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Research Article

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Potensi Spesies Mangrove Untuk Perlindungan Pesisir Mentawai Dan Sumatra Dari Ancaman Megathrust: Tinjauan Sistematis

Potential Of Mangrove Species For Protecting Mentawai And Sumatra Coasts From Megathrust Hazards: A Systematic Review

Ahmad Taufiq[1)] & Alponsin[2)]*

1) *Plant Systematics Laboratory, Department of Biology, Faculty of Mathematics and Natural Sciences, Universitas Andalas, Padang 26251, Indonesia*
2) *Identika Bio Indonesia (IBI), Batusangkar, West Sumatra 27211, Indonesia*

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*)CORRESPONDENCE

email: ahmadtaufiq@sci.unand.ac.id

ABSTRACT

Coastal communities of Mentawai and western Sumatra face recurrent tsunami and erosion hazards associated with the Sunda megathrust. This systematic review evaluated mangrove taxa with evidence relevant to coastal protection. A semantic search in Elicit, covering Semantic Scholar and OpenAlex, identified 1,000 records. Screening followed PRISMA 2020: 993 records were excluded at the title/abstract stage, seven reports were sought, four full texts were assessed, and two studies met the eligibility criteria. Data were synthesized narratively because of heterogeneity in location, threat, and outcome metrics. A post-tsunami field survey from Sri Lanka reported that mature *Rhizophora*, *Sonneratia*, and *Bruguiera* stands resisted extreme hydrodynamic forces, with no adult true-mangrove trees uprooted. An Indonesian study from Bengkalis Island found the greatest wave-reduction factor for *Nypa fruticans* (0.0081-0.0087 m^{-1} at a 6-s period), followed by red mangrove, whereas *Avicennia marina* performed least effectively and had high offshore mortality. The evidence indicates complementary functions rather than a single universally superior species. *Rhizophora* spp. appear suitable for structurally exposed fringes, while *N. fruticans* may strengthen estuarine and landward zones through wave attenuation, sediment trapping, and rapid recovery. However, only two heterogeneous studies were included, neither conducted in Mentawai; local hydrodynamic modeling and field trials are required before implementation.

INTRODUCTION

Mentawai and the western coast of Sumatra are situated adjacent to the Mentawai segment of the Sumatran megathrust, an area with substantial earthquake and tsunami hazard. The exposure of small islands, low-lying settlements, estuaries, and eroding shorelines creates a need for layered risk-reduction measures that combine warning and evacuation systems, engineered structures, spatial planning, and ecosystem-based protection (Megawati and Pan, 2009).

Mangrove forests can reduce hydrodynamic energy by increasing bed roughness, creating drag through stems and roots, and stabilizing sediment. Their protective performance is not determined by forest presence alone. Species, stem diameter, root architecture, stand density, forest width, water depth, and incident wave characteristics jointly influence attenuation (Hashim et al., 2013; Kamil et al., 2021). Consequently, restoration that prioritizes rapid planting without considering local geomorphology and species-specific traits may produce weak or short-lived protection.

Post-disaster observations have shown that mature, structurally complex mangrove stands may withstand extreme wave forces better than degraded stands. In Sri Lanka, the 2004 Indian Ocean tsunami caused greater damage where mangrove vegetation had undergone cryptic ecological degradation, whereas adult trees of several true-mangrove genera remained standing in healthier forests (Dahdouh-Guebas et al., 2005). Species-level evidence from Indonesia is more limited. A study on Bengkalis Island compared three mangrove types and reported different erosion-reduction and survival performances among them (Basir et al., 2024).

The available evidence therefore raises two related questions: which species possess structural traits associated with resistance to acute tsunami loading, and which species are more effective for chronic wave attenuation and

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sediment stabilization? These functions may not be maximized by the same taxon or the same position within a coastal forest.

This systematic review aimed to identify and synthesize species-specific evidence relevant to mangrove-based coastal protection for Mentawai and Sumatra, compare structural mechanisms, wave-reduction performance, tolerance, and recovery, and formulate cautious recommendations for zoned, multi-species coastal management.

RESEARCH METHODOLOGY

Review Design And Reporting

The review was organized according to the PRISMA 2020 reporting framework (Page et al., 2021). It was designed as a systematic qualitative synthesis because the eligible studies differed in geographic setting, hazard type, design, and outcome metrics. No preregistered protocol or registration number was reported in the original Elicit export.

