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Mangroves As Coastal Bioshield

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***Abstract*— Mangroves are wetland eco-systems that has been recognized as soft structures that could provide coastal protection. The frequency and severity of coastal hazards like cyclones, tsunamis, wave erosions, torrential storms and high waves resulting in loss of lives, property damage and environmental degradation have increased. Role of mangroves in coastal protection was recognized after they acted as the first line of coastal defense in natural tragedies such as during the Super Typhoon Haiyan 2013 and Indian Ocean Tsunami 2004.This study focuses on the role of mangroves for coastal protection. Mangroves serve as natural barriers against the intrusion of the sea and dissipates wave action, acts against sea level rise, mitigate the impact of storms, cyclones, devastating tsunami waves and prevents erosion; making it the best bio-shield for coastal stabilization. The study discusses the wave attenuation mechanism of mangroves highlighting wave parameters influencing the attenuation process like wave period, incident wave height etc. and mangrove parameters like species, width, density etc. and reviews the role of mangroves in reduction of wind and storm surges, tsunamis, and cyclones.**

***Keywords*— Mangroves; wave attenuation; storm surges; coastal protection.**

I. INTRODUCTION

The world's coastal margins are among the most densely populated and intensively used places on earth. The combination of population growth and coastal migration has led to high population densities in many coastal areas. However, the characteristics of coastal environments and ocean dynamics pose great challenges to human habitation. Therefore, disaster mitigation in coastal areas is an increasingly important aspect of coastal planning as the coastal environments are continuously reshaped by the natural forces of waves, tides, storm surges, erosion, and deposition.

Coastal hazards like cyclones, tsunamis, wave erosions, torrential storms and high waves are catastrophic resulting in loss of lives, property damage and environmental degradation. To conserve and protect coastal stretches, its unique environment, and its marine area and to promote development through sustainable manner, considering the dangers of natural hazards, different natural and artificial coastal protection measures are opted.

Natural coastal protection follows the concept of building with nature. Among different ecosystems located on coastal areas, mangroves play an important role in providing ecological and societal goods and services, including stabilizing shorelines and helping reduce adverse effects of natural disasters such as tsunamis and hurricanes. So, mangroves can be considered as one of the best coastal defenses.

II. MANGROVES IN COASTAL AREAS

Mangroves are the most productive and bio diverse wetlands on earth offering many products and services including protection of coastlines. They are wetland ecosystems, found in the inter tidal zones of tropical and sub-tropical coastal regions with high annual rainfall, dominating about ¼ th of worlds tropical coastline.

Mangroves are halophytic in nature – tolerant to saline environment. They are viviparous plants- their seeds germinate in the trees itself before falling. Viviparity helps in seedling survival in saline and anaerobic environment and against the wave action. They also possess several special adaptations for growing in saline and anaerobic soil conditions; of which the most prominent one is the root called pneumatophores that help them to respire in the anaerobic soils. They also have stilt roots (arched aerial prop roots) as well as knee roots (above ground looping horizontal cable roots) that provide stability and resistance against wave actions. This complex structure of mangroves with its canopy and trunk helps in the coastal defense.

Mangroves are often categorized by forest type: fringe, overwash, riverine, basin, and dwarf as described in Fig 1 (Lugo and Snedaker 1974). Major mangrove types commonly found are white mangroves, red mangroves, and black mangroves. White mangroves are typically found at higher elevations than either black or red varieties and are rarely flooded, with a maximum height of 15m. They develop prop roots only if remain anaerobic for long. Black mangroves are found in the upper intertidal zone, occasionally experiencing flooded conditions and can withstand high salinities. Red mangroves are present in the mid-intertidal zone along shoreline edges.

