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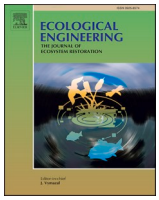
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Are floating mangrove breakwaters effective for wave attenuation? - A Literature Review

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ABSTRACT

Human-induced global warming, caused by greenhouse gases, raises temperatures and sea levels, posing risks to coastal communities and ecosystems. Interest in nature-based alternatives like mangroves and living shorelines is growing due to their ecological benefits and ability to mitigate waves, protecting vulnerable coastlines. Floating breakwaters have demonstrated promise in attenuating waves compared to their submerged counterparts. Similarly, floating mangroves detached from the shoreline and suspended on the water's surface have emerged as an alternative solution due to their potential ability to reduce wave force while providing additional benefits. This review aims to compile information on field, laboratory, and numerical experiments of floating breakwaters and mangroves testing their efficiency for wave attenuation. We found that floating mangroves have the potential for wave reduction, although this differed among mangrove species, with the highest reduction in *Rhizophora* (80 %) followed by *Avicennia officinalis* (55 %), *Sonneratia* (50 %), and *Kandelia candel* (20 %). *Rhizophora spp* was the most studied and likely to be the most effective due to its complex root system. Field trials and feasibility studies showed that testing the wave-reducing ability of this integrated structure is essential to tackle the challenges caused by strong waves. Ultimately, this review seeks to deepen our comprehension of mangrove-based floating solutions. It highlights their significance in protecting coastlines and promoting ecological balance in rising sea levels.

1. Introduction

Carbon dioxide and methane are the primary greenhouse gases that cause global warming. The rise in temperatures elevates sea levels (Filonchyk et al., 2024), surpassing anything observed in the past 2500 years (NASA, 2023). Climate change and rising sea levels have increased the frequency and intensity of natural disasters (Dong et al., 2022), and increased wave energy in the coastal zone (Reguero et al., 2019), causing significant challenges to low-lying coastal cities.

The challenges posed by climate change are combined threats of sea-level rise, storms, erosion, inundation, and rapid degradation of natural coastal systems (Hinkel et al., 2012; Reguero et al., 2021). Furthermore, climate change impacts tourism (Monioudi et al., 2018), global fisheries, and aquaculture (Griggs and Reguero, 2021). Coastal flooding caused by tropical cyclones will be intensified by the combined impacts of sea-level rise and changes in storm frequency and intensity (Griggs and Reguero, 2021). This trend raises concerns among coastal and island residents, who comprise around 44 % of the global population (Dedekorkut-Howes et al., 2020).

Historically, rock revetments, seawalls, levees/floodwalls, and sandbars have been employed to combat coastal erosion, shoreline retreat, and flooding. These methods involve hardening the shoreline to shield against rising water levels and wave impacts. Although effective, these structures can have undesirable consequences such as negative visual impacts, reduced public beach areas, disruption of natural sand supply, and passive erosion (Griggs, 2005). Additionally, hard structures contribute to shoreline encroachment and the narrowing of coastal habitats (Leo et al., 2019). These alterations can disrupt ecological processes and cause habitat loss in aquatic and terrestrial environments.

The increasing cost of coastal armoring has led to alternative approaches that merge "engineering" with "building with nature" for coastal defense (Bridges et al., 2018; NOAA, 2015). "Soft" approaches include beach and dune restoration through vegetation and creating "living shoreline" alternatives (Griggs and Reguero, 2021). These living

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shorelines include coral reefs, mangroves, salt marshes, beach and dune systems, and vegetation (emerged and submerged). These ecosystems attenuate waves, mitigate the effects of sea-level rise, and retain sediments or create land (Temmerman and Kirwan, 2015; Temmerman et al., 2013). Maintaining or recreating natural ecosystems could be a cost-effective adaptation strategy to deliver economic, social, and environmental benefits (Orton et al., 2015; Whelchel et al., 2018). However, soft approaches, like vegetated shorelines and dunes, are susceptible to erosion and removal during severe wave and storm conditions. Long-term sea-level rise can also affect their persistence, particularly where space for migrating landwards is scarce and where conditions for self-adaptation are not favorable. For instance, where hydrology and sediment supply have been heavily altered (Griggs and Reguero, 2021).

Wave action is widely acknowledged as a leading cause of coastal erosion, with increased energy attributed to global warming (Reguero et al., 2019). Thus, designing a structure to safeguard the coastal ecosystem for long-term sustainability is vital. A nature-plus engineering structure for wave dissipation could be a complementary solution. However, information on the effectiveness of floating breakwaters and, specifically, floating mangroves is scarce. Here, we investigate whether mangrove breakwaters are as efficient as natural mangroves or other grey infrastructure in reducing waves in the coastal zone. We review the current literature on the effectiveness of floating mangrove breakwaters for wave attenuation. First, we provide an overview of the characteristics of floating breakwater (FB) that will help achieve this goal. Secondly, we analyze the biological and physicochemical characteristics that make mangroves efficient for coastal protection. Then, we define what is a floating mangrove breakwater and synthesize studies that include (1) field investigations, (2) laboratory experiments, and (3) numerical experiments with a combination of field and/or laboratory works. The goal is to analyze the potential of this innovative solution to ameliorate wave energy in the coastal zone.

2. Floating breakwaters

2.1. The role of floating breakwaters

Breakwaters, called wave attenuators, are coastal structures that lower wave activity in nearshore areas. They reduce coastal erosion and create safer shelters. Safer shelters are engineered or designed structures to withstand or mitigate the impact of coastal hazards, ensuring the safety of those who reside in these areas (Dai et al., 2018). Floating breakwaters (Fig. 1) imitate the functions of natural or artificial breakwaters by reducing wave impact and providing safe docking space. They are used when conventional breakwaters are impractical or temporary protection is needed due to varying water levels (Raju and Arockiasamy, 2022).

Conventional bottom-founded breakwaters have rectangular or trapezoidal shapes to withstand bottom overturning. However, their various shapes and materials pose challenges in effectively working with wave energy distribution. The bottom-founded breakwaters can steepen the foreshore (Ranasinghe and Sato, 2007) and disrupt natural water circulation. It leads to the redistribution of sediment that can result in coastal erosion (Sulaiman and Hidayat, 2020). However, floating breakwaters can be useful as they are not affected by water depth, seabed conditions, and tidal variation. They also have little interference with water circulation compared to bottom breakwaters. Floating breakwaters can be easily repositioned, relocated, and removed. Furthermore, they can be more cost-effective than traditional breakwaters (Chun-Yan et al., 2016).

2.2. Wave attenuation experiments on floating breakwaters

A floating breakwater can reflect, dissipate, or transmit incident wave energy. An ideal floating breakwater aims to maximize dissipation while minimizing both reflection and transmission. However, energy dissipation primarily occurs due to viscous dissipation, turbulence, nonlinear wave breaking, and overtopping (Ozeren et al., 2011). The hydrodynamic efficiency of the floating breakwater system can be measured by calculating wave transmission, reflection, and energy dissipation coefficients. These calculations are performed within the function of wave period and wave height separately (Chun-Yan et al., 2016).

Numerous types of floating breakwaters exist and can be classified into four types: box type, pontoon type, mat type, and tethered type (McCartney, 1985). Furthermore, Dai et al. (2018) suggested additional types including frame, horizontal plate and resonance type, spar buoy, porous floating breakwater, and plastic float modules based on their shapes. Different types of floating breakwaters utilize diverse methods to dissipate wave energy based on shape. So far, several experiments have been conducted, and various innovative floating breakwater systems have been proposed to assess their effectiveness in wave attenuation (Table 1). For instance, Zhang et al. (2020a) studied the hydrodynamic performance of a floating breakwater (Wave Energy Converter) system, considering coastal reflection. Further, Zhou et al. (2022c) proposed parallel twin parabolic arc floating breakwaters to enhance wave attenuation.

There have been many successful FBs. For example, 'V'-shaped floating breakwater was used in the offshores of Cape Canaveral, Florida, in 1999. The aim was to reduce wave conditions from Sea State 3 (wave height 0.5 - 1 m, wind speed of 7–10 knot) to Sea State 2 (wave height of 0.2–0.5 m, wind speed of 4–6 knots) to ensure safe vessel operations (Briggs et al., 2010). The accuracy of the wave data was confirmed by comparing it to numerical results obtained from WAMIT software. Implementing the 'V'-shaped floating breakwater significantly reduced wave height, reaching up to 50 %. Further, Wang and Sun (2010) conducted experimental research on a porous floating breakwater consisting of diamond-shaped blocks to assess its wave attenuation and mooring system force. The results demonstrate that diamond-

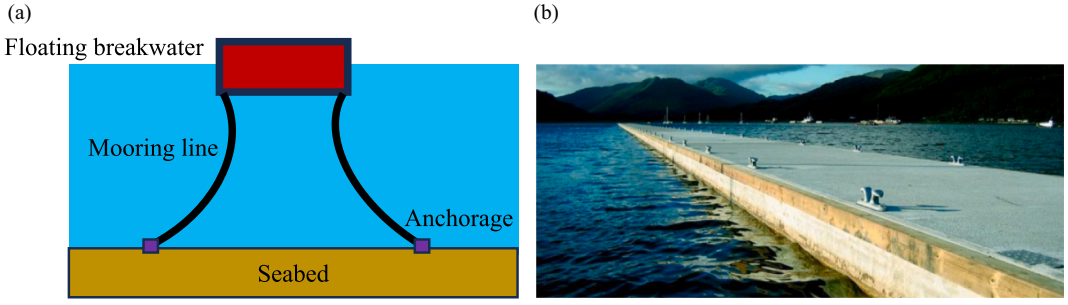


Fig. 1. (a) floating breakwater diagram (b) Example for FB- Holy Loch breakwater in Scotland (Maritime journal.com, 2017) (https://www.maritimejournal.com/breakwater-beats-the-weather-at-holy-loch/470075.article).

Table 1
Wave attenuation Experiments on different types of Floating Breakwaters [Notations: FB-Floating Breakwater, B-Width of the FB, CV-Current velocity, E- laboratory experiment, E_{LOSS} -Value of the dissipation of incident wave energy, F- field experiment, h-FB height, Kr-Reflection coefficient (the ratio of the amplitude of the reflected wave to the incident wave), Kt-Transmission coefficient (ratio of the wave heights of the transmitted and incoming waves), L-Wavelength (distance between two identical points on successive waves: crest to crest, or trough to trough), N -numerical experiment, S/L- relative spacing, wd-water depth, Wgap-Distance between the two pontoons/ gap width].

Type of Floating breakwater	Method	Material	Wave attenuation results	Reference
Single box, double box, and the board net	E	Single, double box FB: rigid thin boards Board net FB: thin plane board, with some rows of net Polyethylene	Board net FB reduces CV by nearly 20 %.	(Dong et al., 2008)
Cylindrical FB system	E	Reinforced concrete	Kt ~ 0.93	(Chun-Yan et al., 2016)
Spar buoy FB (Semi-closed Pipe FB	E,N	Pipe-polyethylene	Kt maximum at S/L = 0.5 Kt minimal at S/L = 0.3	(Liang et al., 2004)
Box type	N	Polyethylene	Kt decreases with the increase of B/L Kt decreases quickly when B/L < 0.25, and decreases slowly when B/L > 0.25	(Sun et al., 2022b)
I-shaped FB	N		I shaped FB outperforms the Box-type FB in wave elimination. Kr rises when B/L = 0.30	(Sun et al., 2022b)
Cylindrical Dual Pontoon-Net Floating Breakwater (CDPNFB)	E,N	Cylinders-reinforced concrete Vertical type-metal sheets Nets-knotless polyethylene Mooring line-stainless steel	Greater vertical net heights interact better with waves, reducing wave reflection and transmission.	(Ji et al., 2017)
Floating pontoon-type breakwater	E	Rubber	Kt < 0.1, occurs at B/L = 1.32 Kr is around 0.80 at B/L = 0.56 ~ 0.65	(Huang et al., 2020)
Porous FB	E	Perforated diamond-shaped blocks	Kt < 0.5 and E_{LOSS} > 0.78 as B/L > 0.323	(Wang and Sun, 2010)
WhisprWave FB	E, N	E- 3D printer fabricates FB	K_t can be decreased to below 0.8 at B/L > 0.3, but it can be increased to over 0.95 if B/L is less than 0.1. FB's performance in attenuating long waves may not be entirely satisfactory.	(Peng et al., 2023)
Plant ecological floating breakwater (PEFB)	E, N		FB with plants shows more effective wave attenuation than without plants	(Sun et al., 2022a)
"⊥" Type FB	E	Hylam sheet	For regular and random waves, Kt < 0.5, at wd/L = 0.094–0.452	(Neelamani and Rajendran, 2002)
Parallel twin parabolic arc FB	N		Rigid twin FB optimize in wave attenuation at W_{gap} = 6.0 m	(Zhou et al., 2022c)
Modular arch-shaped structure (floating forest)	N	-Concrete hulls -Arrays of tubes on the deck area (HDPE or plastic composite materials)	1 km FB can shield a 600 m lee area, reducing wave energy by 40 %–60 % and peak wind speed by 10 %–80 %.	(Wang et al., 2021)
Pneumatic type FB	N		In fixed breakwaters, pneumatic damping effectively reduces transmission when L/B > 2.54, helping to block longer waves.	(Koo, 2009)
Steel FB with truss (FBT)	E	Steel	Kt of the FB is larger when (h/L) $(h/L)_{0.5}$ > 1.2. Kt decreases as the pontoon width and truss increases	(Uzaki et al., 2011)

shaped blocks can reduce incident wave height by dissipating more wave energy than reflecting it (Kt < 0.5, and dissipation of incident wave energy >0.78).

