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Review Article

Mangroves As Coastal Bio-Shield: A Review of Mangroves Performance in Wave Attenuation

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Abstract

Mangroves have been recognized as soft structures that provide coastline protection. The capability of dampening waves helps minimize destruction from catastrophic events including erosive wave attacks, torrential storms, and tsunamis. Mangroves act as the first line of coastal defense in natural tragedies such as during the Super Typhoon Haiyan 2013 and Indian Ocean Tsunami 2004, whereby the leeward mangrove area encountered less damage than the unprotected area. This has further brought the attention of researchers to study the attenuation performance of these coastal vegetations. Based on an extensive literature review, this paper discusses the attenuation mechanism of mangroves, the factors influencing the dissipation performance, studies on mangrove dissipation via different approaches, the dissipation efficiency, mangrove conservation and rehabilitation efforts in Malaysia and implementation of mangrove as coastal bio-shield in other countries. The study highlights that mangrove parameters (such as species, width, density etc.) and wave parameters (such as wave period and incident wave height) are among the contributing factors in mangroves-induced wave attenuation, with different efficiency rates performed by different mangroves and waves parameters. Towards that end, several improvements are proposed for future research such as to incorporate all influencing dissipation factors with specific analysis for each species of mangroves, to perform validation on the studied mangroves attenuation capacity in different settings and circumstances, as well as to address the extent of protection by the rehabilitated mangroves. A systematic and effective management strategy incorporating ecological, forestry, and coastal engineering knowledge should be considered to ensure a sustainable mangroves ecosystem and promising coastline protection by mangroves.

Keywords: Mangroves Ecosystem; Wave Dissipation; Coastal Protection; Rehabilitation; Conservation.

1. Introduction

Mangroves are distinctive ecological ecosystems among those situated between the land and sea along tropical and subtropical coasts. The mangrove coastal vegetations exhibit life-history adaptations to the challenges of both difficult establishment in mobile due to current dynamics and ocean wave influence with high salinity (0-90 degrees/thousand) in aqueous, anoxic sediments [1]. Nonetheless, mangroves provide coastal protection by attenuating wave height and energy, acting as a natural barrier to incoming waves and, therefore, reducing erosion [2]. Globally, mangroves are distinguished into two regions, the West, and the East. The West includes the African coasts of Atlantic, North, and South America, and the East incorporate the African coast. Studies have shown that the East zone represents the higher species richness [3]. According to Spalding (1997), 18,100,000 ha of mangroves have been reported in 1997 [4], which

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degraded to 13,776,000 ha in 2000 [5], and most currently 8,349,500 ha as observed in 2016 [6]. Besides, Asia appears as the largest mangrove distribution in the world and Southeast Asia has been regarded with high species diversity [7].

In recent decades, researchers have alleged the benefits of mangroves trees in 1) maintaining the natural biodiversity of the coast [8], 2) providing vital nursery grounds for juvenile fish and crustaceans [1, 9], 3) providing coastal protection against flooding and erosion directly by dissipating energy [10], and 4) providing substantial carbon sequestration for regulating services [11]. In addition, the mangrove ecosystem also plays a consequent role in the provision of food and shelters to diverse marine and terrestrial organisms [12]. Mangrove's protection role is significant in coastal management whereby mangroves have been regarded as naturally form barrier in defensing the coastline from waves, storms, and winds. The efficiency of mangroves in standing as the first line of coastal buffer in diminishing severe wave actions has been evident [13, 14, 15]. The Indian Ocean Tsunami (IOT) 2004 is commonly associated with the dissipation performance by mangroves.

The affected areas in India during the IOT 2004, Pichavaram and Muthupet revealed that dense mangroves protected the areas with fewer casualties and less property damage recorded [16]. In Sri Lankan village, the densely populated mangroves areas caused only two deaths, meanwhile 6,000 people were found dead in area with no mangrove's protection [17]. Nevertheless, the protection function it provides is not only relevant for tsunami cases but also applicable for other natural calamities such as storm surges and cyclones [18, 19] where the areas with mangroves were less damaged compared to mangrove-free areas [20]. The super-cyclone that struck Orissa, India in 1999 left 7.5 million people homeless with approximately 10,000 death tolls, except those protected area behind the healthy mangroves that suffered less losses [7]. In Philippines, mangroves safeguarded from the great waves impact of Super Typhoon Haiyan in 2013 [21]. These events, apart from similarly evident the buffering capacity of mangroves, have also sent a vivid message that conservation and sustainable management of these coastal vegetations are important to guarantee secure barrier against the natural hazards.

The complex root system, canopy, trunk, and few other geometries attributed by mangroves play vital role in reducing the severe effect of incoming waves, winds, and storms. Although the protection provided seems obvious, but the mechanism and process involved might not be well described. The shielding performance might differ according to various influencing factors too. This paper hereby attempts to review and discuss on wave attenuation mechanism by mangroves, the influential dissipation factors, previous studies on mangrove-induced wave dissipation via field assessments, numerical modeling, and laboratory studies, and the efficiency of dissipation based on extensive literature review. Mangrove conservation and rehabilitation efforts in Malaysia and the mangroves bio-shield implementation in several countries are also highlighted in this paper.

2. Research Methodology

The methodology adopted in this paper is simplified in the flowchart as shown in Figure 1.

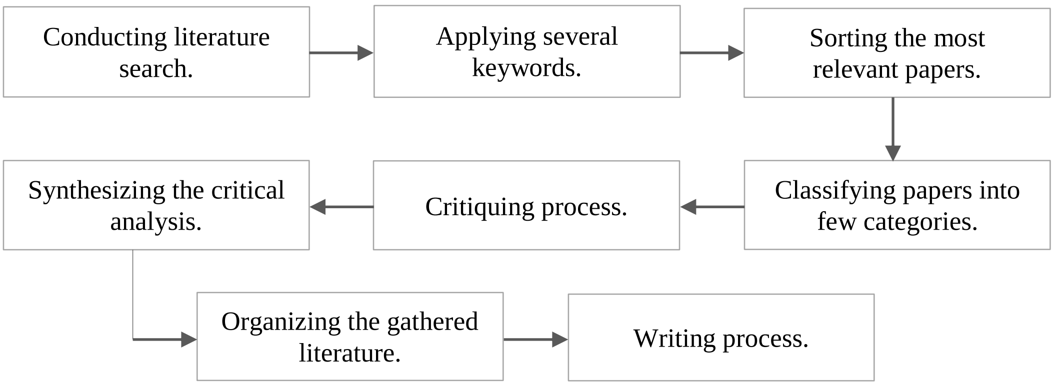

Figure 1. Research flowchart

The literature search was performed in Research Gate and Science Direct databases to retrieve available related papers. Several keywords were applied as search criteria, such as mangroves, mangroves ecosystem, coastal ecosystem, coastal protection, wave dissipation, wave attenuation, mangroves rehabilitation, mangroves conservation, mangroves degradation, Indian Ocean Tsunami, cyclone, typhoon, mangroves Malaysia, and coastal bio-shield to capture papers published before August 2021. Papers obtained were then filtered to sort only the most relevant information and data concerning the topic discussed. Subsequently, papers were classified into few categories. An evaluation and analysis on the literature was critically conducted, followed by the process of synthesizing the critical analysis, organizing the reviewed papers in a summary table according to the specific topic and finally writing process.

