



COASTAL ENGINEERING USING *RHIZOPHORA SP.* MANGROVE NATURAL STRUCTURE FOR WAVE DAMPING

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Abstract

The purpose of the study is to analyze the value of wave damping by the thickness, density, and resilience of the supporting roots of *Rhizophora sp.* mangrove as a wave damper. The method used in the study is the transect-squared method and laboratory tests. Wave measurements were done using SBE 26 during the highest waves. The value of ΔE (%) at Dewi Mandapa Beach risen from 10.74% to 92.79% at a thickness of 5 meters to 50 meters, while at Tanjung Putus Beach risen from 26.23% to 92.41% at a thickness of 5 meters to 30 meters. It is stated that the relationship between them is directly proportional. The root resilience value decreased from 3.1331 (J/m²) to 2.4059 (J/m²), while the energy damping value increased from 3.7578E-04 (J/m²) to 5.5943E-04 (J/m²) at a thickness of 5 meters to 30 meters. It is stated that the relationship of root resilience with wave energy attenuation is inversely proportional. It is concluded that high-density *Rhizophora sp.* mangroves have substantial wave damping ability as a result of the bounciness of the supporting roots.

Keywords: Tanjung Putus Beach, Dewi Mandapa Beach, thickness, density, abrasion barrier

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INTRODUCTION

Mangrove forest is an individual or community type of biome in the intertidal zone that naturally functions as a wave damper and abrasion barrier (Wang, Jia, & Tian, 2019; Friess et al., 2019; Krauss and Osland, 2020). There are various types of mangroves such as *Sonneratia* mangrove, *Avicennia marina* mangrove, *Rhizophora* mangrove, *Bruguiera* mangrove, *Nypa* mangrove and others (Srikanth, Lum, and Chen, 2016; Srivastava and Prasad, 2019; Herison et al., 2024b). that have an important role in the coastal ecosystem. Factors such as mangrove trees, roots, litter, sediment and others contribute to wave damping (Herison et al., 2023; Woodroffe et al., 2016; Herison, 2024a). *Rhizophora sp.* mangrove with large and dense supporting roots are useful in breaking waves (Mantiquila, 2021; Sreelekshmi et al., 2018; Herison et al., 2023) while the litter part contributes to filtering water and reducing some of the wave energy, then the presence of sediments around the mangrove also plays a role in absorbing and reducing the strength of waves.

Large waves gradually erode the coastline causing damage to infrastructure and settlements (Bagindo et al., 2023). Uncontrolled wave energy will pose a threat along coastal areas (Rimba et al., 2023; Hamid et al., 2021). Mangroves have an important role to play in mitigating such issues by acting as natural wave damper. Its dense root system stabilizes the shoreline and reduces abrasion (Stachew, Houette, and Gruber, 2021).

Perhaps wave attenuation research has already been done with other types of mangroves. But in this study, *Rhizophora sp.* mangroves were used as the bounciness of the supporting roots act as wave damper. So, this research is a novelty in wave attenuation with this type of mangrove. The research objective is to analyze the wave damping value by thickness, density, and resilience of *Rhizophora sp.* mangrove supporting roots as a wave damper.

METHODOLOGY

Research Location

The research was conducted in two different locations but with the same type of mangrove, *Rhizophora sp.* The first location was in Gebang Village, Padang Cermin District, Pesawaran Regency. The second location was in Sukrame Village, Punduh Pidada District, Pesawaran Regency. The location was chosen because there was a fairly thick *Rhizophora sp.* mangrove forest (See Figure 1).

