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Review

Mangrove Health: A Review of Functions, Threats, and Challenges Associated with Mangrove Management Practices

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Abstract: Mangroves stand out as one of the most diverse and biologically significant natural systems in the world. Playing critical roles in maintaining the health and productivity of coastal ecosystems, mangroves provide a range of services and functions, including habitat for local fauna and flora, food and other goods, carbon sequestration, and protection from natural disasters such as storm surges and coastal erosion. It is also evident that mangroves face several threats, which have already led to the gradual depletion of mangrove areas worldwide. Based on the analysis of current and related historical literature and data, this review summarises mangrove functions and the threats and challenges associated with mangrove management practices. Our findings suggest that coastal development, expanded aquaculture, deforestation, climate change, and other associated implications such as eutrophication, diseases, and pollution are the major factors posing threats to mangrove sustainability. We also highlight the various challenges, such as land use conflict, a lack of stringent regulatory actions, inadequate policy and government frameworks, and a lack of community awareness, that underlie ineffective mangrove management. The implementation of inclusive and coordinated approaches involving stakeholders from different backgrounds and interests, governmental and non-governmental organisations, and academia is essential for mangrove restoration and sustainable mangrove management by adapting mitigation strategies.

Keywords: carbon sequestration; climate change; coastal development; mangrove biodiversity; mangrove management; microbial communities; mitigation; resilience; sustainability

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1. Introduction

Mangroves are coastal forests stretched between the terrene and the sea in the tropics and subtropics across the world [1]. Mangrove forests represent an assembly of trees and bushes that can thrive in dynamic ecological settings [2] with variable concentrations of soil oxygen [3] and saline water influx [4]. Being biologically diverse, the mangrove forests are known as the “rainforests of the seas” [5]. Due to their unique geographic location (i.e., coastal areas), they are great tourist attractions [6]. Mangrove forests are the dwelling place for local flora and fauna [7], which offer essential goods such as food in terms of aquaculture and agriculture [8], fuel wood, building materials [9], and traditional herbs and medicines [10]. In addition, mangrove forests protect the coastal environment by minimising the severe impacts of natural calamities, including floods [11], storms, and tsunamis [12], buffering salinity changes [13], sequestering atmospheric carbon [14], reducing erosion [15], and fostering biodiversity [16].

Despite their importance, mangroves are now facing high ecological pressure, and one-third of the total mangrove population has been lost globally in the past fifty years [17]. The losses are mainly due to clearance and conversion for aquaculture [18] or agriculture [19], domestic and industrial discharge [20], oil spills [21], and poorly managed dredging for coastal development [22]. Other than anthropogenic activities, implications of climate change, such as soil erosion [23], inundation [24], and storms [25], play a part in mangrove loss.

Mangroves are varyingly distributed in 118 countries and terrains, occupying a total area of 147,000 km^2 of the world [26]. Figure 1 shows the global mangrove forest distribution. Around 75% of the total mangrove population is concentrated in 15 countries [27], of which only 6.9% thrive in protected areas [28]. The majority of mangroves exist in the Southeast Asian region, particularly in Indonesia, Malaysia, and Myanmar [29].

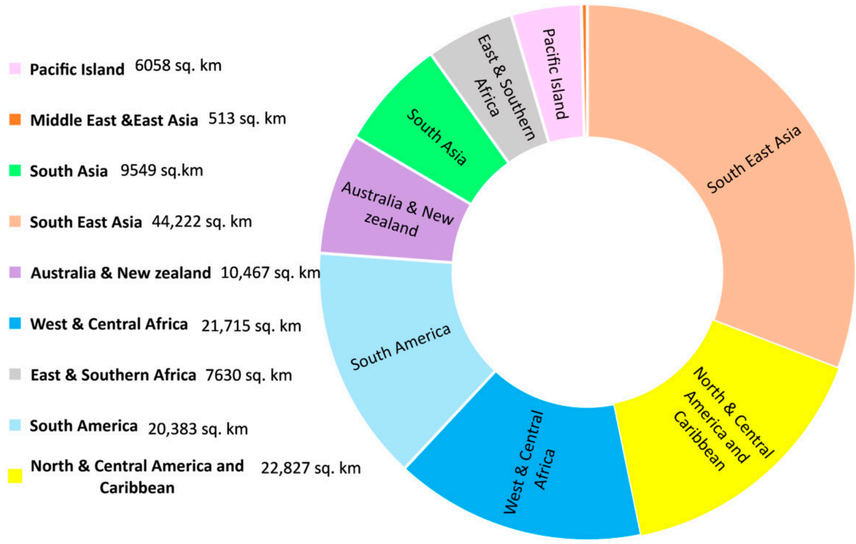

Figure 1. Percentage cover of mangrove forests in different parts of the world. (Data sourced from GMW, 2022).

In this review, we summarise current reported knowledge on multiple aspects of mangroves, ranging from their services and function to threats and challenges, in one frame of reference to develop a comprehensive understanding of insights into the mangrove ecosystem. The idea is to provide an overall view of the global status of mangroves and the challenges they face. A systematic study of the literature has been carried out, comprising articles from the past twenty years. Data from 1996 to 2020, sourced from Global Mangrove Watch (GMW) 2022 and the World Atlas of Mangroves (WAM) 2010, are the basis for the graphical illustrations. This research and resulting recommendations will serve as a reference for conducting further evidence-based studies and will be useful for stakeholders such as governmental agencies, environmental legislators and regulators, and industrialists in designing strategies for mangrove forest conservation and sustainable mangrove management.

2. Biotic Communities Associated with Mangroves

2.1. Habitat for Local Communities

Mangrove ecosystems are habitats for local fauna and flora, providing breeding places, shelter, nesting, and nursing areas [30] (Tables 1 and 2). Mangrove canopies are home to several wild animals, such as monkeys, monitor lizards, snakes, and otters [31]. The canopy also provides shade and shelter to aquatic-based animals, including amphibians and larger reptiles such as crocodiles [32] and dugongs [31]. Several birds inhabit mangroves, notably eagles, kingfishers, herons, plovers, terns, cormorants, egrets, and ibises [33]. On tree trunks, the residing flora includes orchids, ferns, lilies, and vines [34], which are home to invertebrates such as spiders and various insects [35]. Other than that, mangrove roots are swarmed by arthropods (crabs, lobsters, and shrimp) [36]; Molluscs (barnacles, oysters, mussels, and snails) [37]; sponges [38]; worms [39]; jellyfish [31]; and fish such as sea trout, snappers, jacks, tarpon, sea bass, red drums, and snook [40]. Moreover, mangroves host diverse epibiont macroalgal communities on their prop roots, trunks, and mud surfaces [41]. Mangrove habitats provide shallow water and, in many cases, high turbidity and fine sediment suitable for burrowing animals [42]. These factors act to protect animals from their predators by reducing their visibility and lowering their encounter rate with potential predators [43]. Mangrove plants, along with kelps, seagrasses, oysters, and corals, are key foundation species of coastal ecosystems [44]. Foundation species are crucial for maintaining the structure and resilience of an ecosystem [45].

Table 1. List of fauna associated with mangroves.

Group	Common Name	Genus/Species	References
Sponges	*Common Mangrove Sponge*	*Tedania* sp. *Mycale* sp. *Dysidea* sp. *Haliclona* sp.	[46]
Worms	Segmented worms	*Sabellastarte* sp.	[47]
Insects	Ant	*Polyrachis bicolor* sp.	[48]
	Weevils	*Rhynchites* sp.	[49]
	Bettles	*Monolepta* sp.	[50]
Crustaceans	Crabs	*Ilyogynis microcheirum* *Portunus pelagicus* *Uca* sp. *Hippidea* sp.	[51,52]
	Prawns	*Penaeus monodon* *Exopalaemon styliferus* *Metapenaeus affinis* *Parapenaeopsis sculptilis*	[53,54]
	Barnacles	*Balanus* sp. *Euraphia* sp. *Tetraclita* sp.	[55,56]
Mollusks	Oyster	*Crassostrea* sp.	[57]
	Clam	*Tridacna derasa* *Tridacna maxima* *nodontia edentula*	[58–60]
	Sea slug/sea hares	*Dolobella* sp.	[61]
	Venus clam	*Bursa* sp. *Paphia amabilis* *Venus clam Paphia* *Haliotis asinina* *Tectus pyramis* *Echininus cumingii* *Terebralia sulcata* *Rhinoclavis sinensis* *Rhinoclavis vertegus* *Ficus gracilis* *Plicacularia pullus* *Fasciolaria trapezium* *Oliva reticulata* *Mitra mitra* *Trisodos tortuosa* *Anadara maculosa* *Chicoreus brunneus*	[62–66]

Table 1. *Cont.*

Group	Common Name	Genus/Species	References
Echinoderms	Sea urchin	*Protoreaster* sp. *Archaster* sp. *Linckia* sp. *Clypeaster* sp. *Cerithium* sp. *Tripneustes* sp. *Holothuria* sp. *Oreaster albeolatus* *Ophiarachna incrasala* *Echinocardium cordatum* *Diadema setosum* *Laganum laganum* *Echinometra mathaei*	[62,67–69]
	Star fish	*Astropecten* sp. *Protoreaster nodosus* *Linkia laevigata*	[69,70]
	Feather star	*Comanthina bennetti* *Comanthina schlegeli*	[71]
	Sea star	*Luidia* sp. *Culcita novaeguineae*	[72]
Tunicates	Sea squirt	*Didemnum molle* *Atriolum robustum* *Polycarpa aurata* *Rhopalea* sp.	[73]
Fishes	Rabbitfish	*Siganid* sp.	[74]
	Mudskipper	*Periophthalmodon* *Periophthalmus*	[74]
	Spot-tail needlefish	*Strongylura strongylura*	[75]
Amphibians	Mangrove frog	*Fejervarya cancrivora* *Rana cancrivora*	[76]
Reptiles	Snake	*Cerberus rhybchos*	[62]
	Lizard	*Tupinambis indicus*	[77]
	Crocodiles	*Crocodylus porosus*	[78]
Birds	Eagles	*Haliastur indus* *Pitta megarhyncha*	[79,80]
	Kingfishers	*Halcyon senegaloides* *Todiramphus sordidus*	[81]
	Herons	*Nycticorax nycticorax* *Egretta gularis*	[82,83]
	Plovers	*Charadrius* sp. *Pluvialis* sp. *Thinornis* sp.	[84,85]
	Terns	*Sterna paradisaea*	[85]
	Crow	*Corvus splendens*	[86]
	Green pigeon	*Treron olax*	[86]
	Egrets	*Egretta garzetta* *Egretta immaculata* *Egretta nigripes*	[87,88]

Table 1. *Cont.*

Group	Common Name	Genus/Species	References
Mammals	Bats	*Cynopterus brachyotis* *Acerodon jubatus*	[89,90]
	Monkey	*Nasalis larvatus*	[91]
	Dugong	*Dugong dugon*	[92]
	Otters	*Lutrinae* sp.	[93]

Table 2. List of flora associated with mangrove.

