MANGROVE RESTORATION TOWARDS SUSTAINABLE COASTAL ECOSYSTEM MANAGEMENT

ARTICLES FOR FACULTY MEMBERS

Title/Author	Challenges and strategies for sustainable mangrove management in Indonesia: A review / Arifanti, V. B., Sidik, F., Mulyanto, B., Susilowati, A., Wahyuni, T., Subarno, Yulianti, Yuniarti, N., Aminah, A., Suita, E., Karlina, E., Suharti, S., Pratiwi, Turjaman, M., Hidayat, A., Rachmat, H. H., Imanuddin, R., Yeny, I., Darwiati, W., ... Novita, N.
Source	*Forests* Volume 13 Issue 5 (2022) Pages 1-18 https://doi.org/10.3390/f13050695 (Database: MDPI)

Title/Author	Development-aligned mangrove conservation strategy for enhanced blue economy: A successful model from Gujarat, India / Shah, H., & Ramesh, R.
Source	*Estuarine, Coastal and Shelf Science* Volume 274 (2022) 107929 Pages 1-17 https://doi.org/10.1016/j.ecss.2022.107929 (Database: ScienceDirect)

Title/Author	Emergy-based evaluation of world coastal ecosystem services / Liu, C., Liu, G., Yang, Q., Luo, T., He, P., Franzese, P. P., & Lombardi, G. V.
Source	*Water Research* Volume 204 (2021) 117656 Pages 1-10 https://doi.org/10.1016/J.WATRES.2021.117656 (Database: ScienceDirect)

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Title/Author	**Mangroves as coastal bio-shield: A review of mangroves performance in wave attenuation / Kamil, E. A., Takaijudin, H., & Hashim, A. M.**
Source	***Civil Engineering Journal (Iran)*** **Volume 7 Issue 11 (2021)Pages 1964–1981** **https://doi.org/10.28991/cej-2021-03091772** **(Database: Civile Journal)**

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Source	***Results in Engineering*** **Volume 21 (2024) 101765 Pages 1-17** **https://doi.org/10.1016/j.rineng.2024.101765** **(Database: Science Direct)**

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ARTICLES FOR FACULTY MEMBERS

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Source	*Trees* Volume 35 Issue 5 (2021) Pages 1423–1438 https://doi.org/10.1007/S00468-021-02182-Z (Database: SpringerLink)

Title/Author	Remote sensing-based assessment of mangrove ecosystems in the Gulf Cooperation Council countries: A systematic review / Rondon, M., Ewane, E. B., Abdullah, M. M., Watt, M. S., Blanton, A., Abulibdeh, A., Burt, J. A., Rogers, K., Ali, T., Reef, R., Mohtar, R., Sidik, F., Fahrenberg, M., de-Miguel, S., Galgamuwa, G. A. P., Charabi, Y. A. R., Arachchige, P. S. P., Velasquez-Camacho, L. F., Al-Awadhi, T., ... Mohan, M.
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Title/Author	Restoration of coastal ecosystems as an approach to the integrated mangrove ecosystem management and mitigation and adaptation to climate changes in north coast of East Java / Rudianto, R., Darmawan, V., Isdianto, A., & Bintoro, G.
Source	*Journal of Coastal Conservation* Volume 26 Issue 4 (2022) Article No. 37 Pages 1-17 https://doi.org/10.1007/s11852-022-00865-4 (Database: SpringerLink)

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Review

Challenges and Strategies for Sustainable Mangrove Management in Indonesia: A Review

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Abstract: Mangroves are an important ecosystem that provides valuable social, economic, and environmental services. Indonesia has placed mangroves on its national priority agenda in an important effort to sustainably manage this ecosystem and achieve national climate commitments. However, mangrove management is faced with complex challenges encompassing social, ecological, and economic issues. In order to achieve the government's commitments and targets regarding mangrove restoration and conservation, an in-depth study on and critical review of mangrove management in Indonesia was conducted herein. This work aimed to provide a comprehensive analysis of the challenges and strategic recommendations for sustainable mangrove management in Indonesia. SWOT analysis was carried out to understand the strengths, weaknesses, opportunities, and threats related to mangrove management in Indonesia. To address these gaps, we reviewed the existing policies, current rehabilitation practices, environmental challenges, and research and technology implementations in the field. We found that strategies on mangrove ecosystem protection, such as improving the function and value of mangrove forests, integrating mangrove ecosystem management, strengthening political commitments and law enforcement, involving all stakeholders (especially coastal communities), and advancing research and innovations, are crucial for sustainable mangrove management and to support the national blue carbon agenda.

Keywords: mangroves; sustainable management; climate change; blue carbon; mangrove policy; restoration; rehabilitation

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Citation: Arifanti, V.B.; Sidik, F.; Mulyanto, B.; Susilowati, A.; Wahyuni, T.; S.; Y.; Yuniarti, N.; Aminah, A.; Suita, E.; et al. Challenges and Strategies for Sustainable Mangrove Management in Indonesia: A Review. *Forests* **2022**, *13*, 695. https://doi.org/10.3390/f13050695

Academic Editors: Victor H. Rivera-Monroy, Xosé Lois Otero-Pérez, Jorge Lopez-Portillo and Tiago Osorio Ferreira

Received: 21 March 2022
Accepted: 27 April 2022
Published: 29 April 2022

1. Introduction

Mangroves are a unique ecosystem: an interface between terrestrial and marine environments characterized by a high salinity concentration, high temperatures, strong winds and tides, muddy sediments, and anaerobic soils [1]. This type of ecosystem is one of the environmentally and economically valuable ecosystems for many tropical and subtropical countries [2,3] and provides social functions to coastal communities [4].

The role of mangrove forests includes protection against storms and tsunamis [5–7], the regulation of water systems, habitat provision for various fish and other animals, and a source of biodiversity and wood and non-timber forest products [8,9]. Mangrove forest ecosystems are also a source of nutrition and have an aesthetic value for ecotourism activities. Another important function is their role in climate change mitigation activities, where mangroves can store and sequester significantly more carbon than terrestrial forests in tropical and temperate regions [10].

Indonesia has 3.3 million hectares of "mega diversity" mangrove forests across the archipelago, consisting of 2.2 million ha within forest areas and 1.3 million ha outside forest areas [11,12]. The diversity and distribution of mangroves across the archipelago are immense: Java (166 species), Sumatra (157 species), Kalimantan (150 species), Papua (142 species), Sulawesi (135 species), Maluku (133 species), and the Lesser Sunda Islands (120 species) [13]. Despite the significant values of mangroves and their richness, it is estimated that around 637,000 ha or 10–33% of mangrove areas have been degraded and converted over recent decades [13–16], mostly caused by coastal development, such as aquaculture, logging, mining, reclamation, and pollution [13,15,16]. The highest mangrove deforestation occurred during 1987–1998, resulting in a drastic decline in the area covered by mangroves [17].

In response to huge mangrove loss, several regulations regarding mangrove conservation and management were enacted in Indonesia. The Law No. 5 of 1990 on the Conservation of Biological Natural Resources and their Ecosystems has become the basis of the concept of mangrove conservation in Indonesia. According to Law No. 27/2007, which was amended into Law no. 1/2014, on the Management of Coastal Zone and Small Islands, Indonesia allowed logging practices in mangrove areas that adhere to the sustainability of coastal ecological functions. The issuance of this policy was followed up with Presidential Decree No. 73 of 2012 on the National Strategy for Mangrove Ecosystem Management, which regulates the norms, standards, principles, criteria, and indicators of mangrove forest management. The government also issued Presidential Decree No. 73/2015 on the Implementation of the Management of Coastal Areas and Small Islands at the National Level with the aim of managing national coastal areas and small islands in a harmonious, synergistic, integrated, and sustainable way [18].

There are two key sectors that play important role in mangrove management in Indonesia, i.e., the forestry and fisheries and marine sector. The forestry sector has the authority to manage all state mangrove forests, whereas mangroves outside forest areas fall under the authority of the fisheries and marine sector. Therefore, the existing mangrove management policies are generally influenced by the interests and authorities of these two sectors, which are sometimes contradictive and overlapping. The complex social and economic conditions in mangrove areas, along with unclear boundaries between different authorities, have created an overlap in the implementation of laws and responsibilities among the governing institutions.

To sustainably manage mangrove ecosystems and improve coastal community welfare, effective policy implementation must be supported by various action plans or strategies that are prepared based on strategic issues in the concept of sustainable development [13,19–21]. However, there are major challenges in mangrove management that should be addressed by specific strategies and require programs as a measuring tool for achieving the goals of sustainable mangrove management. In this study, we aimed to conduct a comprehensive analysis of the complex constraints faced when managing mangrove ecosystems and to provide strategic recommendations for sustainable mangrove management in Indonesia.

We tried to fill the gaps between existing policies and implementations at the field level that are significant for constructive mangrove management and for supporting Indonesia's blue carbon agenda.

2. Mangrove Governance and Policy

Learning from the previous development of mangrove management policies in Indonesia, most drivers of mangrove forest loss could be effectively managed by policy interventions [21]. Mangrove management policies and regulations having been issued for almost a century (Table 1); however, they have not been optimally implemented in the field, and mangrove degradation still occurs with little or no compliance with existing laws and regulations [22–26]. Violations of the laws and regulations still exist due to the poor law enforcement and discordant policies. In addition, unclear policy objectives between government institutions have often worsened the situation [15,21,27,28], resulting in contradictive management decisions. The main challenge lies in the coordination and communication of related stakeholders, both those with authority and those affected by the policy.

Table 1. Government policies on mangrove forest management in Indonesia *.

<table>
<tr><th>No.</th><th>Policies/Regulations</th><th>Ministry Support</th><th>Guidelines for Mangrove Conservation</th><th>Policy Impact</th></tr>
<tr><td>1</td><td>Law No 5/1990 on the Conservation of Natural Resources and their Ecosystems</td><td>1. Ministry of Environment and Forestry
2. Ministry of Marine and Fisheries</td><td>The basis for implementing area and species conservation in Indonesia</td><td rowspan="7">1. Build public awareness and knowledge regarding environmental damage, especially mangrove ecosystem areas, as well as legal products and law enforcement
2. Sustainability of the mangrove rehabilitation program in coastal areas with mangroves/mangroves that have been degraded/deforested
3. Determination of mangrove ecosystem areas that do not overlap with general use areas</td></tr>
<tr><td>2</td><td>Law No. 41/1999 on Forestry, revised in Law No. 19/2004</td><td>Ministry of Environment and Forestry</td><td>Management of mangrove ecosystems in forest areas, such as regulations on the prohibition of logging and forest encroachment (Article 50)</td></tr>
<tr><td>3</td><td>Law No. 23/2014 on the Regional Government</td><td>District and Provincial Government</td><td>Significant authority given to regional heads in the management of natural resources, and the environment is linked to the existence of mangroves as coastal borders with the status of local protected areas</td></tr>
<tr><td>4</td><td>Law No. 26/2007 on Spatial Planning</td><td>1. Ministry of Public Works
2. Regional level conducted by BAPPEDA</td><td>Does not specifically regulate mangroves, but binds/regulates coastal boundaries and status as local protected areas</td></tr>
<tr><td>5</td><td>Law No. 27/2007 on Sustainable Management of Coastal Areas and Small Islands juncto Law No. 1/ 2014</td><td>Ministry of Marine and Fisheries</td><td>Sustainable management of coastal areas and small islands</td></tr>
<tr><td>6</td><td>Law No. 32/2009 on Environmental Protection and Management</td><td>Ministry of Environment and Forestry</td><td>Arrangements for activities that have the potential to change the landscape (including mangrove conservation)</td></tr>
<tr><td>7</td><td>Government Regulation No. 26/2008 on National Spatial Planning</td><td></td><td>Timber use violations of mangroves and activity bans that can change, reduce the area, and/or pollute the mangrove ecosystem in the mangrove zoning system</td></tr>
</table>

Table 1. *Cont.*

8	Presidential Decree No. 73/2012 on The National Strategy of Mangrove Ecosystem Management	1. Ministry of Environment and Forestry 2. Ministry of Marine and Fisheries	Conservation activities and ecosystem rehabilitation of mangroves in protected and cultivation areas, as well as improvement of the public well-being
9	Presidential Decree No. 73/2015 on the Implementation of Coordination for the Management of Coastal Regions and Small Islands at the National level	Coordinating Ministry of Marine and Fisheries	Sustainable management of coastal areas and small islands
10	Coordinating Ministry of Economy Regulation No. 4/2017 on the Policy, Strategy, Programs, and Performance Indicators of National Mangrove Ecosystem Management	1. Ministry of Environment and Forestry 2. Ministry of Marine and Fisheries	Recovery target of 3.49 million ha of mangroves by 2045

* The policies are focused on management, protection, conservation of biological resources, and disaster mitigation.

Given the many institutions involved in mangrove management, effective and legitimate regulations are needed and can be used as benchmarks for action in mangrove management. The synchronization of land and sea policies for determining mangrove management areas of different authorities is very important to avoid ambiguity for site-level managers and ineffective responsibilities for protecting mangrove forests.