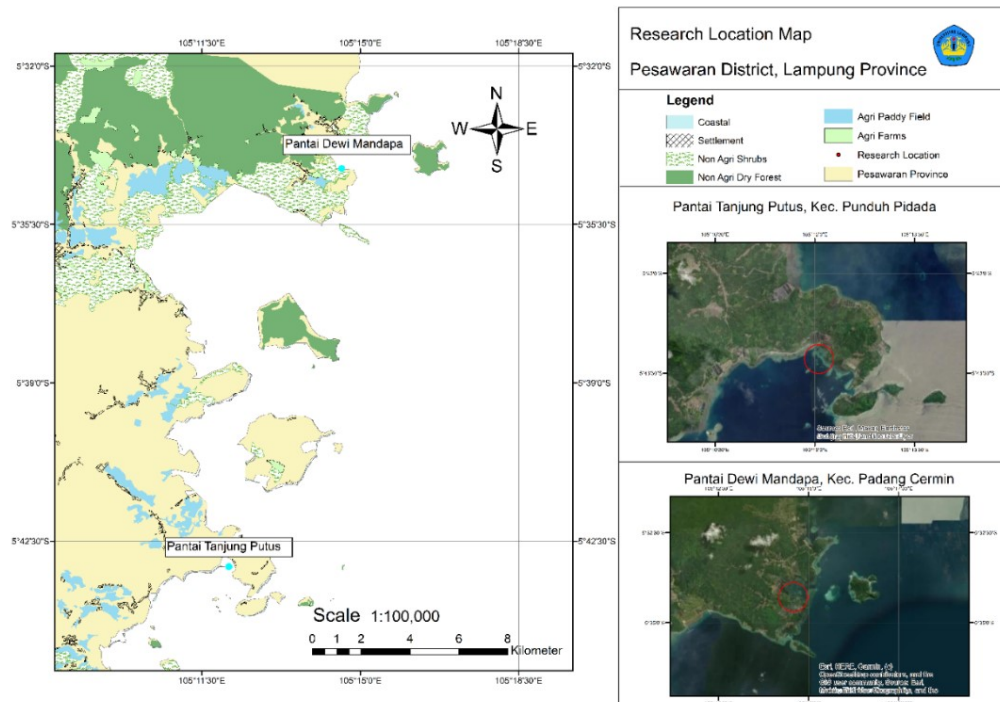


Figure 1: Map of Research Location

Data Collection Equipment

Wave Data

Wave height measurements were made with the SBE 26 tool. This tool is used in previous research on wave damping (Herison et al., 2019). Mangrove thickness that was measured on Dewi Mandapa beach were done on 10 stations with 5 meters intervals of 0-50 meters. On Tanjung Putus beach, it was done on 6 stations with 5 meters intervals of 0-30 meters adjusting to the thickness of the mangrove forest.

Vegetation Data

The tools used to collect mangrove vegetation samples at the research site are as follows:

1. 50 m roll meter to measure the circumference and thickness of the mangrove forest.
2. Rope to mark the quadrat transect plot area.
3. Saw to take supporting root samples.

4. GPS to determine the coordinates of the research location.
5. Buoys for the safety of the researchers and the team.
6. Waterproof camera to document data collection.
7. First aid kit prepared in case of accidents on site.
8. Controls Universal Testing Machine (UTM)/Tensile Testing Machine (See Figure 2).



Figure 2: Universal Testing Machine (UTM)

Controls Tensile Testing Machine is used to determine the strength of supporting roots through tensile testing. It can test specimens up to 500 mm long and the maximum tensile load is up to 500 kN.

Data Collection Process

Waveform Data Collection Process

Wave measurements were conducted using an SBE 26 pressure sensor with a recording duration of 12 hour during peak tidal conditions. Wave data was collected for 12 hours to determine the tidal range. After that, the data collected

was 1-hour data with substantial wave attenuation. Tools were installed one in front of the mangrove forest to measure incident waves and another behind the mangrove stand to record attenuated waves. The steps taken to obtain wave data are as follows:

1. Conduct a pre-survey with the wave measuring instrument technician to check the installation location of the equipment.
2. Determine the location point where wave data will be recorded.
3. Preparing equipment, transportation, backup and safety equipment and illustration of wave data collection (See Figure 3).
4. Travel to the research location using boat transportation.
5. Carry out measurements with each tool installed according to its stations.
6. Retrieval of tools and uploading raw data of wave measurement results.
7. Processing and analysis of wave data at each STA using Microsoft Excel.

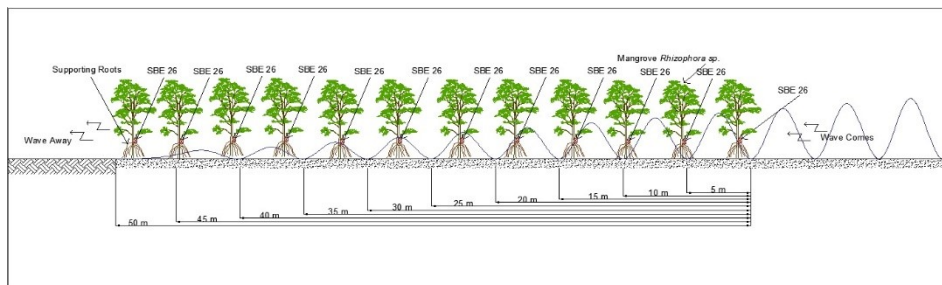


Figure 3: Illustration of wave data collection (side view)

Vegetation Data Collection Process

The methods used in collecting vegetation data are quadrat transect (Sari and Rosalina, 2016) and laboratory tests. Vegetation data were collected using 10 × 10 m plots established along transects perpendicular to the shoreline at 5 m intervals, ranging from the seaward edge to the landward boundary.

For laboratory test, *Rhizophora* sp. supporting roots were randomly sampled at each interval. To ensure a representative average tensile strength value, 10 root specimens per tree were collected from five different trees per station, categorized by diameter class. These specimens underwent tensile testing using a Universal Testing Machine (UTM) at the Materials and Construction Laboratory, Faculty of Engineering, University of Lampung.

Data Processing

Data processing using Microsoft Office applications including Ms. Word and Ms. Excel. Microsoft Excel is a data processing application in the form of numbers.