3. Wave Dissipation by Mangroves

Waves are attenuated by disturbances unraveling at a reduced depth of water within mangrove forests and resistance by mangrove roots, stems, and tree canopies in adequately deep water. Wave energy dissipation caused by wave deformation is merely a function of wave parameters (height, length, and period) and depths, especially in intertidal zone morphology and can be estimated numerically if these parameters are known [1, 22]. According to Parvathy and Bhaskaran (2017), steep slopes' shoal distances become short, while the reduction in the height and part of surface waves may be reflected from the steep bottom [23]. On the other hand, mild slopes have a longer wave traveling distance and the waves will decay on mild slopes via the mangroves.

Wave dissipation in the vicinity of mangroves occurs due to the drag force and bottom friction. Drag force is normally associated with the resistance imposed by mangrove structures such as trunks, roots, and canopies (in cases where mangroves are fully submerged). Bottom friction, on the other hand, is resulted from the bed roughness. Both force and friction act in the opposite direction from the incoming wave (refer to Figure 2).

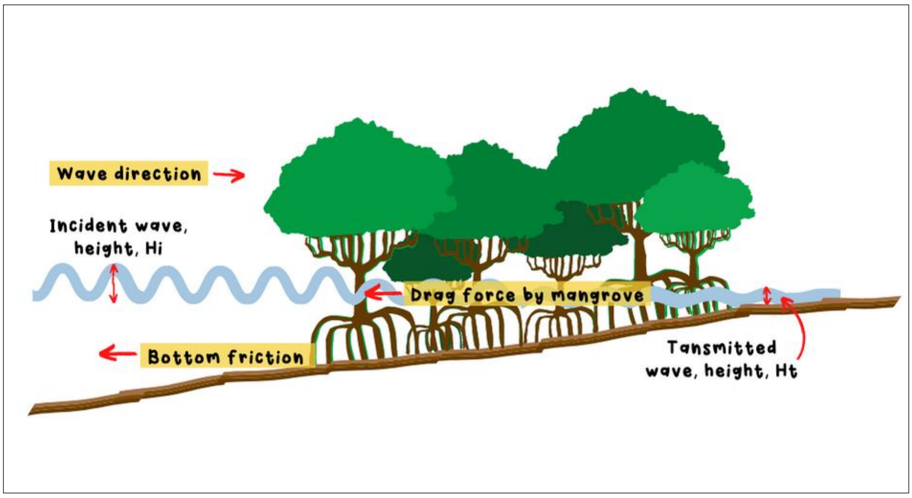

Figure 2. Wave attenuation by mangroves

The drag friction slows down the wave motion's propagation into the mangrove forests [24, 25, 26]. The waves subsequently lose part of their energy and, therefore, attenuating them. When waves travel through the forests, the incident wave height is reduced due to bottom friction and the drag force exerted. The bottom friction alone might be insufficient to attenuate the wave height [27]; hence, mangroves are needed to enhance the force for a net reduction.

Differences between the height of incident waves (H_i) and transmitted waves (H_t) over the distance travelled inside the mangroves is defined as the wave reduction rate (r). Hence, it is important to calculate the rate of reduction. Equation 1 was established by Mazda et al. (2006) for the reduction rate calculation [28]:

$$r = \frac{-\Delta H}{H} \cdot \frac{1}{\Delta x} \tag{1}$$

Where r is the wave height reduction rate per unit distance (m^{-1}), ΔH is the reduction in incident wave height (m), H is the incident wave height (m), and Δx is the distance travelled over the mangroves (m). The reduction rate coefficient as developed by Rasmeemasmuang and Sasaki (2015) is expressed in Equation 2 to represent the dissipation rate of waves [29], as follows:

$$R(\%) = \frac{(H_i - H_t)}{H_t} \times 100 \tag{2}$$

Where R is the coefficient of wave reduction (%), H_i is the incident wave height (m), and H_t is the transmitted wave height (m). Equation 1 differs from Equation 2 such that the distance or width of mangroves is introduced in Equation 1, whereas Equation 2 only addresses the reduction waves. Previous studies revealed that the rate of wave attenuation largely depends on the density of mangrove forests, especially the diameter of the mangrove roots and trunks, and on the spectral characteristics of the incident waves [30].

4. Factors Governing Mangroves Performance in Dissipating Wave

Wave reduction in mangroves occurs due to several factors that can be divided into three categories as follows: 1) mangrove characteristics such as the width, density, species, root diameter, age, and canopy, 2) wave parameters such as wave period and incident wave height, and 3) other external factors such as bathymetry and water depth. Thus, understanding the factors that lead to the wave reduction mechanism is crucial for the management of mangrove areas to protect the coastline. The findings explained that the attenuation performance rate is significantly depending on the parameters of mangroves, waves, and other external factors with linear relationship between the parameters and attenuation are observed in width, structures, density, age, and bathymetry, while water depth is found negatively correlated with dissipation of waves. Relationship with species and incident wave height are dependable on their types of species and wave period.

4.1. Width

The sea wave height decays exponentially as the width of mangroves increases. Studies have found that wave amplitude has an inverse relationship with the width of mangrove forests. According to Lee et al. (2021), the percentage of wave height reduction by mangroves is more than 60% over a 500 m width [2]. On the coast of Vietnam, Bao (2011) confirmed the reduction in wave height over the increment of distance into mangroves [31]. As the waves travel further into the mangroves forest in an increasing distance, more obstruction and interaction occur between the incoming wave and the friction exerts by both mangroves drag coefficient and seabed roughness [32], thus resulting to more losses of wave energy and height.

Considering that mangrove width has a significant role in the reduction of wave intensity, Shahruzzaman (2018) suggested a replantation of minimum width required at their study area so that mangroves can provide adequate coastline protection [33]. The study also highlighted that without sufficient width, an optimum buffering capacity would not be guaranteed even with high vegetation index (high mangroves density, matured mangroves, etc.). Besides, Adytia and Husrin (2019) reported that the mangrove width with four times the wavelength of incident waves is required to fully attenuate the incoming wave height [34].

