, their ecological effectiveness and seedling survival require further validation through post-planting monitoring.

The proposed planting configurations were subsequently used to determine planting density and seedling requirements, thereby linking the ecological assessment with the cost estimation. The species–site matching assessment provided the basis for identifying ecologically suitable species, while the planting

configurations determined the spatial arrangement and number of seedlings required for the 20-ha rehabilitation area.

Overall, the proposed planting design represents a site-adapted planning approach rather than a uniform planting prescription. By incorporating variation in substrate conditions, inundation, and hydrodynamic exposure, the design provides an operational basis for calculating seedling requirements and estimating the initial costs of rehabilitation. As the proposed configurations have not yet been implemented or evaluated in the field, their ecological effectiveness and seedling survival require further validation through post-planting monitoring.

Rehabilitation Cost Estimation

The cost estimation was developed as the final operational component of the proposed rehabilitation planning framework. It was based on the seedling requirements derived from the proposed planting designs and, therefore, reflects the ecological and operational considerations identified through the species–site matching and planting design assessments. The analysis focused on two main components: seedling provision and initial planting activities (P-0). These components represent the primary financial requirements during the establishment phase of mangrove rehabilitation.

The cost estimates presented in this study represent the financial requirements for the initial rehabilitation stage and should not be interpreted as the total long-term cost of ecosystem restoration. Post-planting activities, including long-term maintenance, monitoring, protection, and replacement planting, were not included in the present calculation. This distinction is important because long-term rehabilitation success depends on sustained management beyond the initial planting phase (Hai et al., 2020).

Cost information was obtained through in-depth interviews with the head of the Forest Farmer Group (Kelompok Tani Hutan, KTH) Mutiara Hijau 1 and was verified through local market surveys and official rehabilitation planning documents from the Mangrove RHL Program of BPDAS Way Seputih–Way Sekampung (2022). The cost calculation incorporated the required volumes and prevailing unit prices of the main operational components, including seedling provision, labor, supporting materials, and transportation.

Based on the proposed planting designs for the 20-ha priority rehabilitation area, the total seedling requirement was estimated at 125,269 seedlings. This requirement resulted from the application of multiple planting configurations, including cluster planting, line cluster planting, and three quadrat planting arrangements with different planting densities. The seedling requirement for each proposed planting configuration is presented in Table 7.

Table 7. Seedling Requirement Based on Proposed Planting Design

Planting Method	Area (ha)	Density (seedlings/ha)	Number of Seedlings
Cluster planting	16	6,435	102,960
Line cluster planting	1	4,356	4,356
Quadrat (1 × 1 m)	1	10,201	10,201
Quadrat (1 × 2 m)	1	5,151	5,151
Quadrat (2 × 2 m)	1	2,601	2,601
Total	20	–	125,269

Two alternative seedling provision scenarios were evaluated: a self-managed nursery and the procurement of ready-to-plant seedlings. Under the self-managed nursery scenario, the estimated seedling provision cost was IDR 184,295,900, equivalent to approximately IDR 1,472 per seedling. In contrast, the procurement of ready-to-plant seedlings required IDR 399,057,000, or approximately IDR 3,185 per seedling.

The difference between these scenarios indicates that the method of seedling provision is a major determinant of the initial rehabilitation budget. Local seedling production may reduce the costs associated with purchasing seedlings from external suppliers while providing opportunities for local labor involvement. In addition to its financial implications, the self-managed nursery approach can support community participation in rehabilitation activities (Damastuti et al., 2023). Community involvement has been recognized as an important factor in strengthening local ownership, knowledge transfer, and long-term commitment to rehabilitation activities.

The estimated cost of initial planting activities (P-0) was IDR 217,269,000. The major components included planting labor, bamboo stakes, and transportation. Planting activities required 900 person-days (HOK), while bamboo stakes were provided to support seedling stability under the soft substrate and tidal conditions identified during the site assessment. Previous studies have shown that bamboo-based support systems and other stabilization measures can contribute to sediment stability and create more favorable conditions for

seedling establishment in dynamic coastal environments (Hai et al., 2020; Liu et al., 2025).