This application is needed for calculating wave energy, forming graphs that illustrate the relationship between wave damping variables on mangroves, and identifying equations that show the relationship between these variables.

Ocean Wave Data Processing

Ocean waves refer to the movement of water that occurs due to the rise and fall of air molecules. The prevailing wind transfers its energy to the water so that the stronger the wind blows, the bigger the waves formed. The presence of mangrove forests located on the beach causes damping of wave energy. Wave damping results in a reduction in wave height (Ginting, Putra, and Simanjuntak, 2019). The wave damping value can be seen from the energy difference between the incident wave and the outgoing wave passing through the mangrove. To calculate wave energy, use the following formula (Brown, 1999):

$$E_i = 1/8 \times \rho \times g \times H_i^2 \dots\dots\dots (1)$$

$$\Delta E = 1/8 \times \rho \times g \times (H_i^2 - H_t^2) \dots\dots\dots (2)$$

$$\Delta H = H_i - H_t \dots\dots\dots (3)$$

$$\Delta E (\%) = (\Delta E / E_i) \times 100\% \dots\dots\dots (4)$$

Description:

E= Wave energy (J/m²)

ρ= Water density (Kg/m³)

g= Earth's gravitational acceleration (m/s²)

H= Wave height (meter)

Mangrove Tree Density Data Processing

Density is the number of mangrove trees in an area. In this density, an ecosystem is formed that plays a role in reducing waves. To calculate the density (D_i) of marine mangrove trees then use the formula (Herison et al., 2017):

$$D_i = \frac{n_i}{A} \dots\dots\dots (5)$$

Description:

D_i= Tree density (tree/m²)

n_i= Number of trees in the area (tree)

A= Area (m²)

Using certain criteria, such as number of trees per square meter or percentage, this table divides mangrove density into categories varying from very low to very dense, for mangrove density classification (Rahman, 2020) (See Table 1).

Table 1: Mangrove Density Classification

Classification	Number of trees per m ²
Very low	<0.05
Low	>0.05-0.10
Medium	>0.10-0.15
Dense	>0.15-0.20
Very solid	>0.20

Data Processing of *Rhizophora sp.* Mangrove Roots

Roots have the ability to return to their original state after being subjected to a wave called a gradient (Southwick et al., 2014; Duncan et al. 2018). Laboratory tests were conducted to obtain the maximum load that a single root can withstand. To calculate the resilience of the roots, you can use the following formula (Herison et al., 2023):

$$\text{Resilience} = F_{\text{average}} \times \Sigma \text{root} \dots \dots \dots (6)$$

Description:

F_{average} = Root maximum load (joule)

Σroot = Number of roots in area (root/m²)

Data Analysis

Data analysis is carried out after the data processing is complete. The data analysis includes a comparison between wave damping variables as follows:

1. Relationship of ΔH , ΔE , ΔH (%), ΔE (%) with the thickness of Dewi Mandapa beach mangrove.
2. Relationship of ΔH , ΔE , ΔH (%), ΔE (%) with the thickness of mangrove at Tanjung Putus beach.
3. Relationship of energy reduction percentage ΔH (%), ΔE (%) with time.
4. The relationship between the closeness of the supporting root and ΔE .
5. The relationship of pneumatophores of roots to ΔE .

Natural Structures of *Rhizophora sp* Mangrove

Natural structures are structures that are formed naturally by nature. Everything in nature is formed by the laws of the universe. Mangroves are natural structures that have the ability to reduce the energy of ocean waves. So, mangroves can protect coastal buildings for the survival of the community.

RESULTS AND DISCUSSION

Wave Data Processing

Wave observations were done at the highest wave. The recording results can be viewed with Microsoft Excel in the form of incident and outgoing waves.

The results of data processing are in the form of wave height and wave energy on mangroves. From the data in the table. It can be seen that there is a substantial decrease in energy from a thickness of 5 meters to 10 meters because the first wave to touch the mangrove experiences the greatest damping. As the thickness of the mangrove increases, the percentage value of energy damping increases (See Table 2 & 3).

Table 5: Wave Data Processing Results of Dewi Mandapa Beach

No.	Mangrove Thickness (m)	H Incoming (m)	H Outcoming (m)	ΔH (m)	ΔH (%)	Damping Percentage ΔH (%)	Ei (J/m ²)	ΔE (J/m ²)	ΔE (%)	Damping Percentage ΔE (%)
1	5	0.7009	0.2297	0.4712	67.23	32.77	0.61799	0.551632	89.26	10.74
2	10	0.2297	0.1088	0.1209	52.65	47.35	0.06636	0.051481	77.58	22.42
3	15	0.1088	0.0819	0.0268	24.67	75.33	0.01488	0.006436	43.25	56.75
4	20	0.0819	0.0664	0.0155	18.98	81.02	0.00844	0.002901	34.36	65.64
5	25	0.0664	0.0572	0.0092	13.84	86.16	0.00554	0.001428	25.77	74.23
6	30	0.0572	0.0503	0.0069	12.06	87.94	0.00411	0.000932	22.66	77.34
7	35	0.0503	0.0453	0.0050	9.98	90.02	0.00318	0.000604	18.97	81.03
8	40	0.0453	0.0413	0.0039	8.70	91.30	0.00258	0.000429	16.64	83.36
9	45	0.0413	0.0387	0.0026	6.31	93.69	0.00215	0.000263	12.23	87.77
10	50	0.0387	0.0373	0.0014	3.67	96.33	0.00189	0.000136	7.21	92.79