4.2. Species

Mangroves of different species (such as *Avicennia*, *Sonneratia*, *Rhizophora*, and *Bruguiera*) perform differently in attenuating waves according to the characteristics of each species. It is well-known that the *Rhizophora* species are most effective than other mangrove types. Their attenuating proficiency is due to the complex aerial root structures with greater friction to incoming waves that leads to a higher drag coefficient. The attenuation performance of *Rhizophora* was 57.73% on porosity of 0.9828 [35]. Hashim and Catherine (2013) also reported that 80% of waves can be attenuated by an 80 m wide *Rhizophora* [36]. Meanwhile, in a 100 m wide *Sonneratia* located in northern Vietnam, Mazda et al. (2006) found that up to 50% of wave energy can be reduced [28].

According to Muliddin et al. (2014), a minimum of 79% of waves were attenuated over 1 tree/m^2 *Sonneratia* in their numerical modeling [37]. Additionally, a study by Herison et al. (2017) showed that *Avicennia* can produce an attenuation rate of 0.24 m/km in mangrove forests ranging from 0.5 m to 3 m in height [38]. Besides, Horstman et al. (2014) tested wave dampening in *Sonneratia*, *Avicennia* and *Rhizophora* dominated areas, which demonstrated an attenuation rate of 0.002 m^{-1} in *Sonneratia* and *Avicennia* forests with low density and 0.012 m^{-1} in denser *Rhizophora* [39]. In this case, although the attenuation rate was marked higher in *Rhizophora* forest, but the density acts as another manipulated variable which made them incomparable in terms of dissipation performance due to species.

4.3. Structure

The amount of energy dissipated on the mangrove structures is influenced by factors such as the arrangement of stems, roots, and branches as well as submerged parts of the vegetation. In addition, stem stiffness can also contribute to wave dissipation rates [36]. Wave height along the propagation direction decreases non-linearly with the growth in the wave travel distance due to relation with higher height and stem density, and larger diameter plants [40]. Rasmeemasmuang and Sasaki (2015) has shown a relationship between hydrodynamic factors and botanic factors in wave reduction towards *Rhizophora* systems [29]. Wave energy transmission reduces when the number of trees increases.

In Vietnam, Tusinski and Verhagen (2014) claimed that mangroves' emerging canopy has the highest efficacy in the decaying process of waves compared to the roots, trunks, and submerged canopy [27]. Mazda et al. (2006) also found that thick mangrove leaves have an influence on attenuation rates with a condition that the water depth was high enough to enable the submergence of the leaves [28]. However, Lee et al. (2021) reported different results in Singapore, whereby wave reduction by mangrove roots was 85%-100%, and trunks resulted in 94% of vegetation drag force [2]. Mangrove roots are also the main contributor to the vegetation drag force that increases up to 0-35% under storm conditions. Roots are the most efficient dissipation of wave energy when it comes to shallow water [41].

Bare land, as opposed to mangrove-covered areas, was observed to be less impactful in attenuating the wave height [36]. Teh et al. (2009) found that a 500 m mangrove width in Penang, Malaysia in tsunami wave conditions imposed a reduction ratio of 0.50 compared to 0.55 in the mangrove-free area [14]. This is parallel with the findings reported by Quartel et al. (2007) where the unvegetated mudflat relies only on the bottom friction for wave dampening [25]. This condition demonstrates lower wave reduction due to the absence of additional friction and drag force exerted by the mangrove structures that impeding the flow.

4.4. Density

Previous studies discovered that high mangrove density will impose higher wave dissipation [19, 25, 31, 42]. In a denser mangrove forest, the gaps between the roots and trunks are minimized. Therefore, wave and root-trunk interaction are dominant and increases the tendency for the reduction of wave height [36]. Wolanski (2006) similarly claimed that the densely populated mangroves form the dense interlocking arial roots, thus reducing the porosity and increasing obstruction to the incoming wave [43]. Furthermore, the drag force from these vegetations helps dissipate the wave magnitude. Findings from Iimura and Tanaka (2012) that examined a vegetation model with different densities and its effect in mitigating tsunami wave impact [44] also supported the hypothesis.

The dissipation capability of disturbed mangroves was carried out in the coastline of Singapore by Lee et al. (2021), where they found that the reduction of wave height was intense with the increasing density [2], while Lou et al. (2018) observed a lower transmission coefficient of waves in a denser mangroves forest; however, this was rather significant for deep water than in intermediate wave conditions [45]. All above-mentioned studies concluded the same findings that mangroves density and wave attenuation have a positive correlation in various state of wave conditions. In less dense mangrove forests, the effect of wave breaking plays an important role in wave attenuation [46].

4.5. Age

The age of mangroves refers to the trunk diameter, size of the tree, stem density, and root diameter [36, 47], while according to Latief and Hadi (2006), mangrove age is associated with the size of this vegetation [48]. Alongi (2008) and Danielsen et al. (2005) claimed that, as the age of a tree increases, the higher its resistance to wave destruction [42, 49]. This is due to the high diameter of trunks and firm roots of the matured tree. Meanwhile, younger mangroves can be easily uprooted by erosive waves. Younger mangroves were found to unsuitably withstand extreme and higher waves, resulting in washing away because they are easily uprooted [27]. Hence, due to their weak characteristics, younger mangroves require support such as geo-bags for wave-breaker and fibre-rolls for stabilizing during replantation [50].

4.6. Bathymetry

Higher wave energy attenuated in coastal regions changes directly towards the bathymetric profile [23]. The bathymetric condition also influences the size of waves with an increase in depth along the distance from the coastal regions. Besides, a steeper slope promotes better wave height reduction [27]. This is due to the wave shoaling effect in the steep slope whereby less or no such effect would result in a mild and gentle slope. Current available studies on bathymetry influence are very limited in mangrove-induced wave dissipation scope, hence further research on this is suggested to get a clearer and robust conclusion on the relationship between both parameters.

4.7. Water Depth

The effect of water level on wave attenuation was examined in storm conditions. The wave height reduction rate with elevated water levels during high tides (0.001-0.005m-1) was smaller compared to the elevated water level only (0.002-0.035 m^{-1}). Lee et al. (2021) stated that lower water level creates more turbulence in the bottom layer as proportion to the shallow water depth and influences more water motion [2]. But, in a deeper water depth, the water particles will be less affected by the obstacles, hence causing to less attenuation [51]. Mazda (2006) however hypothesized that higher wave height reduction occurs when the resistance coefficient and water depth are increasing at the same time due to the larger submergence of mangrove branches and leaves [28].

Findings from field experiment conducted by Quartel et al. (2007) was very similar [25]. They reported that the resistance due to the unvegetated sandy bed with increasing water depth resulted in a lower wave height reduction. Meanwhile, in the presence of mangroves forests, the resistance coefficient increased with the increasing water depth, resulting in a higher wave height reduction due to the larger submerged part of mangrove branches and leaves that clogs the water flow. According to Parvathy and Bhaskaran (2017), if the water depth is higher in the steep slope region, the waves attenuate the fastest as they travel through the roots, resulting in more drag resistance [23].