In addition, clarity of policy content, both conceptual and technical, is an important requirement for the effectiveness of implementing a policy. The implementation of regulations in the management of mangrove resources is still weak [29], especially in terms of strengthening local-level institutions. Technical regulations are important to facilitate the implementation of national policies at the provincial level and to avoid different policy interpretations. Therefore, it is necessary to clarify policies, especially on mangrove reforestation for the marine and fisheries sector, considering that the sector's interest in increasing fishery production is very high [15].

Another challenge relates to the triggers of mangrove deforestation and degradation, which are intricate and often related to regional development strategies. Mangrove forest management efforts should consider related stakeholders with various interests (social, economic, and ecological interests) [30]. In many cases, these interests are contradictive. Although several policy initiatives have been developed by offering social and economic incentives to increase community participation in mangrove management, these efforts have faced problems related to an uncertain tenure, land encroachment, elite captures, and unfair benefit sharing. In addition, the involvement of local communities in natural resource management also encounters other challenges, such as a limited capacity, different goals, and limited time needed by the community to develop and maintain sustainable natural resource management [31–33].

Despite some of the challenges faced in mangrove management, an increased understanding of the importance of natural resources to sustain the economy at both the national and local levels, coupled with periodic political and economic crises in many developing countries, has encouraged the development of a new approach to mangrove management. A cross-sectoral and multi-stakeholder participatory approach has become the core strategy in mangrove management in many countries. Brazil, Ghana, and Mexico are some of the countries that have succeeded in developing the co-management of mangroves [34–36]. Co-management requires that key stakeholders, particularly resource-users themselves, play significant roles and responsibilities in the management process. Subsequently, in some countries, the legal framework for some forest tenures has changed from state-based to community-based, such as in Vietnam, the Philippines, and Ecuador [37]. There is ample evidence showing that coastal communities (including indigenous groups) have local wisdom in mangrove management and conservation practices that are integrated into their social structure. In general, where communities are empowered and given legal rights and authority to manage their own forests, community-based management has proven to be effective in rationalizing the use of mangrove goods and services, as in several places in Asia and Africa [37,38].

3. Community Participation in Mangrove Management

Communities play a key role in determining the success of sustainable forest management [38–40]. The dependence of coastal communities on these ecosystems can encourage them to restore and conserve them using their local knowledge [4,41–44]. The willingness to participate in an activity also has correlation with education level and income; those who have a higher education level and a more stable income become more easily involved and can serve as key community actors in mangrove restoration and protection activities [39,45–47].

From a socioeconomic perspective, sustainable mangrove management is full of challenges due to (a) different understandings of the value and benefit of mangrove ecosystems and the urgency of rehabilitation efforts; (b) local involvement not being optimal; (c) the majority of the families living next to the mangrove ecosystem being classified as low-income families; (d) sustainable mangrove ecosystem utilization not yet having been developed; and (e) a high rate of population growth and economic needs having triggered land use and land cover change.

Problems in understanding the ecological value of mangroves may create the conception that the damage or loss of mangrove resources is not always perceived as a loss. Community participation in mangrove management has become difficult to achieve, whereas, in contrast, the participation is easier to ensure when the benefits to be received can be felt immediately, locally, and are real [40,41]. Therefore, information about the benefits/values of mangrove forests, both direct and indirect, needs to be widely disseminated to increase people's awareness of the ecological role of mangrove forests [42]. A specific strategy is also needed, such as offering several incentive scheme options, to increase community willingness to be involved in mangrove management.

Law enforcement and compliance are other challenges in inducing community participation. Unclear sanctions/penalty mechanisms lead to low levels of compliance [43]. Local willingness to participate in mangrove management depends on (1) effective law enforcement; (2) accountable and transparent financial management; (3) fair profit sharing; (4) fair distribution rights and obligations; (5) co-financing from the government or projects; (6) annual income level; (7) and whether one's livelihood depends directly on mangroves. Eventually, the provision of incentives should not only drive local communities to replant new mangroves, but they should also maintain newly planted and old mangroves [32].

The form of the community's involvement in mangrove management varies depending on the regional conditions and the typology of the community. One example of mangrove management that considers community participation in mangroves is widely known as community-based mangrove management (CBMM). CBMM is currently needed to ensure the success of mangrove resources [44,45] and is considered an important factor in minimizing disturbance while assuring the sustainable use of mangrove resources. Communities are also involved in mangrove rehabilitation projects, e.g., providing mangrove seedlings, working in mangrove nurseries, and conducting mangrove plantings.

4. Incentives for Mangrove Ecosystem Services

The provision of incentives for mangrove conservation, as well as dissemination and facilitation to develop environmentally friendly mangrove utilization in coastal communities, is needed to increase the public acceptance of policy implementation and community engagement in mangrove management. The forms of incentive programs offered include the provision of capital, production inputs, training for capacity building, facilitation to market access, and funding [32,43]. The incentive programs requires partnerships and cooperation among the institutions at the site level to support product marketing from up-to downstream [48].

One of the incentive schemes that have succeeded in encouraging community participation in mangrove rehabilitation was initiated by Wetlands International Indonesia through the "Bio-right" scheme, with a success story in Pesantren Village, Pemalang Regency, Indonesia [29]. Bio-right is an incentive scheme that provides a funding mechanism to participating communities. This scheme is an attempt to accommodate the importance of increasing the economic benefits of mangroves while promoting conservation and restoration actions. In the Bio-right scheme, if community-based conservation efforts indicate satisfying results (evaluated based on the survival rate of mangrove plantations or other parameters, according to the contract agreed between the initiator and the community who obtains the microcredit), then the credit will be converted into grants [49].

Another incentive scheme to instigate community participation in mangrove management was developed through the payment for environment service (PES) scheme [21]. The environmental services derived from mangroves are distinguished by ecological functions and economic goods and services. For example, *Avicennia marina* species are able to bind the heavy metals Pb and Copper (Cu), absorb salt, and are resistant to salinity; thus, they can be used as a phytoremediation agent to improve environmental and water quality [50,51]. The environmental services generated from mangrove ecosystems in Southeast Asia are valued at USD 4200 ha^{-1} $year^{-1}$ [52]. If associated with the mangrove area in Indonesia in 2021, which was 3.3 Mha, then the total value that can be generated from the environmental services of the mangrove ecosystem is estimated to be USD 13,860,000,000. The intrinsic economic service value has an impact on the preservation of mangrove ecosystem biodiversity, leading to the encouragement of more intensive rehabilitation activities.

The economic benefits of mangrove ecosystems contribute to the welfare of society and the State. Research in West Kalimantan [53] has shown that the highest estimated value of mangrove protected forests is approximately IDR 27,386,581,500 $year^{-1}$ (77.75%), while the annual indirect, direct, and optional value benefits are IDR 3,869,442,410 (10.98%), IDR 2,929,650,000 (8.32%), and IDR 1,037,800,210 (2.95%), respectively. Community understanding of the ecological benefit (74%) and economic value (74%) of protected forests is relatively high. Another study showed that household income from natural mangrove ecosystem resources in four villages in Central Java, Indonesia, ranges from USD 1202 to 2189 $year^{-1}$ $household^{-1}$ [54], whereas, in the coastal area of Lampung, Indonesia, it ranges from IDR 12,000,000 to 24,000,000 $year^{-1}$ $household^{-1}$ [45]. These values indicate the existing contribution of the income from mangrove ecosystems to coastal communities, but, to determine whether this income is sufficient or not, it must be compared to the regional minimum wage (RMW) of each region.

5. Environmental Challenges

Understanding the biophysical process and other drivers that control mangrove survival is crucial for mangrove rehabilitation. Based upon the Ministerial Regulation Forestry No. P.70/Menhut-II/2008, mangrove rehabilitation is considered successful if the survival rate is 70% or more. A number of studies have reported that failure of mangrove rehabilitation could be caused by environmental constraints, such as tides/abrasion [55], species intolerance to salinity and tidal inundation [55,56] and pests and diseases [55,57]. Propagule supply and wave and tidal flooding are important factors to be considered in mangrove rehabilitation [58]. When the site is lacking in propagule supply, planting the right species in the right habitat is the alternative solution to alleviate mangrove reforestation failures. The establishment of mangrove plantation should consist of the processes that involve selection, site preparation, planting, maintenance, monitoring, and evaluation [59]. Permanent or permeable structural water breaks are also needed if the planting is undertaken in areas with high waves.

The symbiotic relationship between mangrove vegetation and various types of fauna occurs in various forms, both beneficial and destructive. Therefore, controlling pests and diseases is crucial. One type of pest that attacks mangrove plants in Indonesia is crabs from the Crustaceae family, especially from the karma type (*Episesarma* spp.) and wideng crabs [60]. Apart from crustaceans or crabs, several animals that become pests for mangrove plants are pagoda bagworms (*Pagodiella* spp.), bagworms (*Acanthopsyche* sp.), stem borer beetles (*Xanthochroa* sp.), tick leaves (*Prociphilus tessellatus*), barnacles (*Balanus amphitrite*), snails (*Gastropoda* sp.), and shell-less snails (*Vaginula bleekeri*) [61]. Pocket caterpillars are a pest that attack beneath the leaf surface, creating holes. A population explosion of bagworms causes bare leaves at the seedling and sapling levels. The seedling level is the most vulnerable stage to pest attacks. Bagworms attack the shoots [61] and damage the roots, leading to the disruption of the regeneration of mangrove plants [62–64]. Disruption in the vegetation regeneration process can result in the loss of genetic material and a decreasing biodiversity [65].

Marine pollution, such as anthropogenic marine debris (AMD), can also cause damage to mangrove ecosystems. AMD in the form of plastics, cloths, polystyrene, metal, glass, paper, rubber, and leather has been reported to disrupt the productivity of mangroves in Indonesia [66]. It is estimated that Indonesia's marine plastic debris is the second largest production of marine pollution in the world, which is around 0.57–0.6 Mt year^{-1}. A preliminary value of plastic debris accumulation on beaches has been estimated to be 113.58 ± 83.88 g m^{-2} a month [67], or equivalent to 0.40 Mt year^{-1} [68]. AMD can be found especially in big cities on the main islands of Java, Bali, Kalimantan, Sumatra, and Sulawesi [69]. The Indonesian government has targeted a national action plan to minimize marine plastic debris by 70% between 2018 and 2025, with a long-term ambition to achieve near-zero plastic pollution in Indonesia by 2040 [70]. This effort needs synergistic coordination between the central and local governments on strengthening law enforcement and real actions at the field level to deal with hazardous AMD, as well as international cooperation [71,72].

6. Technology Development and Implementation

Research development, technology transfer, and information systems are very important in supporting the success of mangrove forest management in Indonesia. According to the Ministry of Environment and Forestry, the mangrove rehabilitation activity carried out during 2015–2019 (Supplementary Table S1) is incomparable to the rates of mangrove deforestation. However, if the current commitment from the Indonesia government to restore 600,000 ha of degraded mangrove area is reached, it would constitute an important milestone.

Several technologies and advances that are currently being developed to support sustainable mangrove management, rehabilitation, and conservation are outlined below.

6.1. Seed Technology and Genetic Aspects of Mangrove Management

The availability of high-quality seeds in sufficient quantities plays a significant role in the success of mangrove forest rehabilitation [73,74]. To ensure the sustained existence of mangrove plants as genetic material sources, the application of a genetic-based technique to assess the structure and diversity among and within populations is essential. Propagule dispersal—whether by water or through animals—is a key ecological factor for identifying the distribution of mangrove patterns of genetic diversity and populations [75–78]. This allows the occurrence of crosses between individuals with distant relatives and broadens the genetic diversity of the population. The wide genetic distance between populations is a crucial factor for breeding mangrove species [79].

When the seed sources are not enough, producing mangrove seedlings in a nursery is one of the potential efforts to meet the need of large quantities of mangrove planting stock for rehabilitation purposes. Nursery-produced seedlings of the species *Ceriops* spp., *Avicennia* spp., *Bruguiera* spp., and *Rhizophora* spp. have higher survival rates following planting activity (60–80%) compared to the direct planting of their propagule in the field (20–30%) [73,79].

Understanding the phenology of mangrove species is needed to support forest restoration. The success of mangrove forest restoration is also influenced by the existence of pioneer mangrove species [80] because these pioneer species are able to withstand conditions of hydrodynamic pressure and changes in sediment. Previous studies have shown that *Avicennia alba* and *Sonneratia alba* are pioneer species, especially for Southeast Asia and Australia [80,81]. Both have a good growth ability in the seedling phase, despite hydrodynamic changes, and have a fairly wide seed dispersal ability due to their seed characteristics [81–83]. A study of mangrove phenology in Unggas Island, West Sumatra, Indonesia [84], revealed that the flowering and fruiting seasons of *R. apiculata*, *R. mucronata*, and *R. stylosa* occur throughout the year, with the peak season in September to December, July to December, and October to December, respectively. The time spans from the first stage of flowering to the ripening of propagules for the above three species are 22.06, 18.85, and 21.70 months, respectively.