Table 3: Wave Data Processing Results of Tanjung Putus Beach

No.	Mangrove Thickness (m)	H Incoming (m)	H Outcoming (m)	ΔH (m)	ΔH (%)	Damping Percentage ΔH (%)	Ei (J/m ²)	ΔE (J/m ²)	ΔE (%)	Damping Percentage ΔE (%)
1	5	0.0354	0.0181	0.0173	51.22	48.78	0.0016	0.001165	73.77	26.23
2	10	0.0181	0.0106	0.0075	41.39	58.61	0.0004	0.000272	65.65	34.35
3	15	0.0106	0.0077	0.0029	27.72	72.28	0.0001	0.000068	47.76	52.24
4	20	0.0077	0.0065	0.0012	15.36	84.64	0.0001	0.000021	28.36	71.64
5	25	0.0065	0.0060	0.0005	7.99	92.01	0.0001	0.000008	15.35	84.65

No.	Mangrove Thickness (m)	H Incoming (m)	H Outcoming (m)	ΔH (m)	ΔH (%)	Damping Percentage ΔH (%)	Ei (J/m ²)	ΔE (J/m ²)	ΔE (%)	Damping Percentage ΔE (%)
6	30	0.0060	0.0058	0.0002	3.87	96.13	0.0000	0.000003	7.59	92.41

From the wave data processing value, the following relationship can be obtained (See Figure 4 & 5):

1. The relationship between wave parameters and mangrove thickness across both research locations exhibits a consistent physical pattern where the seaward zone, specifically between 5 and 20 meters, provides the most effective coastal protection. At both Dewi Mandapa and Tanjung Putus Beach, absolute wave height ΔH and wave energy ΔE show a substantial decrease within this initial range. For absolute wave height reduction ΔH , Dewi Mandapa follows an exponential decay model $y = 0.2762e^{(-0.112x)}$ ($R^2 = 0.8717$), while Tanjung Putus exhibits a steeper decay rate described by $y = 0.041e^{(-0.174x)}$ with a higher coefficient of determination ($R^2 = 0.9996$). Similarly, the absolute energy attenuation ΔE at Dewi Mandapa ($y = 0.1858e^{(-0.158x)}$) and Tanjung Putus ($y = 0.0029e^{(-0.233x)}$) confirms that while the incident wave energy levels differ, the physical mechanism of dissipation through the *Rhizophora* sp. prop root system remains consistent.
2. The efficiency of wave height damping ΔH shows a substantial decrease as thickness increases beyond 20 meters at both sites. This trend is modeled by the quadratic equation $y = 0.0484x^2 - 3.8805x + 81.933$ for Dewi Mandapa and $y = 0.0384x^2 - 3.3394x + 68.477$ for Tanjung Putus. The decline in interval efficiency in the landward zone (20–50 m for Dewi Mandapa and 20–30 m for Tanjung Putus) is attributed to the fact that the majority of wave energy has already been dissipated by the dense frontal vegetation. Conversely, the cumulative percentage of energy attenuation ΔE increases substantially between 5 and 20 meters. Dewi Mandapa reaches high cumulative efficiency following $y = -0.0522x^2 + 4.5442x - 9.471$, while Tanjung Putus follows $y = -0.0153x^2 + 3.3978x + 6.5764$. These results indicate that the front side of the mangrove forest acts as the primary wave damper, where the most significant energy reduction occurs before the remaining minimal energy penetrates the inner forest zones.

The front side of the mangrove forest that hits the wave is the wave damper with the largest damping value. It is stated on the graph that there is a substantial decrease in energy at a distance of 5 - 20 meters, but at a distance of

20 meters back the energy decrease is no longer substantial. This is due to the energy passing through the mangroves at a distance of 20 meters only a little left.

Relationship of Wave Damping Percentage with Time

The relationship between wave damping percentage and time is a reflection of the interaction between waves and the structure that dampens them. As time passes, the process of energy damping progresses gradually, providing an interesting picture of how a system adapts to the natural stresses of ocean waves.

Based on the percentage relationship graph, there is a substantial difference with a thickness ranging from 5-10 meters, to a thickness of 15-50 meters. This is because wave energy attenuation near the shoreline is less effective at a thickness of 15-50 meters (See Figure 6).