4.8. Incident Wave Height

In hydrodynamic conditions, incident wave heights are decreased due to wave breakage [52]. High wave heights cause wave breakage and produce drag force through the mangroves. In addition, the percentage of drag force due to breakage increases by less than 1%. Previous study has shown that mangroves are more effective in attenuating short period waves, compared to the longer ones (e.g., swell waves, tsunami waves, storm surges) [53]. Short period waves dissipate better even in a narrow strip of mangroves, in which such condition might not be enough for protection from long period wave [26]. In contrary, Brinkman (1997) justified that wave attenuation is independent on the incident wave height. Either short or long period waves, they dissipate at a similar rate [54].

5. Mangroves Dissipation Performance

Previous studies on wave dissipation by mangroves can be classified into several approaches, including laboratory experiments, field assessments, and integration of laboratory and field works with numerical studies. Some numerical studies incorporated simulation and modeling with validation from laboratory and field assessment, while others only adopted numerical assessment such as regression analysis. This proves the vegetation-induced wave dissipation ability of mangroves with a variety of affecting factors being tested over different wave conditions and mangrove species.

5.1. Laboratory Experiments

A laboratory experiment by Hashim and Catherine (2013) explained the effect of different mangrove densities and tree arrangement in dampening wave height [36]. Denser mangrove forests resulted in higher wave reduction, while staggered and tandem arrangements demonstrated only a slight difference in wave attenuation. Besides, mangrove areas showed twice wave reduction compared to non-vegetated areas. The presence of mangroves also exerted greater drag force, contributing to greater energy loss.

Similar laboratory studies focusing on density were also carried out by Pasha and Tanaka (2016, 2017), which highlighted that greater density of emergent vegetation attenuated wave energy more effectively [55, 56]. The effect of the opposing and following current on the dissipation of waves influenced by emergent rigid vegetation was also investigated [57]. The study examined the current with manipulated velocity, water depth, and vegetation density on wave dissipation by coastal vegetation with a larger velocity ratio range. Numerical modeling was implemented to ensure feasibility due to the limitations of maximum generated stable current velocity in experimental works.

Additionally, Kristiyanto and Armono (2013) carried out a study to analyze the relation of wave steepness in the wave dissipation process via both laboratory works and field assessment [35]. Wave steepness was described in terms of wave height and wave period. Data were analyzed using regression analysis in deriving the wave attenuation formula. The ability to dampen waves, known as transmission coefficient (Kt), was determined through the difference in height between the incident wave and transmitted wave. Compared to the above-mentioned studies which experimented the normal wave and current, Strusinska-Correia (2013) tested the attenuation performance over different widths in different tsunami wave conditions [58]. The results showed that reduction was higher in a wider mangroves forest due to the longer distance travelled.

In laboratory studies, the mangrove model representation may result to different values of data depending on the physical characteristics of the mangrove model. For instance, some experiments duplicate the mangrove solely in the form of cylinder, which disregard their important structures like branches, roots, and canopies. Although the findings or theories are still valid and proven, but it might slightly affect the accuracy in the observed values of wave attenuation. Thus, the model with actual resemblance of mangrove should be rather considered. Other than that, the bed friction in the wave flume is usually ignored. Bed properties should be ensured to have almost similar coefficient as the muddy area in the vicinity of mangrove too.

5.2. Numerical Modeling

Numerical studies on wave attenuation are extensive. The vegetation model is usually described as coastal vegetation in general, yet the model is still applicable to mangrove cases. For instance, Iimura and Tanaka (2012) performed modeling to elucidate the effects of varying coastal vegetation density on tsunami energy reduction [44]. Boussinesq-type equations were used by including porosity and resistance terms to resemble the drag force by mangroves.

An experiment was conducted to validate the simulation with a 10% error whereby future improvement of numerical model was required on the back row of vegetation and the boundary between different densities. Water level and velocity reduction were greater as the density increased in both uniform and combined arrangement of vegetation models. The mitigation effects of mangroves on tsunami wave energy, height, and velocities were also analyzed by Teh et al. (2009) [14]. Morison equation was incorporated in the modeling to represent friction provided by the mangroves. This study inputted the mangrove geometries data in Penang, Malaysia, into the run-up model TUNA-RP. The reduction ratios for given velocities and wave heights were found to vary significantly depending on the wave and mangrove parameters.

A similar model as Iimura and Tanaka (2012) [44] was optimized by Adytia and Husrin (2019) in describing the non-linear transformation of tsunami wave attenuation by mangroves [34]. They included an additional term of dissipation due to bottom roughness in the momentum equation. The relation between the required mangrove width over the magnitude of wavelength to produce the respective dissipation rate was simulated. In contrast to long period wave, Van Rooijen et al. (2015) clarified the effect of vegetation in reducing short waves, infragavity waves, and mean flow using XBeach model [59], which was extended with formulations by Mendez and Losada (2004) to account for the wave attenuation by coastal vegetation [60].

Hu et al. (2014) later carried out modeling that enables the quantification of vegetation drag coefficient in current–wave conditions [61]. They tested the attenuation performance in a tidal current, which is often neglected in most studies. However, they estimated that steady current may lead to higher or lower wave attenuation, depending on the velocity ratio. In high and low tides events, mangroves shown higher attenuation ranging from 96% to 97% in high tides, and only 85% to 90% was observed during low tides [62]. The mangrove canopy and root system play a prominent role in reducing the wave height during high and low tides, respectively. Dalrymple empirical model was used with the integration of the forward differencing method which simulated mangroves as non-homogenous forest characteristics that most likely resemble the real mangrove forest.

Abdullah et al. (2019) modeled the effect of wave and mangrove parameters by adopting the Mansard-Funke method and spectral analysis [63]. Wave amplitude, wave period, and mangrove density were studied in terms of their sensitivity in wave energy dissipation. Dissipated wave energy was higher in a smaller wave period with more dissipation over denser mangroves in submerged conditions. The differences between wave heights reduction in different salinity zones, with and without vegetation and mud inputs were observed in Indian Sundarbans (IS) [64]. The study solved other literature gaps which usually assessed mangroves as one general species, whereby in this study all four different dominant mangroves species were encompassed. The output suggested that higher wave attenuation was observed in the hyposaline stations of western IS than to the hypersaline central sector.

Rigid vegetation represented by three types of vegetation models was tested in terms of their wave attenuation [65]. Genetic Programming (GP), Artificial Neural Networks (ANNs), and a laboratory experiment were adopted. More recent studies have also assessed mangrove-induced wave attenuation by treating mangroves as flexible vegetation [66]. The XBeach model, which was commonly associated with wave attenuation by rigid vegetation modeling, was simulated with the flexible vegetation dynamic model. It was proven that modeling is reliable in predicting wave dissipation by flexible vegetation.