Information Sources And Search Strategy

A semantic search was conducted with Elicit, which searched literature indexed through Semantic Scholar and OpenAlex. The exported report was generated on 26 July 2026 and returned 1,000 records from a search corpus described by Elicit as exceeding 138 million academic papers. The query was standardized in this manuscript as: “What mangrove species could best protect Mentawai and Sumatra from megathrust threats?” The original export contained a spelling error in the word “megathrust.” Duplicate removal was not reported; therefore, the 1,000 ranked records were treated as the screening set.

Eligibility Criteria

Studies were eligible when they: (1) examined protection against tsunamis, storm surges, waves, or coastal erosion; (2) were conducted in Mentawai, Sumatra, Indonesia, or evaluated mangrove taxa relevant to Indonesian waters; (3) investigated species-specific structures, distribution, tolerance, or performance; (4) reported quantitative protection outcomes or direct post-disturbance observations; and (5) presented primary research or a systematic analysis with usable data. Studies focused only on general ecology, restoration procedures without performance evaluation, opinion pieces, editorials, or records without retrievable full text were excluded.

Study Selection

All 1,000 records were screened at the title and abstract level using the eligibility criteria. Seven reports were sought for full-text assessment. Three reports could not be retrieved, four were assessed for eligibility, two were excluded because they did not satisfy environmental-tolerance or quantitative-protection requirements, and two studies were included in the qualitative synthesis. The selection process is summarized in Figure 1.

Data Extraction And Synthesis

Elicit was used for initial structured extraction. The fields comprised mangrove species, classification, distribution, root and stem structures, forest characteristics, threat type, quantitative wave or erosion outcomes, survival, environmental tolerance, recovery, geographic context, and comparative effectiveness. The extracted fields were checked for internal consistency against the report and reorganized into study-level and species-level evidence tables. A meta-analysis was not performed because only two heterogeneous studies were eligible and they did not report commensurable effect measures.

Risk Of Bias And Evidence Certainty

The source export did not contain item-level critical appraisal using a validated risk-of-bias instrument. Therefore, no formal pooled risk-of-bias judgment or certainty grade was assigned. Interpretation instead considered study design, directness to Mentawai and Sumatra, outcome quantification, taxonomic clarity, and transferability. This limitation is reported explicitly to avoid overstating the strength of the evidence.

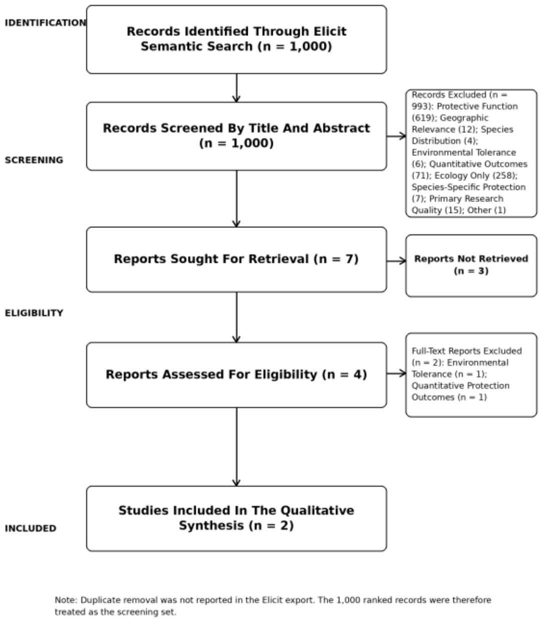

Figure 1. PRISMA 2020 Flow Diagram For Study Identification, Screening, Eligibility, And Inclusion.

RESULTS AND DISCUSSION

Study Selection And Characteristics

The screening process reduced 1,000 records to two eligible studies. The large reduction primarily reflected the exclusion of studies that did not evaluate protective functions or focused only on general ecology. The final evidence base comprised one post-tsunami field survey and one experimental-observational coastal erosion study (Table 1).

The studies were complementary but not directly comparable. The Sri Lankan survey captured ecological response to an extreme, short-duration tsunami, whereas the Bengkalis study measured chronic wave and erosion processes. The Indonesian study was geographically more relevant to Sumatra, but neither study was conducted in the Mentawai Islands. Thus, the synthesis supports functional hypotheses and management priorities rather than a definitive species ranking for Mentawai.