The same planting cost was applied to both seedling provision scenarios because the rehabilitation area, proposed planting designs, seedling requirement, and initial field activities were assumed to be identical. Consequently, the difference between the two scenarios was primarily attributable to the method and cost of seedling provision.

The combined seedling provision and initial planting costs are presented in Table 8. The initial rehabilitation cost was estimated at IDR 401,564,900 under the self-managed nursery scenario and IDR 616,326,000 under the ready-to-plant seedling scenario. These estimates are equivalent to IDR 20,078,245 ha^{-1} and IDR 30,816,300 ha^{-1}, respectively, based on the 20-ha priority rehabilitation area.

Table 8. Comparison of Initial Mangrove Rehabilitation Cost Scenarios

Cost Component	Self-Managed Nursery (IDR)	Ready-to-Plant Seedlings (IDR)
Seedling provision	184,295,900	399,057,000
Initial planting cost (P-0)	217,269,000	217,269,000
Total initial rehabilitation cost	401,564,900	616,326,000
Cost per seedling (IDR/seedling)	3,205	4,920
Cost per hectare (IDR/ha)	20,078,245	30,816,300

The self-managed nursery scenario reduced the estimated initial rehabilitation cost by IDR 214,761,100 compared with the procurement of ready-to-plant seedlings. This difference highlights the potential financial advantage of locally based seedling production when sufficient time, labor, propagule availability, and nursery capacity are available. However, this option also requires advance planning because seedling production must begin sufficiently before field planting.

To facilitate comparison with rehabilitation programs using a common planting density, the estimated costs were standardized to 5,000 seedlings ha^{-1}. The standardized costs were approximately IDR 16,025,000 ha^{-1} for the self-managed nursery scenario and IDR 24,600,000 ha^{-1} for the ready-to-plant seedling scenario. These standardized estimates are compared with existing government rehabilitation cost benchmarks in Table 9.

Table 9. Comparison of Standardized Initial Rehabilitation Costs with Government Cost Benchmarks

Cost Standard	Planting Density (seedlings ha^{-1})	Cost (IDR ha^{-1})
Self-managed nursery	5,000	16,025,000
Ready-to-plant seedlings	5,000	24,600,000
HSPK PDASRH 2025	5,000	24,879,600
SK. 14 BRGM	5,000	46,875,000

The comparison shows that the standardized initial cost estimates, particularly under the self-managed nursery scenario, were lower than the cited government cost benchmarks. However, this comparison should be interpreted carefully because the estimates in this study are limited to seedling provision and initial planting activities and may not include the same scope of post-planting activities covered by other rehabilitation cost standards.

The cost estimates are based on prevailing local prices and the operational assumptions applied during the study. Changes in seedling prices, labor costs, transportation requirements, or the need for replacement planting may affect the final rehabilitation budget. A formal sensitivity analysis was not conducted; therefore, the estimates should be interpreted as baseline costs under the prevailing conditions and assumptions of the study. Future studies could assess the sensitivity of rehabilitation costs to changes in these key cost components.

Overall, the cost assessment provides the final operational link in the proposed rehabilitation planning framework. The species–site matching assessment identified ecologically suitable species, the proposed planting designs translated site conditions into planting arrangements and seedling requirements, and the cost estimation quantified the financial resources required for initial implementation. This sequential integration provides a transparent, site-specific basis for mangrove rehabilitation planning in the Muara Sekampung Protected Forest. Its long-term ecological and economic performance, however, requires further evaluation through post-planting monitoring, assessment of seedling survival, and consideration of long-term maintenance and replacement costs.