Fringing Mangroves	Found along open shorelines and lagoons that are regularly influenced by tidal activity and wave action. Fringing mangroves are often exposed to storm surges and winds and are typically the first line of defense against storms for mangrove dominated coasts.
Overwash Mangroves	Persist on islands and are often completely flooded at high tide. Typically consist of red mangroves (USFWS 1999).
Riverine/Estuarine Mangroves	Located along river floodplains and often fringed by red mangroves, they regularly experience a combination of freshwater from riverine input and seawater from tidal influence. These mangrove communities are some of the most highly productive mangrove forest types due to enhanced nutrient and sediment deposition from tidal exchange (USFWS 1999).
Basin Mangroves	Occur in depressions near inlets. Those near the coast receive tidal exchange but often consist of slow-moving or stagnant water, resulting in high salinities and anaerobic soils. Though often dominated by black and white mangroves, red mangroves dominate when closer to shorelines (Odum, McIvor, and Smith 1982).
Dwarf/Scrub Mangroves	Typically contain trees less than 1.5 m in height. Their stunted growth is usually due to a lack of nutrients, extremely low or high salinities, or rocky/shell-ridden substrates (USFWS 1999).

Fig 1 Summary of Mangrove Forest Type

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The benefits provided by mangroves include: (1) stabilizing of shore lines. (2) providing food, fuel, medicines, and other materials for local communities. (3) providing food and shelter for various organisms. (4) maintains the natural bio diversity of the coasts. (5) acts as breeding, nursery, feeding and refuge ground for a wide array of fishes, molluscs and crustaceans. (6) improves water quality by absorbing nutrients and minerals. (7) helps in carbon footprint reduction. (8) protecting coral reefs, sea grasses and other endangered organisms. (9) protection of the coasts. The coastal protection services provided by the mangroves include:(1) reduction of wind and swell waves. (2) reduction of impacts of storm surges. (3) mitigating the effects of tsunami, cyclones, and hurricanes. (4) reduce coastal erosion and siltation. (5) building up of soil levels to keep up with sea level rise. (6) flood attenuation.

III. MANGROVES FOR WAVE ATTENUATION

Waves propagate energy, rather than water, across space. While the water itself moves orbitally, the waves propagate horizontally, carrying wave energy with them. As wind waves approach the shore, swells are produced by changes in depth. That is, the height increases and the wave period is maintained, but steeper. A progressive crest is slowed down more than a continuous crest until the wave finally breaks the shore and dissipates the wave energy. Wave depth is limited when the water depth is about half the wave wavelength. At this point, the oscillatory motion of the water changes from circular to elliptical. When a depth-limited wave approaches the shore (before it breaks), it only loses energy due to seafloor friction. Surface friction on a smooth bed (substrate) typically causes a net reduction in wave height (i.e., wave attenuation) in the absence of vegetation or uneven surfaces and in the presence of swarming processes that increase wave height is not sufficient for the presence of vegetation provides drag that greatly improves wave attenuation compared to smooth beds.

Mangroves acts as obstacle and creates drag wile flowing around them; thus, dissipating energy and reduces wave height. Wave attenuation occurs due to drag force, caused by the resistance offered by roots, trunks, and canopy of mangroves, which slow down the waves by dissipating the energy, and by bottom friction occurred due to bed roughness (as in Fig 2).

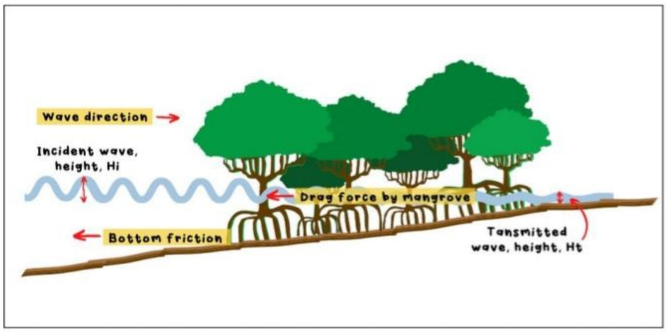

Fig 2 Wave attenuation by mangroves, (Kamil et al, 2021)

The parameters affecting wave attenuation are:

1) Characteristics such as the width, density, species, root diameter, age, and canopy.
2) Wave parameters such as wave period and incident wave height.
3) Other external factors such as bathymetry and water depth.