Mangrove Tree Density Data Processing

Mangrove tree density factor acts as a natural barrier that can help protect coastal areas from coastal abrasion hazards. The results of mangrove tree density using equation (6), (See Table 4 & 5).

The results of *Rhizophora sp.* mangrove density on Dewi Mandapa and Tanjung Putus beach are classified into Very dense. The largest mangrove density is located at the front of the mangrove in contact with the first wave. Therefore, the greatest energy attenuation is located at the front of the mangrove forest.

Comparison of Support Roots and Pneumatophores against ΔE

The results of the supporting root samples that have been taken to the laboratory and tested for tensile tests (See Table 6).

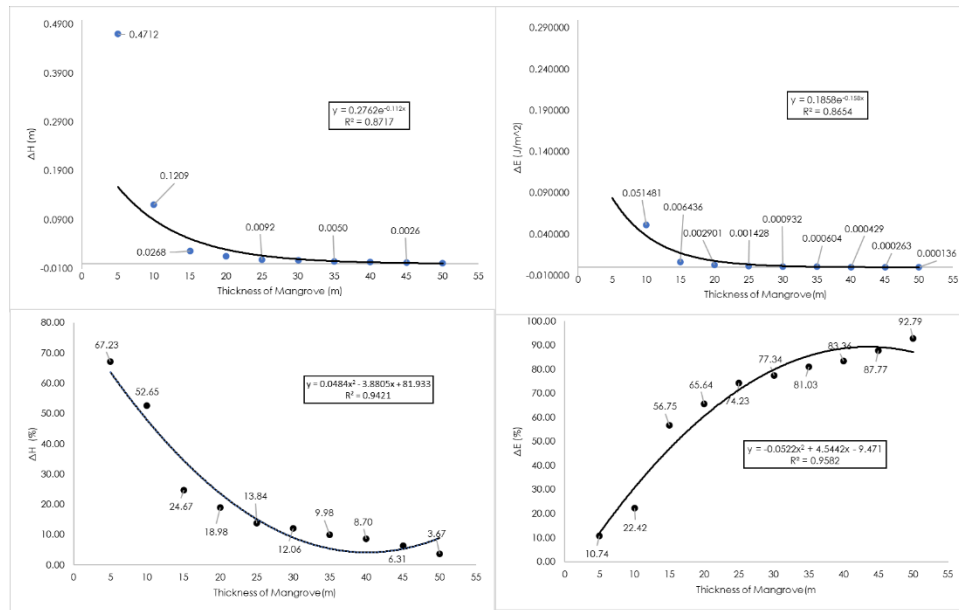


Figure 4: Relationship of ΔH , ΔE , ΔH (%), ΔE (%) with the thickness of mangrove at Dewi Mandapa beach.

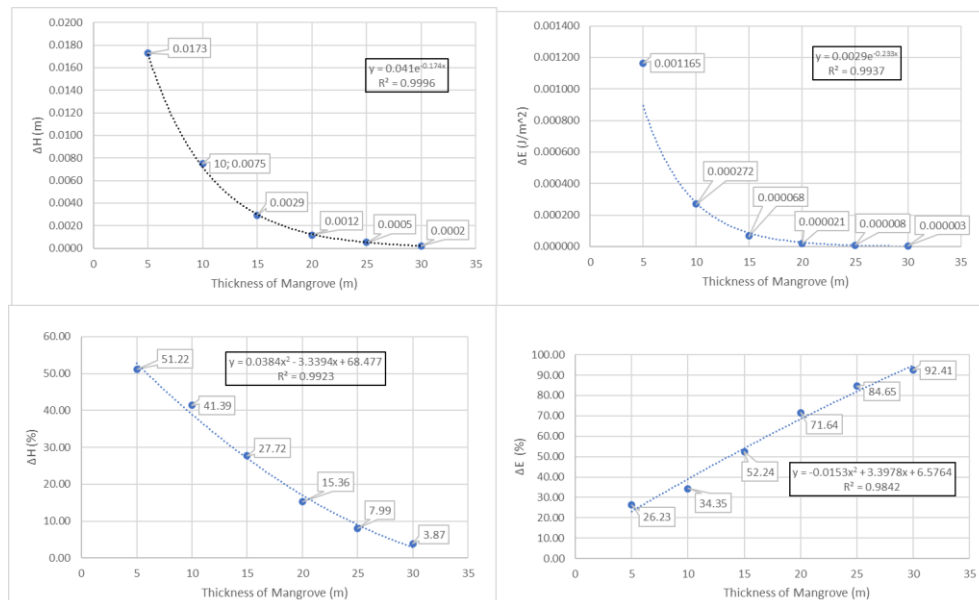


Figure 5: Relationship of ΔH , ΔE , ΔH (%), ΔE (%) with the thickness of mangrove at Tanjung Putus beach.