Table 1. Characteristics of The Included Studies.

Study	Design	Location	Hazard	Taxa Examined	Main Contribution
Dahdouh-Guebas et al. (2005)	Post-tsunami field survey	24 lagoons and estuaries along southern Sri Lanka	2004 Indian Ocean tsunami and storm surge	*Rhizophora spp.*; *Sonneratia spp.*; *Bruguiera spp.*; *Excoecaria agallocha*; *Avicennia marina*; *Nypa fruticans*	Direct observations of survival, structural resistance, forest condition, and post-tsunami recovery
Basir et al. (2024)	Experimental/observational coastal study	Northern Bengkalis Island, Riau, Indonesia	Chronic wave action and coastal erosion	Red mangrove; gray mangrove (*Avicennia marina*); mangrove palm (*Nypa fruticans*)	Species-level comparison of wave-reduction factors, erosion reduction, and field survival

Species Characteristics And Protective Mechanisms

Rhizophora spp. were the most consistently supported taxa for structural resistance. Their stilt or prop-root networks increase frontal area and create a dense near-bed barrier that can dissipate flow and anchor trees. In the post-tsunami survey, adult *Rhizophora* trees remained standing, indicating strong resistance under acute loading (Dahdouh-Guebas et al., 2005). However, resistance of individual trees should not be equated with complete protection of settlements; forest width, density, continuity, bathymetry, and tsunami characteristics remain decisive.

Sonneratia spp. and *Bruguiera* spp. also remained standing after the tsunami. *Sonneratia* was associated with large stem circumference, while *Bruguiera* was associated with broad knee-root systems. These traits suggest complementary mechanical functions: large stems can resist bending and impact, whereas knee roots can increase anchoring and near-bed drag (Dahdouh-Guebas et al., 2005).

Nypa fruticans differed structurally from upright mangrove trees. Its creeping rhizome and long fibrous roots can stabilize sediment and maintain below-ground continuity even when leaves are damaged. The Sri Lankan observations reported new leaf emergence within approximately one month after the tsunami, while the Bengkalis study described root lengths reaching 13 m and strong erosion-reduction performance (Dahdouh-Guebas et al., 2005; Basir et al., 2024). This combination indicates high recovery potential in estuarine and landward environments.

Table 2. Comparative Species Evidence And Implications For Coastal Protection.

Taxon	Structural Basis	Evidence From Included Studies	Interpretation For Mentawai/Sumatra
Rhizophora spp.	Dense prop/stilt roots; strong anchorage; high near-bed drag	No adult trees reported uprooted after the 2004 tsunami; ranked above gray mangrove for erosion reduction	Promising for exposed seaward or mid-intertidal belts where local substrate and hydrology support establishment
Sonneratia spp.	Large stem circumference; robust trunk structure	Adult trees remained standing during the tsunami survey	Potential complementary component where salinity, inundation, and substrate are suitable; evidence is not quantitatively ranked
Bruguiera spp.	Broad knee-root system and anchorage	Adult trees remained standing during the tsunami survey	Potential for mixed stands in less exposed zones; direct quantitative attenuation data remain absent
Nypa fruticans	Creeping rhizome; long fibrous roots; dense fronds; rapid vegetative recovery	Highest reported wave-reduction factor: 0.0081-0.0087 m^{-1} at a 6-s wave period; new leaves emerged within one month after tsunami damage	Strong candidate for estuarine, creek-margin, and landward zones; not necessarily appropriate for high-energy open-coast frontage
Avicennia marina	Fast growth; tolerance of salinity and aridity	Weakest erosion-reduction performance among the three Bengkalis mangrove types; high mortality near offshore areas	More suitable as a supporting or secondary-zone species than as the sole frontline defense
Excoecaria agallocha	Structural traits not adequately reported	Some isolated trees were uprooted in the post-tsunami survey	Evidence is insufficient for species-specific protective recommendations

Taxonomic note: Basir et al. (2024) used the name *Rhizophora mangle* for “red mangrove.” Plants of the World Online places the native range of *R. mangle* outside the Indo-Pacific; therefore, the species identity should be verified before transferring the finding to Indonesian restoration practice (Royal Botanic Gardens, Kew, 2026).