The sea wave height decays exponentially as the width of mangroves increases. When the waves travel through the mangroves further, the obstruction increases leading to the loss of energy and thus the wave height reduces due to increase in drag force and bed roughness. According to Lee et. al (2021), the percentage of wave height reduction by mangroves is more than 60% over a 500m width. Also, the studies by Adytia and Husrin(2019) reported that the mangrove width with four times the wavelength of incident waves is required to fully attenuate the incoming wave height. *Rhizophora* species was found to be the most effective compared to other mangrove types due to complex aerial root structures that offer greater resistance to the incident waves and thus increasing the drag coefficient. Also, high mangrove density with less gap between trunks and roots, form the dense interlocking aerial roots, reduces the porosity, and increases the obstruction to the incoming wave. So, as the density of the mangroves increases, wave reduction capability also increases. The wave attenuation depends on the structural arrangements of mangroves including roots, stems, trunks, and canopy. Prop roots present in *Rhizophora spp*. which form a complex network that can resist the flow of water. But above the prop roots, the trunks offer lesser resistance and hence less wave height reduction. So, they offer high wave attenuation at shallow depths. Pneumatophores are aerial roots that helps in respiration. Species like *Sonneratia spp.* and *Avicennia spp.* have characteristic pneumatophores. They also attenuate wave height at shallow depths.

Species	Characteristics considered	Wave reduction rate, %	Reference
Kandelia candel	Width, m: 100	20	Mazda et al. (1997)
Sonneratia	Water depth : 0.2m Water depth: 0.6m	45 26	Mazda et al 2006
	1)Water depth:1.9-2.1m Width- 20m 2) Water depth: 2.5m Width-40m	50-70 40	Quartel et al 2007
Rhizophora	Width, m: 200 Density, tree/m^2: 0.11 (Sparse) 0.16 (Medium) 0.22 (Dense) 0.36 (Super Dense)	 77 86 88 91	Hashim and Khairuddin (2014)
Rhizophora model	Width, m: 300 ;Density, tree/m^2: 0.5 – 1.7	60	Narayan et al. (2011)
Coastal tree model	Width, m: 100 Density, tree/m^2: 0.3	50	Mazda et al. (2006)

Fig 3 Dissipation Effectiveness of Different Mangrove Species and Characteristics

IV. TSUNAMI MITIGATION BY MANGROVES

Tsunamis are series of waves having wave period 10 min- 2 hours. Tsunamis are caused by earthquakes and landslides disturbing large masses of water. The resulting tsunami waves can travel rapidly over very long distances across the ocean.

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When tsunami waves approach land, they increase in height, sometimes becoming several metres high at the shore resulting in massive destruction and loss of life. The water depths in both storm surges and tsunamis can be similar but tsunamis arrive more quickly as one or a series of waves that may appear and flood an area in a matter of seconds or minutes. Mangroves can resist the waves and decrease the velocity of the flow by the attenuation of the waves. Model simulations using data from hydrological experiments to predict the attenuation of tsunami energy by mangroves were generated by Hiraishi and Harada (2003) based on the 1998 tsunami that destroyed parts of the north coast of Papua New Guinea. The model output suggests a 90% reduction in maximum tsunami flow pressure for a 100-m wide forest belt at a density of 3000 trees per hectare. Also, the studies conducted soon after the 2004 Indian Ocean tsunami reported that mangroves acted as bio shields, with villages located behind them suffering less damage than ones directly exposed to the coast.

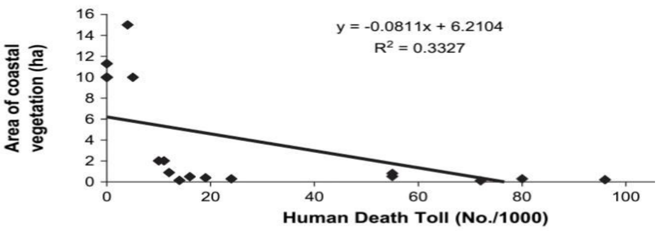

Fig 4 Human death toll after tsunami of 26th December 2004, in relation to area of coastal mangrove vegetation (Kathiresan, et al.2005)

The Indian Ocean Tsunami of December 2004 that caused economic and ecological impact in thirteen Asian and African countries affecting the provinces of Aceh (Indonesia), Sri Lanka, Tamil Nadu (India) and Khao Lak (Thailand) taking a total of 227,898 lives (according to U.S. Geological Survey).Danielsen et al. (2005) studied the proportional damage caused by the tsunami to 12 villages on the southeast coast of India that were hidden by open tree foliage, dense tree vegetation, or no tree vegetation was examined by using satellite imagery and discovered that settlements behind open or dense mangrove forests suffered noticeably less harm than those without it.