Recognizing the advancement in numerical model, assessment of flexible vegetation by waves should gain considerable attention of researchers. It defeats the gap in rigid vegetation assessment that may not address the motions and forces of vegetation. Therefore, more comprehensive result can be achieved in understanding the dynamics driven by mangrove while assessing for their attenuation performance.

Additionally, drag coefficient or Reynolds number and Manning's roughness coefficient are crucial elements in numerical modeling. They represent the frictions from the mangrove structures and seabed which mainly influence the dissipation of waves. Some numerical modeling made only assumptions on the coefficient value or taking the most relevant value from existing coefficients, whereby in reality the coefficients obviously vary according to several factors such as density and species. Future research on the accurate estimation of drag coefficient and Manning's roughness need to be studied in order to reduce this uncertainty.

Another important improvement for numerical modeling is to get more scenarios and conditions to be validated using the model. This is because their study may conclude a strong finding for the specific coastal conditions, topographies, and wave conditions that they simulated only. For more holistic and relevant conclusions on the mangrove protection performance, it is then suggested to evaluate the numerical model which is to be ran and assessed across various conditions and scenarios.

5.3. Field Studies

Almost all waves studied via field approaches are wind-driven waves because of the difficulty in assessing and measuring storm surges or tsunamis conditions. Field studies on the role of mangroves in combating wave energy are numerous with various affecting variables. For instance, Quartel et al. (2007) conducted an assessment in the Red River Delta, Vietnam, to compare the attenuation in the presence and absence of mangroves [25]. The *Kandelia candel* structures such as trunks and roots were emphasized as an additional factor that gave extra drag force compared to bare land. Other than that, Mazda et al. (2006) also discussed the difference of wave attenuation with and without mangroves [28]. However, this study is only limited to the Sonneratia species, which possess different types of roots compared to other species, therefore resulting in different attenuation rates.

A study conducted by Bao (2011) on wave attenuation has been widely used in research related to the adequacy of mangroves in dissipating waves [31]. Field data collected in coastal Vietnam were post-processed and developed into an exponential term incorporating almost all affecting factors including wave parameters and mangrove characteristics. Apart from that, this study was not solely subjected to mono-species mangroves but was rather applicable to all four mangroves of dominant species.

In the coastal waters of Jakarta, Indonesia, the *Avicennia marina* species were evaluated by Herison et al. (2014) with the forest width taken as the manipulated variable [67]. They produced a formula describing the wave attenuation in terms of mangrove width and energy. In an extension of this study, Herison et al. (2017) conducted a similar study with a field data collection in East Lampung Regency, Indonesia [38] later in 2017. They examined another variation of mangrove width and exponential functions were developed on the relationship between mangrove width and wave attenuation.

However, the drawback in both studies lies in the limited scope of wave dissipation-governing factors assessed, in which only forest width was considered in the determination of attenuation performance. Other affecting factors were collected as mentioned in their method; however, these factors were not well-presented in the result and discussion sections as the focus was only on the width of mangroves.

Ismail et al. (2019) studied wave attenuation and mangrove density in terms of root density [68]. The *Rhizophora* species attributing to complex aerial root system was studied. Most studies commonly analyze the effect of root densities on a horizontal basis; however, this study also investigated the effect of vertical density. Horizontally, the root density over certain mangrove widths was determined. On the other hand, vertically, the root density was measured from the bottom towards the top vertical layer. Both density influences on wave attenuation were observed.

While the findings may provide coherent results that support the theories of wave dissipation by mangroves, the assessment should be validated in other different locations too, considering the different setting, hydrodynamics, and wave conditions at each location. It is recommended to ideally conduct the similar field studies to compare the dissipation ability of mangroves across other conditions so that their applicability in other scenarios and circumstances can be addressed for a robust conclusion.

One obvious gap from the previous studies can be seen in the limited scope of wave dissipation governing factors assessed, in which only forest width and density were mostly considered in the determination of attenuation performance. Nonetheless, taking only certain driving dissipation factors while putting little attention to other significant factors would affect the rate of dissipation. For instance, mangrove age will likewise result in different dissipation rates depending on the maturity of the trees, although the high width of mangroves has been considered. In other words, this means that great width alone could not contribute to high dissipation if young mangroves were assessed.

Therefore, all affecting factors including mangrove structures, wave effects, and hydrodynamics should be incorporated in future studies on mangrove-induced wave dissipation. Bao's formulation has it all by incorporating all influencing factors in his formula; but, the limitation is that the formulation may overgeneralize among the species of mangroves as the developed equation fits all dominant species (e.g., *Rhizophora mucronata*, *Sonneratia caseolaris*, *Sonneratia griffithii*, *Aegiceras corniculatum*, *Avicennia marina*, and *Kandelia candel*). As such, this should have also been taken into account because different species act differently with the hydrodynamics of waves as they possess different structural characteristics. Thus, it is recommended that future studies segregate the analysis of different species apart from considering all affecting factors in wave attenuation analysis. A new numerical formula might also be produced for wave attenuation determination, but in a detailed categorization according to mangrove species.

6. Effectiveness of Mangroves in Wave Dissipation

Mangrove effectiveness varies depending on the conditions of vegetation and hydraulic parameters. As studies have experimented on various vegetation parameters and hydraulic conditions, the rate of wave reduction varies as well. Table 1 shows the reduction rate of several mangrove species tested in different vegetation widths and densities. These researches were carried out in variety wave conditions, consisting of normal wind-induced wave, cyclone-induced wave and tsunami wave. Mangroves shielding function from tsunami wave is a debatable issue. Mangroves is claimed incapable for tsunami protection where in some cases, mangroves get uprooted [69] and reduced their protection ability [70] due to the great energy and massive magnitude of tsunami which eventually become land debris that intruded into the land. While mangroves might not totally deplete the disastrous effect of tsunami, but the damages are lessened [36].

Thus, accounting the various parameters taken, the reduction performance in the following cases might not be comparable among cases, but the dissipation function on several wave conditions is still proven.