Group	Common Name	Genus/Species	References
Angiosperm	Seagrasses	*Cymodocea* sp. *Thalassia* sp. *Halodule* sp. *Halophila* sp. *Enhalus* sp.	[94,95]
	Orchids	*Acampe* sp. *Agrostophyllum* sp. *Apotasi* sp. *Ascocentrum* sp. *Bulbophyllum* sp. *Ceratostylis* sp. *Cleisostoma* sp. *Cymbidium* sp. *Dendrobium* sp. *Flickingeria* sp. *Grosourdya* sp. *Habenaria* sp. *Liparis* sp. *Malaxis* sp. *Podochilus* sp. *Pomatocalpa* sp. *Thelasis* sp.	[96–100]
	Lilies	*Crinum* sp. *Hymenocallis* sp. *Nymphaeaceae* sp. *Lycoris* sp.	[101,102]
	Vines	*Cryptostegia grandiflora*	[41]
Bryophytes	Ferns	*Acrostichum* sp. *Waterhousea* sp.	[103,104]
Algae	Marine algae	*Padina* sp. *Ulva* sp. *Ventricaria ventricosa*	[105,106]

2.2. Mangroves Association with Corals and Seagrass

Mangrove ecosystems are partly linked with and support corals and seagrasses [107]. Mangrove ecosystems have a positive impact on seagrass meadow traits such as shoot length, width, and height, shoot density, root length, number of leaves, leaf biomass, and population dynamics [108]. Mangrove roots trap the fine sediments coming from terrestrial sources and intercept turbid water, preventing it from reaching coral and seagrass systems [109]. On the other hand, coral reefs provide tranquil conditions that increase the deposition of fine sediments in adjusting areas, which supports the growth and development of seagrass beds and mangrove forests [110]. Likewise, corals and seagrasses maintain the balance between organic and inorganic carbon contents in coastal areas, subsequently establishing carbon sinks and sources in the mangrove ecosystem [111]. As mangrove forests, coral reefs, and seagrasses are interdependent ecosystems, to effectively store and export blue carbon in tropical coastal areas, it is essential to maintain the health of each of these coexisting ecosystems [112].

2.3. Reservoir of Microbial Communities

Mangroves are reservoirs of diverse microbial communities that include bacteria and fungi [113]. Organic sediments swept into mangroves by tides are inhabited by bacteria that decompose the organic debris and are primary contributors to carbon cycling [114]. Diverse bacteria in these populations are involved in many other essential ecological functions such as nitrogen fixation [115], photosynthesis [116], phosphate solubilisation [117], enzyme production [118], sulfate reduction [119], antibiotic production [120], anoxygenesis [121], and methanogenesis [122] (Table 3). Among fungi, the dominant fungal phyla are *Ascomycetes* and *Basidiomycetes*, which have been reported to be primarily associated with the survival of mangrove plants in waterlogged and nutrient-restricted environments [123] (Table 3). The microbial communities of mangroves improve nutrient availability, support the growth of vegetation, and provide protection from pathogenic bacteria, thereby positively impacting species diversity [124].

Table 3. Major microbial groups inhabiting the mangrove forests.

Group	Phyla	Functions	References
Bacteria	*Actinobacteria*	• Produce highly bioactive compounds such as antibiotics against pathogenic bacteria, anticancer, and antifungals, and protect mangroves from disease	[125]
	Chloroflexota	• Methanogenesis • Produce secondary metabolites from root exudates or soil organic matter that can be utilised by other anode-coupling microorganisms • Anaerobic degradation of organic compounds, e.g., sulfate reduction	[113,114]
	Asgardarchaeota	• Phosphate solubilisation • Major contributors to nitrogen cycling in the mangroves, especially involved in nitrification	[126]
	Bacteroidetes	• Release a wide range of carbohydrate-active enzymes (CAZymes) that target the different glycans in the soil • Phosphorus solubilisation	[45]
	Thermoproteota	• Oxidisation of ammonia • Sulfate reduction • Methanogenesis	[127]
	Calditrichota	• Enable mangroves to survive in hot climates	[128]
	Bacillota	• Maintains electrolyte balance between mangrove plants and microbial species	[129]
	Thermodesulfobacteriota	• Oxidation of the precipitated sulfide • Participate in the elimination of toxic metals • Regulate the sulfur cycle, oxidise reduced sulfide to sulfate, affecting the sulfur biogeochemistry • Converts many metal ions such as Cu, Pb, Cr, Zn, Hg, and As into low-solubility metal sulfides	[124]

Table 3. *Cont.*

Group	Phyla	Functions	References
	Euryarchaeota	• Organic matter decomposition • Ammonia oxidation	[113]
	Firmicutes	• Produce indole-3-acetic acid (IAA) and siderophores • Oxidize hydrogen cyanide and thiosulfate • Produce ammonia and cellulase • Solubilise potassium and zinc	[130,131]
	Halobacterota	• Increase salt tolerance and help with sulfate reduction	[132]
	Nitrososphaerota	• Ammonia oxidation and nitrification	[127]
	Nitrospirota	• Participates in nitrifying process	[122]
	Planctomycetota	• Role in methane metabolism • Ammonia oxidation in mangroves and the exclusive metabolic capacity to combine ammonium and nitrite or nitrate to form nitrogen gas under anoxic condition	[133]
	Pseudomonadota	• Detoxification of pollutants • Carbon and nitrogen fixation in mangrove sediments	[134,135]
	Thaumarchaeota	• Ammonia oxidation	[122]
	Zixibacteria	• Nutrient recycling	[136]
Cyanobacteria	*Cyanobacteriota*	• Key role in carbon and nitrogen fixation • Helps in nitrogen fixation • Cells provide calcium, magnesium, and phosphorous storage in mangrove ecosystems	[137,138]
Fungi	*Ascomycota*	• Develops mycorrhizal associations with roots of mangroves and transports nutrients • Helps plants survive in waterlogged conditions • Acts as decomposers • Produces a variety of extracellular degradative enzymes, which include cellulase, xylanase, pectinase, and amylase	[123,139]
	Basidiomycota	• Involved in detritus processing, phosphate solubilisation, and cellulose degradation	[140]

3. Mangrove Ecosystem and Economic Functions and Services

There are several functions of mangrove forests other than as habitats for flora and fauna: They act as a carbon sink (blue carbon storage) [141], maintain water quality [142], protect coastal land from natural disasters [143], and support coral and seagrass ecosystems [144] (Figure 2). In addition, mangroves provide livelihood opportunities for coastal communities through aquaculture, fodder, timber, and ecotourism [8].

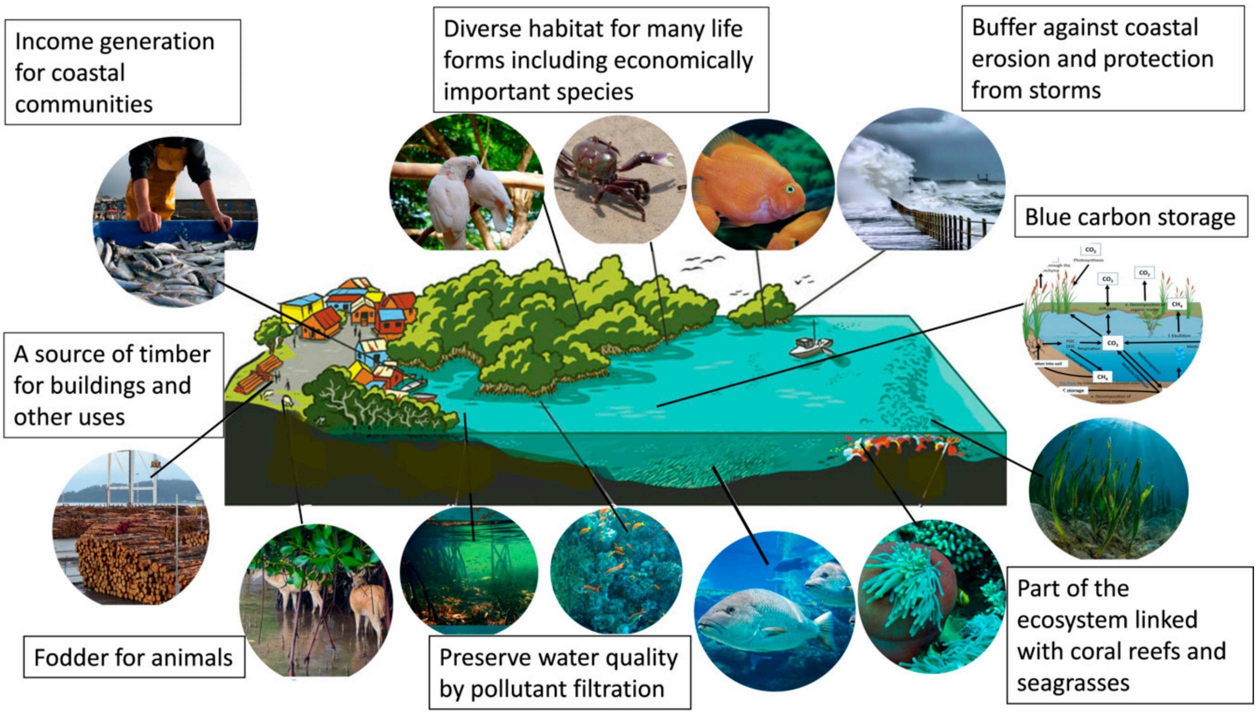

Figure 2. Functions and services of an intact mangrove ecosystem.