Studies related to the genetics of mangrove species, especially the molecular aspects, in Indonesia are still very limited. An initial study of mangroves along the coastlines of Java Island was performed by using isozyme markers [85]. The results showed that, along the northern coast of Java, the populations of *Sonneratia alba* had higher similarity with each other than those of the southern coast. It was concluded that gene flow and genetic exchange might be affected by isolation due to the distance, sea current direction, and their connectivity [86]. Another study conducted in the Krakatoa area found a lack of genetic variation in *A. marina* in severely contaminated habitats, which are quite significant compared to moderately and non-contaminated habitats [87].

Morphological and inter-simple sequence repeat (ISSR)-based marker research conducted on *Avicennia* in Java showed that the existing mangrove grouping is based on the similarity of characteristics, not on the origin of the plant [88]. Sequence-related amplified polymorphism (SRAP) markers in the Banggai Islands showed a low genetic diversity of *R. apiculata,* thus exhibiting a greater risk of extinction, especially on small islands [89]. However, the breeding strategy is very important in supporting the successful development of mangrove rehabilitation. Breeders are challenged to explore the potential of mangroves, especially in mangrove species that produce non-timber forest products (food and medicine) [90].

6.2. Integrated Mangrove Sowing System (IMSS) using Unmanned Aerial Vehicle (UAV) Technology

The integrated mangrove sowing system (IMSS) helps to accelerate the mangrove rehabilitation process in the sites with limited access, human resources, and infrastructure or uninhabited areas. IMSS is a combination of mangrove rehabilitation mapping and monitoring using UAVs and satellite technology (Figure 1). Seed balls are deployed using UAV technology with a modified payload capacity. The most commonly used seeds in IMSS are *Avicennia* sp. and *Sonneratia* sp. based on their abundant availability and continuous production throughout the year [87]. Knowledge on phenology, germination rate, and seed ball coating determines the survival rate of the seeds in the field. The seed balls function to protect mangrove seeds from biotic and abiotic stresses, while the composition of the seed ball carrier in the form of essential nutrients and a compact structure increases the ability and viability of the seeds sown through the UAV system (Figure 2) [91]. The development of mangrove seed ball sowing technology in Indonesia is currently being tested under various natural constraints, such as tidal conditions, sediment variations, mangrove species zonation, and different levels of salinity.

6.3. The Importance of Microbes in a Mangrove Ecosystem

The interaction of mangroves and microbes in the root system in the process of nutrient exchange is essential for determining the success of the mangrove rehabilitation process. Microbial activity (bacteria and fungi) is responsible for transforming nutrients into mangrove ecosystems because such ecosystems have nutrient-deficient conditions [92,93]. Arbuscular mycorrhizal (AM) fungi constitute an advanced ecological method for mangrove rehabilitation that significantly improves plant root health and the natural regeneration of mangroves. AM fungi have an ecological function in increasing the tolerance of mangrove species to environmental stress, as well as the mangrove growth performance in natural plant communities. In addition, variations in AM colonization among different mangrove tree species and the capability of AM fungi in terms of P absorption could be of great importance in establishing diverse wetland vegetation communities and supporting the existence of a high species diversity [94]. The nutritional status of sediments and the role of AM fungi are important topics of ecological research in the process of nutrient exchange in mangrove ecosystems. While research on the existence and role of mycorrhizal fungi in mangroves is still rare in Indonesia, much information is provided by other countries (Supplementary Table S2).

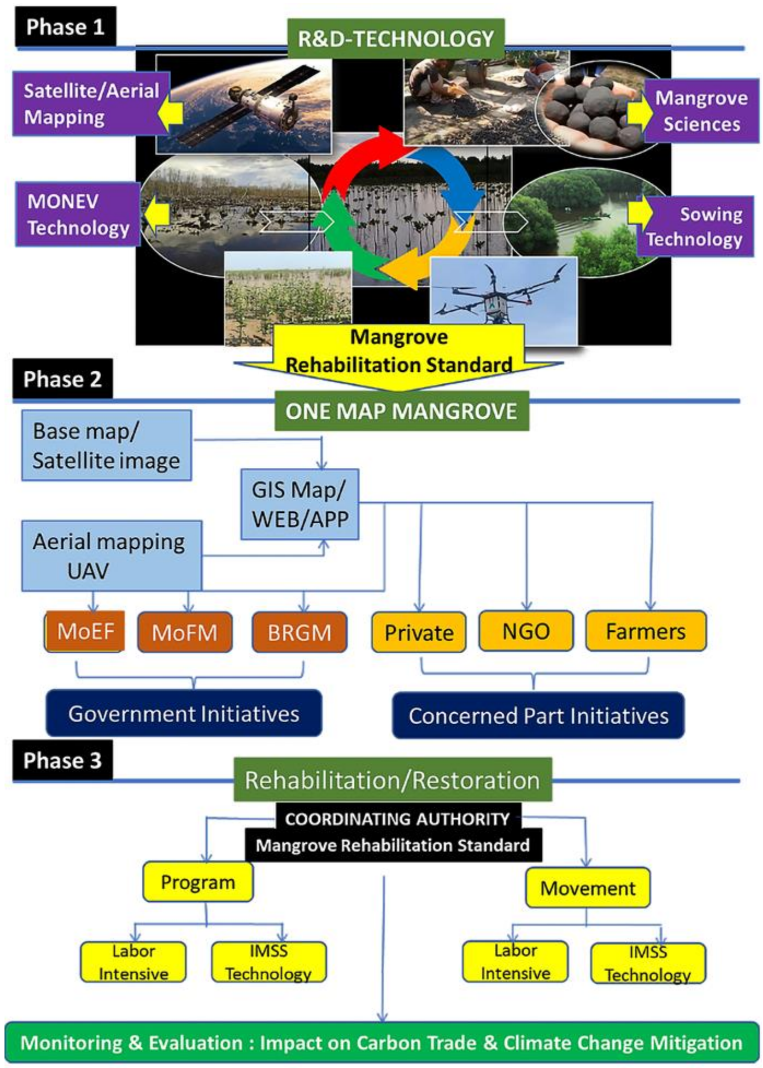

Figure 1. Advanced ecology-based mangrove rehabilitation strategy with the integrated mangrove sowing system (IMSS). UAV, unmanned aerial vehicle; GIS, geographic information system; NGO: non-government organization; MoEF, Ministry of Environment and Forestry; MoFM, Ministry of Fisheries and Maritime; BRGM, Peatland and Mangroves Restoration Agency.

AM fungi are present in the mangrove root system of mangrove species with different salinity gradient zones. *Glomus* sp. is the most dominant species among the 45 AM fungi species that belong to five genera, namely, *Acaulospora* sp., *Glomus* sp., *Scutellospora* sp., *Gigaspora* sp., and *Enterophospora* sp. The AM fungi *Glomus* and *Acaulospora* inoculated on two *Sonneratia* mangrove species have significantly increased plant growth and nutrient absorption. This finding shows AM fungi's vital role and contribution in building a sustainable mangrove ecosystem [95]. The accumulation of diazotrophs as nitrogen fixers in the rhizosphere of *R. stylosa* increases the nitrogen supply to the roots of mangroves. This suggests that sediment microbes (including bacteria nitrogen fixers) are the key to increasing productivity and are an indicator tool for the rehabilitation and conservation of mangrove ecosystems [93,96].

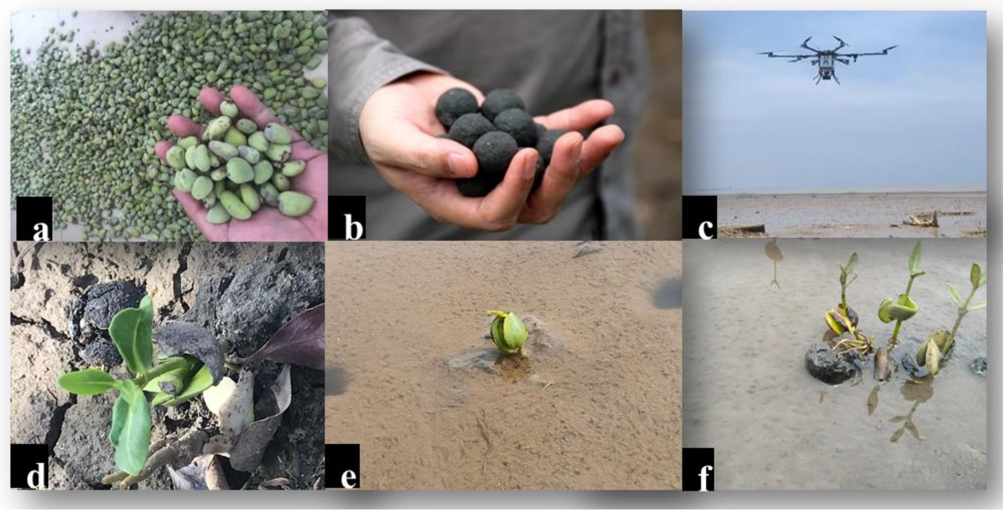

Figure 2. Advanced ecological-based mangrove rehabilitation techniques in order to accelerate successes and increase mangrove diversity with sowing seed balls by UAVs: (**a**) seeds of *Avicennia marina;* (**b**) mangrove seed balls; (**c**) UAV sowing seed ball system; (**d**) germination of *A. marina* seed balls in dry sediment; (**e**) germination progress of *A. marina* two weeks after sowing in wet sediment; (**f**) fast continuation germination of *A. marina* four weeks after sowing. (Documentation: Maman Turjaman and Consortium of Integrated Mangrove Sowing System).

6.4. Application of a Mangrove Silviculture System

There has been a long history of mangrove silvicultural systems in Indonesia. The first mangrove silvicultural regulation was promulgated during the Dutch colonization period in Indonesia on 1 July 1938 [13]. This regulation was made to manage the development of mangroves in Central Java, particularly in Cilacap city. Another result in Bengkalis mangroves (Riau province) recommended that a clear-cutting system is only applicable for areas often inundated by high tides [97]. In 1958, the standard clear-cutting system suggested by the Forest Research Institute was implemented [13]. The Forest Planning and Production Agency recommended the strip-wise selective logging system in 1972 [98]. In 1978, the Indonesian government (c.q. Directorate General of Forestry) issued Decree No. 60/Kpts/Dj/I/1978, which introduced a new silvicultural system, namely, the mother tree method. The mother tree method accommodates intensive natural regeneration in logged-over areas in order to become more ecologically resistant to numerous disturbances [99].

Previous research on the mother tree system has shown significant growth of the secondary forest, which formed a second generation cycle of mangroves in Bintuni Bay [99]. Permanent plots of five commercially dominant mangrove species (*R. mucronata*, *R. apiculata*, *B. gymnorrhiza*, *B. parviflora*, and *Ceriops tagal*) in Bintuni Bay, West Papua, have yielded moderate stands to be utilized. The forest structure is close to the primary forest, and *R. apiculata* has shown the best growth. Thus, the above five species are suitable for cultivation in logged-over areas due to their ability to form mature stands, and thus can potentially be utilized without changing the species dominance.

In addition to Bintuni Bay, a silvicultural system to rehabilitate mangrove areas was also employed along the northern coast of Java Island by Perhutani state company in 1960. Other rehabilitation systems run by Perhutani, a state-owned company, have introduced intercropping ponds, pond forests, or embankment trench ponds [13], consisting of several canals (2–5 m width and 1 m depth) with mangrove trees in the center of the pond. The ratio between ponds and forests varies: 20%:80% in Cikalong (West Java) and 40%:60% in Cilacap (Central Java)—although the optimal ratio is 54% ponds and 46% forests.

The success of mangrove rehabilitation activity in Indonesia can be seen in Supplementary Table S3. The success state of rehabilitation activities is guided by Forestry Ministerial Regulation No. P.70/Menhut-II/2008, requiring the survival rate to be 70% or more. To date, several planting designs and techniques have been applied to increase successful rehabilitation, including cluster, square, and zig zag planting designs [59]. Among these applied techniques, the mound technique provides the best seedling survival rate of more than 80% for *Rhizophora* spp. at three years old.

One good example of a successful mangrove rehabilitation story in Indonesia is that of Perancak estuary, Bali. A comprehensive strategy from planning to biophysical study and ground checking was carried out to assure the success of the planting activities. Furthermore, understanding the relationship between vegetation characteristics and hydrological and edaphic conditions is an important determinant of mangrove rehabilitation success [100]. This mangrove rehabilitation approach is comparable to the approach of mangrove rehabilitation along the Yucatan Peninsula, Mexico, which is based on the relationships among the geomorphology, hydrology, structural, and functional characteristics of mangroves [101].

7. Landscape Approach

Currently, the government uses mangrove landscape units (MLUs) to evaluate the rehabilitation programs in Indonesia. MLUs are defined as mangrove typology units of the same tidal area, with a suitable land system that functions optimally to provide ecological and socioeconomic services. The analysis of determining mangrove landscapes throughout Indonesia has resulted in 130 units of mangrove landscapes, comprising 16 units in Java, 23 units in Sumatra, 27 units in Kalimantan, 11 units in Bali and Nusa Tenggara, 20 units in Sulawesi, 11 units in Maluku, and 18 units in Papua [102].