Table 1. Dissipation Effectiveness of Different Mangrove Species and Characteristics

Species	Mangrove characteristics	Wave Reduction Rate, %	Reference
Kandelia candel	Width, m: 100 Density, tree/m²: Not provided	20	Mazda et al. (1997) [71]
Avicennia	Width, m: 3, 5, 10, 20, 50 Density, tree/m²: Not provided	60 - 98	Herison et al. (2017) [38]
Sonneratia	Width, m: 100 Density, tree/m²: 0.08	50	Mazda et al. (2006) [28]
Rhizophora	Width, m: 400 Density, tree/m²: 0.2	30	Yanagisawa et al. (2009) [69]
Rhizophora	Width, m: 200 Density, tree/m²: 0.11 (Sparse) 0.16 (Medium) 0.22 (Dense) 0.36 (Super Dense)	77 86 88 91	Hashim and Khairuddin (2014) [72]
Rhizophora	Width, m: 50 Density, tree/m²: 11 (Sparse) 16 (Medium) 22 (Dense)	65 74 81	Hashim and Catherine (2013) [36]
Rhizophora model	Width, m: 300 Density, tree/m²: 0.5 – 1.7	60	Narayan et al. (2011) [73]
Coastal tree model	Width, m: 100 Density, tree/m²: 0.3	50	Mazda et al. (2006) [28]
Mangrove model	Width, m: Not provided Density, tree/m²: 0.175	49 - 55	Samiksha et al. (2019) [74]

Based on Table 1, it can be summarized that almost all studies did not consider bottom friction calculation, except for Yanagisawa et al. (2009) and Samiksha et al. (2019) [69, 74]. As previously explained, bottom friction is the driving factor influencing the wave reduction, along with the vegetation drag force. Field experiments commonly neglect the individual effect from the bottom friction and rather assume the friction, likewise, as the vegetation drag force. This may result in value overestimation and contribute to some errors. However, Mazda et al. (2006) justified that the bottom friction is negligible only if the water depth is higher, to which the bottom friction appears to be insignificant in reducing the wave height [28]. More accurate data can probably be produced from numerical modeling where several models can include and simulate the bottom friction coefficient in the analysis.

7. Mangroves Rehabilitation and Conservation Efforts in Malaysia

Recognition of the vital role of mangroves as a natural wave barrier has raised awareness on the importance of mangrove conservation and rehabilitation. Besides being destroyed due to climatic changes [75, 76] and natural hazards (e.g., tsunami, cyclone, and erosion [77, 78]), land development has also resulted in mangrove losses. Clear-cutting to make room for human activities such as aquaculture ponding and coastal urbanization [79, 80, 81], as well as land-use changes have unfortunately led to ecosystem alteration that causes the degradation of mangroves. This signifies that sustainable mangrove management, conservation, and rehabilitation are crucial for maintaining the effective defense mechanism of mangroves.

The establishment of protected areas in undisturbed regions is the most popular strategy for conserving mangrove ecosystems. Wildlife sanctuaries, national parks, and nature reserves are among the common initiatives [82]. The latest statistics by the Forestry Department of Peninsular Malaysia showed that 90,000 hectares of mangroves in Peninsular Malaysia are classified as Permanent Forest Reserve [83]. By the year 2018 in Sarawak, 11,084 hectares and 12,950 hectares of mangroves have been gazetted as Permanent Forest Estate and Totally Protected Area, respectively [84]. Meanwhile, Mangrove Forest Reserve in Sabah covers approximately 234,680.27 hectares as of 2020 [85].

Since 2005, the Tree Planting Program with Mangroves and Other Suitable Species Along National Coastlines has been regarded as the national rehabilitation program in Malaysia [86, 87] with the aim to restore the ecosystem of mangroves. Comp-Pillow and Comp-Matt planting techniques introduced (refer Figure 3) in this project are among the known techniques in the mangrove research and development area [88]. Both were tested in the mangrove restoration area of Sungai Haji Dorani in Kuala Selangor [89]. Back in 2008, another coastal rehabilitation effort was carried out in Sungai Haji Dorani for sediment trapping and stabilization through the rehabilitation of mangroves [90].

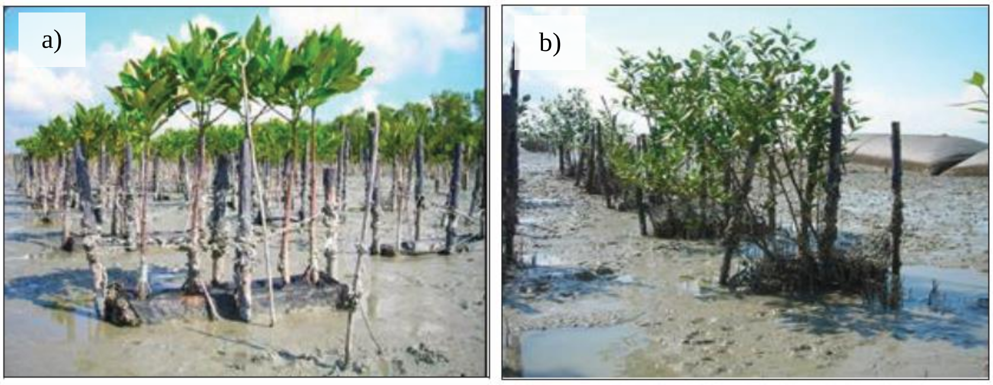

Figure 3. a) Comp-Matt technique for *Rhizophora apiculata* planting, b) Comp-Pillow technique for *Avicennia alba* planting [88]

Mangrove roots are widely known for their functionality to accumulate sediments and, thus, stabilizing the shoreline [91, 92, 93]. The coastal structure consisting of the detached breakwater was adopted in this project along with the biotechnical approach for mangrove planting to aid in suitable site conditions for mangroves to establish, grow, and prevent from being washed away by strong waves. Monitoring revealed that 30% of the planted saplings survived after eight months, indicating moderate success. This also means that more than half the mortality rate of saplings was recorded in the project.

On the west coast of Peninsular Malaysia, the rehabilitation efforts are mostly significant, especially after the Indian Ocean Tsunami struck in December 2004. Based on an interview with the coastal communities near Kuala Teriang, Langkawi, mangrove replantation has been implemented at the site along with the discovery of some bamboos expected to be used as techniques during the replantation. This is further proven when a study claimed that the replantation in Kuala Teriang to Sungai Melaka was among the successful efforts [94]. Geotubes of 100 m long were laid in the front beach area for coastal protection measures. In addition, replantation in Lekir, Perak was claimed to have failed even after several attempts have been done.

Sabah with the largest coverage of mangroves in Malaysia [82, 95] was optimistic with its conservation and restoration efforts to date [96]. The enforcement of Forest Enactment 1968 under the state legislature has assured the conservation status of the mangroves, where harvesting for domestic use is only allowed on a small scale. An area of 738 hectares has been rehabilitated throughout four years since 2006. Subsequently, from 2011 to 2014, the Sabah Forestry Department initiated a collaboration with the International Society for Mangrove Ecosystems to enhance the mangrove rehabilitation effort. A total of 1,396.4 ha of mangrove degraded areas have been restored by the end year of 2020 [85].

Currently, the Malaysian Government channels specific allocation in Budget 2021 to support mangrove replantation in Tanjung Piai, Johor, and Kuala Sepetang, Perak, as part of natural resources and biodiversity preservation effort. The Government had also allocated approximately RM48 million for mangrove rehabilitation under the 9th Malaysia Plan, with RM8 million for research and development areas [79, 97]. Nevertheless, one of the common challenges encountered in the rehabilitation project would be the funding issue [85, 96]. The allocation was often inadequate to allow for more sustainable efforts to be performed in the country.