3.1. Carbon Sink

Mangroves play an important role in mitigating the effects of greenhouse gases generated by anthropogenic activities such as deforestation, agriculture, and industrial processes. This mitigation involves removing CO_2 from the atmosphere, after which mangrove flora sequester carbon in their above- and below-ground biomass [141]. Mangroves, as a carbon sink, can hold an estimated 1023 Mg/hectare of carbon [145]. Various studies have confirmed that mangroves have a faster carbon sequestering capacity than other ecosystems, such as grasslands or tropical rainforests [146]. According to a report from the Global Mangrove Alliance (GMA) 2022 [147], the total organic carbon stored in mangrove forests at a global level is estimated at around 21,896.56 Mt CO_2e with 2817.23 Mt CO_2e stored in above-ground biomass and 19,079.32 Mt CO_2e stored in the upper 1 m of soil [148]. It can be seen from Figure 3 that the carbon storage capacity varies quite considerably for different countries, with Indonesia having a relatively strong capacity compared to the other countries. In mangroves, carbon-rich soils extend from 0.5 m to ~3 m in depth and accommodate 49%–98% of the carbon stored by the mangrove ecosystem [149]. Figure 3 represents the organic carbon storage capacity of mangrove forests in various countries as above-ground biomass (data derived from GMW version 0.3, 2020) [150]. As mangroves store a considerable amount of carbon, the destruction of this habitat disturbs the carbon sink and emits huge amounts of carbon back into the atmosphere, significantly contributing to climate change. Therefore, protecting and restoring mangrove habitats can reduce the impact of climate change [151]. Although it would be great to consider many more countries in this discussion, due to the brevity of the paper, only 12 countries have been included that have the most robust data, as shown in Figure 3.

Figure 3. Above-ground carbon storage capacity of mangrove forests in different countries in 2020. Each country has mangrove forests with different carbon storage capacities, which are presented in ranges of carbon storage measured in metric tons of equivalent carbon (Mt CO_2e) with each range represented by a different colour. The *x*-axis is a scale bar of the percentages of the total forests in each country that fall into each carbon storage range. (Data sourced from GMW, 2022).

3.2. Natural Water Filters

Mangrove forests act as natural water filters for coastal areas, improving the water quality by trapping sediments and other solid impurities with their roots [142]. This reduces the flow of sediments into offshore waters, thereby reducing erosion [152], maintaining clean habitats for seagrass beds and coral reefs, and contributing to SDG 14, which talks about life below water [153]. Mangroves can grow in saline water and filter 90% of sodium ions (Na^+) from the surrounding seawater [154]. Their roots comprise a three-layered pore structure in the root epidermis, which facilitates Na^+ filtration [155]. Additionally, mangrove roots, such as pneumatophores and prop roots, create a low-energy environment, allowing wastewater-containing contaminants to reside for an extended period [156]. Mangrove plants also sequester other metals, including the heavy metals Zn, Mn, and Cu [157]. The study of the mechanisms by which mangrove plants filter water has led to novel water treatment technology: Researchers at Virginia Tech (Virginia Polytechnic Institute and State University, USA) [158] have developed a "synthetic tree" water purifier system inspired by the water filtration technique used in mangrove plants. Specifically, a synthetic tree is composed of a nano-porous "leaf" to produce suction via evaporation, a vertical column of glass tubes similar to the xylem vessels of the tree, and filters attached to the tube inlets, mimicking roots [158]. In another recent study, a group of engineers from Yale University (New Haven, CT, USA) invented a water purification device that mimics the desalinisation ability of mangrove trees based on the principle of cohesion-tension theory in mangroves. In this technique, synthetic leaves can generate highly negative pressures that allow desalination through a reverse osmosis (RO) membrane [159].

3.3. Barriers to Natural Disasters

Mangroves not only prevent soil and coastal erosion by retaining sediments in their aerial roots [152] but also act as barriers against natural disasters. The canopy, trunk, and roots of mangrove plants restrain storm surges [143] and waves [160]. In the aftermath of the Asian tsunami on 26 December 2004 [161], Hurricane Katrina on 23 August 2005, on the US Gulf Coast [162], and the Transoceanic tsunami on 23 January 2022 [163], persuasive evidence emerged from field studies in several countries justifying the role of mangroves as natural barriers protecting coastal habitats and communities. It is quite evident after the tsunami survey that the intact and dense mangroves with higher structural complexity near coastal areas offered fewer fatalities and minimal damage to assets as compared to the areas where mangroves had either been destroyed or transformed to alternate land uses [164,165].

3.4. Livelihood Opportunities for Coastal Communities

About 90% of the global mangrove forests grow in economically less privileged countries [166]. Approximately 100 million people live within a 10 km range of mangrove forests and directly benefit from this ecosystem as a source of livelihood opportunities [167].

3.4.1. Aquaculture

Mangroves are considered hotspot locations for aquaculture [168]. The species commonly reared include various fish, shrimp/prawns, crabs, molluscs, and other invertebrates [169]. Approximately 80 million tonnes of fish were produced globally through aquaculture in 2022 [170]. Extensive mangrove-associated aquaculture has been observed in Indonesia, Malaysia, and the Philippines [171]. Mangrove-associated aquaculture accounts for 21% (1.4 million tons annually) of the coastline fisheries of the ASEAN (Association of South East Asian Nations) region [172]. Of the annual fish and seafood resources, fin fish alone contribute around 1.09 million tons [173], while shrimp/prawn contribute around 0.4 million tons [174]. In addition, fish products from these aquaculture activities are a principal source of food for coastal communities.

Large-scale aquaculture [175], fish farming in cages or in ponds [176], and integrated rice-fish farming [177] have reduced pressure on overexploited fisheries by diversifying fish production other than wild stocks. Small-scale aquaculture, in particular, enables fish farmers to provide food for their families while generating income from the sale of surplus stock [178]. Such activities also create employment opportunities through various enterprises ranging from the processing, distribution, and sale of fish linked to the aquaculture value chain [179]. These livelihood opportunities facilitate the sustainable mangrove ecosystem's ability to successfully contribute to the outcomes of various sustainable development goals set by the United Nations, such as SDG 1, SDG 2, SDG 8, SDG 11, SDG 13, SDG 14, and SDG 15. (The detailed agenda of these SDGs can be seen at https://www.un.org/development/desa/disabilities/envision2030.html, accessed on 11 July 2023) [180].

3.4.2. Fodder, Timber and Traditional Medicines

Mangroves also provide fodder, timber, and medicine resources for coastal indigenous communities (Figure 2). Cattle, sheep, goats, and buffaloes are domestic animals that are generally fed on mangrove foliage [181]. Mangrove foliage, particularly from *Avicennia marina*, is considered healthy fodder for domestic animals (Mitra, 2020). Mangrove wood, being highly resistant to rot and insects, is frequently utilised as timber as well as for fuel wood [182]. *Rhizophora* spp., *Xylocarpus* sp., *Bruguiera* sp., and *Sonneratia* sp. are significantly important for timber due to the durability of their wood and their large trunk size [183]. The timber of these species is used for small watercraft, shipbuilding, and for making utensil handles, furniture, poles, piles, and other building materials [184]. Mangrove firewood has been widely used as an energy source by rural communities.

Mangrove services also include the provision of traditional medicine for treating skin ailments and stomach issues [185]. Extracts from mangrove-associated species, for example, *Abonnema* and *Nypa fruticans*, have shown antimicrobial activity against some plant and animal pathogens [186]. The bioactive compound ecteinascidin, extracted from the mangrove tunicate *Ecteinascidia turbinate*, has been reported to show strong in vivo activity against various cancerous cells [187]. Furthermore, the bark of *Ceriops* sp. is a good source of tannin, and its decoction is used in Vedic medicine to stop haemorrhage and in the treatment of malignant ulcers [188].

3.4.3. Ecotourism

Ecotourism refers to the form of tourism that focuses on responsible travel that minimises environmental impact and supports local communities [189]. Ecotourism in mangrove regions places a strong emphasis on mangrove conservation, education of visitors about the mangrove forest, and providing economic benefit to local communities [190]. Ecotourism syndicates three key aspects, viz., (i) ecology, which includes the existence of the elements upon which the mangrove ecosystem depends and also its conservation efforts [191], (ii) financial revenue generated as a result of ecotourism activities in sustainable mangroves, a share of which is expended to maintain the ecosystem [192], and (iii) empowerment and engagement of the local community in the ecotourism business [193]. The species diversity of both fauna and flora and the unique characteristics of mangrove plants have been a great attraction for ecotourism [194]. Mangrove areas offer several forms of ecotourism activities, such as sports and recreational activities such as fishing, boating, and camping [195]; educational and research tourism in the form of field trips to mangroves to observe and study the mangrove vegetation and life inside the mangroves [196]; and health tourism as sites for self-meditation and other therapy [197]. Many mangrove forests have been established as tourist attractions by governmental or non-governmental organisations in different regions [198]. For example, areas of mangrove forest in Bali, Indonesia, have been established by local communities for the purpose of ecotourism and to maintain the conservation of biodiversity, landscapes, and the ecosystem overall [199]. Ecotourism activities carried out by these community groups are supported and fostered by the relevant stakeholders of the region and/or the state government and have been incorporated as a part of their CSR (corporate social responsibility) program [200]. The use of mangroves for ecotourism is in accordance with the development directions of the Sustainable Development Goals (SDGs), 12, 13, 14, 15, and 17 [201].