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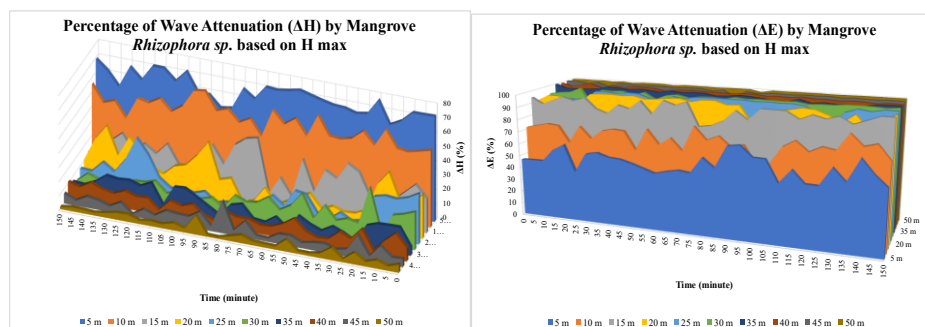


Figure 6: Relationship of energy reduction percentage ΔH (%), ΔE (%) with time.

Table 4: Density Data for Dewi Mandapa Beach

NO	Mangrove Thickness (meter)	Area Observation (m ²)	Mangrove Tree Quantity (tree)	Mangrove Density (number of tree/m ²)
1	10	200	37	0.19
2	20	400	46	0.12
3	30	600	49	0.08
4	40	800	52	0.07
5	50	1000	55	0.05

Table 5: Density Data for Tanjung Putus Beach

NO	Mangrove Thickness (meter)	Area Observation (m ²)	Mangrove Tree Quantity (tree)	Mangrove Density (number of tree/m ²)
1	10	200	52	0.31
2	15	300	76	0.26
3	20	400	97	0.25
4	25	500	118	0.24
5	30	600	136	0.24

Table 6 Results of Rhizopora sp Root Data Processing

Thickness (m)	F average (Joule)	Number of roots (items/m ²)	Resilience (J/m ²)	Wave Energy Attenuation (J/m ²)
5	1.0107	310	3.1331	3.7578E-04
10	1.0107	520	2.6277	4.4674E-04
30	1.0107	970	2.4509	4.5943E-04

Table 7: Results of *Avicennia marina* Root Data Processing (Herison et al., 2023)

Thickness (m)	F average (Joule)	Number of roots (items/m ²)	Resilience (J/m ²)	Wave Energy Attenuation (J/m ²)
5	1.6E-06	19,140	3.06E-04	0.7485
10	1.6E-06	35,640	2.85E-04	1.3389
30	1.6E-06	66,240	2.64E-04	1.6115

Laboratory tests were conducted to determine the capacity of the roots to withstand the load. It is determined that one root can withstand an average wave of 1.0107 Joules on the supporting root and 1.6E-06 Joules on the pneumatophores (Herison et al., 2023). This difference in value is based on the difference in physical form between the supporting roots and the pneumatophores. The root thickness value is inversely proportional to the dampened energy because the thicker the mangrove, the less energy dampened by the roots.

The relationship between resilience and energy reduction is as follows:

1. The relationship between resilience and wave energy attenuation of *Rhizophora sp* mangrove species with mangrove thickness of 5 meters to 30 meters is described by the equation $y = -8E+07x^2 + 59934x - 7.8768$ with a coefficient of determination (R^2) of 0.9768. At a thickness of 5 meters the y-value of 3.1131 J/m² at a thickness of 30 meters drops to 2.4509 J/m². This shows a decrease in the value of resilience along with the increase in the thickness of *Rhizophora sp* mangrove (See Figure 7).
2. The relationship between the resilience and wave energy attenuation of *Avicennia marina* mangrove species with mangrove thickness of 5 meters to 30 meters is described by the equation $y = -4E-05x^2 + 6E-05xx - 0.0003$ with a coefficient of determination (R^2) of 0.9709. At a thickness of 5 meters the y value of 3.06E-04 J/m² at a thickness of 20 meters dropped to 2.64E-04 J/m². This shows a decrease in the value of resilience along with the increasing thickness of *Avicennia marina* mangrove (See Figure 8).

It is stated that the resilience value of *Rhizophora sp* supporting roots is greater than *Avicennia marina* Pneumatophores based on the research results.

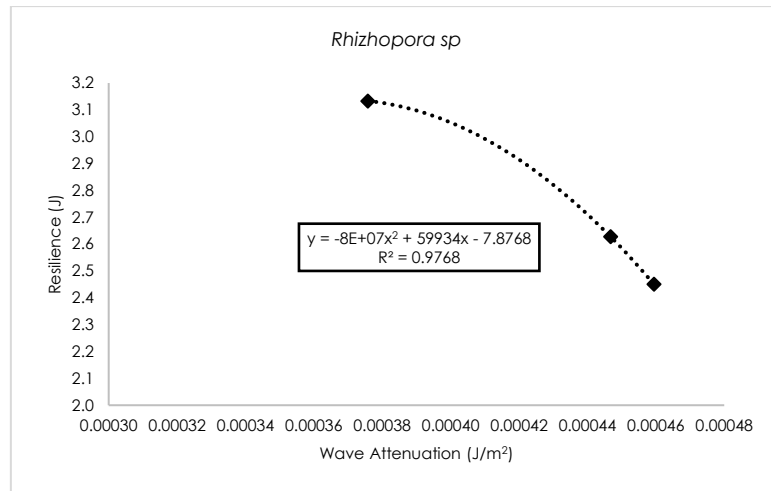


Figure 7: Relationship between the resilience of the supporting root and ΔE , *Rhizophora Sp*