Pontoon and box-type FBs are the most common floating breakwaters as they are easy to fabricate, install and they are effective at attenuating waves by damping and reflection (Dai et al., 2018). Ji et al. (2017) used physical models to study the hydrodynamic behavior of a dual pontoon floating breakwater attached to one or more plane nets. The results showed that the new floating breakwater outperforms traditional dual pontoon FBs. This is especially evident when handling long periods and large amplitude waves. Huang et al. (2020) experimented with the performance and hydrodynamic response of a flexible floating pontoon-type breakwater. They found that this breakwater performs better with a more considerable relative breadth (Kt can be smaller than 0.20 for B/L > 1.0). Continuous pontoons without gap configuration perform best for relatively long waves (Kt < 0.5 with B/L ≥ 0.5). Overall, FBs are used in various forms and are effective at different B/L ratios. For example, Kt can be decreased below 0.8 at B/L > 0.3 and can be increased to over 0.95 at B/L < 0.1 in the WhisprWave FB (Peng et al., 2023).

3. Mangroves

3.1. The role of mangroves

Mangroves are halophytic plants (Spencer et al., 2022), widespread across coastal regions of tropical and subtropical latitudes (Veettil et al., 2019). They are among the most productive ecosystems in the world (Kathiresan and Bingham, 2001). Mangroves are distributed across 123 countries and territories, comprising 73 species (Spalding et al., 2010). The total global mangrove coverage is 147,359 km^2 (Bunting et al., 2022). Mangroves possess distinctive traits such as aerial roots for anaerobic soil growth and viviparous seeds for propagule dispersal. They also have salt excretion mechanisms for removing excess salt and rapid canopy formation. These traits collectively enable them to thrive in saline and waterlogged conditions (Hogarth, 2015; Sandilyan and Kathiresan, 2012). Their structure attenuates waves and decreases water levels, while their intricate root systems effectively trap sediments and mitigate erosion (Marois and Mitsch, 2015; Montgomery et al., 2018). Mangroves naturally protect coasts against flooding, erosion, sea level rise, and storm surges (Guannel et al., 2016).

Moreover, mangroves are efficient carbon sinks, storing 15 % of the total coastal carbon in sediments despite only occupying 5 % of the global coastal area (Ranjan, 2019). They can store up to four times more carbon than terrestrial forests (Leal and Spalding, 2022). Consequently, mangroves have gained significant scientific attention as natural systems for mitigating greenhouse gas emissions (Donato et al., 2011; Fourqurean et al., 2012). Mangroves are vital food sources, breeding areas, and nurseries for various terrestrial and marine organisms. This includes numerous commercially valuable species and juvenile reef fish (Igulu et al., 2014). Also, mangroves are habitats for birds, insects, mammals, reptiles, sponges, algae, and bivalves (Hogarth, 2007). These habitats host high species densities and are productive enough to sustain coastal fisheries for prawns and fish (Manson et al., 2005). Several studies have assessed their immense value on a global scale, considering their economic, ecological, and cultural importance. Mangroves support more fish production, equivalent to 265 kg per hectare yearly (Jänes

et al., 2020). In places like the Gulf of California, the small fishing businesses connected to mangroves make up 32 % of all catches and bring in about US $37,500 for every hectare of mangrove fringe habitat (Aburto-Oropeza et al., 2008). Mangroves also contribute to intermediate services such as nutrient cycling. Moreover, they have recreational and tourism significance (Carugati et al., 2018; Kristensen et al., 2008; Rivera-Monroy et al., 2017).

3.2. Wave attenuation experiments on mangroves

Different studies emphasize the importance of mangroves in wave attenuation (Kamil et al., 2021). Various factors influence the ability of mangroves to reduce wave height and strength, including forest structure, geomorphology, and hydrodynamic conditions (Fig. 2). Two main energy dissipation mechanisms in mangrove forests are wave motion attenuation by trunks, branches, and roots and bottom friction (Hadi et al., 2003). The mangrove roots and trunks obstruct the wave's orbital motion (Othman, 1994) and create additional friction, increasing resistance to incoming waves (Hashim and Catherine, 2013). The wave-trunk interaction in a less dense forest influences the wave height only slightly, especially for a smaller incident wave height. For a more significant incident wave height, the wave-trunk interaction causes a wave height reduction of about 20 % over 100 m forest. Wave breaking significantly impacts wave attenuation in sparse forests, but wave-trunk interactions in denser forests overshadow this effect (Vo-Luong and Massel, 2008).

Furthermore, Sánchez-Núñez et al. (2020) found that mangroves attenuate waves through drag forces, friction, and wave reflection from prop-roots, oysters, shallow nearshore profiles, and cliffed edges (a high area of rock with a very steep side on a coast). In addition to mangrove forests, intertidal bare mudflats also significantly reduce wave height and dissipate wave energy, regardless of distance and tidal regime (Loi et al., 2024). Besides bottom friction, tree density, incoming wave heights, and root submergence control the wave attenuation rate within mangrove forests (Lekshmy Devi et al., 2021). When comparing the wave height reduction for similar water depths (h = 1.25–1.55 m), the reduction by mangroves was higher by bottom friction only (Quartel et al., 2007).

Wave reduction differs among species and can be caused by the drag forces of *Sonneratia* sp. (Mazda et al., 2006). *Kandelia candel*'s drag force effect on long-period waves is weak due to the absence of pneumatophores compared to *Bruguiera* spp. and *Rhizophora* spp. (Mazda et al., 1997). The vertical configuration of *Sonneratia* sp., with its complex composition of trunks, pneumatophores, and leaves, makes it unsuitable to apply parameters like the apparent drag coefficient, unlike *Kandelia* sp. (Mazda et al., 2006). The drag force due to the dense network of trunks, branches, and above-ground roots was the leading cause of the high rate of wave reduction (Quartel et al., 2007). Seedlings exhibited more wave attenuation due to higher drag forces impacting incident waves than half-submerged mature trees. This highlights the notable attenuation ability of the seedlings (Zhou et al., 2022b). Despite *Rhizophora* species showing better wave energy attenuation with their roots than *Ceriops*, densely populated *Ceriops* remain effective in reducing wave energy (Hadi et al., 2003). Thick leaves also cause wave reduction, which is insignificant if waves do not reach leaf height (Mazda et al., 2006). Additionally, Teh et al. (2009) indicated that reducing wave heights and velocities depends on factors such as wave height, period, wavelength, and mangrove characteristics, including forest width and density.

Wave height decreases (93–98 %) exponentially on mild slopes (1:80, 1:40). However, on steeper slopes, the decrease is more gradual and influenced by factors like water depth, shoaling, breaking, and reflection (Parvathy and Bhaskaran, 2017). In summary, different mangrove species vary in their ability to attenuate waves, depending on factors such as mangrove vegetation characteristics, geological factors, and hydrodynamic conditions. Understanding the complex interaction of these factors is essential for effective coastal protection and management strategies.

3.2.1. Field experiments

Field experiments are carried out in natural settings rather than controlled laboratory environments. Wave reduction experiments have been conducted across a tidal flat and contiguous mangrove area in the Red River Delta, Vietnam (Quartel et al., 2007). Wave height reduction

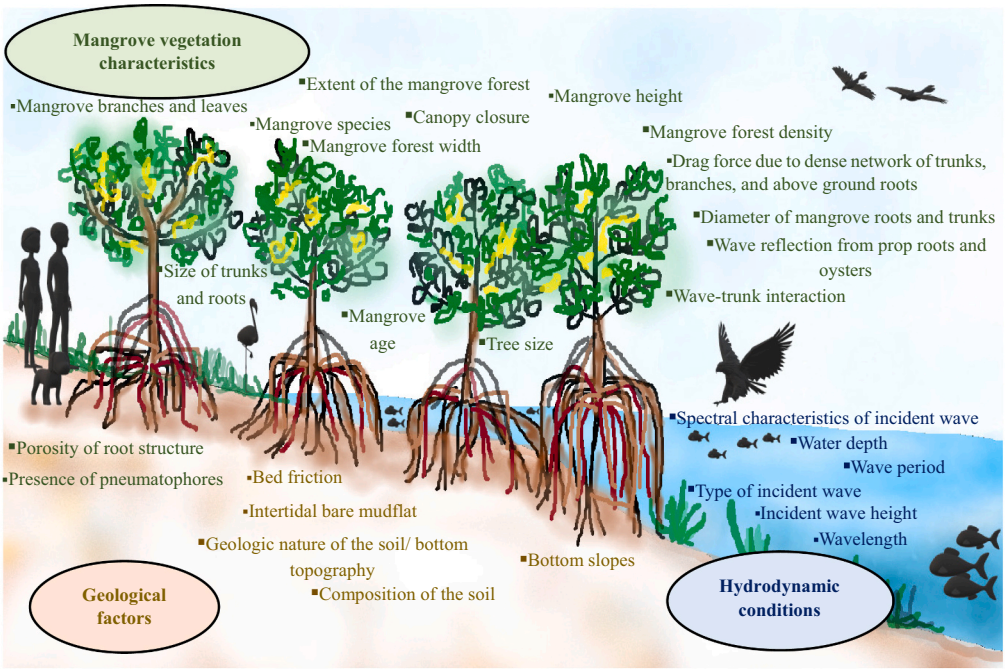


Fig. 2. Factors influencing the wave attenuation capacity of mangrove ecosystem (Illustration by K.Risheharan, 2024 based on Bao, 2011; Burger, 2005; Fatimah et al., 2008; Hashim et al., 2013; Loi et al., 2024; Mazda et al., 1997; Mazda et al., 2006; Parvathy and Bhaskaran, 2017; Quartel et al., 2007; Rasmeemasmuang and Sasaki, 2015; Teh et al., 2009; Vo-Luong and Massel, 2008).

by mangroves was 5–8 times greater compared to bottom friction alone. Bao (2011) analyzed the connection between wave height and mangrove forest structures. It was determined that a minimum forest width of 40 m is needed for coastal protection in Vietnam. Wave-breaking changes due to mangrove loss were estimated through wave evolution modeling (Sánchez-Núñez et al., 2020). The results revealed that mangroves contribute to wave attenuation through drag forces, friction, wave breaking, wave reflection from prop-roots, oyster presence, shallow nearshore profiles, and cliffed edges. Furthermore, wave attenuation was measured both horizontally and vertically in relation to *Rhizophora* root density. In a 12-m forest, *Rhizophora* roots reduced wave height by 11 % (Ismail et al., 2019), supporting the earlier findings of Bao (2011).

Another study on wave energy dissipation in disturbed mangroves at Pulau Ubin, Singapore, found that mangroves with higher vegetation density reduced wave height by 80 % within 50 m. In contrast, less dense mangroves achieved a 70–92 % reduction over longer distances (Lee et al., 2021). The distance needed for over 80 % wave height reduction was greater than that reported by Doughty et al. (2017), which required only 1.7 m ± 0.3 m for a 90 % reduction, likely due to lower stem and root densities in Pulau Ubin's mangroves. A comparison with research in the Mekong Delta showed similar widths required for wave attenuation (>99 % of wave attenuation in less than 100 m) in degraded mangroves (Phan et al., 2015). However, the wave attenuation model by Phan et al. (2015) incorporated *Sonneratia* and *Rhizophora* species, which have higher stem densities and lower root densities. Despite differences, the study supports the potential for wave reduction in disturbed mangrove forests (Lee et al., 2021).