V. STORM SURGE REDUCTION BY MANGROVES

Mangroves are found in tropical and subtropical environments, so many of them are in areas vulnerable to cyclones, hurricanes, and typhoons as well as the storm surges, they cause. Storm surges happen when strong winds and low atmospheric pressure elevate coastal water levels, forcing sea water to flood ashore. Mangroves' capacity to lessen storm surges and the damage they cause can be assessed by three methods: 1) direct observation of water level heights. 2) numerical modelling. 3)observations on the impact caused.

Factors that determine the impact of storm surges: extend of inundation (flooded area), depth of flooding, peak water level, duration of inundation and the height of waves. Dense forests having species with aerial roots and more area of canopy projected was to reduce more wave height. Mangroves play a role in maintaining topographical features by influencing the depth of streams and strengthening stream banks, thus reducing storm surges. Mangrove tree roots also hold the soil together, reducing levee erosion, trapping sediment, and forming levees near streams. Storm surge reduction rate is the decrease in water level per meter of inland distance. Water level reduction is most at the seaward edge of mangroves and decreased further inland.

The factors governing surge height and reduction are hurricane size and forward speed, geometry of coastline, nearshore bathymetry, and surface roughness.

VI. MANGROVE SURFACE ELEVATION AND SEA LEVEL RISE

Sea level rise due to global warming and melting of glaciers has led to flooding of many coastal areas and resulting in damage of properties and loss of lives. The colonizing of mangroves changes the environment as it slows down water flow, reduces wave energy, promotes sedimentation and increasing soil volume by the presence of roots. This increases soil surface height and it may continue if the soil inputs exceed soil losses, till reaching a balance or till the mangrove vegetation is outcompeted by terrestrial vegetation. The elevation of the soil surface within a mangrove area is referred to as the surface elevation within the mangrove and change in its height is known as surface elevation change.

The factors affecting surface elevation are as follows:

Aerial root type and density: Krauss et al. (2003) investigated the influence of root type on vertical accretion in three river basins in Micronesia. They looked at three different functional root types: prop roots in Rhizophora spp, knee roots in Bruguiera gymnorrhiza,and pneumatophores in Sonneratia alba. In the Enipoas River basin, Pohnpei, accretion rates were higher among prop roots (11.0 mm/yr) than among pneumatophores (7.2 mm/yr), knee roots (9.3 mm/yr) and bare soil controls (9.4 mm/yr). According to Young and Harvey's (1996) study, the higher densities of pneumatophores are effective at promoting sedimentation.

Tree density: As the tree density increases, surface elevation rate also increases. Older plants could not survive at the higher densities used here.

Amount of mangrove leaf litter: Even though there is significant positive correlation between litter biomass (g/m2) and vertical accretion (mm/year), no relationship exists if the leaves are washed away by tidal action or it decays easily.

Forest type: Cahoon and Lynch (1997) measured elevation change and accretion in fringe, basin and island mangroves of Rookery Bay, Florida and found that accretion rates were highest in the fringe forests (7.2 and 7.8 mm/yr) and lowest in the overwash forest on the sheltered island (4.4 mm/yr).

Sub surface processes: The sub surface processes and the factors affecting their contribution to surface elevation change are root growth and decomposition, compaction/compression and shrink and swell of soils.

Surface elevation rises by increase in sedimentation, accretion and sub surface expansion by swelling, root growth and rebound; it falls by erosion, shallow subsidence by root decomposition, shrinkage, compaction, and compression.

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VII. OTHER USES OF MANGROVES

Mangrove systems protect coasts from flooding, caused by heavy rains from tsunamis and storms. The 1991 severe flood disaster in Bangladesh would surely have been minimized had 300 km2 if mangrove areas had not been cleared earlier for shrimp farming and rice cultivation. The flood protection capacity of mangroves is further extended in areas prone to tidal flooding, depending on the root system response, as roots facilitate sedimentation. In addition to flood protection, mangroves prevent seawater from seeping inland and prevent groundwater salinization. Very strong changes in groundwater salinity are often observed at interfaces between salt flats and mangroves. This suggests that mangrove systems can alter groundwater salinity levels by significantly reducing them.