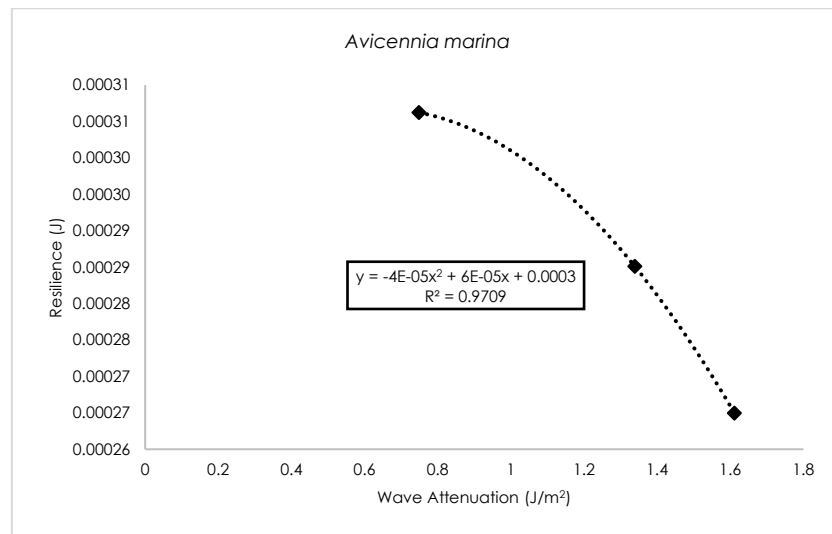


Figure 8: Relationship between the resilience of the pneumatophores and ΔE , *Avicennia marina* (Herison et al., 2023)

Comparison of Wave Energy Absorption (ΔE) Values with *Avicennia marina* Mangrove

In mangrove ecosystems, wave attenuation is an important function performed by mangrove vegetation to protect the coast from abrasion due to ocean waves.

Among the various mangrove species in nature, *Rhizophora sp.* with its strong and serpentine root system, often stands out in this role compared to other mangrove species.

The main difference in wave attenuation between *Rhizophora sp.* and other mangrove species lies in their physical structure. *Rhizophora sp.*, with its towering, densely growing supporting roots, effectively catches and breaks waves. These towering roots form a strong barrier to water flow, dampening the energy of waves and reducing their speed before they reach the shore. This helps reduce coastal erosion and stimulates sediment deposition, gradually expanding the coastal area.

On the other hand, other mangroves may not have root systems as strong and complex as *Rhizophora sp.* While they still provide protection against waves, their ability to dampen waves may be less effective than that of *Rhizophora sp.*.

Rhizophora sp. mangrove produces wave attenuation values, namely at a thickness of 5 meters obtained 10.74%, up to a thickness of 50 m obtained 92.79%. With the equation $y = -0.0522x^2 + 4.5442x - 9.471$, with a value of $R^2 = 0.9582$. Whereas in previous studies using *Avicennia marina* mangroves and produced a wave attenuation value of 3 meters obtained 50%, at a thickness of 5 meters obtained 54%, up to a thickness of 50 meters obtained 92% with the equation $y = -0.0592x^2 + 4.0142x + 39.267$ nilai $R^2 = 0.9265$. To see the comparison of the percentage of wave attenuation by *Rhizophora sp.* with *Avicennia marina* mangrove (See Table 8).

Table 8: Percentage of wave attenuation by mangroves.

Station	Wave attenuation percentage (%)	
	<i>Rhizophora sp.</i>	<i>Avicennia marina</i>
STA 1(5)	10.74	54
STA 2 (10)	22.42	83
STA 3 (20)	65.64	91
STA 4 (50)	92.79	92

From the table 8, a comparison chart can be seen (See Figure 9).

The wave attenuation graph between *Rhizophora sp.* and *Avicennia marina* mangroves shows a substantial difference in the efficiency of coastal protection against ocean waves. The wave attenuation graph for *Rhizophora sp.* shows a steeper rise than that of *Avicennia marina*.

In the zoning of mangrove growth, *Avicennia marina* formerly do the damping because the mangrove is in the zone seaward zone (area near the sea) while *Rhizophora sp.* do waves damping after being dampened by mangrove *Avicennia marina* foremost because mangrove *Rhizophora sp.* is in the mid zone (mid area).