Zhou et al. (2022b) examined wave attenuation across an *Aegiceras corniculatum* tidal flat in Qixing Island, Nanliu Delta, focusing on mangrove age. They found that wave height decreased by 58 % in the seedling-sapling zone and 80 % in the sapling-adult zone. Seedlings (0.66 m) had a greater drag effect on waves compared to half-submerged mature trees (1.2 m), due to stronger drag forces, resulting in higher wave attenuation. Further, biomorphodynamic field data was collected during a storm caused by Typhoon Sinlaku over a mangrove wetland in the Nanliu Delta (Zhou et al., 2022a). Along a 415 m wide *A. corniculatum* transect, wave height was reduced by 56.3 %. The highest wave damping occurred in areas with 4 to 5-year-old trees, while the unvegetated lower tidal wetland had the lowest damping ability. The study also showed that *A.corniculatum* had a higher wave-damping effect during storms than normal weather conditions (Zhou et al., 2022a). Wang et al. (2023) studied the horizontal structure development of mangrove forests from seedlings to maturity. They found that *A. corniculatum* seedlings often form discrete or agglomerated clusters, but as they grow, the agglomerated structure stabilizes. These dense clusters are effective at reducing wave energy, helping sediments settle, and raising tidal flats, which creates favorable conditions for seedling survival. As the propagules grow, the agglomerated structures become stronger, spreading across the tidal flat due to their resilience against hydrodynamic forces (Wang et al., 2023).

Montgomery et al. (2018) showed that mangrove vegetation properties such as pneumatophores, seedlings, trees, and branches play a key role in sheet flow by impeding water exchange across the forest, reducing water levels, and slowing flood wave propagation, findings align with (Seujip et al., 2024). In contrast, for creek flow, Montgomery et al. (2018) found minimal mangrove impact on flow restriction. In the Somone Lagoon, the spatial distribution of mangroves enables both sheet and creek flow during tidal circulation. Tidal dissipation by the mangroves depends on the water level inside the mangrove, with stronger dissipation occurring during spring tides (highest point: 1.4). In contrast, lower dissipation occurs during neap tides (lowest point: 0.65), when the tide barely reaches the mangroves (Seujip et al., 2024). Kitheka (1997) observed similar tidal behavior in the mangroves of Gazi Bay, Kenya.

Overall, existing field studies have indicated that mangroves effectively reduce wave energy, but only when forests are extensive. Also, these studies have primarily focused on *Avicennia, Sonneratia, Rhizophora, Aegiceras corniculatum*, and *Kandelia candel*. However, other mangrove species may exhibit different responses, necessitating additional field research. Furthermore, some experiments only addressed mangroves at the genus level, such as *Rhizophora*. However, there are various species within this genus (e.g., *Rhizophora apiculata, Rhizophora mucronata, Rhizophora stylosa*), each potentially having distinct wave attenuation capabilities. Hence, further studies are necessary to explore this variability.

3.2.2. Laboratory experiments

In laboratory studies, waves are generated in controlled settings like wave flumes or basins. These waves then interact with model coastal vegetation, which can be natural or simulated. These studies' limitations are the small scale of laboratory models, potentially leading to different findings compared to actual conditions. However, researchers can precisely control and simulate conditions in the laboratory, including wave types, plant arrangement, and plant density. This controlled environment enables the examination of various wave types, such as wind waves, storm surges, and tsunamis.

Rasmeemasmuang (2014) conducted a conceptual experiment on wave reduction caused by *Rhizophora*'s root and trunk system. Various frequencies of regular waves were generated, and a *Rhizophora* model was created using steel bars with 20 roots per tree. Different water depths, forest widths, and densities were tested in a wave flume. The results indicate that as the relative water depth increases (0.6–1.0), the wave reduction coefficient decreases (34 %–27 %). This is because shallow water has a higher root density, increasing the chances of wave-root interactions compared to deeper water. Furthermore, waves experience more bottom friction in shallow water, leading to a reduction in wave height. A hydrodynamic study in a laboratory wave flume indicated that as the water depth increases from 0.2 m to 0.4 m, the impact of the *Rhizophora* roots gradually diminishes (Wang et al., 2022a). This study further supports the findings of (Rasmeemasmuang, 2014), indicating that wave attenuation is higher in shallow water compared to deeper areas.

Additionally, during high waves like tsunami events, the drag force exerted by branches and leaves may also play a role in wave attenuation. The wave attenuation characteristics of *Rhizophora mucronata* were investigated using scaled physical models. These models were made from the original mangroves to ensure identical biomechanical properties (Lekshmy Devi et al., 2021). It was observed that wave decay adheres to the exponential decay model of Kobayashi et al. (1993) in determining damping parameters. Bottom friction was adjusted by incorporating the mean particle size of the soil. This was done to address the bottom friction effect of the root soil. Moreover, a specific drag value of 8.78 was derived for *Rhizophora mucronata.* This underscores the significance of incorporating root soil bottom friction in physical model studies simulating field conditions. Further research is required to examine the effects of wave attenuation on leaves and branches during high waves.

A laboratory study analyzed wave height reduction with different mangrove tree (*Rhizophora*) densities and arrangements (Hashim and Catherine, 2013). They found that a staggered arrangement of mangrove models resulted in higher wave reduction than the tandem arrangement (differences less than 10 %). But, in (Lu et al., 2024)'s study, a tandem arrangement was used in the laboratory artificial mangrove forests (*Kandelia obovata*) to simplify planting mangroves in the field. While previous research indicates that a staggered configuration offers superior wave attenuation (Hashim and Catherine, 2013), the tandem layout was chosen for its practical benefits, including ease of positioning saplings and facilitating their on-site planting (Lu et al., 2024). Meanwhile, another experiment shows that the highest energy dissipation occurs with the annular arrangement (17 %), followed by the rectangular arrangement (15 %), and the staggered arrangement (13 %) (Chen et al.,

2024).

Tomiczek et al. (2020) demonstrated that increasing the thickness of *Rhizophora* mangroves reduced cross-shore force on structures by 11 % to 65 % compared to a baseline without mangroves. Kelty et al. (2022) assessed a moderate-sized *Rhizophora* forest, finding wave height decay rates of 0.008–0.021 m^{-1} for high-density and 0.004–0.010 m^{-1} for low-density configurations. LiDAR was used to measure the projected area and estimate the effective diameter. Weaver and Stehno (2024) used a modular dowel mangrove design (MDMD), accurately representing live mangroves with a 2.5 % average deviation in wave tank simulations. In a forest with 0.6 m cross-shore thickness and 1 prop root per 50 cm^2 density, the MDMD achieved wave attenuation of 27 % to 35 %, reducing wave energy by 40 % to 60 %. This wave reduction led to a 50 % to 70 % decrease in sediment erosion (Weaver and Stehno, 2024). Moreover, lateral erosion rates of mangrove soils under wave influence revealed that *Kandelia obovata* experienced a higher erosion rate (0.066 ± 0.017 %/hour) than *Sonneratia apetala* (0.019 ± 0.003 %/hour). It highlights significant differences in erosion resistance between these mangrove species under wave influence (Wang et al., 2024). Meanwhile, (Abdullah et al., 2019) found that a 3 m mangrove forest with densities ranging from 0.25 trees/m^2 to 1 tree/m^2 could dissipate 16 % to 64 % of the incident wave energy (Abdullah et al., 2019). The Mansard-Funke 3-point method was used to separate the recorded wave signal into incident and reflection waves.

In summary, various laboratory wave flume tanks or wave basin experiments have been conducted to study different wave types, including wind waves, storm surges, and tsunamis. Findings suggest that higher wave attenuation occurs in shallow water compared to deeper areas. This is attributed to higher root density and increased bottom friction in the shallower regions. Also, some studies indicate that wave attenuation caused by mangroves contributes to decreased soil erosion. However, the results highlight the need to explore incorporating vegetation flexibility to improve the model's accuracy in simulating natural conditions.

3.2.3. Numerical experiments

Numerical studies use fundamental equations to simulate energy dissipation rates in wave dissipation. These simulations cover nearshore hydrodynamics, exploring coastal flooding from long waves like tsunamis. The mathematical formulas employed enable a comprehensive understanding of these phenomena. Moreover, the potential of mangrove forests to mitigate wave energy is also modeled (Yanagisawa et al., 2009). The equations in these mathematical models can be solved using either analytical (Teh et al., 2009) or numerical methods (Massel et al., 1999; Suzuki et al., 2012). For an example, Deep Neural Network (DNN) model was developed as an alternative to the comparatively inefficient wave model calculation to predict the attenuation of tsunami waves by mangrove forests effectively (Adytia et al., 2024).

Fatimah et al. (2008) investigated the ArMS (Artificial Mangrove Root System), a submerged breakwater resembling mangrove roots. They reported numerical findings on its hydraulic performance. Flow-3D®, a computational fluid dynamics software simulation, strongly correlates with experimental wave transmission coefficient results. FLOW-3D enables us to tackle engineering challenges using extensive 3D modeling and fluid simulation features. It produces numerical predictions of fluid flow phenomena governed by the laws that control fluid motion (Hu, 2012). Various mangrove species exhibit different root systems. While *Rhizophora* species have commonly been considered for mangrove models, this study also used their prop roots as a model. Wave transmission coefficients decrease from 0.95 to 0.13 as the structure porosity decreases from 0.95 to 0.75. Similarly, creating models for other species like *Avicennia* with pencil roots, *Bruguiera* with knee roots, and *Xylocarpus granatum* with buttress roots is necessary. These models will help evaluate their wave attenuation capabilities.

Wave damping by the mangrove forests on Banyuglugur Beach, Indonesia, was analyzed using the Delft3D-Coupling model, which integrates Delft3D-Flow and Delft3D-Wave (Agung Wiyono, 2024). Delft3D-Flow and above mentioned Flow-3D® (Fatimah et al., 2008) are both computational fluid dynamics (CFD) tools, but they have distinct features and applications. Delft3D-Flow simulates multidimensional hydrodynamics, modeling unsteady flow and transport from tidal and meteorological forces (Deltares, 2024a). Delft3D-Wave simulates wave propagation, wind-driven wave generation, and dissipation across various depths, considering topography, wind, and currents (Deltares, 2024b). Results show that mangroves with an average width of 50 m can dampen waves by 52.8 % and reduce wave height by 39 % compared to incoming waves (Agung Wiyono, 2024).

Wu et al. (2001) modeled the tidal currents in mangroves, specifically focusing on predicting current velocities in channels and tidal creeks. The findings indicated that the drag force induced by the mangrove trees played an important role in the hydrodynamic processes. The blockage from the mangrove trees also played an important role when the mangrove trees' porosity was less than 0.8. In a straight creek, blockage decreased peak current. This was attributed to tidal floodplains in the mangrove swamp system acting as water storage rather than passageways. Vo-Luong and Massel (2008) developed a predictive model for wave propagation through non-uniform mangrove forests. Numerical calculations show that energy dissipation mainly results from wave breaking and interactions with tree trunks. While wave breaking is crucial in sparse forests, it has a minor impact compared to interactions with tree trunks in denser forests.

Zhang et al. (2020b) investigated mangroves' nonlinear wave attenuation function in Da Guan Sha, Beihai City, China. Six transects were laid perpendicular to the coastline, and field measurements and numerical models were combined. These measures were integrated into the Dalrymple model to calculate wave attenuation rates. The Simulating WAve Nearshore (SWAN) model helps simulate how waves move in coastal waters under specific conditions (Massel et al., 1999; Vanegas et al., 2017). It has a part called the 'Dalrymple wave propagation model', a formula incorporated into SWAN, that helps to predict how waves move through vegetation (Dalrymple et al., 1984; Montgomery et al., 2019; Negm and Nassar, 2016). The Dalrymple wave propagation model is widely accepted as an empirical model for calculating the wave height decreasing rate and is an efficient and effective evaluation method (Zhang et al., 2020b). The results indicated that the canopy was mostly responsible for wave attenuation during high tide and the roots and stems during low tide. This study suggested that the wave attenuation function for mangroves is non-linear and instead has an "U" distribution pattern. Using the SWAN model, Parvathy and Bhaskaran (2017) found that mangroves' wave attenuation varies with the bottom slope. Mangroves reduce wave energy by 93–98 % on mild slopes (1:80, 1:40), 84 % on a 1:20 slope, and 67 % on a steep slope (1:10). Wave height decreases exponentially on mild slopes but more gradually on steeper slopes due to factors like water depth, shoaling, breaking, and reflection.