This approach is aimed at managing mangrove ecosystems that meet social, economic, and environmental purposes [103,104]. Therefore, mangrove ecosystem management should foster a dynamic and balanced interaction between nature and humans [105]. However, although the landscape management approach has the potential to meet social and environmental goals on a local scale, to address global challenges, it requires a strong national commitment [106].

8. SWOT Analysis

We formulated a strategy for managing mangrove forests in Indonesia by identifying two factors that resulted from the condition and situation of the mangrove forests, namely, external (opportunities and threats) and internal (strengths and weaknesses) strategic factors. SWOT analysis aims to systematically identify various factors in formulating a strategy [107] by emphasizing existing strengths and opportunities and concurrently reducing weaknesses and threats. SWOT analysis is useful for analyzing the overall situation and achieving the objectives of an activity plan [108–116]. Strategy formulation with SWOT analysis is carried out according to existing data, and endeavors to use the situation and development of an activity to achieve goals. We generated SWOT based on the characteristics of mangrove forests and the social conditions of the community living in the mangrove areas (Figure 3).

Based on the identification of internal factors, six indicators were identified as strengths and six as weaknesses, while, for the external factors, seven indicators were found as opportunities and seven as threats.

These internal and external factors (Table 2) are indicators of leverage in the preparation of strategies and provide basic information that support sustainable mangrove forest management.

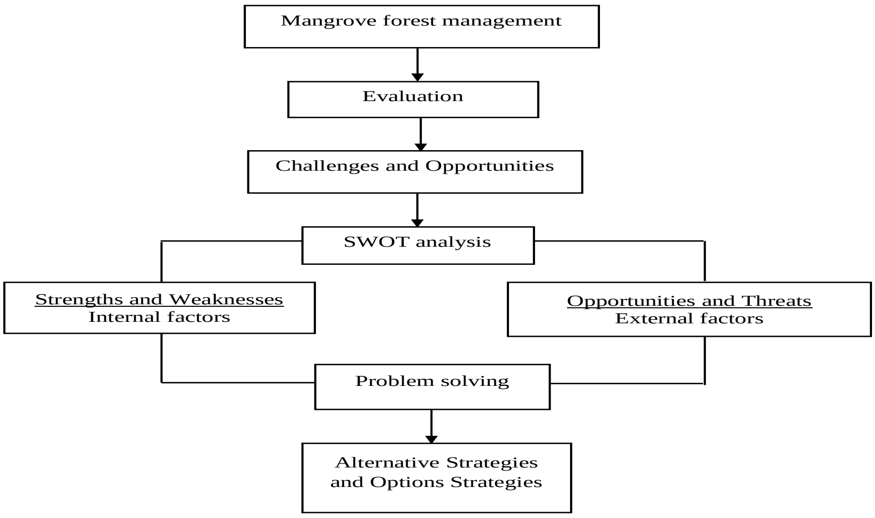

Figure 3. Stages of strategy formulation using SWOT analysis [117].

Table 2. Internal and external factors in SWOT [117].

	INTERNAL FACTORS		
	Strengths		Weaknesses
S1	Indonesia has an area of 3.3 million hectares of mangrove forest	W1	Implementation of policies, regulations, and laws is still ego-sectoral
S2	Mangrove ecosystems are unique habitats full of biodiversity	W2	Utilization of mangrove forests is still not in accordance with the carrying capacity of the mangrove ecosystem
S3	Mangrove ecosystems have multiple ecological, economic, and social functions and benefits	W3	Population increase
S4	The existence of regulations and laws related to the management of mangrove forests in Indonesia	W4	Not yet optimal support from institutions at the site level
S5	Positive understanding of the community regarding conservation efforts	W5	Weak monitoring, control, and evaluation by the government
S6	It is one of the assets of Indonesia's natural resource strategy	W6	The success rate of rehabilitation and restoration is still low
	EXTERNAL FACTORS		
	Opportunities		Threats
O1	Utilization supported by policies and regulations	T1	Mangrove forest degradation
O2	Benefits of high economic value	T2	Exploitation of the forest not according to land capability
O3	Product diversification of NTFP mangroves	T3	Decreased diversity of flora and fauna
O4	National rehabilitation program	T4	Loss of or reduction in mangrove habitat
O5	A harvest shelter that supports marketing of the produce	T5	Utilization of NTFPs without considering their sustainability
O6	Access to transportation that supports marketing of the produce	T6	Changes in the land cultivation system
O7	Rehabilitation technology and utilization pattern techniques	T7	Climate change affecting crop patterns

The formulation of mangrove forest management strategies in Indonesia is focused on opportunities and weaknesses to optimize sustainable management. Such strategies are expected to be the answer to the problem of mangrove forest degradation and to hinder the failure of the rehabilitation program, as this decreases the multifunctional benefits of mangrove forests. There are five strategies formulated that exploit opportunities (O) and cover weaknesses (W), which are:

1. Vertical and horizontal coordination and cooperation between agencies and related parties (W1, W4, W5, O1, and O5).
2. Capacity-building of local governments in carrying out their authority and obligations to manage mangrove ecosystems in accordance with local conditions and aspirations (W5, W6, and O1).
3. Development of advanced study, science, technology, and information systems needed to enforce sustainability of mangrove ecosystems (W2, W3, W6, O4, and O7).
4. Management of mangrove ecosystems through partnerships between the government, local communities, and businesses with the support of international institutions and communities as part of the efforts to meet global environmental commitments (W3, W5, O2, O3, O5, and O6).
5. Awareness-raising and training for the community to develop processed commodities from mangroves (S3, S6, O1, O2, O3, and O6).

Strong coordination and commitment among stakeholders are needed to build up the above priority strategies. Several alternative strategies must be supported by priority programs as a measuring tool to achieve goals. Furthermore, the sustainable mangrove forest management model requires five main elements, which are goals, changes, ecosystem indicators, constraints, and institutions related to mangrove forest management [117].

In increasing the capacity of the authority and the interests of local governments, it is necessary to plan and implement management and supervision, as well as the monitoring and evaluation of the activities laid out in the applicable rules and policies [118,119]. Strategies to increase the capacity of the central and local governments require institutional effectiveness, which is determined by the effectiveness of social interactions, including participation in the regulatory process to create a sense of ownership. Other important aspects also include communication, information, interpretation, and the meaning of the contents of the regulations that involve knowledge and experience, as well as power networks.

9. Conclusions

Indonesia has expressed a strong commitment to protect the remaining mangroves and restore those that have degraded. This action must be supported by all stakeholders at all levels to ensure the sustainability of mangrove ecosystems. Challenges are still faced in mangrove ecosystem management, including weak law enforcement, conflicting policies, a lack of community involvement, natural disturbances and constraints, and a lack of in-depth research and innovations.

Several strategies have been carried out for the management of the national mangrove ecosystem in Indonesia. These strategies include (1) ecosystem protection with the principle of sustainability, (2) improving the function and value of mangrove forests, (3) integrated mangrove ecosystem management, (4) strengthening political commitments and law enforcement, and (5) increasing the support and involvement of all stakeholders, including coastal communities, to reinforce the implementation of national strategic policies for the sustainable management of mangrove ecosystems. Developing research, science, and technology, as well as information systems, is also needed to strengthen the sustainable management of mangrove ecosystems and to achieve the global environmental commitments [120]. Hence, there is a requirement for global multidisciplinary collaborative research programs and concrete actions on mangrove management, especially to address challenges in climate change, the degradation of mangroves, and microbial diversity, pollution, and socioeconomic issues.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f13050695/s1, Table S1: Mangrove rehabilitation in Indonesia (2015–2019); Table S2: Mangrove species associated with arbuscular mycorrhizal (AM) fungi; Table S3: Mangrove rehabilitation research conducted in Indonesia.

Author Contributions: Each author (V.B.A., F.S., B.M., A.S., T.W., S., Y., N.Y., A.A., E.S., E.K., S.S., P., M.T., A.H., H.H.R., R.I., I.Y., W.D., N.S., S.S.H., W.Y.S. and N.N.) equally contributed as main contributors to the design and conceptualization of the manuscript, conducted the literature reviews, performed the analysis, prepared the initial draft, and revised and finalized the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This study was supported and funded by the Bezos Earth Fund through Yayasan Konservasi Alam Indonesia (YKAN) and The Mushroom Initiative (TMI).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors extend their thanks to the Ministry of Environment and Forestry and the Ministry of Marine Affairs and Fisheries of Indonesia for providing them the opportunity to conduct research and explore the mangrove forests in Indonesia.

Conflicts of Interest: The authors declare no conflict of interest.

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ARTICLES FOR FACULTY MEMBERS

MANGROVE RESTORATION TOWARDS SUSTAINABLE COASTAL ECOSYSTEM MANAGEMENT

Title/Author	**Development-aligned mangrove conservation strategy for enhanced blue economy: A successful model from Gujarat, India / Shah, H., & Ramesh, R.**
Source	***Estuarine, Coastal and Shelf Science*** **Volume 274 (2022) 107929 Pages 1-17** **https://doi.org/10.1016/j.ecss.2022.107929** **(Database: ScienceDirect)**

Estuarine, Coastal and Shelf Science 274 (2022) 107929

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

Development-aligned mangrove conservation strategy for enhanced blue economy: A successful model from Gujarat, India

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A R T I C L E I N F O

Keywords:
Mangrove conservation
Restoration
Ecosystem services
Coastal development
Adaptive management
Blue economy

A B S T R A C T

Mangrove protection and restoration have been prioritised in India, and as a result of concerted interventions by key maritime states, mangrove cover has increased significantly in the last few decades. Mangrove restoration efforts have received considerable attention in the States of Gujarat, Tamil Nadu, Odisha, and Andhra Pradesh for their role in the mitigation of storms and cyclones. The *'community-based restoration'* strategy, in particular, is credited with expansion of mangrove regions across India. This study highlights the mechanism of successful mangrove restoration and conservation through various efforts of the government, private sector, and the coastal community in the state of Gujarat, India.

Despite rapid coastal development, mangrove cover has also steadily increased in the last few decades in the State, clearly indicating a balanced approach towards enhancing blue economy. This is credited to the vision of the Government of Gujarat, India for putting in place appropriate policies and their effective implementation. Restoration of degraded mangrove and afforestation of new mangroves were made successful by applying scientific transplantation of saplings, utilization of local resources, involvement of public and private sectors and efficient monitoring activities. The Government of Gujarat has developed a comprehensive approach to integrate diverse sectors to effectively conserve mangroves and adopting a community-based restoration model. Such efforts at the regional level are the first-ever large-scale restoration and afforestation measures in India.

1. Introduction

Mangroves form a distinct habitat in the coastal intertidal areas especially, they are an unlimited natural protector. Mangroves are distributed circum-tropically in 123 countries, with a total global mangrove cover of 13.76 million ha (Bunting et al., 2018) which is 1% of the tropical forests of the world. Globally, mangroves are considered the second-largest ecosystem service providers, next only to coral reef ecosystems, for the dependent coastal communities. They harbour rich biodiversity and are known to serve as breeding and nursery grounds for a wide variety of organisms, particularly commercially important finfish and shellfish.

Coastal development is considered a long-standing threat to mangrove ecosystems. In general, land-use change including urban development, aquaculture ponds, agriculture (rice), and over-exploitation of timber are the main driving forces (Romañach et al., 2018). Globally, 62% of global losses of mangrove areas between 2000 and 2016, primarily caused by conversion to aquaculture and agriculture (Goldberg et al., 2020). However, careful planning, as well as appropriate policies and actions, can ensure coastal development while simultaneously ensuring conservation of the ecologically sensitive and important mangrove ecosystems. The need for large-scale participation by communities, inclusive project governance, integration of local work into national policies and practices, sustaining livelihoods and income, simplification of carbon accounting and verification methodologies to lower barriers to entry, are identified as critical for these types of projects (Dencer-Brown et al., 2022). There has been a reduction in global loss rates, *due to* improved monitoring, changing industrial practices, expanded management and protection (Friess et al., 2020). However, there is limited information from South Asia on various green initiatives aimed towards conservation of mangrove ecosystems. In India, mangroves have an estimated cover of 4975 sq. km representing 0.15% of

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https://doi.org/10.1016/j.ecss.2022.107929
Received 10 December 2021; Received in revised form 29 May 2022; Accepted 2 June 2022
Available online 8 June 2022
0272-7714/

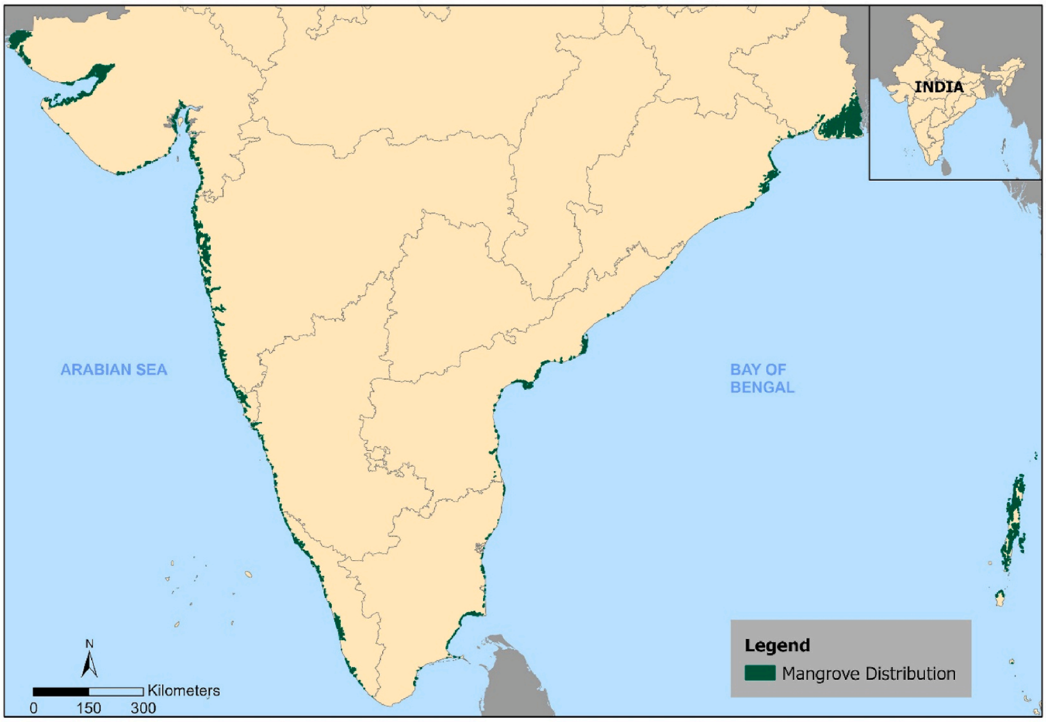

Fig. 1. Distribution of mangroves along the coast of India.