Comparative Wave Protection And Erosion Reduction

The post-tsunami evidence suggests that healthy forests dominated by characteristic mangrove taxa provide greater resistance than ecologically degraded forests. The waterward fringe absorbed the greatest force and sustained damage, but mature true-mangrove trees were not uprooted. This finding emphasizes forest quality and structural continuity rather than area alone. A mapped mangrove polygon can appear intact while species replacement, fragmentation, or reduced stem density weakens its protective function (Dahdouh-Guebas et al., 2005).

The Bengkalis study provided the only quantitative comparison. *Nypa fruticans* had wave-reduction factors of 0.0081-0.0087 m^{-1} at a 6-s wave period and 0.0077-0.0085 m^{-1} at an 8-s period. It was ranked as the most effective of the three mangrove types for reducing erosion. Red mangrove ranked above gray mangrove, whereas *Avicennia marina* showed the weakest reduction and high mortality near offshore positions (Basir et al., 2024).

These findings should not be interpreted as proof that *Nypa fruticans* is universally superior to *Rhizophora* spp. The two taxa were evaluated under different hazards and structural contexts. Tsunami resistance involves extreme, transient loading, impact by debris, and possible inundation far beyond ordinary tides. Chronic erosion involves repeated lower-energy waves, tidal currents, and sediment transport. A rigid prop-rooted tree belt may perform strongly under acute loading, while rhizomatous *Nypa* stands may excel in sustained sediment trapping and recovery.

Implications For A Zoned Multi-Species Strategy

The most defensible management implication is a zoned, multi-species approach. *Rhizophora spp*. may provide structural resistance in suitable seaward and middle intertidal settings, provided planting does not ignore natural zonation, elevation, sediment, and tidal exchange. *Sonneratia spp.* and *Bruguiera spp.* could diversify stand architecture and reduce reliance on a single taxon. *Nypa fruticans* may be particularly valuable in estuaries, tidal creeks, sheltered bays, and landward zones where its rhizome network can stabilize sediment and facilitate rapid recovery.

Avicennia marina should not be dismissed, because its tolerance and colonizing ability can be useful in restoration. Nevertheless, the evidence reviewed here does not support using it as the sole frontline species for the most exposed sites. Species selection should follow local reference ecosystems and hydrodynamic conditions rather than a generalized planting target.

Mangroves should also be treated as one element of risk reduction, not as a substitute for evacuation planning, early warning, setback regulation, or engineered protection in densely populated areas. The protective value of a belt will vary with forest width, density, maturity, topography, bathymetry, and event magnitude. Local modeling is therefore essential before assigning design-level protection claims.

Limitations And Research Priorities

The evidence base was very small: only two studies met the eligibility criteria, the studies used different designs and outcomes, and neither was conducted in Mentawai. One study was a preliminary post-tsunami survey and did not quantify wave-height reduction by species. The Bengkalis study offered quantitative wave-reduction factors but focused on chronic erosion rather than tsunami loading. A formal risk-of-bias assessment and certainty grading were unavailable from the source export. In addition, the taxonomic label used for red mangrove in the Bengkalis paper requires verification.

Future research should combine field inventories, species verification, high-resolution elevation and bathymetry data, hydrodynamic modeling, and controlled measurements of attenuation across natural and restored stands in Mentawai. Priority variables include root frontal area, stem density, forest width, age structure, sediment stability, wave period, water depth, deris loading, survival, and recovery. Comparative trials should evaluate locally occurring *Rhizophora*, *Sonneratia*, *Bruguiera*, Avicennia, and Nypa communities rather than importing a single-species prescription.

CONCLUSION

The available evidence does not identify one universally superior mangrove species for all megathrust-related coastal hazards. *Rhizophora spp.* have the strongest direct evidence of structural resistance to extreme tsunami forces, supported by prop-root architecture and survival of mature trees. *Nypa fruticans* has the strongest quantitative evidence for chronic wave and erosion reduction in the Indonesian study and demonstrated rapid post-tsunami recovery. *Sonneratia spp.* and *Bruguiera spp.* may provide complementary structural diversity, whereas *Avicennia marina* appears less suitable as the sole frontline species in highly exposed settings.

For Mentawai and western Sumatra, a zoned multi-species strategy is more scientifically defensible than a single-species recommendation. However, this conclusion is provisional because it is based on only two heterogeneous studies and no direct Mentawai field evidence. Local taxonomic verification, hydrodynamic modeling, ecological suitability assessment, and long-term monitoring are required before operational implementation.

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