Comparing numerical models with field studies in mangrove research involves balancing accuracy and control. Field studies provide accurate, real-world data but need more control. Numerical models, while simplified, offer controlled simulations. Both are important, with field studies validating models, and a combined approach often provides a comprehensive understanding of mangrove wave attenuation. Numerical models can fill data gaps and explore various scales, complementing field research.

3.2.4. Synthesis of attenuation experiments

Several experiments have summarized the wave attenuation across diverse conditions using different types of mangroves (Table 2, Annex-1). In laboratory tests, *Rhizophora* demonstrates a significant wave

reduction coefficient of 80 % (Hashim and Catherine, 2013). However, *Kandelia candel* exhibits a much lower wave reduction of 20 % in field conditions (Mazda et al., 1997). The sequence of wave reduction coefficients is *Rhizophora* (80 % in laboratory condition) > *Avicennia officinalis* (55 % in numerical study) > *Sonneratia* (50 % in field study) > *Kandelia candel* (20 % in field study) (Mazda et al., 2006; Teh et al., 2009).

In a study to support their claims, Kathiresan and Rajendran (2005) and Fatimah et al. (2008) pointed out the intricate root system of *Rhizophora*. This intricate root system is believed to be the reason behind the superior wave energy attenuation in *Rhizophora*. Ismail et al. (2019) also affirmed that *Rhizophora* species exhibit more effective wave attenuation than *Avicennia* species. Additionally, Hadi et al. (2003) found that *Rhizophora* species better mitigate tsunami effects than *Avicennia* species. Specifically, Kathiresan and Rajendran (2005) identified *Rhizophora apiculata* and *Rhizophora mucronata* as effective protectors against tsunami damage. This effectiveness is attributed to the complex aerial root structure of these species.

However, Mazda et al. (2006) and Mazda et al. (1997) reported a different perspective. They indicated that the drag coefficient follows the order of *Sonneratia* sp. < *Kandelia candel* < *Bruguiera* spp., and *Rhizophora* spp. It is probably *Bruguiera* spp. and *Rhizophora* spp. that have intricated and large prop roots or numerous pneumatophores, compared to *Kandelia candel*. *Kandelia candel* has no pneumatophores. Interestingly, despite *Rhizophora* spp. having the highest drag coefficient, *Sonneratia* outperforms *Kandelia candel* regarding wave reduction coefficient. The reason might be that, in field tests, factors beyond the drag coefficient influence the wave attenuation performance of *Sonneratia* and *Kandelia candel*. These include maturity, coexisting species, and site-specific conditions like sediment type, water depth, and wave energy levels.

4. Floating breakwater with an ecological approach

4.1. Integrating with aquatic plants

In this section, we explore experiments that involve integrating floating structures with various types of plants. We particularly emphasize the ecological implications of these combinations. The intention is to study the interactions between man-made floating structures and plant life in an ecological context. The mentioned nature-based solutions include seaweed, common reed, and mangroves. These plants are chosen for their unique properties, which contribute to the effectiveness of the floating breakwaters. Seaweed may provide flexibility and resilience, while common reeds and mangroves could contribute structural stability and ecological benefits. Below are a few examples from different studies that show how plants and structures work together.

4.2. Using seaweed and common reed nature-based solutions

Sun et al. (2022c) proposed a kelp-box-type floating breakwater. It exhibited higher wave attenuation performance compared to traditional box-type FBs. A kelp-box-type floating breakwater with longer kelp, denser planting, and more rows improves wave attenuation, especially for long waves. With 20 cm and 30 cm kelp lengths, wave attenuation increases by 16 % and 25 %, respectively. Planting intervals of 3 cm, 2 cm, and 1 cm increase wave attenuation compared to no kelp at a 1.7 s wave period. The increases are 8.7 %, 9.5 %, and 10.1 %, respectively. Three rows of kelp reduce the wave transmission coefficient by 24.4 %.

Table 2
Mangrove wave attenuation studies: Field, Laboratory and Numerical experiments across diverse environmental conditions [Notations: D-Density, d-tree diameter, E-Laboratory experiment, F-Field experiments, H-Wave height (difference between the elevations of a crest and a neighboring trough), Kt-Transmission coefficient (ratio of the wave heights of the transmitted and incoming waves), L-Wavelength (distance between two identical points on successive waves: crest to crest, or trough to trough), N-Numerical experiment, SD-Stem diameter, T-Wave period (average time between crests or troughs of waves), W-Width of mangrove forest, wd-water depth].

Method	Type of wave	Conditions	Mangrove species	Wave attenuation results	Source
F		W-50 m	*Avicennia*	H reduce-1 m-0.3 m	(Othman, 1994)
N		When the porosity of the structure decreases from 0.95 to 0.75 for H/L = 0.005	Artificial mangrove root system (ArMS)	Kt decreases from 0.95 to 0.13	(Fatimah et al., 2008)
N	Tsunami	D- 0.2 trees/m^2, SD- 15 cm, W-400 m, H-3.0 m, T-30 min	*Rhizophora* spp.	Reduce inundation depth by 30 %	(Yanagisawa et al., 2009)
F	Tsunami	250 km (19 locations)- southern coast of Sri Lanka About 200 km (29 locations)-Andaman coast of Thailand	*Rhizophora apiculata* and *Rhizophora mucronata*	Through field survey and analysis of drag force coefficient using representative tree species, tested effectiveness in protecting from tsunami damage. Densely populated (d > 0.1) trees reduce the tsunami current velocity, while (d > 0.3) trees trap broken branches and man-made debris.	(Tanaka et al., 2006)
F			*Aegiceras corniculatum* (AC)	H reduction of 58 % over 275 m in seedling-sapling zone 80 % over 1000 m in sapling-adult area	(Zhou et al., 2022b)
E	Solitary wave and Tsunami bore		*Rhizophora* sp.	Kt =20 % and 10 % for solitary waves and Tsunami bore, respectively	(Strusińska-Correia et al., 2013)
E	Tsunami wave	For a density of 3–5 trees/100 cm^2 to 7–8 trees/100 cm^2	*Rhizophora*	First 1 m W reduce 23–32 % at wd-0.15 m, 31–36 % at wd-0.05 m. Increasing W(2 m,3 m) further reducing by 39–50 % at wd-0.15 m, 34–41 %,wd-0.05 m.	(Ismail et al., 2012)
E		T = 1.0 s	*Rhizophora*	Kt of vegetation with the stem, root, and canopy (an above-ground portion of a vegetation type, formed by plant crowns) ranges from 0.21 to 0.83	(He et al., 2019)
E		W-18 m	*Rhizophora* sp	-H decay rates 0.008–0.021 m^{-1} (at D-0.75 stems/m^2) -H decay rates 0.004–0.010 m^{-1} (D- 0.375 stems/m^2)	(Kelty et al., 2022)
F		W-12 m	*Rhizophora* sp.	H reduction 3.27 % -20.66 %, averaging at 11 %.	(Ismail et al., 2019)
F,N		W ≥ 100 m.	Mangrove forest, including mainly *Avicennia marina*	Decreasing rate of H- 85 % -90 % at low tide and 96 % - 97 % at high tide	(Zhang et al., 2020b)
E		W-3 m, D- 0.25 trees/m^2 and D-1tree/m^2		Dissipate 16 %–64 % of incident wave energy	(Abdullah et al., 2019)

Moreover, turbulent kinetic energy and vortices contribute to wave dissipation in kelp-box-type floating breakwater.

Further, (Li et al., 2022) conducted experimental and numerical studies on a twin pontoon floating breakwater with kelp in a two-dimensional wave flume. The results showed that this floating breakwater outperformed the traditional twin pontoon floating breakwater for wave attenuation. The wave transmission coefficients of the added kelp with a single row of 30 cm kelp length decreased by 15.8 %–7.0 % for 2.85 s–5.38 s waves, compared with the traditional pontoon. Additionally, the twin pontoon floating breakwater with kelp (TPFBK) with three rows decreased by 29.7 %–16.5 %. The single row of densely planted kelp to TPFBK in wave attenuation performance is improved mainly by enhancing the reflection ability of wave energy.

In contrast, the kelp array's multi-row arrangement enhances wave energy's dissipation. Therefore, the TPFBK with a multi-row arrangement effectively utilizes space and enhances wave energy dissipation performance. However, (Sun et al., 2022c) and (Li et al., 2022) share similarities in their research. Their findings indicate that multi-row arrangements of floating breakwaters with kelp plants increase wave dissipation compared to breakwaters without kelp plants.

Landmann et al. (2022) proposed using Artificial Floating Islands (AFIs) as an alternative to traditional revetments for dampening ship waves and protecting shorelines. Large-scale physical model tests were conducted using organic, reed-based gabions (common reed-*Phragmites australis*). The results showed that the transmitted wave height of the incident waves was reduced by 50 % for the most minor wave periods ($T \leq 1.5$ s), with incident waves reflected between 20 % and 50 %. Moreover, the incident wave energy was dissipated by up to 85 %, particularly for the smallest wave height and period ($H = 0.10$ m, $T = 1.5$ s). Finally, this study concluded that the floating islands are well-suited for attenuating small to medium wavelengths caused by vessels in marinas or wind in fetch-limited areas. These islands offer ecosystem services and integrated revetment options without additional land use requirements.

Hopkins et al. (2022) tested the effectiveness of the Emerald Tutu, a Nature-based solution, in reducing nearshore waves. The findings indicate that floating nearshore mat networks can protect coastlines from wave impacts. Further, it concluded that wave attenuation is high with a low wavelength (1.8 m), reaching 0.97 in a dense network. Zhu et al. (2020) tested the combination of floating shellfish farms and submerged aquatic vegetation patches for wave attenuation. Results showed that floating farms attenuate short waves while submerged aquatic vegetation attenuates longer waves. The drag coefficients are 1.3 and 1.95, respectively. This supports a tiered nature-based solution for coastal protection against storm waves.

4.3. Floating mangroves

Experiments on mangrove wave attenuation and floating breakwaters have been mostly conducted independently, with only a few studies integrating mangroves and floating breakwaters. In September 2012, a small-scale floating mangrove model was developed in Qatar using *Avicennia marina* (Böer et al., 2014). While the concept's effectiveness has been demonstrated, a larger prototype with replicas is needed to obtain precise scientific data with reliable statistics.

The "Rhizolith Island" proof-of-concept design (Fig. 3) was created in 2016. It aimed to restore declining mangrove forests and regenerate flooded seashores in Cartagena, Colombia (Larsen and Hubeli, 2018). The concrete mix was designed to balance the strength of mangrove roots up to maturity. However, it allowed the roots to break once the mangroves were fully grown.

Floating mangroves could reduce wave action and increase mangrove areas on the coast. These mangroves are detached from the shoreline, float freely on the water's surface, and could expand coastal mangroves in areas where mangrove replantation or afforestation is impossible. They could be strategically placed where they could offer the most effective coastal protection. The concept of floating mangroves could become a complementary solution in mitigating wave impacts in the coastal zone and serve as a viable plantation option. For example, communities rely on wood harvesting for local subsistence. In Africa (e.g., Madagascar), many mangrove forests are used for cooking (Elmqvist et al., 2007).

The feasibility study conducted by (Henry et al., 2017) analyzes the potential of floating mangroves. It aims to gather theoretical data and justifications for developing a prototype. The study also highlights the beneficiaries and potential impacts of this innovative approach. In 2019, Ashley studied a floating mangrove pontoon's stability and wave attenuation with a physical model (scale-8.33:1). The stability and wave reduction changed with wave periods, leading to stable pontoon movements. The pontoon design was considered effective for coastal defense, especially in areas with shorter wave periods. The results highlighted the technology's potential for mangrove development. However, more research, including a full-scale pilot project and qualitative data, is needed to fully understand its benefits (Kiran et al., 2022).

Kiran et al. (2022) explored the feasibility of establishing a floating mangrove plantation as a nature-based solution to enhance the Maldives' adaptive capacity to climate change. The feasibility study concluded that stakeholders want to conduct a pilot project for floating mangrove pontoons in the Maldives. Establishing a pilot project is recommended to gather qualitative data and better understand the advantages of floating mangroves.