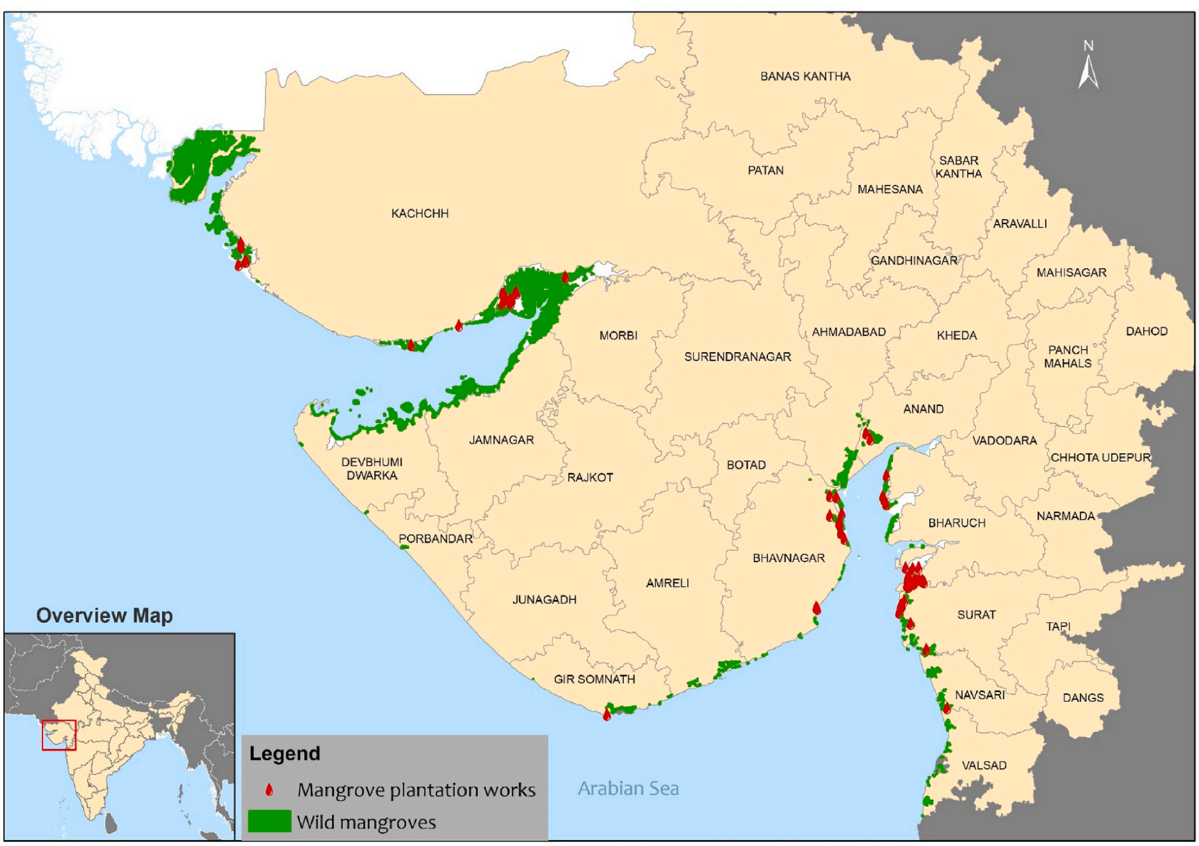

Fig. 2. Distribution of mangroves along the Gujarat coast. The mangrove plantation undertaken by various agencies (Government, Industries and NGOs) is indicated in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

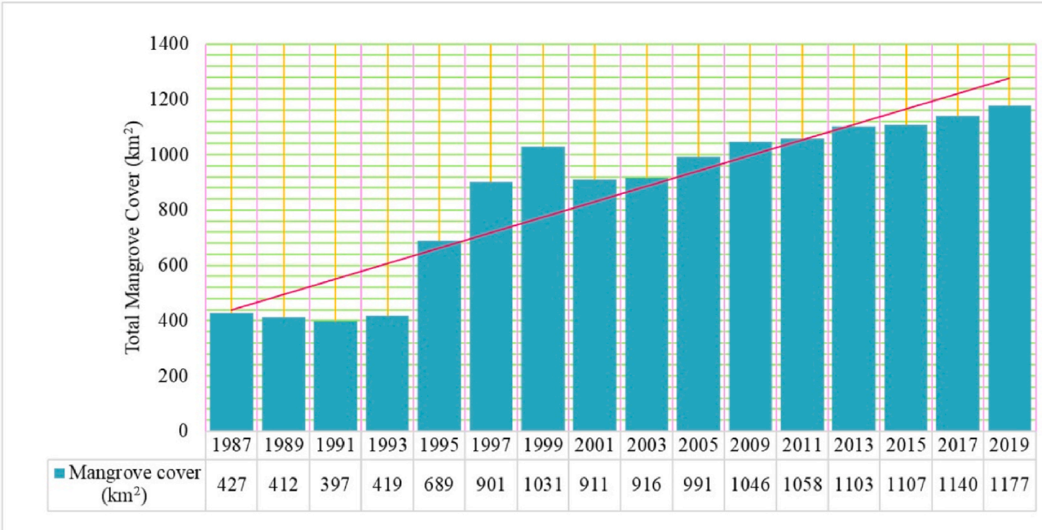

Fig. 3. Trend in Mangrove cover of Gujarat from 1987 to 2019 (Source: FSI, 2019).

Table 1
District-wise mangrove cover in the Gujarat State (FSI, 2019).

S. No.	District	Moderately dense mangrove (km^2)	Open mangrove (km^2)	Total (km^2)
1	Ahmedabad	0.87	30.18	31.05
2	Amreli	0.00	2.37	2.37
3	Anand	0.00	7.25	7.25
4	Bharuch	13.35	31.09	44.44
5	Bhavnagar	5.90	15.73	21.63
6	Jamnagar	28.06	201.44	229.50
7	Junagarh	0.00	3.33	3.33
8	Kachchh	116.41	678.36	794.77
9	Navsari	0.00	12.97	12.97
10	Porbander	0.00	1.00	1.00
11	Rajkot	0.90	2.63	3.53
12	Surat	3.87	16.40	20.27
13	Vadodara	0.00	3.00	3.00
14	Valsad	0.00	2.16	2.16
	Total	169.36	1007.91	1177.27

total geographical area of the country (FSI, 2019). About 57% of mangroves occur along the east coast; 31% along the west coast and the remaining 12% in the Andaman and Nicobar Islands (Fig. 1). The mangrove habitats of India are broadly categorized into three different classes as deltaic (east coast of India), estuarine and backwater (west coast of India), and insular mangroves (Andaman & Nicobar Islands) (Mandal and Naskar, 2008). The mangrove cover is larger and widespread on the east coast compared to the west because of its distinctive geomorphological setting with a gentle slope. In contrast to the east coast, the west coast of India has a steep continental shelf and lacks major deltas and rivers and is dominated by sandy and rocky substratum (Mamidala et al., 2022).

The mangroves of Gujarat have the second largest mangrove cover (1103 sq. km) in India, distributed over four regions (i.e. Kachchh, Gulf of Kachchh, Saurashtra and South Gujarat) indicating a consistent increase in cover during the last decade. This is largely due to the persistent conservation and restoration efforts through effective governance and policy implementation, which is required to be documented to encourage mangrove conservation efforts. The mechanism of successful mangrove restoration and conservation in the light of intense coastal development, through various efforts of the government, private sector, and the coastal community in the state of Gujarat, India is highlighted. Such large-scale efforts are a push towards enhancing the "new blue" initiatives, where mangrove conservation is uncompromised for land and sea based economic development.

2. About Gujarat

Gujarat is the westernmost state of India with a varied terrain, physiography with the longest coastline of ~1600 km, constituting 24% of coast. At present, Gujarat has 42 ports including the busy seaports of Kandla and Mundra, with a total capacity of 466 MMTPA as of 2015-16 (GIDB, 2021). In recent decades, Gujarat has become one of the most industrialized states, with a significant presence in sectors such as pharmaceuticals, chemical, refining and petrochemical, ceramics, textiles, automobile production, etc. Gujarat is one of the top producers of marine fish and a leading sea salt producer. The marine areas of Gujarat is particularly known for the Single Point Moorings (SPM) to handle crude (Petroleum) Oil (please see Graphical abstract), and also has one of the largest Marine National Parks and Sanctuary of the country. The state has also witnessed a 7.82% compound annual growth rate (CAGR) for its gross state domestic product (GSDP) between the years 2015 and 2020. This growth has attracted an increased rate of foreign direct investments (FDI) in the state (www.ibef.org/). The parallel progress made by the state in terms of conservation and economic development has been achieved without one activity derailing another. The state has displayed the importance of integration and sustainable development and that both conservation and development can co-exist with proper sustainable planning and execution at ground level.

2.1. Mangrove ecosystems of Gujarat

The topography of Gujarat State is a blend of uplands, gulfs, wetlands, and coastal plains. Gulf of Kachchh and the Gulf of Khambhat. The two most important and diverse mangrove ecosystems of Gujarat (Fig. 2), are characterized with pronounced tidal influence (macro-tidal regime), that drains the black soil of the bedrock valley to the adjacent coastal waters. Selvam (2003) classified mangroves of Gujarat as of 'drowned-river valley type'. A total of 15 species belonging to 10 genera and 6 families have been recorded as true mangrove species (Ragavan et al., 2016). The mangroves have developed under an extremely arid

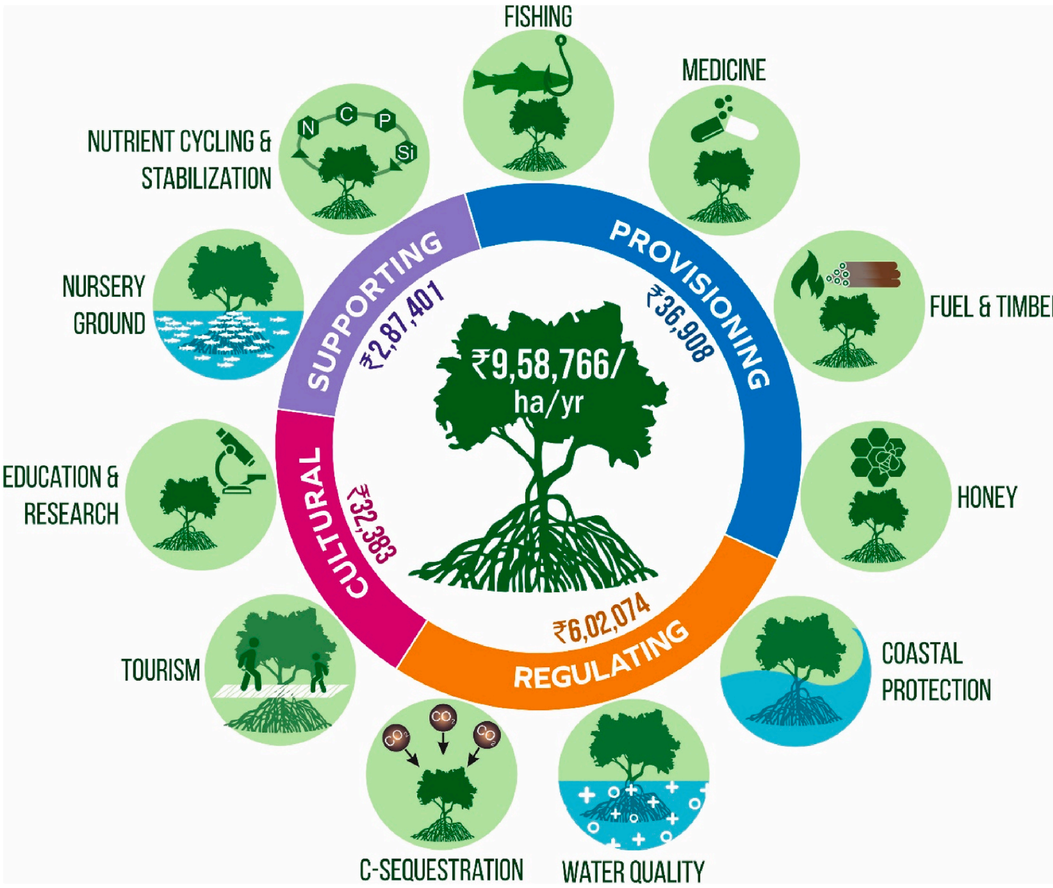

Fig. 4. Goods and services of mangrove ecosystems. Estimated values of the services are in 2011 Indian Rs/ha/yr.

climate; with very little freshwater discharge from the perennial rivers and hence the marine processes are dominant throughout the year. Sediment characteristics indicate that the inundation is due to a rise in sea level and thus the mangroves of Gujarat are classified as belonging to the drowned-valley type (Selvam, 2003). The overall changes in mangrove cover in the State of Gujarat during 1987–2019 and the district-wise mangrove extent are provided in Fig. 3 and Table 1.