In 2014, the Sabah Forestry Department had suggested an additional allocation for the mangrove project, yet this remains insufficient in 2020 and eventually restricts the scope of its rehabilitation effort. Prior to the national rehabilitation project as stated previously, the State Governments have added their own budget to run the national project. This explains that, instead of the Federal Government alone, the State Government should be more considerable to support similar biodiversity projects through some allocation in the state budget.

After all, every effort from individuals to the government sectors and everyone in between including the non-governmental organizations (NGOs), institutions of higher learning, related agencies, stakeholders, and local communities matters in the conservation and rehabilitation efforts from national to small scale projects. A study by Martinez-Espinosa (2020) by interviewing the local communities near the Matang Mangrove Forest Reserve (MMFR) revealed that the surrounding communities are willing to show their participation in the management and decision-making process of the current management [98].

Public participation and community involvement are also among the key components influencing these efforts. The local community's participation would instill not only awareness but also ownership towards the mangroves. Aside from that, a profound understanding of forestry, ecological engineering, and coastal engineering must be incorporated for the sustainable and proper planning of mangrove conservation and rehabilitation purposes. This includes the consideration of site-species suitability, planting techniques, environmental aspects of soil and water pH, salinity, hydrology, and wave energy. Thus, better protection to safeguard the coastline can be served with not only extensive conserved and rehabilitated mangroves sprawl, but also the promising mangrove structures that can withstand severe waves and wind attacks.

8. Implementations of Mangroves as Coastal Bio-shield

The rehabilitation and conservation efforts implemented by several countries have signified mangroves as an important element in protecting their coastline and served as a coastal bio-shield. These countries are including Sri Lanka, Philippines, Gulf Coast of South Florida, and Caribbean Nations, to name a few. The conservation and restoration efforts were made significant especially after evidently benefitted as protection during tsunami, cyclone, and typhoon events.

Mangrove's coverage in Philippines has been degraded to make way for aquaculture activities such as fish and prawn ponding which were increasing. While numerous replantation efforts with huge allocations were implemented, the mortality rates turned out to be higher, with only 10% to 20% rates of newly planted mangroves survived [99]. Two main factors were analyzed concerning the poor survival which are including wrong species matched with site unsuitability. Despite planting according to their ecology, *Rhizophora* species were chosen instead of the natural colonizer in the sandy substrate coastline area, *Avicennia* and *Sonneratia* species. This preference was rather preferred since *Rhizophora* species are having large propagule which would not have to undergo intensive nursery period due to the smaller seedlings of the other two species. Moreover, the occurrence of *Rhizophora* species is commonly in the sheltered area, which explains the high mortality when planted in the fringing coastal area that is most suitable for *Avicennia and Sonneratia.* Figure 4 indicates *Avicennia marina* that colonizes naturally in the respective coastal area versus the favorable species of *Rhizophora* that suffered low survival rates.

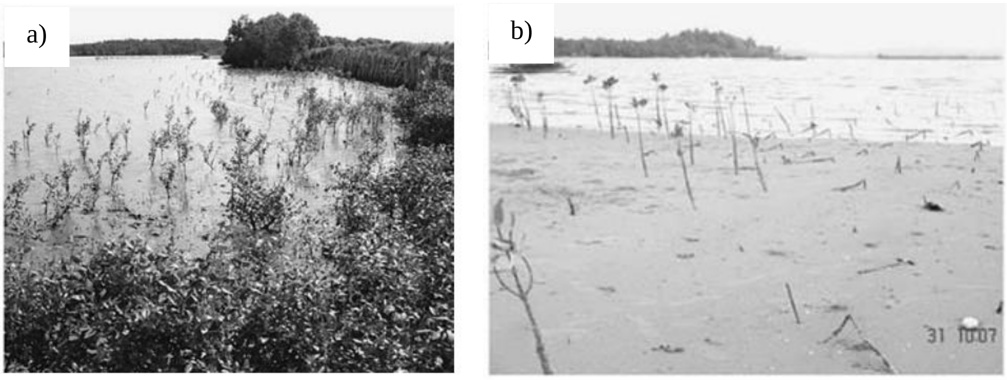

Figure 4. Colonization of a) *Avicennia marina* species, b) *Rhizophora* species at the similar habitat [99]

More recent, the protective role of mangroves has brought more attention when the country was hit by Super Typhoon Haiyan in 2013. The disaster was claimed as the deadliest in Philippines [100] and has resulted an estimated death toll of 6,293 people with 28,689 and 1,061 injured and missing, respectively as recorded on 3 April 2014 [101]. The severe storm surges and strong wind caused great losses in lives, property, and livelihood in several islands in the Visayas region [21]. This region, as claimed by [99] was the most vulnerable to typhoon events compared to the bigger islands of Luzon and Mindanao, thereby mangroves replantation was implemented for their buffering function. Aside that, another success replantation was reported in Kalibo Island which supported shoreline stabilization and created protecting zone from typhoon. Despite being low-funded project, Kalibo demonstrated high survival rate and revealed that regular maintenance is the key. As of 2021, the government implemented the Enhance National Greening Program as an extension to National Greening Program in 2011-2016, an initiative to grow 1.5 billion trees in 1.5-million-hectare land for restoration of degraded forest [102].

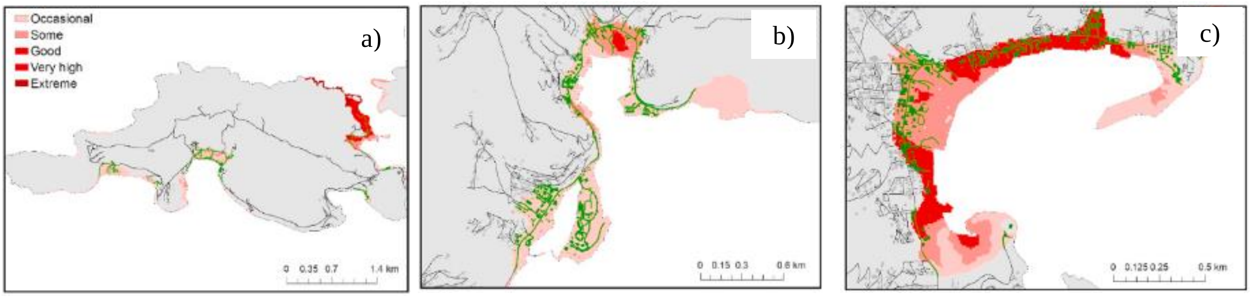

Figure 5. Level of protection as indicated by pink-red shades in coastal areas of (a) Jost Van Dyke, (b) Sea Cows Bay, and (c) East End [103]

British Virgin Island, Caribbean benefitted the protective nature of mangrove ecosystem in reducing flood risk especially in three coastal areas of Jost Van Dyke, Sea Cows Bay, and East End [103]. The prediction from their vulnerability model shown that the flood risk can be diminished up to 475m inland even with a small-scale mangroves restoration. They projected a suitable area of 2.8 km^2 for red mangrove replantation within the three areas which can serve protection from flooding up to 200 m inland at Great Harbour and White Bay, Jost Van Dyke, 300 m inland at Sea Cows Bay, and 475 m inland at the East End. As forecasted, at least 167 buildings in Jost Van Dyke, 285 buildings in Sea Cows Bay, and 268 buildings at East End will receive protection, including the schools, clinic, worship places etc. They also suggested that species - site suitability and effective methods are important to be accounted in any replantation efforts to be successful. Figure 5 depicts the flood protection that may be served by the restoration of red mangroves at the three identified areas.