Floating mangroves have the potential to offer a range of benefits associated with traditional mangroves, including aesthetics, carbon sequestration, climate regulation, erosion control, and mitigation of coastal hazards, as outlined in section 3. Additionally, they present advantages related to floating breakwaters, as detailed in section 2. Some strengths and weaknesses of floating mangroves have been identified (Fig. 4).Two drawbacks indicate that the development of floating mangroves may pose challenges as they can shade benthic vegetation underneath them (Raju and Arockiasamy, 2022).

The potential of floating mangroves has been shown by (Böer et al., 2014), (Larsen and Hubeli, 2018), and (Henry et al., 2017). However, more precise data on wave attenuation experiments is needed to support this claim. Moreover, no experimental results on floating mangrove wave attenuation have been published. Therefore, it is crucial to investigate and understand how effective floating mangroves are in providing their wave reduction efficiency as coastal protection benefits.

Several approaches are being considered regarding future measures on mangrove-based protection against storms. Key approaches include restoration and conservation, integrated coastal structures, and community engagement. Restoring degraded mangrove areas or planting new mangroves in regions lacking natural buffers can significantly increase coastal resilience. Technological advances, such as remote sensing, can enhance the success rate of these efforts by ensuring optimal site selection and planting density. Diverse species should be planted based on local environmental conditions, as different mangrove species exhibit varying capacities for wave attenuation and storm protection.

As mentioned before, hybrid solutions that integrate mangroves with engineered structures, such as floating breakwaters could provide promising approaches. These combined systems enhance mangrove wave-damping abilities while providing additional storm protection, particularly in areas where traditional ecosystems struggle to establish. Floating mangroves could be useful in deep waters or areas with shifting shorelines; moreover, they may provide benefits for harvesting and contribute to coastal stabilization and restoration efforts. Rather than wave reduction, they offer co-benefits like carbon sequestration, fishery production, pollutant reduction, food production and tourism (Henry et al., 2017).

In the Maldives, floating mangroves present a viable option, allowing for offshore placement without occupying limited coastal space (Kiran et al., 2022). However, deploying floating mangroves requires careful



Fig. 3. Rhizolith Island prototype, exhibited in Cartagena, Colombia- Courtesy of [CEMEX, Larsen and Hubeli (Syracuse University/APTUM Architecture), 2018].

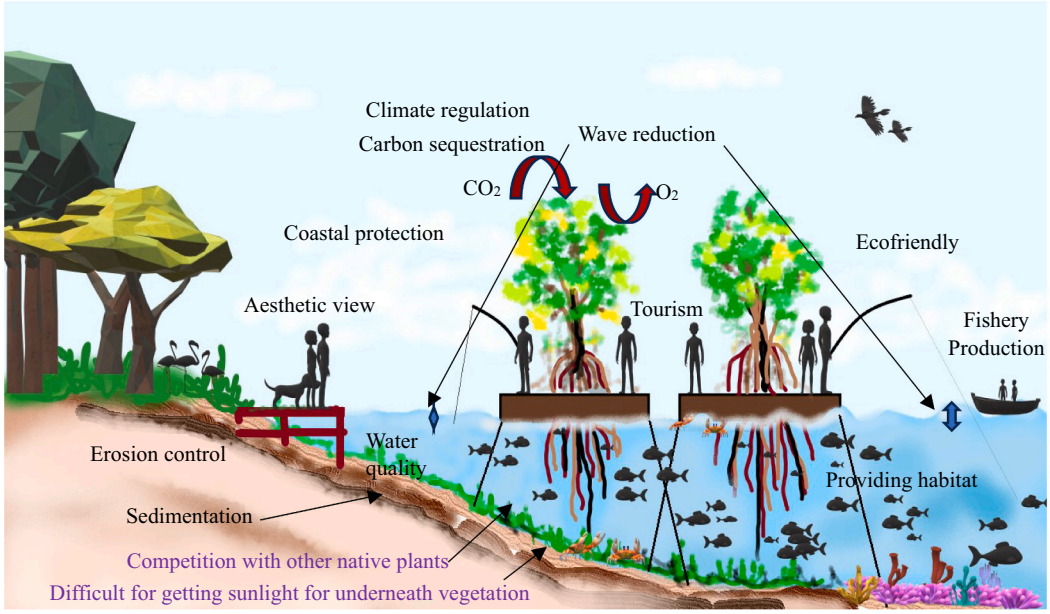


Fig. 4. Schematic diagram of floating mangrove: Weighing the benefits (Pros in Black Font) and drawbacks (Cons in Purple Font) - Illustrated by K.Risheharan, 2024, Source: (Henry et al., 2017; Kiran et al., 2022; Ranjan, 2019; Manson et al., 2005; Montgomery et al., 2018; Guannel et al., 2016; Carugati et al., 2018). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

consideration of costs, technical challenges, and community involvement. Installation over sensitive benthic habitats may disturb these areas due to anchoring (Benjamins et al., 2024). Therefore, adaptive planning that includes various strategies and co-management approaches is essential. A thorough analysis of environmental, geomorphological, socioeconomic, and institutional factors should be conducted prior to installation. Additionally, developing clear policies and regulations through collaborative efforts is crucial for successful deployment (Henry et al., 2017).

Mangroves and moored barges are used individually for coastal protection and beach restoration. The conceptual paper discusses the integration of mangroves with moored floating barges for coastal protection (Raju and Arockiasamy, 2022). The concept involves towing a barge to a designated location, mooring it to the seafloor, and planting mangroves along the shoreline. Once the mangroves are well-established, the barges can be unmoored and removed. Research in numerical and laboratory settings is essential to assess this concept under storm conditions.

Community-based mangrove management is important for long-term success because it helps involve local people in protecting these ecosystems. Educational programs and financial support can encourage communities to participate in restoration efforts. It is also essential to include mangroves in national climate adaptation plans, with governments and organizations promoting their conservation as a natural solution. With the right approaches, mangrove forests can serve as a cost-effective and sustainable defense against the increasing threat of storms.

5. Conclusion

Mangroves and floating breakwaters, acting as nature-based engineering structures, possess significant wave attenuation power (at least 20 % reduction). However, there needs to be a broad consensus on the global effectiveness of integrating mangroves with floating breakwaters. Examples of floating mangroves include “a small-scale floating mangrove model” created in Qatar in 2012, “Rhizolith Island” in 2016, and “Ashley’s floating mangrove pontoon” in 2019. While the effectiveness of the concept has been demonstrated, existing literature highlights the importance of developing larger prototypes. This approach with replicas aims to obtain more precise scientific data. Further, the feasibility studies indicated the potential of floating mangroves.

This literature review highlights that mangroves and floating

breakwaters can significantly reduce wave impact on the coast, with *Rhizophora* being the most efficient mangrove species (80 % reduction). Wave attenuation is followed by *Avicennia* (55 %), *Sonneratia* (50 %), and *Kandelia candel* (20 %). Their reduction is similar to those of floating breakwaters, exhibiting transmission coefficients (Kt) of less than 0.1 at a B/L ratio of 1.32 (Huang et al., 2020). While only a few studies have explored these combined structures, there is potential for their use in coastal zones with limited space for mangrove restoration. The floating mangrove could have advantages like aesthetics, durability, and low maintenance compared to conventional structures. It could contribute to carbon sequestration, erosion control, and coastal hazard mitigation. However, it has drawbacks like vulnerability to extreme waves, competition with benthic native plants, and sunlight obstruction for benthic macrophytes. However, considering the current needs and the impacts of climate change, it is vital to develop and rigorously test suitable floating mangrove structures. This will support effectively mitigating the effects of global warming.

Moreover, several factors must be considered when designing floating mangrove breakwaters to maximize their benefits. These include mangrove species in the intertidal zone, growth rate, tidal variations, and mooring systems of floating breakwater. Additionally, considerations involve the location in the coastal area, design, surface area, material, and water depth. In conclusion, this review paper underscores the conceptual developments and comparisons between new and existing concepts. It also emphasizes the necessity for further experiments to be conducted. These efforts aim to develop the most promising solutions. They focus on better understanding the intricate interaction between mangroves and floating breakwaters.

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CRediT authorship contribution statement

K. Risheharan: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **J. Baumeister:** Writing – review & editing, Supervision, Investigation, Formal analysis. **M.F. Adame:** Writing – review & editing, Supervision, Investigation, Formal analysis.

Declaration of competing interest

The authors state no financial or personal conflicts of interest in the reported work.

Data availability

No data was used for the research described in the article.

Appendix A. Annex- 1

Table 3
Equations for Mangrove Wave Attenuation in Field, Numerical, and Laboratory Studies. [Notations: A-Flow facing area per mangrove tree, a- Coefficient related to the incident wave height, b- Coefficient combining the water level and vegetation features, C_d-Drag coefficient, C_D-Bulk drag coefficient, C_D^{local}- Time dependent local drag coefficient, d_{root}-Mean root diameter, E-Laboratory experiment, EF_{inc} -Incident wave energy flux, EF_{ref} -Reflected wave energy flux, EF_{trans}- Transmitted wave energy flux, E_{loss}- Energy loss of the tsunami wave from tsunami bore height, E_m- Energy loss caused by the obstruction of mangroves, F-Field experiment, F_{max}- Maximum wave force, f – Vegetation induced resistance horizontal force, H-Wave height, H_{m0}- Significant wave height, Hnv-Wave height at the embankment toe without mangrove vegetation, Hs - Significant wave height, H_{Si}-Significant wave heights of incident waves, H_{Sp} - Transmitted wave heights, HSVF - Hydraulic submerged volume fraction, HSVI-Hydraulic submerged volume index, Hv-Wave height at the same location considering the presence of a mangrove foreshore, KC-Keulegan-Carpenter number, Kd-Dissipation coefficient, $K_{m\ -}$ Ratio of the energy loss caused by the obstruction of mangroves to the total energy loss, Kr-Wave reflection coefficient, Kt-Wave transmission coefficient, Le- Effective characteristic length, N-Numerical experiment, n-Number of mangrove plants in the model element, R-Wave attenuation rate, r-Wave attenuation ratio, Re- Reynolds number, $r_{\Delta Hi}$ - Wave reduction coefficient, T_p- Peak period, u-fluid velocity, u_c-Depth-averaged velocity, u_r -Ursell Number, W-Width of mangrove forest, x-Distance from meteorological station, β -Wave damping factor, ψ -Fitting constant, ρ-Water density].

Method	Equation/model	Mangrove species	Wave attenuation results	Source
F	$H_S = a \times x + b$	*Aegiceras corniculatum*	56.3 % H attenuation level at W-415.5 m	(Zhou et al., 2022a)
F	$R = -0.0023 \times e^{-0.64Cd} + 0.0025$	*Aegiceras corniculatum*	largest wave height attenuation rate: 3×10^{-3}	(Zhou et al., 2022b)
F	$r_{\Delta Hi} = (H_{Si}–H_{Sp}/H_{Si}$ X 100 (%)	*Sonneratia caseolaris (L.) Engler*	$r_{\Delta Hi-=}$0.12–0.8	(Loi et al., 2024)
N,E	$Kt = \sqrt{\frac{EFtrans}{EFinc}}$, $Kr = \sqrt{\frac{EFref}{EFinc}}$ $Kd = \sqrt{1 - Kr^2 + Kt^2}$	Mangrove trees	52 % wave reduction at high density vegetation, 17 % at low density vegetation K_r- 0.2 to 0.45	(Torabbeigi et al., 2024) (Lin, 2004)
E	$\beta = \psi$ * HSVF. $\beta = (6.67 \times 10^4 \pm 2.20 \times 10^3)$ * HSVI	*Rhizophora* sp.	Wave attenuation ability β by canopy −61 %, stem-23 %, root −16 %	(Zhang et al., 2023)
F,N	$C_{D=}\ (12.29/KC)^{1.62} + 1$ $KC = u_c\ T_P/d_{root}$	*Rhizophora*	H decreased by 34 % at 63 m in mangrove forests, r = 0.01 m^{-1}.	(Lopez-Arias et al., 2024)
E	$K_m = E_m/\ E_{loss}$	Mangroves	88.14 % of the tsunami bore energy loss.	(Chen et al., 2024)
E	$C_D^{local} = -0.86 + (\frac{3.63}{KC_{Le}^{local}})^{0.56}$	*Rhizophora*	F_{max} decreased from 0.4 N to 0.25 N at H-0.07 m.	(Wang et al., 2022b)
E	$C_d = 0.95 + 11.39KC^{-1.09}$	Mangroves	Wave dissipation-50 %	(Hu et al., 2021)
E (Fdata)	$C_D = 0.60 + (18.7/u_r)^{1.11}$	*Kandelia obovata*	Energy dissipation of regular waves was 2–10 % higher than irregular waves.	(Lu et al., 2024)
F	$\frac{\Delta H}{Hnv}(\%) = 100\frac{Hnv - Hv}{Hnv}$	*Sonneratia apetala*	canopy causes most wave energy dissipation-over 30 %	(Gijon Mancheno et al., 2024)
N	$f = -\frac{1}{2}\rho C_d A\|u\|un$	Mangroves	Surge attenuation up to 1.4 m (233 cm per km) at W-600 m	(De Dominicis et al., 2023)
E	$C_d = 0.35 + 3652Re^{-1.116}$	Mangroves	Breaking induced by opposing currents for up to 87 % of total dissipation	(Hu et al., 2022)

References

Abdullah, F.A.R., Husrin, S., Bachtiar, H., 2019. Experimental data analysis of wave attenuation in mangroves. J. Phys. Conf. Ser. 1245, 012095. https://doi.org/10.1088/1742-6596/1245/1/012095.