Conclusion

This study develops a site-specific mangrove rehabilitation planning framework for the Muara

Sekampung Protected Forest by integrating species–site matching, planting design, seedling requirements, and initial rehabilitation cost estimation. The framework translates biophysical site conditions into species recommendations and proposed planting configurations, providing a structured basis for linking ecological considerations with operational and financial planning. The findings also indicate that variations in substrate and hydrological conditions should be considered when developing rehabilitation strategies rather than applying a uniform planting approach across the entire rehabilitation area. By linking ecological suitability with planting arrangements, seedling requirements, and alternative seedling provision scenarios, the proposed framework provides practical support for rehabilitation planning and resource allocation. However, the findings should be interpreted within the scope of a planning assessment. This study did not evaluate post-planting seedling survival, long-term ecological recovery, or the full costs associated with maintenance, monitoring, and replacement planting. Therefore, the proposed framework provides a site-specific basis for rehabilitation planning but does not demonstrate the long-term ecological effectiveness of the recommended species or planting designs. Future research should validate the proposed planting configurations through field-based monitoring of seedling survival and growth, evaluate subsequent ecological recovery, and compare rehabilitation costs based on the number of seedlings that successfully survive and establish. Such evaluations would strengthen the evidence base for assessing the ecological and economic performance of site-specific mangrove rehabilitation strategies.

Acknowledgments

This research was funded by the FINCAPES (*Flood Impacts, Carbon Pricing, and Ecosystem Sustainability*) project, a collaborative program between the University of Waterloo and IPB University. The authors would like to express their sincere gratitude to all parties who contributed to the implementation of this study through fieldwork facilitation, technical assistance, and support in data collection, which greatly contributed to the successful completion of this research.

Author Contributions

All authors contributed to writing this article.

Funding

No external funding.

Conflicts of Interest

No conflict interest.

References

Agaton, C. B., & Collera, A. A. (2022). Now or later? Optimal timing of mangrove rehabilitation under climate change uncertainty. *Forest Ecology and Management*, *503*, 119739. https://doi.org/10.1016/j.foreco.2021.119739

Amanta, N. N. (2026). *Rehabilitasi hutan mangrove di kawasan pesisir Desa Purworejo, Pasir Sakti, Lampung Timur, Sumatera*. IPB University.

Ayu, S. M., Najib, N. N., Yumna, Y., Witno, W., Maria, M., Liana, L., Sada, N. H., & Pitra, P. (2023). Soil Physical Characteristics of The Mangrove Ecosystem in Bone Bay, Palopo City. *PLANTA TROPIKA*, *11*(2), 105–114. https://doi.org/10.18196/pt.v11i2.16646

Basyuni, M., Al Habib, A., Slamet, B., Sulistiyono, N., Putri, L. A. P., Bimantara, Y., Yusraini, E., & Lesmana, I. (2019). Assessment of one-year mangrove reforestation using Rhizophora apiculata seedlings in Lubuk Kertang village, North Sumatra. *IOP Conference Series: Earth and Environmental Science*, *260*(1), 012114. https://doi.org/10.1088/1755-1315/260/1/012114

Dahdouh-Guebas, F., Jayatissa, L. P., Di Nitto, D., Bosire, J. O., Lo Seen, D., & Koedam, N. (2005). How effective were mangroves as a defence against the recent tsunami? *Current Biology*, *15*(12), R443–R447. https://doi.org/10.1016/j.cub.2005.06.008

Damastuti, E., van Wesenbeeck, B. K., Leemans, R., de Groot, R. S., & Silvius, M. J. (2023). Effectiveness of community-based mangrove management for coastal protection: A case study from Central Java, Indonesia. *Ocean and Coastal Management*, *238*, 100202. https://doi.org/10.1016/j.ocecoaman.2023.106498

Dookie, S., Jaikishun, S., & Ansari, A. A. (2024). Soil and water relations in mangrove ecosystems in Guyana. *Geology, Ecology, and Landscapes*, *8*(3), 445–469. https://doi.org/10.1080/24749508.2022.2142186

Gedan, K. B., Kirwan, M. L., Wolanski, E., Barbier, E. B., & Silliman, B. R. (2011). The present and future role of coastal wetland vegetation in protecting shorelines: Answering recent challenges to the paradigm. *Climatic Change*, *106*(1), 7–29. https://doi.org/10.1007/s10584-010-0003-7