Mangroves were overexploited for utilization of wood products in Kenya [104]. This has led to mangroves losses aside from other factors such as oil pollution, climate change and salt extraction. The poor cutting planning in mangrove management made the degradation worsen. However, recognition of many other good benefits from mangroves ecosystem had become a turning point for restoration effort. Kenya Marine and Fisheries Research Institute (KMFRI) was pioneering the effort in 1991 and up to 2007, more than a million trees have been replanted with survival rates ranging from 10% to 70% depending on the plantation areas [105]. However, main issue arose in mangrove management whereby there was shortage in basic information and data for the development of inclusive management plan as well as lacking participation from the community.

In Bangladesh, they first implemented the replantation efforts in 1966 [106]. Approximately 60 km mangroves have been planted in the frontal area of their low-lying land by 2013. *Sonneratia apetala*, among other mangroves planted species, was the top successful in the replantation [107]. *Sonneratia apetala* created maximum friction and obstruction to the water flow. While this species appeared as the most outstanding in the attenuation performance from storm surges, the *Sonneratia* planted area were inclined to pest attacks. Hence, multispecies plantation is recommended where the potential species that can colonize in the same muddy substrate zonation would be *Avicennia officinalis* and *Bruguiera gymnorhiza*. They emphasized that for an optimum protection, mangroves should be implemented alongside with other engineering hard structures. A similar claim was also made by [108] which explained construction and maintenance cost of the hard structures can be reduced due to a lower height of structure design.

Thailand encountered massive degradation of mangroves between 1975 and 1996 due to conversion to shrimp ponding. Initially, the areas shown in Figure 6 were all mangroves. Nevertheless, the mangroves were cleared to allow for aquaculture activities which they left only a few lines of mangroves in the frontal areas for protection purpose [29]. Unfortunately, these small coverages of mangroves were unable to withstand the severe wave actions and thus, resulting to mangroves mortality and loss of protection line. This scenario made the coastal communities realized that rehabilitation is required for secure protection. The replantation was however reported high in mortality rates because of strong waves and pest attacks. Thereby, the incorporated various structures such as rock revetments, bamboo breakwaters, concrete-pile breakwaters, and sand sausages or geo-tubes to enhance the growth rates yet, few drawbacks were discovered, e.g., expensive, difficult installation, low materials durability, short lifetime durations and even less effective in dissipating waves.

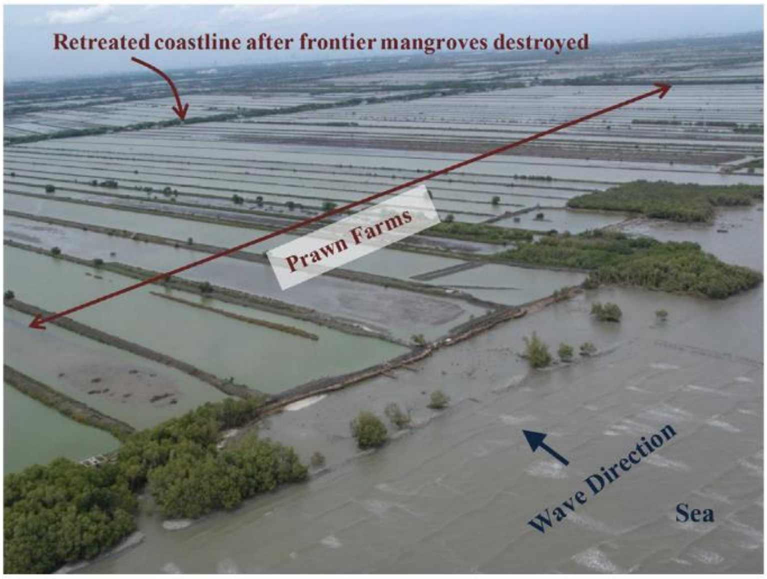

Figure 6. Conversion of previously planted mangroves area into shrimp ponding [29]

9. Conclusions

Protection against coastal hazards has been identified as an important service offered by mangrove ecosystems. Mangroves demonstrate an impressive resistant towards the incoming severe wave. Their developed and dense structures mitigate the forceful impacts and reduced the wave height and energy. This paper highlights that the performance and effectiveness of mangroves in wave dissipation is relying on various governing factors including mangroves parameters such as width, density, species, age, and hydraulics factors such as water depth, bathymetry, and incident wave height. After reviewing previous research, the following recommendations for future research are proposed:

- Regardless of numerous field assessment, laboratory experiments and numerical modeling have been carried out in proving the dissipation capacity of mangroves, but the focus is commonly concentrated on few influencing factors of mangroves parameters only. While all parameters are important, future study incorporating all governing dissipation factors should be developed where the specific analysis for each species of mangroves need to be considered. This could be possible with the integration of numerical modeling.
- Despite the evidence that support every study approach, there is still a need to validate the hypothesis in different locations and scenarios so that strong and holistic conclusion can be drawn. Different settings may have different affect to the attenuation process, e.g., in terms of bathymetry, wave conditions etc. More comprehensive findings across variety topographies and scenarios may reduce uncertainty.
- The extent of protection of the rehabilitated mangroves is still uncertain and has not been fully addressed, hence their efficacy should be studied to guarantee sufficient protection by mangroves.

In addition to that, previous studies on mangroves protection role suggested the idea of proper coastal management, maintenance and administration are required in conserving and restoring mangroves ecosystem for long term protection security by this vegetation towards the coastline. Acknowledging the possibility of frequent and increasing coastal resilience to future natural disasters, therefore effective conservation and rehabilitation are a pressing concern.

10. Declarations

10.1. Author Contributions

Conceptualization, T.H.; writing—original draft preparation, K.E.A.; writing—review and editing, K.E.A.; visualization, K.E.A.; supervision, T.H.H., A.M.; funding acquisition, H.A.M., T.H. All authors have read and agreed to the published version of the manuscript.

10.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

10.3. Funding

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10.5. Conflicts of Interest

The authors declare no conflict of interest.

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