Aburto-Oropeza, O., Ezcurra, E., Danemann, G., Valdez, V., Murray, J., Sala, E., 2008. Mangroves in the Gulf of California increase fishery yields. Proc. Natl. Acad. Sci. 105, 10456–10459. https://doi.org/10.1073/pnas.0804601105.

Adytia, D., Tarwidi, D., Saepudin, D., Husrin, S., Kasim, A.R.M., Romlie, M.F., Samsudin, D., 2024. Deep neural network-based prediction of tsunami wave attenuation by mangrove forests. MethodsX 13, 102791. https://doi.org/10.1016/j.mex.2024.102791.

Agung Wiyono, R.U., 2024. Numerical simulation of wave reduction with mangrove forest using Delft3d modeling at Banyuglugur beach. Int. J. GEOMATE 26 (118). https://doi.org/10.21660/2024.118.4354.

Bao, T.Q., 2011. Effect of mangrove forest structures on wave attenuation in coastal Vietnam. Oceanologia 53 (3), 807–818. https://doi.org/10.5697/oc.53-3.807.

Benjamins, S., Williamson, B., Billing, S.-L., Yuan, Z., Collu, M., Fox, C., Hobbs, L., Masden, E.A., Cottier-Cook, E.J., Wilson, B., 2024. Potential environmental impacts of floating solar photovoltaic systems. Renew. Sust. Energ. Rev. 199. https://doi.org/10.1016/j.rser.2024.114463.

Böer, B., Huot, C., Sutcliffe, M., 2014. Floating Mangroves: the solution to reduce atmospheric carbon levels and land-based marine pollution?. In: In In book: Sabkha Ecosystems: Volume IV: Cash Crop Halophyte and Biodiversity Conservation https://doi.org/10.1007/978-94-007-7411-7_24.

Bridges, T.S., Bourne, E.M., King, J.K., Kuzmitski, H.K., Moynihan, E.B., Suedel, B.C., 2018. Engineering with Nature: An Atlas. U.S. Army Engineer Research and Development Center, Vicksburg, MS, USA.

Briggs, M., Ye, W., Demirbilek, Z., Zhang, J., 2010. Field and numerical comparisons of the RIBS floating breakwater. J. Hydraul. Res. 40 (3), 289–301. https://doi.org/10.1080/00221680209499944.

Bunting, P., Rosenqvist, A., Hilarides, L., Lucas, R.M., Thomas, N., Tadono, T., Worthington, T.A., Spalding, M., Murray, N.J., Rebelo, L.M., 2022. Global Mangrove Extent Change 1996–2020: Global Mangrove Watch Version 3.0. Remote Sens. 14 (15). https://doi.org/10.3390/rs14153657.

Burger, B., 2005. Wave Attenuation in Mangrove Forests. Numerical Modelling of Wave Attenuation by Implementation of a Physical Description of Vegetation in SWAN. M. Sc. Thesis.. Delft University of Technology.

Carugati, L., Gatto, B., Rastelli, E., Lo Martire, M., Coral, C., Greco, S., Danovaro, R., 2018. Impact of mangrove forests degradation on biodiversity and ecosystem functioning. Sci. Rep. 8 (1), 13298. https://doi.org/10.1038/s41598-018-31683-0.

Chen, C., Peng, C., Nandasena, N.A.K., Yan, H., 2024. Experimental investigation on tsunami impact reduction on a building by a Mangrove forest. Estuar. Coast. Shelf Sci. 301. https://doi.org/10.1016/j.ecss.2024.108756.

Chun-Yan, J., Yu-Chan, G., Cui, J., Zhi-Ming, Y., Xiao-Jian, M., 2016. 3D experimental study on a cylindrical floating breakwater system. Ocean Eng. 125, 38–50. https://doi.org/10.1016/j.oceaneng.2016.07.051.

Dai, J., Wang, C.M., Utsunomiya, T., Duan, W., 2018. Review of recent research and developments on floating breakwaters. Ocean Eng. 158, 132–151. https://doi.org/10.1016/j.oceaneng.2018.03.083.

Dalrymple, R.A., Kirby, J.T., Hwang, P.A., 1984. Wave Diffraction due to areas of Energy Dissipation. J. Waterw. Port Coast. Ocean Eng. 110 (1), 67–79. https://doi.org/10.1061/(ASCE)0733-950X(1984)110:1(67).

De Dominicis, M., Wolf, J., van Hespen, R., Zheng, P., Hu, Z., 2023. Mangrove forests can be an effective coastal defence in the Pearl River Delta, China. Commun. Earth Environ. 4 (1). https://doi.org/10.1038/s43247-022-00672-7.

Dedekorkut-Howes, A., Torabi, E., Howes, M., 2020. When the tide gets high: a review of adaptive responses to sea level rise and coastal flooding. J. Environ. Plan. Manag. 63 (12), 2102–2143. https://doi.org/10.1080/09640568.2019.1708709.

Deltares, 2024a. 3D/2D Modelling Suite For Integral Water Solutions: Functional Description, pp. 1–47.

Deltares, 2024b. 3D/2D Modelling Suite For Integral Water Solutions: Wave, pp. 1–219.

Donato, D.C., Kauffman, J.B., Murdiyarso, D., Kurnianto, S., Stidham, M., Kanninen, M., 2011. Mangroves among the most carbon-rich forests in the tropics. Nat. Geosci. 4 (5), 293–297. https://doi.org/10.1038/ngeo1123.

Dong, G.H., Zheng, Y.N., Li, Y.C., Teng, B., Guan, C.T., Lin, D.F., 2008. Experiments on wave transmission coefficients of floating breakwaters. Ocean Eng. 35 (8–9), 931–938. https://doi.org/10.1016/j.oceaneng.2008.01.010.

Dong, L.Q., Cao, J.M., Liu, X., 2022. Recent developments in sea-level rise and its related geological disasters mitigation: a review. J. Marine Sci. Eng. 10 (3). https://doi.org/10.3390/jmse10030355. Article 355.

Doughty, C.L., Cavanaugh, K.C., Hall, C.R., Feller, I.C., Chapman, S.K., 2017. Impacts of mangrove encroachment and mosquito impoundment management on coastal protection services. Hydrobiologia 803 (1), 105–120. https://doi.org/10.1007/s10750-017-3225-0.

Elmqvist, T., Pyykonen, M., Tengo, M., Rakotondrasoa, F., Rabakonandrianina, E., Radimilahy, C., 2007. Patterns of loss and regeneration of tropical dry forest in Madagascar: the social institutional context. PLoS One 2 (5), e402. https://doi.org/10.1371/journal.pone.0000402.

Fatimah, E., Wahab, A.K.A., Ismail, H., 2008. Numerical modeling approach of an artificial mangrove root system (ArMS) submerged breakwater as wetland habitat protector. COPEDEC VII, Dubai, UAE Paper No: F-01.

Filonchyk, M., Peterson, M.P., Zhang, L., Hurynovich, V., He, Y., 2024. Greenhouse gases emissions and global climate change: Examining the influence of CO2, CH4, and N2O. Sci. Total Environ. 935. https://doi.org/10.1016/j.scitotenv.2024.173359.

Fourqurean, J.W., Duarte, C.M., Kennedy, H., Marbà, N., Holmer, M., Mateo, M.A., Apostolaki, E.T., Kendrick, G.A., Krause-Jensen, D., McGlathery, K.J., Serrano, O., 2012. Seagrass ecosystems as a globally significant carbon stock. Nat. Geosci. 5 (7), 505–509. https://doi.org/10.1038/ngeo1477.

Gijon Mancheno, A., Vuik, V., van Wesenbeeck, B.K., Jonkman, S.N., van Hespen, R., Moll, J.R., Kazi, S., Urrutia, I., van Ledden, M., 2024. Integrating mangrove growth and failure in coastal flood protection designs. Sci. Rep. 14 (1), 7951. https://doi.org/10.1038/s41598-024-58705-4.

Griggs, G.B., 2005. The impacts of coastal armoring. Shore Beach 73 (1), 13–22.

Griggs, G., Reguero, B.G., 2021. Coastal adaptation to climate change and sea-level rise. Water 13 (16). https://doi.org/10.3390/w13162151.

Guannel, G., Arkema, K., Ruggiero, P., Verutes, G., 2016. The power of three: coral reefs, seagrasses and mangroves protect coastal regions and increase their resilience. PLoS One 11 (7), e0158094. https://doi.org/10.1371/journal.pone.0158094.

Hadi, S., Latief, H., Muliddin., 2003. Analysis of surface wave attenuation in mangrove forests. Proc. ITB Eng. Sci. 35 (2), 89–108.

Hashim, A.M., Catherine, S.M.P., 2013. A laboratory study on wave reduction by mangrove forests. APCBEE Proc. 5, 27–32. https://doi.org/10.1016/j.apcbee.2013.05.006.

Hashim, A.M., Catherine, S.M.P., Takaijudin, H., 2013. Effectiveness of mangrove forests in surface wave attenuation: a review. Res. J. Appl. Sci. Eng. Technol. 5 (18), 4483–4488.

He, F., Chen, J., Jiang, C., 2019. Surface wave attenuation by vegetation with the stem, root and canopy. Coast. Eng. 152. https://doi.org/10.1016/j.coastaleng.2019.103509.

Henry, J.-C., Böer, B., Khan, M.A., Gul, B., Ahmed, A., Araya, A., Godt, M.C., Ndiaye, G. O., Tangem, E.P., 2017. Feasibility study for the establishment of floating mangroves in UNESCO coastal biosphere reserves for the production of biomass for fuel, afloat on the world's tropical oceans (countries of close consideration: Cameroon, Djibouti, Eritrea, Kenya, Pakistan, Senegal, Somalia, Tanzania and Sudan). UNESCO, African Union Commission, HOAREC, and University of Karachi (ISHU), p. 217. http://creativecommons.org/licenses/by-sa/3.0/igo/.

Hinkel, J., van Vuuren, D.P., Nicholls, R.J., Klein, R.J.T., 2012. The effects of adaptation and mitigation on coastal flood impacts during the 21st century. An application of the DIVA and IMAGE models. Clim. Chang. 117 (4), 783–794. https://doi.org/10.1007/s10584-012-0564-8.

Hogarth, P., 2007. The mangrove community: Marine components. In: Hogarth, P. (Ed.), The Biology of Mangroves and Seagrasses. Oxford University Press. https://doi.org/10.1093/acprof:oso/9780198568704.003.0006.

Hogarth, P.J., 2015. The Biology of Mangroves and Seagrasses. Oxford university press.

Hopkins, J., Lutsko, N., Cira, G., Wise, L., Tegeler, J., 2022. The Emerald Tutu: floating Vegetated Canopies for Coastal Wave Attenuation. Front. Built Environ. 8. https://doi.org/10.3389/fbuil.2022.885298.

Hu, H.H., 2012. Computational fluid dynamics. In: Fluid Mechanics, pp. 421–472. https://doi.org/10.1016/b978-0-12-382100-3.10010-1.

Hu, Z., Lian, S., Wei, H., Li, Y., Stive, M., Suzuki, T., 2021. Laboratory data on wave propagation through vegetation with following and opposing currents. Earth Syst. Sci. Data 13 (10), 4987–4999. https://doi.org/10.5194/essd-13-4987-2021.