4. Major Threats to Mangrove Ecosystems

Mangrove forests are home to some of the world's most endangered plant species [202] (Table 2). Deforestation is aggressively practiced in many mangrove areas for the purpose of land use for farming, aquaculture, and coastal development [203]. Over one-third (35%) of total mangrove populations have been lost over the past 50 years [17]. Asia has contributed to 36% of the mangrove losses so far [204]. Figure 4a illustrates the mangrove loss in the twelve affected countries, documented in the years 2010, 2015, and 2020. Mangrove losses are highest in Indonesia, followed by Myanmar and Australia. The rate of mangrove loss over the last decade was estimated at 0.04% per year globally [205] and surpasses the losses of tropical rainforests and coral reefs, the two other most highly threatened ecosystems [206]. According to Global Mangrove Watch, the global area of mangroves has decreased by 5245.24 km^2 from 1996 to 2020 [150,207], as shown in Figure 4b. Among the 64 species of mangrove plants in the world, a total of 12 species have been declared threatened species by the International Union for Conservation of Nature (IUCN) Red List [208] (Table 4). Interestingly, although the African continent has several mangrove areas, all of the species are listed as "least concern" in the ICUN red list, with none mentioned as critically endangered, endangered, vulnerable, or near threatened.

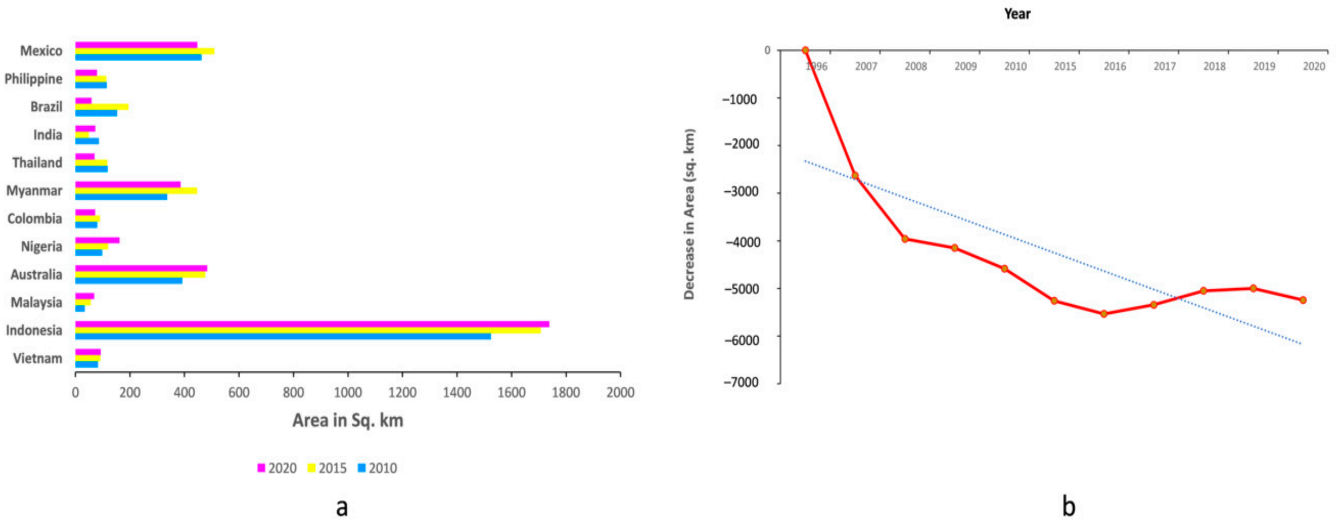

Figure 4. (**a**) Mangrove loss in different countries from 2010 to 2020; (**b**) global net mangrove area changes from 1996 to 2020. Red line represents the change in mangrove area in different years from 1996 to 2020, while blue dotted line reflects the trend of change in area, which is towards overall decline in mangrove area from year 1996 to 2020 (Data sourced from GMW, 2022; WAM, 2010).

The overall threats to mangroves have been categorised into three groups based on D. Alongi's classification of threats [209] (Figure 5). Among them, coastal development, expanding aquaculture and agriculture, and the acquisition of timber for domestic use are severe threats [210]. Climate change, eutrophication, and hydrological alteration are considered moderate threats [211], and diseases, tourism, and pollution (noise/thermal/chemical/oil) come under low-level threats to mangrove ecosystems [212].

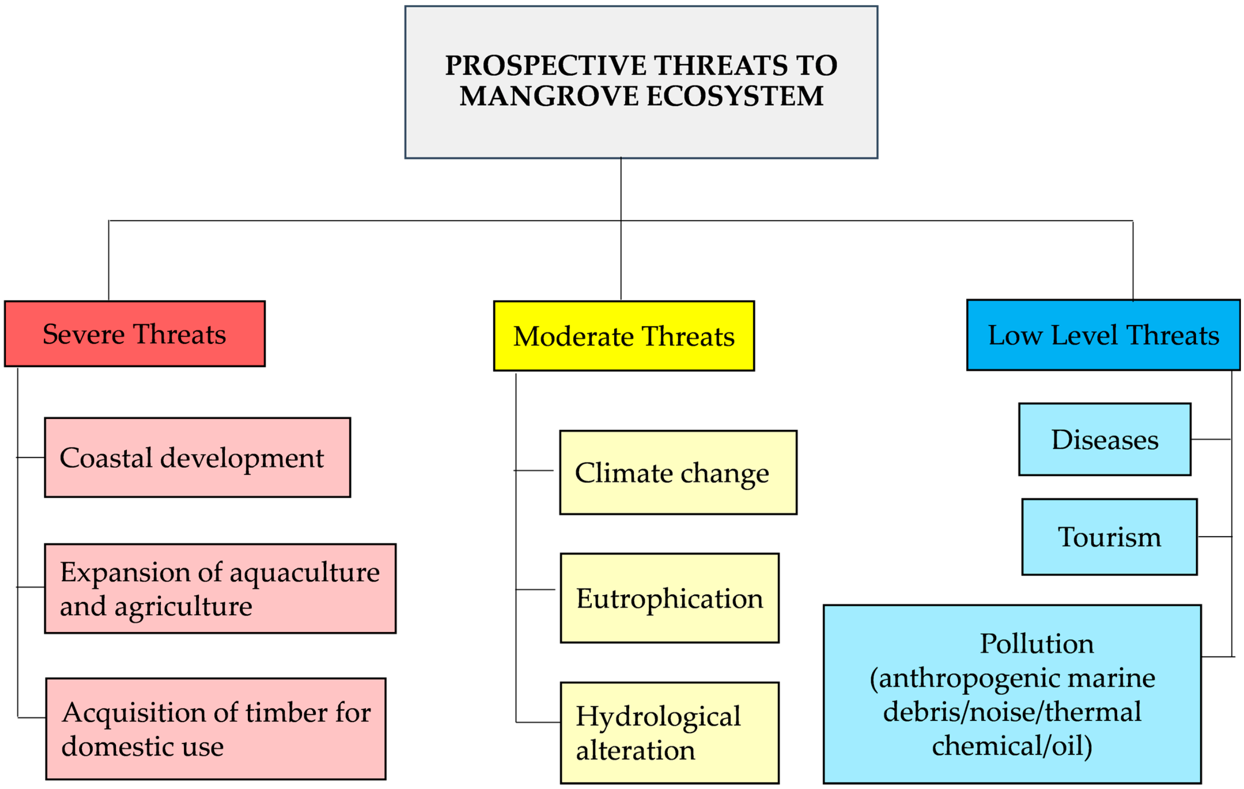

Figure 5. Prospective threats to mangrove ecosystem. (Adapted from D. Algoni, 2002 [209]).

Table 4. International Union for Conservation of Nature (IUCN) red list of mangrove plant species.