Gnanappazham, L., & Selvam, V. (2014). Response of mangroves to the change in tidal and fresh water flow – A case study in Pichavaram, South India. *Ocean & Coastal Management*, *102*, 131–138. https://doi.org/10.1016/j.ocecoaman.2014.09.004

Gorman, D., Vanderklift, M. A., & Lafratta, A. (2022). Quantitative Analysis of Methodological and Environmental Influences on Survival of Planted Mangroves in Restoration and Afforestation. *Forests*, *13*(3), 404.

https://doi.org/10.3390/f13030404

Grzyb, T., Kulczyk, S., Derek, M., & Woźniak, E. (2021). Using social media to assess recreation across urban green spaces in times of abrupt change. *Ecosystem Services*, *49*, 101297. https://doi.org/10.1016/j.ecoser.2021.101297

Haan, J. H. (1931). Het een en ander over de Tjilatjap'sche vloedbosschen. *Tectona*, *24*, 39–76.

Hafidhin, D., Kusmana, C., & Rusdiana, O. (2026). Penentuan areal potensial dan evaluasi kondisi biofisik sebagai dasar rehabilitasi mangrove di Hutan Lindung Muara Sekampung. *Jurnal Silvikultur Tropika*, *17*(2), 123–135. https://doi.org/10.29244/j-siltrop.17.02

Hai, N. T., Dell, B., Phuong, V. T., & Harper, R. J. (2020). Towards a more robust approach for the restoration of mangroves in Vietnam. *Annals of Forest Science*, *77*(1), 18. https://doi.org/10.1007/s13595-020-0921-0

Hashim, R., Kamali, B., Tamin, N. M., & Zakaria, R. (2010). An integrated approach to coastal rehabilitation: Mangrove restoration in Sungai Haji Dorani, Malaysia. *Estuarine, Coastal and Shelf Science*, *86*(1), 118–124. https://doi.org/10.1016/j.ecss.2009.10.021

Imchen, M., Kumavath, R., Barh, D., Vaz, A., Góes-Neto, A., Tiwari, S., Ghosh, P., Wattam, A. R., & Azevedo, V. (2018). Comparative mangrove metagenome reveals global prevalence of heavy metals and antibiotic resistome across different ecosystems. *Scientific Reports*, *8*(1), 11187. https://doi.org/10.1038/s41598-018-29521-4

Kusmana, C. (2014). Distribution and Current Status of Mangrove Forests in Indonesia. In *Mangrove Ecosystems of Asia* (pp. 37–60). Springer New York. https://doi.org/10.1007/978-1-4614-8582-7_3

Kusmana, C., & Chaniago, Z. A. (2017). Kesesuaian Lahan Jenis Pohon Mangrove Di Bulaksetra, Pangandaran Jawa Barat Land Suitability Mangrove Trees Species in Bulaksetra, Pangandaran West Java. *Journal of Tropical Silviculture*, *8*(1), 48–54. https://doi.org/10.29244/j-siltrop.8.1.48-54

Kusmana, C., Istomo, & Purwanegara, T. (2010). *Manual teknik budidaya mangrove*. Institut Pertanian Bogor.

Kusmana, C., Istomo, W., C., B., S., S., I., T., T., & Sukarjo, S. (2008). *Manual silvikultur mangrove di Indonesia*. Korea International Cooperation Agency.

Kusmana, C., & Onrizal, O. (1998). Evaluasi Kerusakan Kawasan Mangrove dan Arahan Teknik Rehabilitasinya di Pulau Jawa. In *Lokakarya Pembentukan Jar. Kerja Pelestari Mangrove*. Lokakarya Pembentukan Jaringan Kerja Pelestari Mangrove.

Kusmana, C., Wilarso, S., Hilwan, I., Pamoengkas, P., Wibowo, C., Tiryana, T., Triswanto, A., Yunasfi, & Hamzah. (2005). *Teknik rehabilitasi mangrove*. Fakultas Kehutanan Institut Pertanian Bogor.