Hu, Z., Lian, S., Zitman, T., Wang, H., He, Z., Wei, H., Ren, L., Uijttewaal, W., Suzuki, T., 2022. Wave breaking induced by opposing currents in submerged vegetation canopies. Water Resour. Res. 58 (4). https://doi.org/10.1029/2021wr031121.

Huang, G., Sun, Z., Song, Y., Zhang, N., 2020. Effect of motions on the performance and mooring tension of a floating pontoon-type breakwater. Ships Offshore Struct. 17 (3), 661–675. https://doi.org/10.1080/17445302.2020.1861708.

Igulu, M.M., Nagelkerken, I., Dorenbosch, M., Grol, M.G., Harborne, A.R., Kimirei, I.A., Mumby, P.J., Olds, A.D., Mgaya, Y.D., 2014. Mangrove habitat use by juvenile reef fish: meta-analysis reveals that tidal regime matters more than biogeographic region. PLoS One 9 (12), e114715. https://doi.org/10.1371/journal.pone.0114715.

Ismail, H., Abd Wahab, A.K., Alias, N.E., 2012. Determination of mangrove forest performance in reducing tsunami run-up using physical models. Nat. Hazards 63 (2), 939–963. https://doi.org/10.1007/s11069-012-0200-y.

Ismail, I., Husain, M.L., Satyanarayana, B., Ibrahim, S., Zakaria, R., 2019. Root density analysis and wave attenuation ability of rhizophora species at Kemaman, Terengganu. Earth Sci. Malaysia 18-24. https://doi.org/10.26480/esmy.01.2019.18.24.

Jänes, H., Macreadie, P.I., Zu Ermgassen, P.S.E., Gair, J.R., Treby, S., Reeves, S., Nicholson, E., Ierodiaconou, D., Carnell, P., 2020. Quantifying fisheries enhancement from coastal vegetated ecosystems. Ecosyst. Serv. 43. https://doi.org/10.1016/j.ecoser.2020.101105.

Ji, C., Cheng, Y., Yang, K., Oleg, G., 2017. Numerical and experimental investigation of hydrodynamic performance of a cylindrical dual pontoon-net floating breakwater. Coast. Eng. 129, 1–16. https://doi.org/10.1016/j.coastaleng.2017.08.013.

Kamil, E.A., Takaijudin, H., Hashim, A.M., 2021. Mangroves as coastal bio-shield: a review of mangroves performance in wave attenuation. Civil Eng. J. 7 (11), 1964–1981. https://doi.org/10.28991/cej-2021-03091772.

Kathiresan, K., Bingham, B.L., 2001. Biology of mangroves and mangrove ecosystems. Adv. Mar. Biol. 40, 81–251. https://doi.org/10.1016/S0065-2881(01) 40003-4.

Kathiresan, K., Rajendran, N., 2005. Coastal mangrove forests mitigated tsunami. Estuar. Coast. Shelf Sci. 65 (3), 601–606. https://doi.org/10.1016/j.ecss.2005.06.022.

Kelty, K., Tomiczek, T., Cox, D.T., Lomonaco, P., Mitchell, W., 2022. Prototype-scale physical model of wave attenuation through a mangrove forest of moderate cross-shore thickness: LiDAR-based characterization and reynolds scaling for engineering with nature. Front. Mar. Sci. 8. https://doi.org/10.3389/fmars.2021.780946.
Kiran, S., Dansie, A., Glamore, W., 2022. Floating Mangrove Plantations in the Maldives (Honours Thesis). University of New South Wales, Sydney, Australia.
Kitheka, J.U., 1997. Coastal tidally-driven circulation and the role of water exchange in the linkage between tropical coastal ecosystems. Estuar. Coast. Shelf Sci. 45, 177–187.
Kobayashi, N., Raichle, A.W., Asano, T., 1993. Wave attenuation by vegetation. J. Waterw. Port Coast. Ocean Eng. 119, 30–48. https://doi.org/10.1061/(ASCE)0733-950X(1993)119:1(30).
Koo, W., 2009. Nonlinear time–domain analysis of motion-restrained pneumatic floating breakwater. Ocean Eng. 36 (9–10), 723–731. https://doi.org/10.1016/j.oceaneng.2009.04.001.
Kristensen, E., Bouillon, S., Dittmar, T., Marchand, C., 2008. Organic carbon dynamics in mangrove ecosystems: a review. Aquat. Bot. 89 (2), 201–219. https://doi.org/10.1016/j.aquabot.2007.12.005.
Landmann, J., Hammer, T.C., Günther, H., Hildebrandt, A., 2022. Large-scale investigation of wave dampening characteristics of organic, artificial floating islands. Ecol. Eng. 181. https://doi.org/10.1016/j.ecoleng.2022.106691.
Larsen, J., Hubeli, R., 2018. Rhizolith Island: Prototyping a Resilient Coastal Infrastructure: 2018 Intersections Proceedings, Design & Resilience. https://doi.org/10.35483/acsa.aia.inter.18.6.
Leal, M., Spalding, M.D., 2022. The State of the World's Mangroves 2022. Global Mangrove Alliance.
Lee, W.K., Tay, S.H.X., Ooi, S.K., Friess, D.A., 2021. Potential short wave attenuation function of disturbed mangroves. Estuar. Coast. Shelf Sci. 248. https://doi.org/10.1016/j.ecss.2020.106747.
Lekshmy Devi, C.A., Jairaj, P.G., Balan, K., 2021. Laboratory investigations on wave attenuation characteristics of Rhizophora Mucronata poir using physical models with bottom friction. Environ. Fluid Mech. 21 (2), 361–381. https://doi.org/10.1007/s10652-020-09777-z.
Leo, K.L., Gillies, C.L., Fitzsimons, J.A., Hale, L.Z., Beck, M.W., 2019. Coastal habitat squeeze: a review of adaptation solutions for saltmarsh, mangrove and beach habitats. Ocean Coast. Manag. 175, 180–190. https://doi.org/10.1016/j.ocecoaman.2019.03.019.
Li, C., Zhang, H., Zhang, H., Sun, B., Yang, S., 2022. Wave-attenuation and hydrodynamic properties of twin pontoon floating breakwater with kelp. Appl. Ocean Res. 124. https://doi.org/10.1016/j.apor.2022.103213.
Liang, N.-K., Huang, J.-S., Li, C.-F., 2004. A study of spar buoy floating breakwater. Ocean Eng. 31 (1), 43–60. https://doi.org/10.1016/s0029-8018(03)00107-0.
Lin, P., 2004. A numerical study of solitary wave interaction with rectangular obstacles. Coast. Eng. 51 (1), 35–51. https://doi.org/10.1016/j.coastaleng.2003.11.005.
Loi, L.T., Phong, N.T., Nguyen, L.T., 2024. Intertidal bare mudflat and wave attenuation: a case study in the Vietnamese Mekong Delta. Ecol. Eng. 206. https://doi.org/10.1016/j.ecoleng.2024.107320.
Lopez-Arias, F., Maza, M., Calleja, F., Govaere, G., Lara, J.L., 2024. Integrated drag coefficient formula for estimating the wave attenuation capacity of Rhizophora sp. mangrove forests. Front. Mar. Sci. 11. https://doi.org/10.3389/fmars.2024.1383368.
Lu, Y., Luo, Y., Zeng, J., Zhang, Z., Hu, J., Xu, Y., Cheng, W., 2024. Laboratory study on wave attenuation by elastic mangrove model with canopy. J. Marine Sci. Eng. 12 (7). https://doi.org/10.3390/jmse12071198.
Manson, F.J., Loneragan, N.R., Skilleter, G.A., Phinn, S.R., 2005. An evaluation of the evidence for linkages between mangroves and fisheries: a Synthesis of the literature and identification of research directions. Oceanogr. Mar. Biol. Annu. Rev. 483–515.
Maritime journal.com, 2017. Breakwater beats the weather at holy Loch. http://www.maritimejournal.com/news101/marine-civils/port,-harbour-and-marine-construction/breakwater_beats_the_weather_at_holy_loch (Accessed 29 January 2024).
Marois, D.E., Mitsch, W.J., 2015. Coastal protection from tsunamis and cyclones provided by mangrove wetlands – a review. Int. J. Biodiv. Sci. Ecosyst. Serv. Manag. 11 (1), 71–83. https://doi.org/10.1080/21513732.2014.997292.
Massel, S.R., Furukawa, K., Brinkman, R.M., 1999. Surface wave propagation in mangrove forests. Fluid Dynam. Res. 24, 219–249.
Mazda, Y., Magi, M., Kogo, M., Hong, P., 1997. Mangrove as a coastal protection from waves in the Tong King delta, Vietnam. Mangrove Salt Marshes 1, 127–135.
Mazda, Y., Magi, M., Ikeda, Y., Kurokawa, T., Asano, T., 2006. Wave reduction in a mangrove forest dominated by Sonneratia sp. Wetl. Ecol. Manag. 14 (4), 365–378. https://doi.org/10.1007/s11273-005-5388-0.
McCartney, B.L., 1985. Floating Breakwater Design. J. Waterw. Port Coast. Ocean Eng. 111, 304–318.
Monioudi, I.N., Asariotis, R., Becker, A., Bhat, C., Dowding-Gooden, D., Esteban, M., Feyen, L., Mentaschi, L., Nikolaou, A., Nurse, L., Phillips, W., Smith, D.A.Y., Satoh, M., Trotz, U.O.D., Velegrakis, A.F., Voukouvalas, E., Vousdoukas, M.I., Witkop, R., 2018. Climate change impacts on critical international transportation assets of Caribbean Small Island Developing States (SIDS): the case of Jamaica and Saint Lucia. Reg. Environ. Chang. 18 (8), 2211–2225. https://doi.org/10.1007/s10113-018-1360-4.
Montgomery, J., Bryan, K., Horstman, E., Mullarney, J., 2018. Attenuation of tides and surges by mangroves: contrasting case studies from New Zealand. Water 10 (9). https://doi.org/10.3390/w10091119.
Montgomery, J.M., Bryan, K.R., Mullarney, J.C., Horstman, E.M., 2019. Attenuation of storm surges by coastal mangroves. Geophys. Res. Lett. 46 (5), 2680–2689. https://doi.org/10.1029/2018gl081636.
NASA, 2023. Vital signs of Sea level. https://climate.nasa.gov/vital-signs/sea-level/.
Neelamani, S., Rajendran, R., 2002. Wave interaction with '⊥' type breakwaters. OceanEngineering 29, 561–589.
Negm, A., Nassar, K., 2016. Determination of wave reflection formulae for vertical and sloped seawalls via experimental modelling. Proc. Eng. 154, 919–927. https://doi.org/10.1016/j.proeng.2016.07.502.
NOAA, 2015. Guidance for Considering the Use of Living Shorelines, pp. 1–36. https://www.habitatblueprint.
Orton, P., Talke, S., Jay, D., Yin, L., Blumberg, A., Georgas, N., Zhao, H., Roberts, H., MacManus, K., 2015. Channel Shallowing as Mitigation of Coastal Flooding. J. Marine Sci. Eng. 3 (3), 654–673. https://doi.org/10.3390/jmse3030654.
Othman, M.A., 1994. Value of mangroves in coastal protection.pdf. Hydrobiologia 285, 277–282.
Ozeren, Y., Wren, D.G., Altinakar, M., Work, P.A., 2011. Experimental investigation of cylindrical floating breakwater performance with various mooring configurations. J. Waterw. Port Coast. Ocean Eng. 137 (6), 300–309. https://doi.org/10.1061/(asce)ww.1943-5460.0000090.
Parvathy, K.G., Bhaskaran, P.K., 2017. Wave attenuation in presence of mangroves: a sensitivity study for varying bottom slopes. Int. J. Ocean Clim. Syst. 8 (3), 126–134. https://doi.org/10.1177/1759313117702919.
Peng, N.N., Lau, W.K., Wai, O.W.H., Chow, K.W., 2023. Computational and experimental studies of wave–structure interaction: wave attenuation by a floating breakwater. Phys. Fluids 35 (4). https://doi.org/10.1063/5.0142991.
Phan, L.K., van Thiel de Vries, J.S.M., Stive, M.J.F., 2015. Coastal mangrove squeeze in the Mekong Delta. J. Coast. Res. 31 (2). https://doi.org/10.2112/JCOASTRES-D-14-00049.1, 233-243, 211.
Quartel, S., Kroon, A., Augustinus, P.G.E.F., Van Santen, P., Tri, N.H., 2007. Wave attenuation in coastal mangroves in the Red River Delta, Vietnam. J. Asian Earth Sci. 29 (4), 576–584. https://doi.org/10.1016/j.jseaes.2006.05.008.
Raju, R.D., Arockiasamy, M., 2022. Coastal protection using integration of mangroves with floating barges: an innovative concept. J. Marine Sci. Eng. 10 (5). https://doi.org/10.3390/jmse10050612.
Ranasinghe, R.S., Sato, S., 2007. Beach morphology behind single impermeable submerged breakwater under obliquely incident waves. Coast. Eng. J. 49 (1), 1–24.
Ranjan, R., 2019. Optimal mangrove restoration through community engagement on coastal lands facing climatic risks: the case of Sundarbans region in India. Land Use Policy 81, 736–749. https://doi.org/10.1016/j.landusepol.2018.11.047.
Rasmeemasmuang, T., 2014. Conceptual experiment of wave attenuation due to mangrove root systems: Unpublished.
Rasmeemasmuang, T., Sasaki, J., 2015. Wave reduction in Mangrove Forests. In: Handbook of Coastal Disaster Mitigation for Engineers and Planners, pp. 511–535. https://doi.org/10.1016/b978-0-12-801060-0.00024-1.
Reguero, B.G., Losada, I.J., Mendez, F.J., 2019. A recent increase in global wave power as a consequence of oceanic warming. Nat. Commun. 10 (1), 205. https://doi.org/10.1038/s41467-018-08066-0.
Reguero, B.G., Storlazzi, C.D., Gibbs, A.E., Shope, J.B., Cole, A.D., Cumming, K.A., Beck, M.W., 2021. The value of US coral reefs for flood risk reduction. Nat. Sustain. 4 (8), 688–698. https://doi.org/10.1038/s41893-021-00706-6.
Rivera-Monroy, V.H., Lee, S.Y., Kristensen, E., Twilley, R.R., 2017. Mangrove Ecosystems: a Global Biogeographic Perspective. Springer. https://doi.org/10.1007/978-3-319-62206-4.
Sánchez-Núñez, D.A., Mancera Pineda, J.E., Osorio, A.F., 2020. From local-to global-scale control factors of wave attenuation in mangrove environments and the role of indirect mangrove wave attenuation. Estuar. Coast. Shelf Sci. 245. https://doi.org/10.1016/j.ecss.2020.106926.
Sandilyan, S., Kathiresan, K., 2012. Mangrove conservation: a global perspective. Biodivers. Conserv. 21 (14), 3523–3542. https://doi.org/10.1007/s10531-012-0388-x.
Seujip, M.S., Bertin, X., Sakho, I., Diouf, M.B., 2024. Impact of mangrove on tidal propagation in a tropical coastal lagoon. Environ. Earth Sci. 83 (2). https://doi.org/10.1007/s12665-023-11349-5.
Spalding, M., Kainuma, M., Collins, L., 2010. World Atlas of mangroves. In: Earthscan in the UK and USA. https://doi.org/10.4324/9781849776608.
Spencer, T., Möller, I., Reef, R., 2022. Mangrove systems and environments. In: Treatise on Geomorphology, pp. 675–712. https://doi.org/10.1016/b978-0-12-818234-5.00094-8.
Strusińska-Correia, A., Husrin, S., Oumeraci, H., 2013. Tsunami damping by mangrove forest: a laboratory study using parameterized trees. Nat. Hazards Earth Syst. Sci. 13 (2), 483–503. https://doi.org/10.5194/nhess-13-483-2013.
Sulaiman, D., Hidayat, H., 2020. The role of geotextile tube as low-crested breakwaters in restoring severe beach erosion problem at Pebuahan Beach in Bali Island. Coast. Eng. Proc. 36v, 53.
Sun, B., Zhang, H., Li, C., Li, Z., 2022a. Wave-attenuation performance and hydrodynamic characteristics of a plant ecological floating breakwater. Ships Offshore Struct. 1-16. https://doi.org/10.1080/17445302.2022.2108219.
Sun, B., Zhang, H., Yang, S., Yang, L., Chen, S., Li, C., 2022b. The hydraulic characteristics and shape optimisation of submerged Box-type floating breakwater. Ships Offshore Struct. 17 (10), 2329–2339. https://doi.org/10.1080/17445302.2021.1990601.
Sun, B., Li, C., Yang, S., Zhang, H., Song, Z., 2022c. Experimental and numerical study on the wave attenuation performance and dynamic response of kelp-box type floating breakwater. Ocean Eng. 263. https://doi.org/10.1016/j.oceaneng.2022.112374.
Suzuki, T., Zijlema, M., Burger, B., Meijer, M.C., Narayan, S., 2012. Wave dissipation by vegetation with layer schematization in SWAN. Coast. Eng. 59 (1), 64–71. https://doi.org/10.1016/j.coastaleng.2011.07.006.