3. Mangrove ecosystem goods and services

Mangroves provide a wide variety of ecosystem goods and services (Fig. 4) of which regulating services are the most relevant. Coastal protection and carbon sequestration alone contributed to INR 754 billion and INR 1.65 billion, respectively, based on 2012-13 prices (Anneboina and Kumar, 2017). Additionally, mangroves are one of the richest warehouses of biological and genetic diversity of the world. It is estimated that 90% of the marine organisms spend part of their life in this ecosystem and 80% of the global fish catches are dependent on mangroves (Sandilyan et al., 2012; Anneboina and Kumar, 2017). In addition, mangroves and their associated biota are identified as promising sources of natural and novel drugs against multi-drug resistant microbes (Sachithanandam et al., 2019). A meta-analysis carried out by National Centre for Sustainable Coastal Management (NCSCM) indicated that the aggregated economic value of mangroves of India ranges between INR 92,662/ha/yr (minimum) and INR 33,61,144/ha/yr (maximum) (NCSCM, 2018, Fig. 4). However the cultural importance of this ecosystem remains mostly unaccounted, for example, the sacred grove of the mangrove, *Avicennia marina*, located near the famous temple of Shravan Kavadia in Kachchh, Gujarat (Tripathi et al., 2013).

The coast of Gujarat experiences two cyclonic storm seasons (May to June; advancing southwest monsoon and September to November; retreating monsoon) per year. It is estimated that over 120 cyclones originating in the Arabian Sea had passed through the coast over the last 100 years. The coastal districts prone to cyclones and storm surges include Kachchh, Junagadh, Narmada, Rajkot, Jamnagar, Porbandar, Amreli, Bhavnagar, Kheda, Surat, Vadodara, Ahmedabad, Anand, Bharuch, Kheda, and Valsad. The list of cyclones that had landfall at the Gujarat coast during the period 1981–2021 is provided in Table 2. Due to the recent Cyclone "Taukte" in May 2021, severe damages to life and property were observed and the damages were estimated at US$ 1.4 billion (Shastri, 2021).

The Gujarat State Disaster Management Agency (GSDMA) has prepared a Hazard Risk Vulnerability Atlas which consists of the cyclone hazard zonation for May to June (advancing southwest monsoon) and September to November (retreating monsoon) and the wind speed at taluka (Block) level (Fig. 5). This atlas indicates that extensive areas of the Saurashtra coast, and the Gulf of Kachchh, are highly vulnerable. The report also emphasizes the importance of mangroves in safeguarding the ecological security of coastal areas (GIDR, 2020). Mangroves along the coast of Gujarat were observed to aid in disaster risk reduction, prevention against soil erosion and sand storms, thus protecting the agriculture fields and settlement. It was also observed that the extent of the risk reduction, depended on the mangrove species, the width, and the density of the mangrove area (Srivastava, 2020).

Table 2
List of tropical cyclones have made landfall/damaged in Gujarat State from the year of 1981–2021 (Source: GSDMA, 2016-17).

S. No	Year	Classification	Affected region(s)
1	November 1981	Very severe cyclonic storm: 01B	Gujarat Coast
2	November 1982	Extremely severe cyclonic storm: arb 01	Porbander
3	June 1985	Cyclonic storm: ARB 02	Dwaraka
4	June 1996	Severe cyclonic storm: ARB 01	Gujarat
5	June 1998	Extremely severe cyclonic storm: ARB 02	Porbander
6	June 1998	Cyclonic storm: ARB 05	Gujarat Coast
7	May 1999	Cyclonic storm: ARB 01	International border with Pakistan
8	21–29 May 2001	Extremely severe cyclonic storm: 2001 India cyclone	Kandla, Kosamba, Jamnagar, Valsad
9	7–13 October 2001	Cyclonic storm	Southern Gujarat
10	30 September –10 October 2004	Severe cyclonic storm: Onil	Porbandar
11	21–24 September 2006	Severe cyclonic storm: Mudka	Porbandar, Rajkot
12	30 May - 7 June 2010	Very severe cyclonic storm: Phet	Ra Gulf of Kuchcch region
13	10–14 June 2014	Cyclonic storm	South Coast of Gujarat
14	25–31 October 2014	Extremely severe cyclonic storm: Nilofar	Kutch, and Saurashtra
15	22–24 June 2015	Deep depression	Gir-Somnath, Amreli, Rajkot
16	29 November - 6 December 2017	Very severe cyclonic storm: Ockhi	Surat, and Dahanu
17	10–17 June 2019	Very severe cyclonic storm: Vayu	Saurashtra, Kutch, and Diu
18	22–25 December 2019	Very severe cyclonic storm: Hikaa	South Coast of Gujarat
19	30 October - 7 November 2019	Extremely severe cyclonic storm: Maha	Diu
20	14–19 May 2021	Cyclone: Tauktae	Saurashtra

3.1. Mangrove restoration initiatives in India

Restoration of mangroves has a long history with increasing understanding on its use in coastal protection in Singapore (Friess, 2017), Sri Lanka (Ranasinghe, 2012), Thailand (Barbier, 2006), Mahakam Delta (East Kalimantan, Indonesia) (Dutrieux et al., 2014), and Nigeria (Zabbey and Tanee, 2016). In India, the MS Swaminathan Research Foundation (MSSRF) launched a major program in 1996 for restoration of mangrove wetlands of the east coast of India, with financial support under the India Canada Environment Facility (ICEF) and in collaboration with the Ministry of Environment and Forests and the Forest Departments in the States of Tamil Nadu, Andhra Pradesh, Odisha, and West Bengal. More recently, a community-centred joint mangrove management (JMM) approach was successfully used in the Pichavaram mangrove, Tamil Nadu, following the joint forest management principles (Selvam and Thamizoli, 2021) The area under mangroves in India increased by 9.9% since 2001 (from 4482 sq. km in 2001 to 4663 sq. km in 2010, and 4975 sq. km in 2019).

3.2. Mangrove restoration initiatives in Gujarat

Gujarat had extensive mangrove forest cover half a century ago, but was depleted to its lowest level in the 1970s (Gujarat Biodiversity Board, 2012). The extent of the cover was below 400 sq. km in the early 1980s. Declaration of the Marine Sanctuary in the Gulf of Kachchh in 1980 and the Marine National Park in 1982 promoted mangrove restoration and conservation initiatives and the Mangrove Conservation and Development Project was initiated in 1993. Besides, mangrove restoration programmes were implemented by the State Forest Department as well as the Gujarat Ecology Commission (GEC) during 2002–2007 with financial support from the ICEF. The project was aimed at the development of mangrove cover in the identified wastelands, outside of the protected forest areas of the Gulf of Kachchh and Khambhat, (Viswanathan et al., 2011).

3.2.1. Government initiatives for mangrove restoration

The Forest Department of Gujarat began small-scale mangrove afforestation in 1983 with the planting of *Avicennia marina,* which was later scaled up to cover a massive area in the intertidal mudflats (Singh, 2012). To encourage participation of the local community, extensive meetings in coastal villages, ecological education, and public awareness programmes were held. The mangrove extent of Gujarat was evaluated in the 1990s, and in 1993-94, a comprehensive mangrove conservation and development scheme was prepared. This project, which was named as an 'excellent conservation project' for the year (1993) in the country by the Indian Council of Forestry Research and Education (ICFRE), Dehradun, provided the groundwork for mangrove restoration in the state. The list of state government sectors actively involved in mangrove restoration programmes in Gujarat is provided in Table 3.

3.2.2. Private sector initiatives

With the closure of the Restoration of Mangroves project (REMAG) in 2007, there was a demand to continue with the mangrove restoration activities with community participation. GEC thus extended the programme, but in a transformed manner by inviting participation from major private industries located in the coastal areas. It sought investments from the private sector through Corporate Social Responsibility (CSR) in mangrove development-related activities and encouraged them to work alongside community-based organisations (CBO). A list of private limited companies involved in the mangrove restoration project in various coastal areas of Gujarat is given in Table 4.

3.3. Case studies of restoration initiatives in Gujarat

The experiences of restoration initiatives provide a road map for mangrove conservation and sustainable resource use. Mangrove restoration projects can be recognized as general prototypes to demonstrate to the policymakers and decision-makers, and to plan future restoration efforts (Ellison et al., 2020). The efforts to restore mangroves in Gujarat can be directly linked to the increasing mangrove extent in the state, undertaken by both the state government and private sectors as mentioned earlier. From 1983-84 to 2007-08, the Gujarat Forest Department (GFD) planted approximately 50,000 ha of mangroves in coastal areas and islands of the state (Pandey and Pandey, 2011).

The GFD uses two ways to promote extension of mangrove habitats in addition to maintaining the existing mangrove areas:

i) restoration of degraded mangrove habitats; and
ii) creation of new mangrove habitats at suitable intertidal sites.

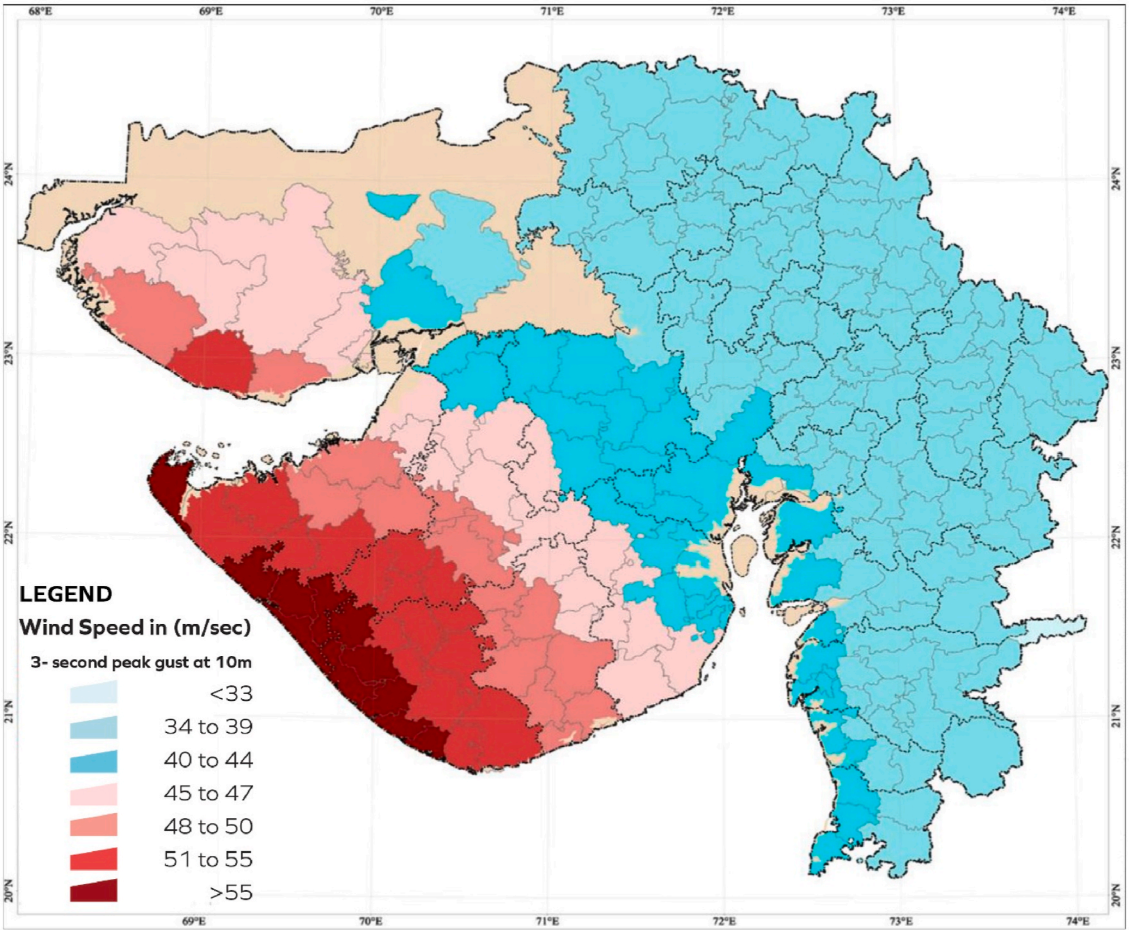

Fig. 5. Gujarat cyclone hazard risk map (Source GSDMA, 2016–2017).