At a thickness of 5-10 meters, *Avicennia marina* mangrove performs greater damping than *Rhizophora sp.* mangrove, while at a distance of 5-20 mangrove *Rhizophora sp.* performs damping more consistently up to a thickness of 20 m. (See Figure 9)

Comparison Graph of Percentage of Wave Energy with Mangrove *Avicennia marina* with Time

The wave energy percentage graph is a reflection of how the two mangrove species, *Avicennia marina* and *Rhizophora sp.*, evolved and adapted to changes in the water environment over time. *Avicennia marina*, with its wider roots and denser branches, shows a steady trend in absorbing wave energy over time. On a continuously changing surface, *Avicennia marina* remains a consistent coastal guard, serving a critical role in stabilizing the shoreline and providing protection against erosion.

From the two graphs, *Rhizophora sp.* mangroves display more complicated dynamics in interaction with wave energy over time. This comparison between the two mangrove species reflects their unique adaptations to a changing environment. While *Avicennia marina* showed stability in response to wave energy over time, *Rhizophora sp.* showed the ability to adapt and evolve as their environmental conditions changed. Both, albeit with different strategies, play an important role in maintaining the balance of valuable mangrove ecosystems (See figure 10).

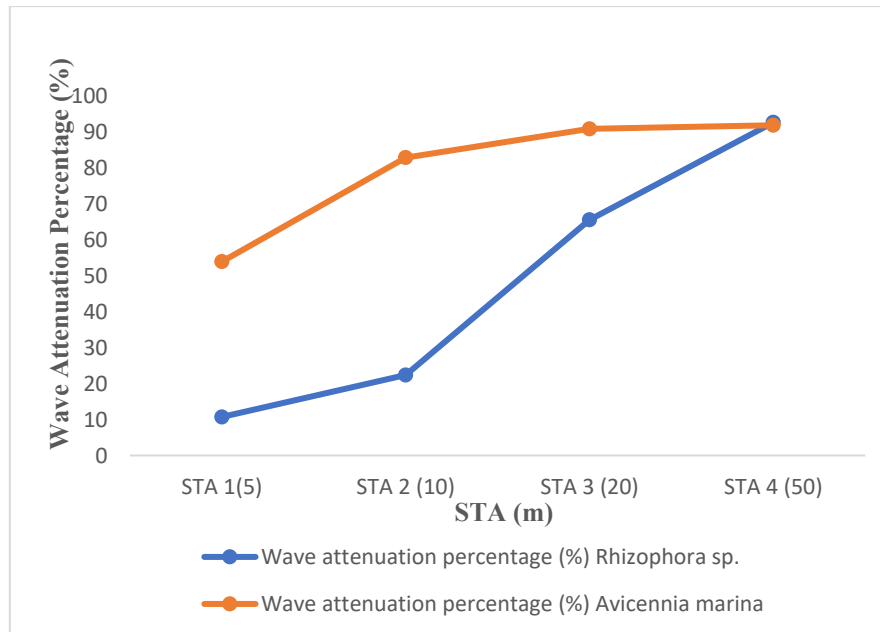


Figure 9: Comparison graph of wave attenuation between *Rhizophora sp* and *Avicennia marina*.

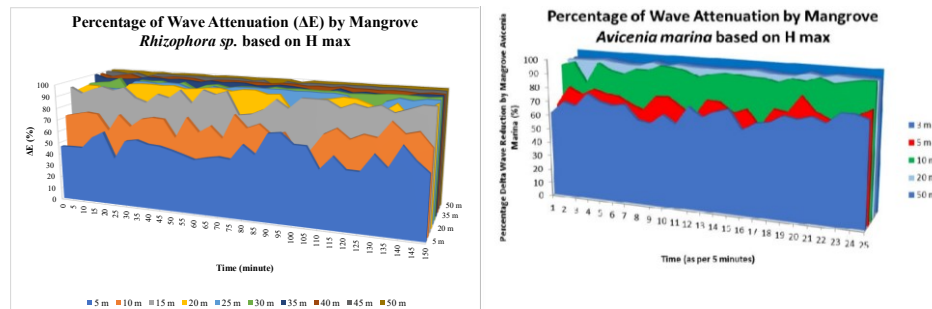


Figure 10: Comparison of attenuation percentage by mangrove *Rhizophora sp.* with *Avicennia marina*

Mangroves as Natural Structure

Considering the results of wave attenuation by mangroves that are large enough, this can be utilized for the survival of coastal communities. Mangroves can become a natural structure that can replace man made structures, namely breakwater to protect shore buildings such as ports, groins, and beaches as tourist attractions.

CONCLUSION

It is concluded that high-density *Rhizophora sp.* mangroves have substantial wave damping ability as a result of the bouncing power of the supporting roots. When the wave first touches the mangrove forest, there is a decrease in wave energy by approximately 50%. This shows that *Rhizophora sp.* mangroves play an important role as a natural structure in protecting the coast from ocean waves.

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