Tanaka, N., Sasaki, Y., Mowjood, M.I.M., Jinadasa, K.B.S.N., Homchuen, S., 2006. Coastal vegetation structures and their functions in tsunami protection: experience of the recent Indian Ocean tsunami. Landsc. Ecol. Eng. 3 (1), 33–45. https://doi.org/10.1007/s11355-006-0013-9.

Teh, S.Y., Koh, H.L., Liu, P.L.F., Ismail, A.I.M., Lee, H.L., 2009. Analytical and numerical simulation of tsunami mitigation by mangroves in Penang, Malaysia. J. Asian Earth Sci. 36 (1), 38–46. https://doi.org/10.1016/j.jseaes.2008.09.007.

Temmerman, S., Kirwan, M.L., 2015. Building land with a rising sea. Science 349, 588–589.

Temmerman, S., Meire, P., Bouma, T.J., Herman, P.M., Ysebaert, T., De Vriend, H.J., 2013. Ecosystem-based coastal defence in the face of global change. Nature 504 (7478), 79–83. https://doi.org/10.1038/nature12859.

Tomiczek, T., Wargula, A., Lomónaco, P., Goodwin, S., Cox, D., Kennedy, A., Lynett, P., 2020. Physical model investigation of mid-scale mangrove effects on flow hydrodynamics and pressures and loads in the built environment. Coast. Eng. 162. https://doi.org/10.1016/j.coastaleng.2020.103791.

Torabbeigi, M., Akbari, H., Adibzade, M., Abolfathi, S., 2024. Modeling wave dynamics with coastal vegetation using a smoothed particle hydrodynamics porous flow model. Ocean Eng. 311. https://doi.org/10.1016/j.oceaneng.2024.118756.

Uzaki, K.-I., Ikehata, Y., Matsunaga, N., 2011. Performance of the wave energy dissipation of a floating breakwater with truss structures and the quantification of transmission coefficients. J. Coast. Res. 27 (4), 687–697. https://www.jstor.org/stable/41315841.

Vanegas, G.C.A., Osorio, A.F., Urrego, L.E., 2017. Wave dissipation across a Rhizophora mangrove patch on a Colombian Caribbean Island: an experimental approach. Ecol. Eng. 130, 271–281. https://doi.org/10.1016/j.ecoleng.2017.07.014.

Veettil, B.K., Ward, R.D., Quang, N.X., Trang, N.T.T., Giang, T.H., 2019. Mangroves of Vietnam: Historical development, current state of research and future threats. Estuar. Coast. Shelf Sci. 218, 212–236. https://doi.org/10.1016/j.ecss.2018.12.021.

Vo-Luong, P., Massel, S., 2008. Energy dissipation in non-uniform mangrove forests of arbitrary depth. J. Mar. Syst. 74 (1–2), 603–622. https://doi.org/10.1016/j.jmarsys.2008.05.004.

Wang, H.Y., Sun, Z.C., 2010. Experimental study of a porous floating breakwater. Ocean Eng. 37 (5–6), 520–527. https://doi.org/10.1016/j.oceaneng.2009.12.005.

Wang, C.M., Han, M., Lyu, J., Duan, W., Jung, K., 2021. Floating forest: a novel breakwater-windbreak structure against wind and wave hazards. Front. Struct. Civ. Eng. 15 (5), 1111–1127. https://doi.org/10.1007/s11709-021-0757-1.

Wang, Y., Yin, Z., Liu, Y., 2022a. Experimental investigation of wave attenuation and bulk drag coefficient in mangrove forest with complex root morphology. Appl. Ocean Res. 118. https://doi.org/10.1016/j.apor.2021.102974.

Wang, Y., Yin, Z., Liu, Y., 2022b. Laboratory study on the drag coefficient for mangrove forests in regular waves. Ocean Eng. 255. https://doi.org/10.1016/j.oceaneng.2022.111522.

Wang, R., Dai, Z., Huang, H., Liang, X., Zhou, X., Ge, Z., Hu, B., 2023. Dramatic changes in the horizontal structure of mangrove forests in the largest delta of the northern Beibu Gulf, China. Acta Oceanol. Sin. 42 (7), 116–123. https://doi.org/10.1007/s13131-022-2126-x.

Wang, H., Xie, M., Chen, O., Zhou, Z., Cao, H., Wei, W., 2024. Investigation on the soil resistance to wave-induced lateral erosion under different mangrove forests. J. Sea Res. 200. https://doi.org/10.1016/j.seares.2024.102517.

Weaver, R.J., Stehno, A.L., 2024. Mangroves as coastal protection for restoring low-energy waterfront property. J. Marine Sci. Eng. 12 (3). https://doi.org/10.3390/jmse12030470.

Whelchel, A.W., Reguero, B.G., van Wesenbeeck, B., Renaud, F.G., 2018. Advancing disaster risk reduction through the integration of science, design, and policy into eco-engineering and several global resource management processes. Int. J. Disaster Risk Reduct. 32, 29–41. https://doi.org/10.1016/j.ijdrr.2018.02.030.

Wu, Y., Falconer, R., Struve, J., 2001. Mathematical modelling of tidal currents in mangrove forests. Environ. Model. Softw. 16, 19–29.

Yanagisawa, H., Koshimura, S., Goto, K., Miyagi, T., Imamura, F., Ruangrassamee, A., Tanavud, C., 2009. The reduction effects of mangrove forest on a tsunami based on field surveys at Pakarang Cape, Thailand and numerical analysis. Estuar. Coast. Shelf Sci. 81 (1), 27–37. https://doi.org/10.1016/j.ecss.2008.10.001.

Zhang, Y., Li, M., Zhao, X., Chen, L., 2020a. The effect of the coastal reflection on the performance of a floating breakwater-WEC system. Appl. Ocean Res. 100. https://doi.org/10.1016/j.apor.2020.102117.

Zhang, Y., Yang, Y., Yang, K., Tan, X., Sun, X., Leng, B., Zhou, C., Zhu, B., 2020b. Non-linear wave attenuation quantification model improves the estimation of wave attenuation efficiency of mangroves. Estuar. Coast. Shelf Sci. 245. https://doi.org/10.1016/j.ecss.2020.106927.

Zhang, R., Chen, Y., Lei, J., Zhou, X., Yao, P., Stive, M.J.F., 2023. Experimental investigation of wave attenuation by mangrove forests with submerged canopies. Coast. Eng. 186. https://doi.org/10.1016/j.coastaleng.2023.104403.

Zhou, X., Dai, Z., Carniello, L., Long, C., Wang, R., Luo, J., Huang, Z., 2022a. Linkage between mangrove wetland dynamics and wave attenuation during a storm–a case study of the Nanliu Delta, China. Mar. Geol. 454. https://doi.org/10.1016/j.margeo.2022.106946.

Zhou, X., Dai, Z., Pang, W., Wang, J., Long, C., 2022b. Wave attenuation over mangroves in the Nanliu Delta, China. Front. Mar. Sci. 9. https://doi.org/10.3389/fmars.2022.874818.

Zhou, B., Zheng, Z., Jin, P., Wang, L., Zang, J., 2022c. Wave attenuation and focusing performance of parallel twin parabolic arc floating breakwaters. Energy 260. https://doi.org/10.1016/j.energy.2022.125164.

Zhu, L., Huguenard, K., Zou, Q.-P., Fredriksson, D.W., Xie, D., 2020. Aquaculture farms as nature-based coastal protection: Random wave attenuation by suspended and submerged canopies. Coast. Eng. 160. https://doi.org/10.1016/j.coastaleng.2020.103737.