Table 3
Details of mangrove plantations through government initiatives in Gujarat.

S.No.	State sector agencies	Area (ha) planted	
	Gujarat Forest Department (between 1983-84 and 2007-08)	~50,000	
Other initiatives		Area (ha) planted	% share
	Gujarat Heavy Chemicals Limited (GHCL)	50	0.81
	Gujarat Maritime Board (GMB)	120	1.95
	Gujarat Mineral Development Corporation (GMDC)	170	2.76
	GSPC Pipavav Power Company (GPPC)	10	0.16
	India Canada Environment Facility (ICEF)	4101	66.51
	Ministry of Environment and Forests (MoEF)	300	4.87
	Government of Gujarat (GoG)	1415	22.95
	Total	**6166**	**100**

Field Methods:

(a) Criteria for site selection

Suitable site selection for mangrove plantation was found to be the single most important criterion that determines the plantation success. Effective scientific inputs on the site (slope, soil type, salinity, tidal flushing, water logging, etc.) and selection of site-specific plantation technique could make plantation highly successful. Among various site selection criteria, physical stability, rate of siltation, exposure to waves and tidal currents, tidal amplitude, tidal flushing (at least 15 days/month), tidal inundation time, intertidal gradient, availability of freshwater, soil texture (silty clay/muddy substrates), local species distribution, presence of propagules, natural regeneration and good accessibility were considered. Prior to the site selection, field visits were organised by technical teams as part of the feasibility study. In addition socio-economic details of the villages were also collected. Other, factors such as availability of labour and ease of access to the site were also considered. The technical and socio economic data were used to prepare GIS-based maps, and plantation sites were selected after consultation with the private sector partners and local communities.

Table 4
Mangrove restoration initiatives by industries in Gujarat (GEC, 2012; Mitra and Zaman, 2015).

Industry name	Site(s)/District	Plantation year	Total area covered (ha)
Gujarat Maritime Board, Gandhinagar	Dholai/Navsari; Magdalla/Surat; Ghogha/Bhavnagar; Jakhau/Kachchh	2006–08	120
NIKO Resources Ltd, Vadodara	Dandi/Surat		250
Mundra Port & Special Economic Zone Ltd, Adani, Ahmedabad	Dandi/Surat	2006–11	700
Bayer Crop Science, Bharuch	Kantiyajal/Bharuch	2007–08	10
Gujarat Mineral Development Corporation, Ahmedabad	Nanicher/Kachchh		30
Gujarat Pipavav Port Ltd., Mumbai	Dandi/Surat; Kantiyajal/Bharuch	2007–10	500
Ambuja Cement Ltd., Ahmedabad	Karanj/Surat	2008–10	150
Hazira LNG Pvt. Ltd., Hazira, Surat	Karanj/Surat		300
Essar Bulk Terminal Ltd., Hazira, Surat	Dandi/Surat; Ankalva/Bharuch	2008–11	300
GSPC Pipavav Power Co. Ltd., Gandhinagar	Kantiyajal/Bharuch; Karanj/Surat		110
Gujarat Heavy Chemical Ltd., Sutrapeda	Rohino Island & Tarsara/Bhavnagar		100
Pipavav Shipyard	Kantiyajal/Bharuch	2009–10	5
ABG Shipyard, Dahej	Nada/Jambusar; Ankalva/Bharuch	2009–11	100
Anjan Cement (Jaypee Group)	Muhadi/Kachchh		100
Petronet LNG, Dahej	Nada/Jambusar; Ankalva/Bharuch	2009–12	350
Ultratech Cement Ltd.	Rohino Island & Tarsara/Bhavnagar		100
Adani Petronet Pvt. Ltd	Dandi/Surat	2010–11	100
Essar Steel Pvt. Ltd.	Dandi/Surat		100
KRIBHCO	Kantiyajal/Bharuch		100
Larsen and Toubro	Karanj/Surat		100
Coastal Gujarat Power Ltd., TATA Power	Kantiyajal/Bharuch	2010–12	800
India Rayon	Madhavad Kotda/Junagadh		50
Kandla Port	Nakti creek/Kachchh; Satsaida Bed/Kachchh		200
Total			4675

(b) Plantation techniques

Seasonally collected seeds were collected from mature trees mostly from the nearest mangrove forest during morning hours, at low tide. Mangrove seedlings were reared in the nursery for plantation in suitable areas. Mangrove nurseries were developed in polythene bags/pots (1000 or less in number) parallel to the tidal water sources to ensure daily flushing the nursery beds. The nursery sites were placed close to plantation sites in order to help seeds or propagules acclimate to the environmental conditions at the site and to reduce the transportation cost of grown-up saplings to plantation sites. In order to avoid water logging due to tidal fluctuations, in polythene bags, each nursery bed was provided with efficient natural drainage system. About 20 cm raised nursery beds are preferred to avoid any water logging, in contrast to the common practice of using sunken nursery beds in other coastal states of India.

Direct seed sowing, propagule plantation, and nursery reared seedling plantations (Polybag method) are common examples of the adopted mangrove plantation methods. Propagules of various species are planted to enhance the biodiversity of mangroves in selected plantation sites. Between 2014-15 and 2020-21, the plantation activities in Gulf of Kachchh, Gulf of Khambhat, and Surat regions were carried out utilising three different mangrove plantation models: (i) direct seed sowing, (ii) fishbone channel plantations and (iii) raised bed plantations. “Direct seed sowing” is a low-cost method in terms of labour and time, requiring less manpower with minimum skills. Plantation in large areas could be completed within a short time with this method. Initial survival rate after first round of dibbling was observed to be poor. In the fishbone channel plantations technique, the intertidal areas with limited scope of tidal inundation are prepared by improving inundation conditions by excavating channels similar to the fish bone structure, making it suitable for the growth of mangroves. During 2006-07, fishbone channel plantation was tested in a 25-ha location with low tidal inundation (GEER, 2009). This method however, is less used for mangrove afforestation along the coast of Gujarat. In the areas with high tidal amplitude along the entire coastline plantations are carried out on raised beds. In 1-ha area, around 20 raised beds (1 m × 1 m x 0.3 m) are prepared, with about 80–100 *Avicennia* seeds sown in each bed. Because of the high tidal amplitude, interventions to increase inundation is usually unnecessary because the tidal currents inundate most of the coastal area.

(c) Selection of species

Involvement of skilled manpower and sound understanding of the scientific principles of plantation ensures cost effective plantation with higher rates of success. It is well established that high species richness of mangroves facilitates the occurrence of high levels of diversity and ecosystem functioning (Zvonareva et al., 2020). Despite this, considering the high success rate of survival and establishment, *Avicennia marina* is highly recommended for plantation activities compared to other mangrove species (such as *Ceriops* spp., and *Rhizophora* spp.) due to the unique environmental conditions. However, based on local conditions (salinity, tidal range, minimum plant spacing, etc.) *Ceriops* sp. (knee roots) and *Rhizophora* sp. (stilt-rooted species) propagules are also planted directly in raised beds or sown directly on the ground.

(d) Monitoring mechanisms

The mangrove restoration activities were monitored using multi-temporal LISS-III and LISS-IV (IRS) remote sensing data covering the

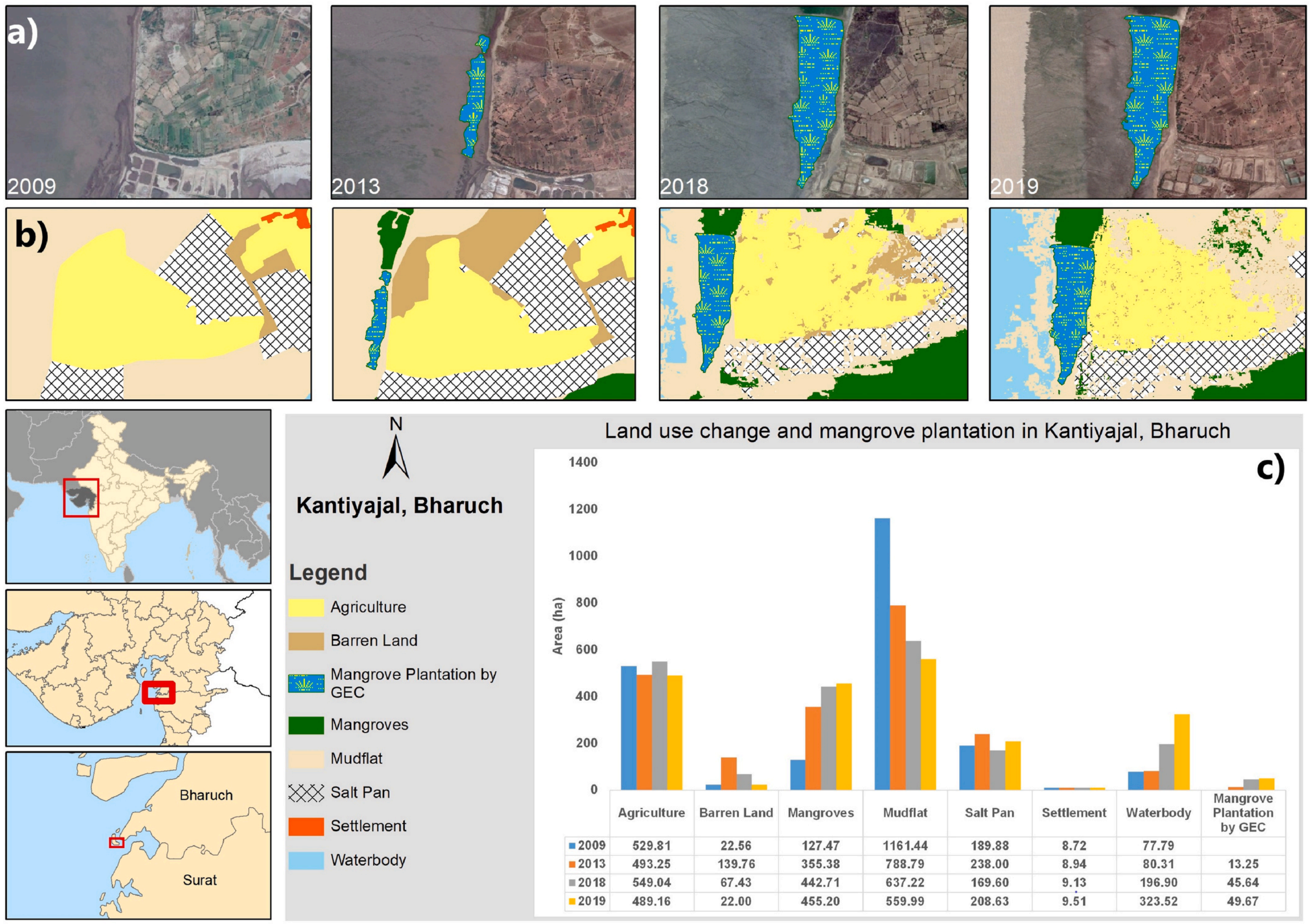

Fig. 6. Land use change and mangrove plantation in Kantiyajal, Gujarat. (a) Year wise progress in mangrove restoration; (b) year wise change in major land use types (c) land use change statistics from 2009 to 2019 (ha: Hectares).

entire coast of Gujarat. The multi-temporal remote sensing images of low tide conditions were analyzed and compared, to estimate the success of mangrove plantation (Upadhyay et al., 2015). The temporal changes in species distribution, density, health status, as well as other vegetation coverage surrounding the plantation sites were also analyzed wherever relevant. In the field, survival of planted seedlings in the identified sites were monitored by the State Forest Department, periodically and an assessment was made using uniform grids of equal size (100 × 100 m). In each of the grid, 10% of the area was randomly selected and all surviving saplings within the grid were counted. Data collected from this random plot (grid) method on surviving saplings density and sapling height were used to assess the survival rate. Additionally, each plantation site was assessed for the parameters such as initial density adapted, seedling survival per unit area (%), branching, seedling height, number of leaves and pneumatophore density on a scale from zero to ten. The total scores are used to assess the overall performance of the plantation. Locals residing adjacent to the plantation sites assisted the monitoring process based on local knowledge of the site conditions.

The survival rate of planted mangroves, measured within months to 3 years after of plantation was the single most common indicator of its success. Spatial area cover, height of the planted trees and survival rate of seedlings per unit area are a few major criteria for the estimation of survival rates and plantation success. . The local CBO, which is the primary implementing agency at the grassroot level in Gujarat, are trained by the GEC on field methodologies, organization of groups for management, record keeping and accounting, through various subject experts and exposure visits to sites where successful plantations are reported. Additional trainings were provided to supervisors and mangrove workers on mangrove plantation related activities including preparation of the beds, creation of embankment, filling up of bags with the suitable soil type, seedling transplantation, monitoring the growth of the saplings and reporting the survival rates.