<table>
<tr><th>Country</th><th>Total Species</th><th>Critically Endangered (CR)</th><th>Endangered (EN)</th><th>Vulnerable (VU)</th><th>Near Threatened (NT)</th><th>Data Deficient (DD)</th><th>Least Concern from All (LC)</th></tr>
<tr><td>Indonesia</td><td>47</td><td>Sonneratia griffithii
Bruguiera hainesii</td><td>Camptostemon philippinense
Heritiera globose</td><td>Avicennia rumphiana</td><td>Aegialitis rotundifolia
Aegiceras floridum
Sonneratia ovata</td><td>Aglaia cucullata
Excoecaria indica</td><td rowspan="9">Acrostichum speciosum
Bruguiera gymnorhiza
Pemphis acidula
Acrostichum aureum
Acrostichum danaeifolium
Avicennia germinans
Conocarpus erectus
Laguncularia racemosa
Rhizophora mangle
Rhizophora racemosa
Avicennia schaueriana
Acanthus ebracteatus
Acanthus ilicifolius
Aegialitis annulata
Aegiceras corniculatum
Avicennia marina
Bruguiera cylindrica
Bruguiera exaristata
Bruguiera parviflora
Bruguiera sexangula
Camptostemon schultzii
Ceriops australis
Ceriops tagal
Cynometra iripa
Dolichandrone spathacea
Excoecaria agallocha
Heritiera littoralis
Lumnitzera littorea
Lumnitzera racemosa
Nypa fruticans
Osbornia octodonta
Rhizophora apiculata
Rhizophora mucronata
Rhizophora stylosa
Scyphiphora hydrophylacea
Sonneratia alba
Sonneratia caseolaris
Sonneratia lanceolata
Xylocarpus granatum
Xylocarpus moluccensis
Avicennia alba
Avicennia officinalis
Kandelia candel
Sonneratia apetala
Kandelia obovate</td></tr>
<tr><td>Malaysia</td><td>40</td><td>Bruguiera hainesii
Sonneratia griffithii</td><td>Heritiera fomes
Heritiera globose</td><td>Avicennia rumphiana</td><td>Aegiceras floridum
Ceriops decandra
Sonneratia ovata</td><td>Aglaia cucullata
Excoecaria indica</td></tr>
<tr><td>India</td><td>37</td><td>Sonneratia griffithii</td><td>Heritiera fomes</td><td></td><td>Aegialitis rotundifolia
Ceriops decandra</td><td>Aglaia cucullata
Excoecaria indica</td></tr>
<tr><td>Myanmar</td><td>36</td><td>Sonneratia griffithii</td><td>Heritiera fomes</td><td></td><td>Aegialitis rotundifolia
Ceriops decandra</td><td>Aglaia cucullata
Excoecaria indica</td></tr>
<tr><td>Thailand</td><td>35</td><td>Sonneratia griffithii</td><td>Heritiera fomes</td><td></td><td>Aegialitis rotundifolia
Ceriops decandra
Sonneratia ovata</td><td>Aglaia cucullate</td></tr>
<tr><td>Australia</td><td>35</td><td></td><td></td><td>Avicennia integra</td><td>Sonneratia ovata</td><td></td></tr>
<tr><td>Philippines</td><td>34</td><td></td><td>Camptostemon philippinense</td><td>Avicennia rumphiana</td><td>Aegiceras floridum
Sonneratia ovata</td><td>Aglaia cucullate</td></tr>
<tr><td>Vietnam</td><td>33</td><td></td><td></td><td></td><td>Aegiceras floridum
Sonneratia ovata</td><td></td></tr>
<tr><td>Colombia</td><td>12</td><td></td><td></td><td>Avicennia bicolor
Mora oleifera
Pelliciera rhizophorae
Tabebuia palustris</td><td>Rhizophora samoensis</td><td></td></tr>
<tr><td>Nigeria</td><td>7</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

4.1. Severe Threats

4.1.1. Coastal Development Leading to Degradation

Coastal development poses a severe threat to mangrove ecosystems. Coastal development includes the formation of resorts, desalination plants, power plants, nuclear plants, harbour facilities, docks, dams, and aquaculture ponds [213]. Figure 6 presents some developmental activities near coastlines. Coastal development is inevitably accompanied by grave issues such as soil erosion [214], pollution [215], and altered hydrology [216], which hinder the rehabilitation of any adjacent mangrove forests. Coastal development also often causes the blockage or divergence of rivers that previously passed through mangroves before entering the sea, leading to changes in alluviation [217], infiltration [218], salinity [219], and temperature [220]. These changes adversely affect not only the mangrove plant population but also aquatic life, including fish, shrimp/prawns, and other edible species [221].

Figure 6. Coastline development activities in different regions. (**a**) Warehouse construction in Herald, New Zealand; (**b**) mangrove creek dam construction in Mangrove Cay, Bahamas; (**c**) resort construction in Abu Dhabi, UAE; and (**d**) port construction in Java, Indonesia. (Source: Coastline Stock Photos).

4.1.2. Expansion of Aquaculture/Agriculture Leading to Over-Exploitation of Mangrove Forests

Aquaculture practices, primarily for large-scale shrimp/prawn farming, have destroyed gigantic areas of the mangrove forests [222]. Globally, shrimp farming and other forms of aquaculture have been reported as the main reasons for the conversion of 52% of the mangrove forest areas in the last three decades [203]. Several Southeast Asian countries, such as Indonesia, Myanmar, and Malaysia, have lost up to 10% of their mangrove areas in just twelve years (from 2000 to 2012) due to aquaculture [223]. Thailand and Vietnam, which are considered hotspots for aquaculture, have lost their mangrove forests at a rate of 0.09 km^2/year between 1990 and 2020 [224]. In Vietnam, 1020 km^2 of mangrove areas have undergone conversion for aquaculture over the last three decades, followed by Thailand and Bangladesh with the loss of 694 km^2 and 65 km^2, respectively [203]. About 2055 km^2 of mangrove wetlands have been converted into shrimp and other fish farms in the Philippines. Furthermore, Indonesia has lost 2110 km^2 of the total mangrove area as a result of aquacultural activities [225], with Java alone seeing 90% of the mangroves compromised for aquaculture and agriculture-related activities [226]. Similarly, a large area of the mangrove forests in India has been destroyed due to expanded aquaculture. In India, about 40% of mangrove habitats on the western coastline have been transformed for aquaculture [227]. Large-scale shrimp farming has been one of the key factors in the decline of mangrove forests in Ecuador and Honduras (Latin America), with mangrove losses of 216 km^2 and 115 km^2, respectively [203].

The increasing agricultural activity near mangrove areas is another main driver of deforestation, particularly in Latin America and South Asia [228]. Enormous mangrove areas in the Philippines and Indonesia have been replaced by agriculture. The escalating trends of growing oil palm plantations in Thailand, Malaysia, Indonesia, and Colombia have caused the drastic conversion of mangrove forests in these areas [229]. Similarly, around 150,000 ha of mangroves have been destroyed only for agriculture practices in India and Bangladesh during the last 100 years [227]. In addition, in Central America, mangrove forests have been cleared for cattle grazing and industrial farming [230]. These practices are encouraged by the growing international market value of shrimp/prawns, resulting in local policy changes to allow mangrove clearing to support aquaculture [231]. Public sector funding for fisheries has been a key driver of mangrove conversion for aquacultural development [232]. The increase in shrimp farms has promoted mangrove deforestation, which has caused the loss of their ecological and socio-economic functions and the salinization of groundwater, along with other implications such as the introduction of non-native species, excessive use of fishmeal in shrimp feed, and overharvesting of wild stock [233]. Adding to the problem is that poorly managed fish and shrimp/prawn ponds are susceptible to pollution and disease, leading to abandonment and leaving behind a degraded habitat. This sweeping conversion not only destroys the mangrove forests but also disrupts fish and shrimp breeding, impacting fishery stocks [234,235].

4.1.3. Deforestation for Acquisition of Timber

Mangroves have been overexploited for timber and fuel for decades [9]. An estimated 26% of existing mangrove loss is from deforestation for fuel and timber [236]. Usually, mangroves are harvested without any precise management framework, resulting in an unjustifiable decline in the forest yield [237]. Deforestation of mangroves has been linked to worsened impacts from climatic variables such as flooding, hurricanes, drought, precipitation, salinity, and rises in sea level and sea surface temperature, which have drastic effects on coastal environments and communities [225]. Mangrove deforestation has also resulted in CO_2 emissions to the atmosphere and soil organic carbon (C) loss in mangrove soils [238]. Mangrove forests have always been significant for their biodiversity, but extensive forest tree cutting to fulfil domestic needs has resulted in the loss of not only flora but habitat for wildlife in mangrove ecosystems [184,239].

4.2. Moderate Threats

4.2.1. Climate Change

Climate change is causing a rise in sea level, increased temperature, increased CO_2 concentration, oceanic acidification, and changes in precipitation/storm patterns, all of which have negative effects on mangroves and lead to the extinction of mangrove species [240]. The predicted outcomes of different climate change factors are summarised in Table 3. Among all the components of climate change, rises in sea levels and increases in oceanic acidification are the greatest threats to mangroves [241]. Since 1993, the average rise in sea level has been at a rate of 0.3 cm per year. The USA National Oceanic and Atmospheric Administration [242] predicted sea level rises as high as 1.5 to 2.5 m by the end of this century.

The oceanic uptake of CO_2 slows down global warming by reducing the CO_2 concentration in the atmosphere; however, this also leads to major changes in the chemical composition of seawater through acidification [243]. An increase in oceanic acidity caused by the absorption of atmospheric CO_2 decreases the bioavailability of plant nutrients such as phosphorus and molybdenum and increases the absorption of toxic metals such as aluminium [244], which are detrimental to mangrove species. In the last 250 years, 560 billion tons of CO_2 have been absorbed by the oceans, thereby increasing the acidity of surface waters by 30% [245]. Over the last four decades, the pH level of ocean surface water has declined at a rate of 0.02 pH units per decade [246]. Continuous CO_2 uptake by seawater will further intensify oceanic acidification in the future, impacting ocean biogeochemical cycling [247] and potentially having lethal consequences for mangroves and marine life [248] Table 5.

Table 5. Impact of climate change implications on mangrove forests.