Lee, J. S. H., Abood, S., Ghazoul, J., Barus, B., Obidzinski, K., & Koh, L. P. (2014). Environmental Impacts of Large-Scale Oil Palm Enterprises Exceed that of Smallholdings in Indonesia. *Conservation Letters*, *7*(1), 25–33. https://doi.org/10.1111/conl.12039

Lewis, R. R. (2005). Ecological engineering for successful management and restoration of mangrove forests. *Ecological Engineering*, *24*(4), 403–418. https://doi.org/10.1016/j.ecoleng.2004.10.003

Liu, Q., Liu, X., Zhu, X., Hou, P., Deng, C., Gao, H., Wang, Q., Zheng, C., & Guo, H. (2025). Experimental study on the restoration and protection of mangrove tidal ecosystems flat located in a high wave area. *Estuarine, Coastal and Shelf Science*, *323*, 109386. https://doi.org/10.1016/j.ecss.2025.109386

Nguyen, L. T. M., Hoang, H. T., Choi, E., & Park, P. S. (2023). Distribution of mangroves with different aerial root morphologies at accretion and erosion sites in Ca Mau Province, Vietnam. *Estuarine, Coastal and Shelf Science*, *287*, 108324. https://doi.org/10.1016/j.ecss.2023.108324

Ofori, S. A., Asante, F., Boatemaa Boateng, T. A., & Dahdouh-Guebas, F. (2023). The composition, distribution, and socio-economic dimensions of Ghana's mangrove ecosystems. *Journal of Environmental Management*, *345*, 118622. https://doi.org/10.1016/j.jenvman.2023.118622

Peny, M. N., Rehatta, B. M., Merryanto, Y., Tisera, W. L., & Anakotta, A. R. F. (2025). Pengaruh Kerapatan Mangrove Terhadap Laju Transpor Sedimen di Kawasan Ekowisata Mangrove Oesapa Barat, Kota Kupang. *Journal of Marine Research*, *14*(1), 105–116. https://doi.org/10.14710/jmr.v14i1.46781

Rahadian, A., Kusmana, C., Setiawan, Y., & Prasetyo, L. B. (2022). Adaptive Mangrove Ecosystem Rehabilitation Plan based on Coastal Typology and Ecological Dynamics Approach. *HAYATI Journal of Biosciences*, *29*(4), 445–458. https://doi.org/10.4308/hjb.29.4.445-458

Sidik, F., Lawrence, A., Wagey, T., Zamzani, F., & Lovelock, C. E. (2023). Blue carbon: A new paradigm of mangrove conservation and management in Indonesia. *Marine Policy*, *147*, 105388. https://doi.org/10.1016/j.marpol.2022.105388

Usman, A. H. A., Hartoyo, A. P. P., & Kusmana, C. (2022). The growth performance of Rhizophora apiculata using the cut-propagule method for mangrove rehabilitation in Indonesia. *Biodiversitas Journal of Biological Diversity*, *23*(12), 6366–6378. https://doi.org/10.13057/biodiv/d231234

Watson, R. A. (1928). *Tidal classification and coastal processes*. Admiralty Hydrographic Office.

Willemsen, P. W. J. M., Horstman, E. M., Borsje, B. W., Friess, D. A., & Dohmen-Janssen, C. M. (2016). Sensitivity of the sediment trapping capacity of an estuarine mangrove forest. *Geomorphology*, *273*, 189–201. https://doi.org/10.1016/j.geomorph.2016.07.038

Yang, L., Ai, Y., Huai, W., & Yang, Z. (2025). Experimental study on the spatial traits of sedimentation driven by discontinuous nearshore vegetation patches. *Journal of Hydrology*, *653*, 132745. https://doi.org/10.1016/j.jhydrol.2025.132745

Yusuf, D. N., Prasetyo, L. B., Kusmana, C., & Machfud. (2017). Geospatial approach in determining anthropogenic factors contributed to deforestation of mangrove: A case study in Konawe Selatan, Southeast Sulawesi. *IOP Conference Series: Earth and Environmental Science*, *54*(1), 012049. https://doi.org/10.1088/1755-1315/54/1/012049