VIII. MANGROVES AS COASTAL BIOSHIELD

Mangroves are currently under threat due to climatic changes, natural disasters like tsunami, cyclones etc, clearing of land for urbanization and other human activities. So, mangrove rehabilitation and conservation become necessary to implement mangroves as coastal bio-shield to protect coasts from tsunamis, cyclones, and hurricanes.

In Philippines, the mangrove cover that was degraded due to excessive aquaculture activities was tried to restore but only 10-20% successful as they chose Rhizhophora species instead of the natural colonizer in sandy substrate area, Avicennia and Sonneratia species.

The British Virgin Islands in the Caribbean benefited from the protective nature of mangrove ecosystems by reducing the risk of flooding, especially in three coastal areas: Jost van Dyke, Sea Cowes Bay and the East End. They predicted areas suitable for red mangrove replantation of 2.8 km2 within three regions, at least 167 buildings in Joest van Dyke, 285 buildings in Sea Cowes Bay, and 268 buildings in the East End were found to be protected.

In Malaysia, since 2005, the reforestation program of mangroves and other suitable species along the national coast has been considered as the National Restoration Programme, with the aim of restoring the mangrove ecosystem. The Comp-Pillow and Comp-Matt planting techniques introduced in this project (see Figure 5) are among the well-known techniques in mangrove research and development. Sabah has the highest mangrove cover in Malaysia, with a total of 1,396.4 hectares of degraded mangrove areas restored by the end of 2020.

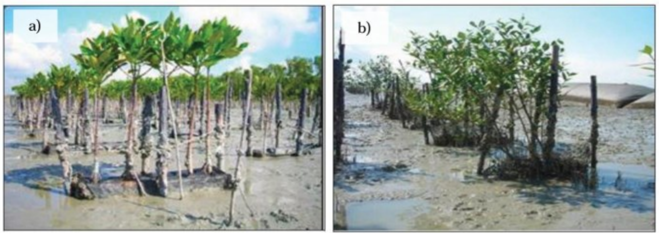

Fig 5 a) Comp-Mat technique for Rhizophora apiculata planting, b) Comp-Pillow technique for Avicennia alba planting, Raja Sulaiman et. al 2018.

Oil pollution, climate change, salt extraction and over exploitation for wood products lead to decline of mangrove cover in Kenya. Kenya Marine and Fisheries Research Institute (KMFRI) was pioneering the effort in 1991 and up to 2007, more than a million trees have been replanted with survival rates ranging from 10% to 70% depending on plantation area.

For the sustainable mangrove conservation and rehabilitation, a thorough grasp of forestry, ecological engineering, and coastal engineering along with participation from public and local communities must be ensured considering the compatibility of the site's species, planting methods, and environmental factors like pH, salinity, hydrology, and wave energy so as to survive strong waves and wind attacks and provide superior protection to secure the shoreline.

IX. CONCLUSION

Mangroves have been recognized as soft structures that provide coastline protection by minimizing destruction from catastrophic events including erosive wave attacks, torrential storms, and tsunamis. This paper has highlighted the role of mangroves in reducing the disastrous impact of cyclones, tsunamis and hurricanes by wave attenuation relying on mangrove characteristics like width, tree density, age, type of species etc. All studies have found that mangroves are able to attenuate wind and swell waves. The level of wave attenuation varies between 0.0014 /m and 0.011 /m. The protection levels were measured by numerical models found that about 13 to 66% wave height was reduced over 100m of mangroves. The highest reduction rate occurred at the edge of the mangroves as waves begin to pass through them. Mangroves play an important role in reduction of impact of storm surges by reducing water level and wave energy. Storm surges were reduced in a range of 5 to 50 cm per kilometer of mangrove width. Also, 75% of surface waves height was reduced. Mangroves reduce the risk of flooding and helps to keep up with sea level rise by influencing the surface elevation by different surface and sub surface processes. From the measurements taken by SET-MH method, it was evident that mangrove surfaces are rising at similar rates to sea level. The services offered by mangroves in coastal defense and protection are immense, making it one of the best bio-shield. The mangrove population is declining and extent of mangrove protection is still uncertain, so mangrove protection is a pressing concern. As the frequency and severity of coastal disasters are increasing, the need for conservation and rehabilitation of mangroves for coastal protection is of utmost importance.

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