Threat/Challenge	Forecast Changes	Outcome	References
Rise in sea level	Sea levels may rise 1.5 to 2.5 m by 2099.	• Inland progression of mangrove forests (where possible) • Offshore erosion, exposing more nutrients and contributing to eutrophication, may increase secondary productivity	[242]
Rise in temperature (air and water)	Temperatures may rise by 4 °C by the end of 21st century.	• Increased aridity and reduced survival of local flora and fauna • Expanion of the latitudinal range of mangroves • Increases in water vapour pressure deficit • Changes in biodiversity owing to changes in phenological patterns of growth and reproduction	[249]
Increased CO_2 in atmosphere and oceanic acidification	The pH level of the oceans is gradually increasing, thereby making them more acidic. Consequently, CO_2 level by the end of the century, may be double or triple that of today's level.	• Decreased availability of plant nutrients • Change in respiration and primary production • Increased water uptake competence • Change in flowering period leading to desynchronisation of pollinators with plants • Changes in faunal diversity and distribution	[243,244]
Changes in precipitation/storm patterns	The frequencies of storms and rainfall are projected to increase approximately 25% until 2050, and the intensity of storms andprecipitation will also be increased.	• Changes in composition and growth of mangrove species owing to variations in salinity and soil moisture content • Increased precipitation/evaporation ratio will increase primary production • Changes in faunal diversity	[250]

4.2.2. Eutrophication

Eutrophication is the enrichment of nutrients, mainly from anthropogenic activities, causing excessive growth of aquatic plants and algae [251]. The augmentation of nutrient-rich organic pollutants into mangroves discharged from nearby aquaculture, agriculture, and other industrial practices results in eutrophication [252], leading to the growth of harmful algal bloom (HAB) species such as *Phaeocystis globosa* and the toxic diatom *Pseudo-nitzschia pseudodelicatissima*. Algal blooms drastically affect mangrove ecosystems and also deteriorate coastal water quality [253]. Algal mats covering the pneumatophores (breathing roots) and leaves of mangroves hamper respiration and photosynthetic processes in the mangroves [254]. Moreover, algae settle and form a thick coat over sedentary organisms, including corals, sponges, and anemones, restricting the penetration of sunlight, which may affect the primary productivity of their symbionts [255]. Furthermore, the presence of algal blooms near coastlines leads to fish and other aquatic species avoiding the bloom areas, which then has a negative impact on the livelihoods of local communities that are dependent upon traditional fisheries in the region [256]. In addition, the proliferation of both toxic and non-toxic phytoplankton changes the density of species due to inter-specific competition between phytoplankton and zooplankton species. Other than that, a rise in relative sea level due to climate change, which is responsible for coastal erosion, also contributes to increasing the rate of nutrient input and results in increased secondary productivity. In addition to eutrophication, a high concentration of nitrogen in soils contributes to the acidification process, which leads to the leaching of base cations [257]. Moreover, imbalances in the dissolved nutrient proportions in the water result in changes in nutrient stoichiometric ratios (Si:N, N:P, and Si:P) [258]. These changes seriously alter the mangrove ecosystem and impact the food web dynamics significantly [259].

4.2.3. Altered Hydrological Flow

Anthropogenic alterations in hydrological flow near mangrove forests through various structures such as roads, sea defences, and drainage canals have devastating impacts on the natural hydrological flow [260]. For example, roads that are built across tidal flats block the natural flow of water and make the mangrove soil dry and hypersalinised [261]. Fluctuations in freshwater currents coming down from inland dams and irrigation also affect mangroves by altering their salinity and resulting in mangrove loss [262]. For instance, in Pakistan, the Indus Delta freshwater incurrent has been reduced by up to 90% due to diversion [263]. This affected the bed load composition and reduced the uniform sediment deposition in those mangrove areas [264]. Moreover, altered hydrological flow in mangrove areas is responsible for suppressing fluvial processes such as transportation and sediment deposition and is one of the crucial factors inhibiting the natural restoration process of mangroves through secondary succession [265].

4.3. Low Level Threats

4.3.1. Diseases

Relatively few scientific articles report on diseases of Mangrove species. The first study related to diseases of mangroves was carried out on the Caribbean Island of Puerto Rico by Stevens (1920) and reported leaf spot disease of the mangrove species *Rhizobea mangle* caused by the fungal pathogen *Anthostomella* [266]. Another disease known as "top dying" that affects the mangrove species *Heritiera fomes*, a tree locally known as "sundri", has been reported to affect around 20% of the total mangroves in Bangladesh [267]. However, very little is known about the underlying cause of the disease. In this disease, the upper part of the plant is the first to show symptoms with the loss of leaves, followed by branches, due to the invasion of insects and wood-rotting fungi [268]. Several studies have shown an association between an increase in heavy metals and the emergence of "top dying" disease in mangroves [269]. Similarly, in Africa, a high degree of infestation by an unknown gall-inducing fungus was reported that causes mortality in *Rhizophora* species [270]. Another case of microorganism involvement in mangrove decay was reported on the Queensland coast of Australia, where *Halophytophthora* sp. was considered to be associated with the mortality of *Avicennia marina* trees [271].

4.3.2. Tourism

Although the mass tourism industry contributes to the economic development of countries, it can highly influence the environmental integrity of mangrove ecosystems [272]. One of the significant impacts of mass tourism occurs when there are frequent tours on cruise boats, which produce hydrological waves that cause erosion of the banks of waterbodies [273]. The heavy scouring of sediment causes degradation of the soil structure and eventually results in the uprooting and loss of mangrove trees, thereby rendering the water channels wider and shallower. This alters the hydrology and morphology of the affected rivers and estuaries [274]. The other major environmental issue associated with tourism is increased local waste and litter, which pollute the estuarial waters and harm the health of marine life [275].

4.3.3. Pollution

Marine litter refers to any stable, manufactured, or processed solid materials discarded or disposed of near/in marine or coastal environments [276]. Marine litter has been found throughout the marine shelves, such as beaches, the sea surface, the water column, and the seafloor, and ingested by marine or coastal biota [277]. Notably, plastics are the most abundantly found litter [278]. Marine litter has been classified into macro-litter, meso-litter, and micro-litter. Macro-litter, including macroplastics, is marine litter that is larger than 5.0 mm in size. These include a wide variety of plastics, from small plastic fragments to large objects such as shipwrecks and trawl bags. Meso-litter, including mesoplastics, is marine debris in the range of 5–25 mm and usually originates from the breakdown of macro-litter. Shoreline recreational activities are the main source of meso-litter. On the other hand, micro-litter as well as microplastics are particles <5 mm in size and are usually categorised as fragments, fibres, pellets, foam, or film [279,280]. The increasing quantity of litter has now been recognised as a growing global problem. Inadequate management of particularly non-degradable litter in coastal areas can lead to its augmentation in mangrove forests, affecting mangrove ecosystem services [281].

Other than local waste and litter, chemical pollution such as oil/petroleum, inorganic chemicals, natural gas, and other polluting materials also causes significant degradation of the mangrove forests [282]. Sewage, wastewater, and rubbish periodically released by ships, the mismanagement of waste generated, and accidental spillages occurring on deep-sea ports located near mangroves can significantly contribute to the damage of mangrove ecosystems and result in the loss or degradation of natural habitats that can also harm marine life in mangroves [283]. Leaked oil that settles with the tide and smothers aerial and prop roots impairs the physiological processes of mangrove plants [284]. The presence of trace metals, polycyclic aromatic hydrocarbons (PAHs), polyvinyl pyrrolidone (PVP) (microplastics) [285], and persistent organic pollutants (POPs) [286] has been observed in different mangrove compartments (water, sediments, and biota) [287]. These chemicals have toxic effects on mangrove ecosystems, with potential knock-on adverse impacts on populations and biodiversity [288]. For instance, oil pollution is reported as one of the threats to mangrove forests on the East African coast, as they are adjacent to the route that is frequently used for the transportation of oil from the Persian Gulf to the Atlantic Ocean [283].

5. Challenges for Mangrove Management

Despite current awareness of the significance and implications of threats to mangrove ecosystems, the management of mangrove areas has always been difficult because of several challenges. The main challenges to the effective management of mangrove areas are discussed below.

5.1. Land-Use Conflicts

Mangroves are often located in areas that are also valuable for aquaculture, agriculture, and coastal development. This leads to conflict between different stakeholders over land use, resource access, and management property. This is especially challenging in mangrove areas, where the land is currently inhabited by local populations. For example, in Kerala, India, there was a decision to zone an area under the Coastal Zone Regulation-1 (CRZ-1), by the Union Ministry of Environment, Forest, and Climate Change, Kerala, India, with the intention of protecting the mangrove biodiversity. Under the proposed CRZ-1, people who lived in these zones would be displaced from their traditional lands to new places. This led to conflicts between local people who owned property within the mangrove zone, with local village councils opposing the initiative of the government authorities. The lack of consensus prevented this program from reaching its goal, thereby making it ineffective [289]. A lack of consensus in such cases mainly arises due to a lack of awareness of the ecological and socio-ecological significance of mangroves [164] among the local communities. Only when ecosystem services offered by mangroves are considered communal goods with open access can they be beneficial to local communities. If there are poorly defined property rights, there is a possibility of uncontrolled exploitation [290]. The unrestrained exploitation of mangroves can damage the ecosystem and decrease the provision of mangrove services [291], which also increases the risk of poverty prevalence in the region [292]. Therefore, it is necessary to educate people, especially those who are residing near coastal areas and are directly dependent on mangrove goods and services [293], to put in place measures to prevent opportunists from elsewhere from unsustainably exploiting the ecosystem.

5.2. Low Stringency in Regulatory Action

The lack of stringent regulation is a challenge to the protection and conservation of mangroves in many regions. For instance, in Cancún City, Mexico, the mangrove-fringed lagoon area has been replaced by hotels and luxurious buildings in the past few decades [294]. The roads built along the coasts to approach these buildings have significantly compromised the natural hydrological links between habitats. The legal protection act that had been implemented to safeguard mangroves was withdrawn due to mounting pressure from coastal developers. The governments, from local through regional to national levels, have not successfully and effectively regulated the escalating coastal tourism industry in the region [295]. The lack of regulations to control the expansion of tourist infrastructure on this island has affected the natural balance of the coastal ecosystem. Consequently, chronic erosion near the coast has increased the vulnerability of mangroves over the last few decades [296].

5.3. Inadequate Policy and Government Frameworks

In many countries, policies and government frameworks related to mangrove management are weak in legal binding or non-existent, leading to poor management and unclear liability for the associated stakeholders [297]. Inadequate policy and government frameworks act as barriers to sustainable coastal management and marine restoration [298]. For example, in the Philippines, the government has given support in the form of loans for aquaculture development, declared a policy of fisheries development, and extended aquaculture permits from 10 to 25 years [299]. However, the government failed to adequately administer the aquaculture industry at both the local and national levels to ensure mangrove protection [299,300]. Similarly, in Australia, jurisdictive intricacy and a lack of operational policy within coastal management policies have made management ineffective and limited coastal and marine restoration as compared to terrestrial ecosystem restoration [298]. Mangrove restoration in Australia is mostly regulated through a framework mapped to curtail environmental harm (e.g., from coastal development) rather than developing a framework to achieve net environmental benefit [301]. This lack of a legislative framework that facilitates restoration and the lack of clear jurisdiction in marine and coastal environments hamper the initiation of large-scale restoration projects that could facilitate mangrove ecosystem rehabilitation [302].

6. Strategies for Mitigating Mangrove Loss by Augmenting Resistance and Resilience to Threats

Having recognised the threats and challenges, the planning and implementation of sustainable management strategies for mangrove ecosystems is necessary to prevent further mangrove loss and accelerate restoration and conservation. Such strategies should primarily focus on smart land use planning, the establishment of sustainable catchment activities, the development of integrated regional monitoring networks, and community education and outreach.

6.1. Smart Land Use Planning

Smart land use planning for mangroves starts with the essential steps of identifying and mapping the extent of mangroves in the area to ensure their preservation and sustainable use [303]. Geographical information systems (GIS) can be used for smart land use planning of mangrove areas by integrating spatial and non-spatial data to identify areas suitable for sustainable conservation [304]. In addition, tools such as SWOT (strengths, weaknesses, opportunities, and threats) analysis, OKR (objectives and key results), and PEST (political, economic, socio-cultural, and technological) analyses [305,306] can be used to identify impacts on a mangrove ecosystem. The information obtained by employing these tools is critical as it can support appropriate zoning regulations and management strategies with considerations of economic feasibility, social acceptability, and environmental fidelity for that area [307]. Based on the ecological significance and critical condition of the habitat, protected areas should be established where development and human activity are restricted. Guidelines and regulations that control the extent and intensity of development activities in and around a mangrove-protected area could include limits on land use changes, buffer zones, and a minimum setback distance from mangroves [308]. Implementing regular monitoring and evaluation of the effectiveness of the land use planning strategies is essential to determining whether the measures are achieving their intended outcomes. Engaging stakeholders, especially local communities, can ensure that all needs and perspectives are taken into account. Overall, smart land use planning for mangroves requires a comprehensive approach that balances conservation, sustainable use, and community needs [309].

6.2. Managed Catchment Based Activities

A catchment area, also known as a watershed or drainage basin, is a geographical area that contributes water to a particular stream, river, or sea [310]. All the precipitation falling within a catchment area flows into a common outlet, such as a river mouth [311]. Catchment areas are important because they can affect the quality and quantity of water that flows into the mangrove ecosystem [312], which can affect mangrove species diversity. A large catchment area that receives a lot of rainfall can result in a dilution of the salinity levels, which is less suitable for mangroves, which require brackish water to survive. On the other hand, if a catchment area is small and receives little rainfall, there may be insufficient fresh water flowing into an ecosystem to support the mangrove species that are more sensitive to high salinity [313].

In addition to the effect of salinity on species diversity, water catchment area qualities can also impact sediment and nutrient input to mangrove ecosystems. If a catchment area is heavily disturbed, such as through deforestation or agricultural/aquacultural activities, there may be increased sediment and nutrient runoff that can harm mangroves by smothering roots or causing algal blooms that deplete oxygen levels in the water [314].

Catchment-based activities such as coastal development, clearance of areas for agriculture, construction of aquaculture ponds, and harbour points can also result in land subsidence. This in turn can lead to flooding and land loss, with consequences for properties, agricultural production, and food security, especially in agriculture-dependent coastal areas [315]. Therefore, managing catchment areas is crucial for the conservation and restoration of mangrove ecosystems. Minimising human impact on catchment areas, such as by reducing deforestation, improving sustainable agricultural practices [314], and setting clear guidelines for other human activities responsible for the release of pollutants, can help ensure that the water quality in the mangrove ecosystem remains suitable for mangrove growth and survival [316]. By organising cleaning programs involving the local community, ecological disturbances to mangrove forests can be minimised. The removal of solid waste and trapped debris on a regular basis is needed to complement coastal pollution management [317].

6.3. An Integrated Regional Monitoring Network to Access Impact of Climate Change

Shared international and interstate marine and land borders in many mangrove regions, especially in Southeast Asia, make the establishment of an integrated regional monitoring network important to facilitate the preservation and sustainable use of mangroves. This involves setting up a system to collect, analyse, and report data on the health and status of mangrove ecosystems from local through regional to national levels [318]. This requires the collaboration of different stakeholders, including scientists, environmental consultants, metrologists, and government agencies [319]. The impacts of climate change vary in time and space, making it hard to predict the actual responses of mangroves to climate change [320]. Therefore, there is a need to keep climatic changes under systematic surveillance [321]. Data from the monitoring of climate change can be used to develop machine-learning models to efficiently predict any future adverse effects on mangrove forests [322]. This will enable the assessor to better understand the mangrove's responses to climate change and to determine the mitigative alternatives to the corresponding adverse effects [298].

6.4. Mangroves Restoration/Reforestation

Restoration is the process of supporting the recovery of an ecosystem that has been degraded, overexploited, or destroyed [323]. Mangrove restoration acts as a strategy to safeguard the functions and economic benefits of the ecosystem, such as coastal protection, environmental mitigation, the establishment of silviculture, sustainable utilisation of mangrove goods, habitat, coastal food sources, and the provision of community living [324]. Restoration can be categorised into (i) ecological restoration and (ii) hydrological restoration [325]. Ecological restoration refers to the process of repairing the damage caused by humans to the diversity and dynamics of native ecosystems via replanting/reforestation [326]. Replanting/reforestation can comprise single or multiple species. In the process, trees are planted in areas that were formerly forested and where the site conditions have not been degraded since the removal of mangrove cover [327,328]. Ecological restoration of areas previously inhabited by mangroves could reduce losses due to climate change, but it has a low success rate because of the high mortality of the transplanted seedlings [329–331].

On the other hand, hydrological restoration refers to the modification of water flow and drainage by using breakwaters and coir logs [332]. It has been reported that mangroves could recover naturally if environmental conditions such as hydrology, soil and water pH, soil structure, nutrient concentration, etc., are suitable [333]. The calm area protected by the breakwater and the correct hydrologic pattern could provide suitable environmental conditions that facilitate the natural re-establishment of mangroves [334]. However, hydrological restoration can be compromised due to sediment burial and poorly anchored coir logs [335]. Therefore, to increase restoration success, an integrated engineering strategy that includes multi-species restoration and hydrology-based approaches can be promoted [336–338]. A sustainable mangrove restoration also requires capacity building in the communities and institutions and the development of various tools to identify restoration strategies appropriate to the affected area that are also in accordance with the prospective stakeholders and investors. In addition, monitoring and reporting procedures will provide a more robust approach for future mangrove restoration projects [339].

6.5. Community Education and Outreach

Community education and outreach for mangrove conservation are critical for promoting the sustainable management of mangrove ecosystems [300]. This starts with the identification of key stakeholders, such as local communities, governmental agencies, non-governmental organisations (NGOs), universities, and schools, and the development of educational materials that explain the significance of mangroves, their role in protecting the environment, and the benefits that mangroves provide for economic activities such as aquaculture as well as for wildlife [207]. The long-term benefits of maintaining sustainable, functioning mangroves are often compromised by a need for short-term economic gains in terms of developmental activities that adversely affect the mangroves, especially in economically less-developed countries with high development stress to accommodate population growth [340]. Conducting training workshops for community members and stakeholders to enhance their knowledge about mangroves and their ecological significance can improve mangrove sustainability [341]. Training should also include planting, restoration, and conservation techniques. Moreover, the use of social media platforms to share success stories and tips for conservation can raise awareness of mangroves and their importance [342]. Through community education and outreach initiatives, it is possible to raise awareness of the importance of mangrove conservation, promote sustainable practices, and ensure that this vital ecosystem continues to thrive for generations to come [343].

7. Conclusions and Future Prospects

Mangroves are an important coastal wetland ecosystem that is both indicative of and essential for planetary health. They are unique and valuable ecologically, as they offer a wide range of ecosystem services, including habitat provision for local fauna and flora, support for coral and seagrass ecosystems, carbon sinks, natural water filters, and barriers to natural disasters. In addition, mangroves facilitate aquaculture and agriculture and are a source of fuel, timber, and traditional medicines. However, mangroves face a range of threats, including extensive coastal development, overexploitation for fisheries and agriculture, deforestation, eutrophication, altered hydrological flow diseases, mass tourism, and pollution. These threats have resulted in significant declines in mangrove areas worldwide, making mangroves one of the most threatened ecosystems on the planet. In order to protect and restore mangrove ecosystems, sustainable management of mangrove areas is required. However, this is challenging due to land use conflicts, a lack of stringent regulatory action, inadequate policy and government frameworks, and a lack of awareness and education. Figure 7 presents a summary of mangrove ecosystem services, functions, and threats in the context of ecosystem management. The balance between mangrove ecosystem services, functions, threats, and mitigation strategies is crucial to avoiding ecosystem collapse. Different mitigation strategies, such as smart land use planning for mangrove areas, management of catchment-based activities, development of integrated regional monitoring networks, and community education and outreach, can be adopted to minimise mangrove loss and maximise the restoration of mangroves. Brought together, these strategies can not only augment mangrove resistance and resilience to threats but can also help overcome the challenges that currently obstruct effective and sustainable mangrove management.

It is evident that despite being of great value in many ways, mangrove forests have often been overlooked in terms of their value, ecological implications, and associated economic impacts of their depletion. Considerable mangrove losses can be directly linked to loopholes in policies, legislation, regulation, and management. To reverse the trends of mangrove loss and decrease the vulnerability of coastal communities, it requires a serious commitment by local and national governments to design, develop, and implement robust and broad-ranging policies. Some recommendations that could be a way forward for improved, cohesive, integrated, and effective management to protect and conserve mangroves from further damage are suggested in Table 6.

Table 6. Recommendations for mangrove protection, restorationss, and conservation at the global level.

Process/Activity	Impact	Contributors
Accentuate the importance of mangroves in carbon sequestration at national and international platforms that address climate change, as mangroves are less discussed in the international dialogues on carbon emission settlement eligibility of ecosystems in the United Nations Framework Convention on Climate Change (UNFCCC) [344].	This would support the implementation of mangrove projects for the reduction of carbon emissions. This can have direct bearing on the implications of SDG 13, i.e., Climate Action.	United Nations, voluntary carbon markets traders from regional through national to global level.
Develop the schemes for "Blue Carbon" (mangrove) under UNFCCC. The UNFCCC refers insignificantly to blue carbon ecosystems, which makes them unworthy to the carbon markets [345]. On the contrary, when it comes down to green carbon (terrestrial forests), there are well established market mechanisms focusing on greenhouse gas (GHG) emissions reduction owing to deforestation. Such tools need to be applied to mangrove ecosystems.	This would accelerate the investigations, designing, and development of more internationally coordinated procedures for mangroves carbon credits under blue carbon scheme and can directly contribute to SDG 13, i.e., Climate Action.	United Nations, voluntary carbon markets, traders from regional through national to global levels.

Table 6. *Cont.*

Process/Activity	Impact	Contributors
Integrate mangrove management policies with legal systems that could provide accredited scenarios for effective mangrove management by ensuring proper legislation, regulation, and enforcement, and compliance by stakeholders from local through regional to national levels.	This would help to define entitlement to ownership, access, and the rights of use of mangrove forests. Moreover, this can enhance legal, financial, and technical capacity for effective mangrove management. Moreover, it can be in line with SDG 8, which is about Decent Work and Economic Growth.	National and international policymakers and law enforcement bodies, and other stakeholders and beneficiaries.
Emphasise the intense socio-economic impacts of mangrove degradation on prevailing indigence in many rural coastal communities. This can be achieved by raising public awareness through extended outreach regarding the socio-economic importance of the mangroves and the implications of their loss. Global initiatives such as The Economics of Ecosystems and Biodiversity (TEEB) will be helpful in this regard.	Healthy mangrove forests contribute to the food security of millions of people around the world. Information and exchange of existing knowledge on ecosystem services and functions, their economic valuation, and alternative mangrove management approaches would help build a stronger case for interventions. It would also help to refine existing management approaches/practices if the Sustainable Development Goals to eliminate extreme poverty (SDG 1) and end hunger (SDG 2) set by the United Nations (UN) are to be achieved.	Socio-economists and regional forestry departments, FAO, NGOs, and academia.
Include the role of mangroves as a key factor in climate change adaptation in the national disaster risk reduction plans and action framework. The environmental impact assessment can be carried out during planning and installation of the artificial coastal defence systems in/or near mangrove forests. Evaluation of the risks posed to the mangroves and all associated ecosystem services and functions can be taken into account. Consideration should also be given to using mangroves alongside the built substructure as "hybrid engineering", where mangroves alone may not be sufficient.	Such initiatives would encourage stakeholders to protect and restore mangroves as a part of natural coastal infrastructure. This would also signify mangroves for their roles in minimising vulnerability and increasing the resilience to climate change impacts. This can be related to SDG 11 Sustainable Cities and Communities and SDG 15 Life on Land.	Disaster risk reduction authorities and other voluntary groups, organisations such as the WHO, UN, etc.
Introduce some economic incentives in terms of pollution taxes, subsidies, merchandise permits, and performance bonds.	This would instigate environmentally responsible behaviour among people and improve local livelihoods, which is in connection with SDG 8 regarding Economic Growth. If properly applied with a command and control strategy, this would lead to desirable outcomes such as mangrove restoration and enhancement.	Socio-economists, banking sector, ministry of finance, and public development.
Promote the clean development mechanism (CDM) practices in provision of mangrove restoration and conservation.	This would encourage accounting for ongoing carbon sequestration and stock, which is one of the agenda of SDG 13, i.e., Climate Action.	United Nations, national and local governments, and NGOs.

Table 6. *Cont.*

Process/Activity	Impact	Contributors
Encourage and finance the developing countries to reduce the loss of mangrove forests, restore areas, and/or establish new mangrove areas. The structure and protocol of REDD+ (reducing emissions from deforestation and forest degradation, plus the sustainable management of forests, and the conservation and enhancement of forest carbon stocks) supported by FAO could serve as a tool for the development of national and international financing mechanisms.	Since REDD agenda is to offset GHG emissions, counter deforestation, and forest degradation while generating revenue, which can also be used to incentivise the relevant stakeholders and also contribute to SDG 8, i.e., Decent Work and Economic Growth.	FAO, international and national governments, and environmental legislators.
Organise community-based poverty reduction programmes in areas where mangrove restoration and management are practiced. Where suitable, alternatives to mangrove dependency for consumables in the local community must be introduced.	If applied appropriately, these attempts can be successful in enhancing the ecological settings of mangroves as well as the living status of local communities. Moreover, this would help to meet MDG 1 (Millennium Development Goal) to eradicate extreme poverty and hunger.	Government, NGOs, and local bodies.
Highlight the severity of mangrove biodiversity loss and degraded ecosystems through experts in the fields of economics, science, and technology.	Mangrove degradation has significant socio-economic impacts. This would inform policymakers to ramp up enterprises in mangrove management, restoration, and comprehensive cost-effective analysis prior to making policy decisions.	Environmental consultants, ministry of education and information technology, NGOs, and academia.

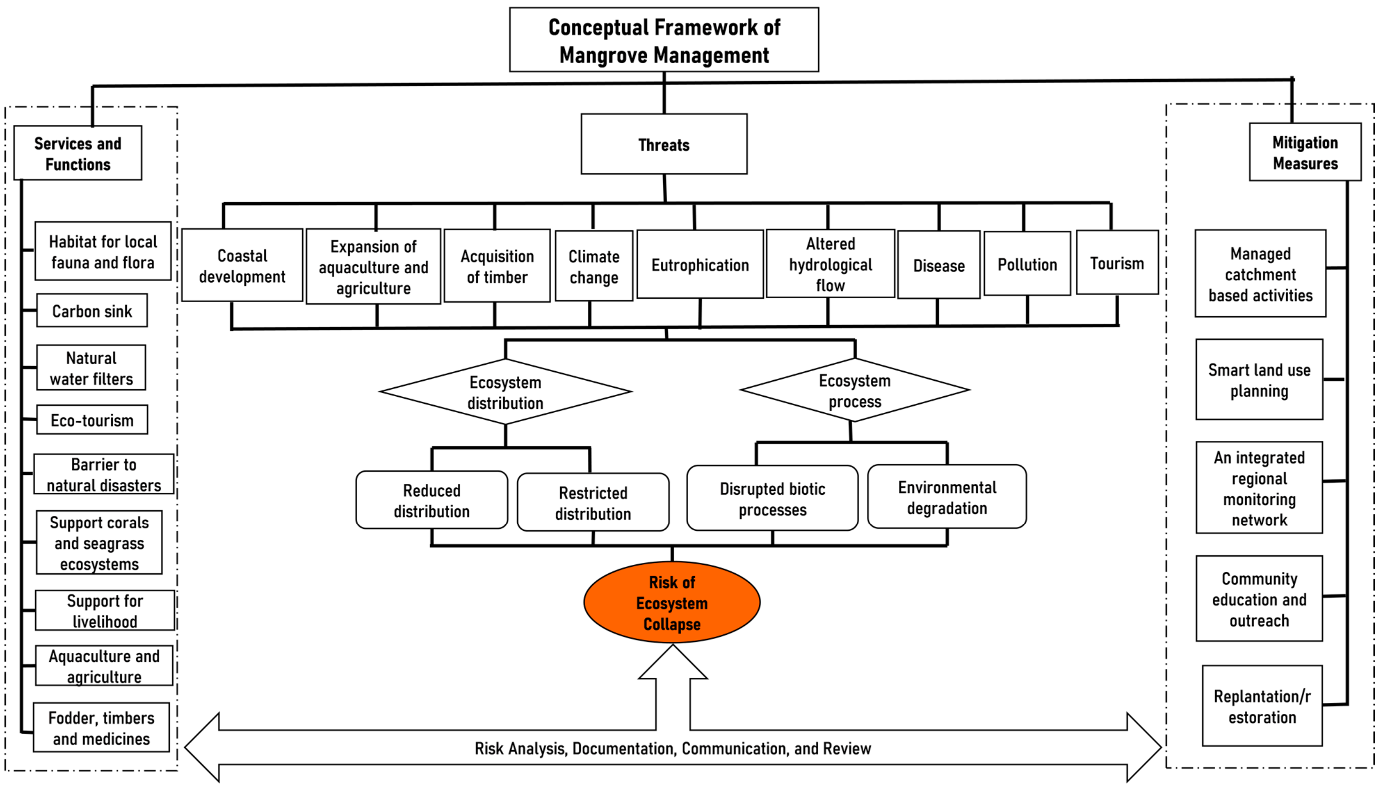

Figure 7. A conceptual framework of mangrove management.

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