3.4. Gujarat Ecology Commission

Gujarat Ecology Commission (GEC) has been working to restore mangroves along the coast since 2002, with the help of the Gujarat Forest Department, the Indo-Canada Environment Facility, the World Bank, and private industries. The REMAG project, which ran from 2002 to 2007, was funded by the India–Canada Environment Facility (ICEF) and was implemented by GEC. The programme has given a considerable impetus to mangrove restoration projects based on Public–Private Partnerships (PPP). To enhance the socioeconomic conditions of coastal settlements, the REMAG initiative was integrated into the World Bank-funded Integrated Coastal Zone Management (ICZM) Project. Private sector investments in mangrove development/restoration activities have

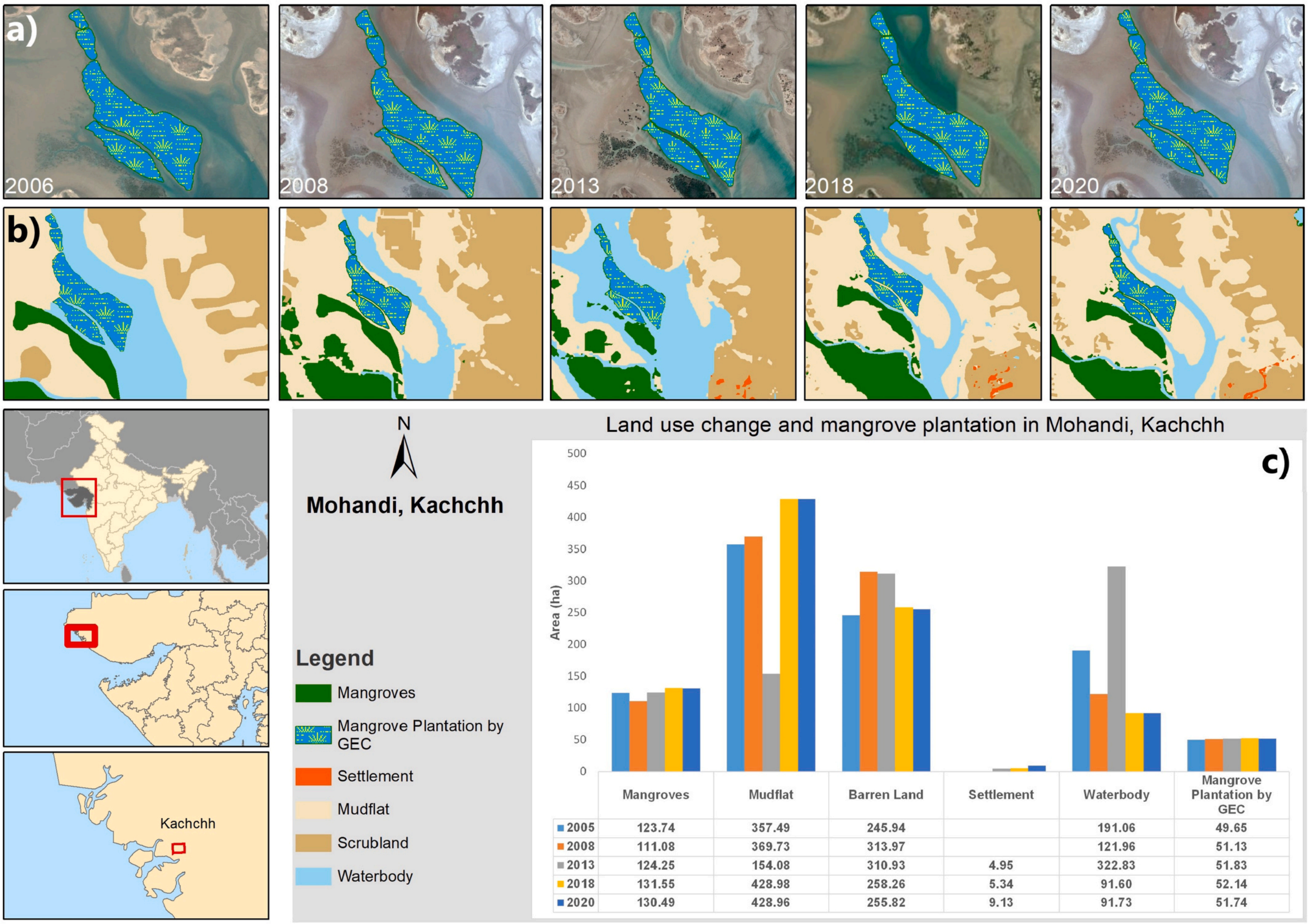

Fig. 7. Land use change and mangrove plantation in Mohandi, Gujarat. (a) Year wise progress in mangrove restoration; (b) year wise change in major land use types (c) land use change statistics from 2009 to 2019 (ha: Hectares).

been encouraged to a larger extent, with a commitment to enhance community participation and corporate environmental responsibility (CER) (Viswanathan, 2016).

After a synthesis of ecological and socioeconomic information on mangrove services and values, the project was implemented methodically and sequentially. Communities were brought on board and consulted during every key step in project implementation since socio-economic linkages are crucial to mangrove management. Restoration activities were adapted to the individual site characteristics in collaboration with each private sector partner. These partners contributed to the restoration project by providing necessary funding to scale up restoration work, and by supporting monitoring of the newly planted sites. By adopting the PPP model in mangrove restoration, several alliances between the industry, public agencies and local communities are formed to promote an ecologically viable, socially responsible and sustainable project. Several private sector partners (prominent industries of the state) have been the funding and involved in collaborative monitoring with GEC for various mangrove restoration activities as their legal commitment (i.e. through Corporate Social Responsibility (CSR)) to conserve the natural ecosystems.

In developing the mangrove restoration strategies for project implementation, three overall dimensions were considered (GEC, 2012):

(i) Socio-economic - focusing on assisting local communities in building and strengthening their livelihoods;
(ii) Ecological - striving to increase the importance of mangroves as bio-shields, and
(iii) Governance - focusing on building stable and strong institutions for the effective governance of mangrove ecosystems

The project accomplished bringing together three primary stakeholders (community, industry, and government) to create a single platform for mangrove ecosystem conservation. The establishment of CBO to implement the projects was undertaken. Local people living near mangrove regions and relying on mangrove ecosystem services, were directly or indirectly involved in the project, and their capacity to sustainably manage the mangroves was enhanced through training programmes throughout the project phase. Over 20 industries contributed to the mangrove planting initiative by supporting and monitoring various operations (e.g. suitable site selection for plantation, physico-chemical properties of soil and water, land elevation and the tidal pattern, post plantation monitoring) within the programme, and demonstrating a long-term commitment to mangrove conservation. Through GEC, the government has anchored the entire initiative by organising and giving technical assistance to the community and

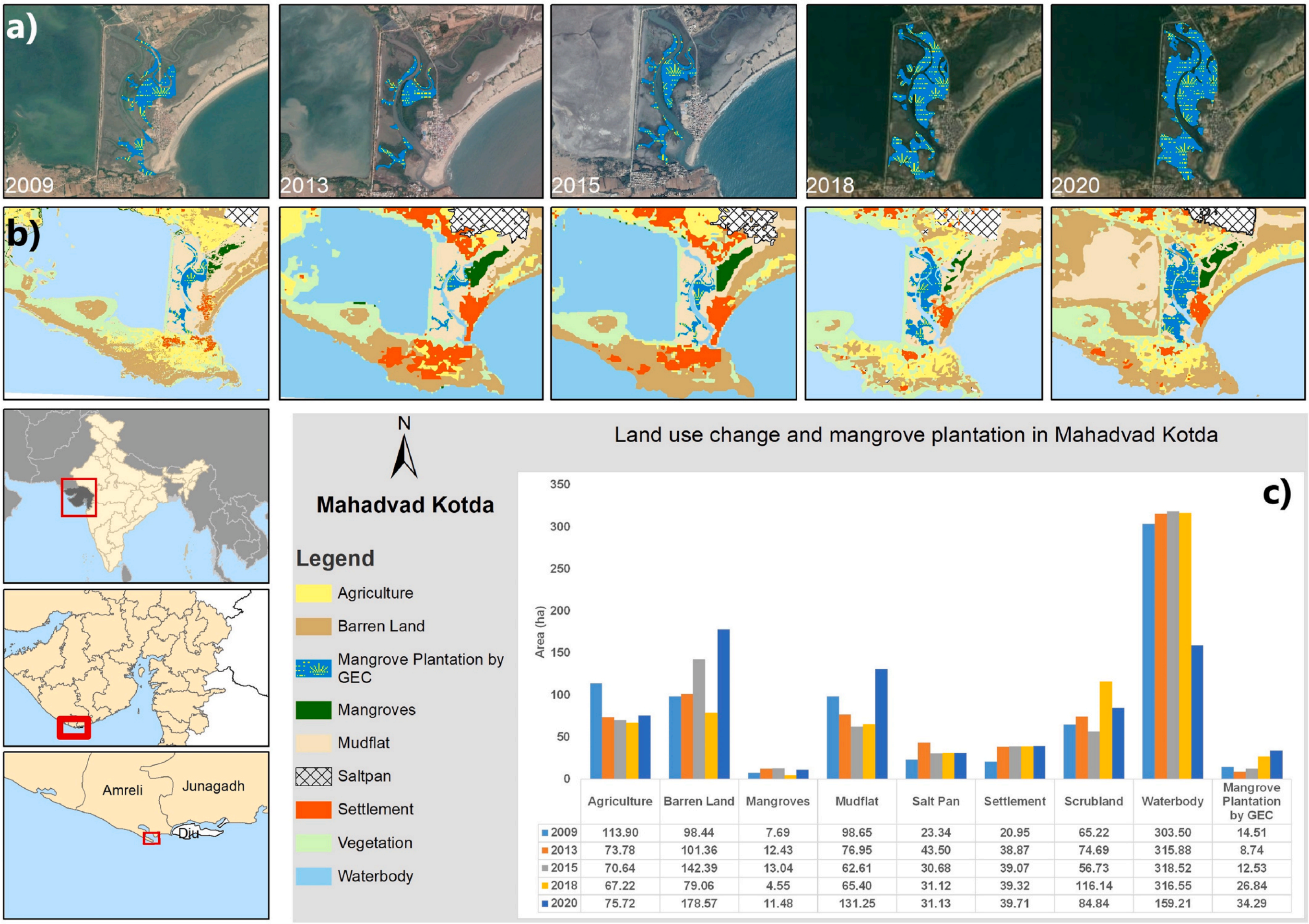

Fig. 8. Land use change and mangrove plantation in Mahavad Kotda, Gujarat. (a) Year wise progress in mangrove restoration; (b) year wise change in major land use types (c) land use change statistics from 2009 to 2019 (ha: Hectares).

industry in the mangrove restoration. Field observations indicate that the innovative approach of involving communities and other stakeholders has resulted in increased local knowledge in promoting mangrove restoration and eventually in enhanced mangrove cover in the State of Gujarat. Between 2003–2004 and 2011–2012, over 12,000 ha of mangrove plantations were developed in the State. The PPP approach has been used to establish nearly 35% of these mangrove plantations. A total of 176 CBOs comprising ~170 coastal communities throughout the 9 coastal districts has been established. GEC has chosen several non-profit organisations to serve as Project Implementation Partners (PIP), who act as facilitators for community mobilization, CBO formation and registration, micro-planning, and project-related activities, such as seed collection, nursery development, plantation development, and land development, among others (Viswanathan, 2016).

3.5. India ICZM project

The India Integrated Coastal Zone Management (ICZM) project was launched by the Government of India in 2010 through the Ministry of Environment, Forest and Climate Change, with funding from the World Bank, to develop and implement an improved strategic management approach for coastal zones of India to ensure sustainable development, livelihood enhancement, and economic growth. Gujarat was one of the three states involved in the preparation of the ICZM plan for a pilot stretch (Gulf of Kachchh) and the implementation of priority activities. The GEC, in its capacity as the State Project Management Unit (SPMU), collaborated with several state-level organisations and specialised agencies as Project Execution Agencies (PEAs). One of the key strategies adopted in the ICZM project was planting of mangroves for preventing coastal erosion. Between 2010-11 and 2014-15, about 195 sq. km of mangrove plantations were undertaken through community participation (GEC, 2015; World Bank ICR, 2020). The growth of this large-scale mangrove plantation is evident as per records of the Forest Survey of India and through high-resolution satellite imagery, in addition to other field-based monitoring measures, on an annual basis.

3.6. Private sector initiatives

Some of the most popular enterprises in the state have partnered with the mangrove restoration programme (Table 4). These industries contributed significantly to mangrove restoration in two ways: (i) by providing critical finance for scaling up restoration activities, and (ii) by assisting in monitoring the new plantations (GEC, 2012). It is important to note that most of the time, the industries have come to GEC for assistance, technical advice, and monitoring. GEC identifies suitable plantation sites and forms CBO to execute the work. GEC is also responsible for technical training on direct propagule dibbling method for the villagers, as well as monitoring and reporting to the corporations.

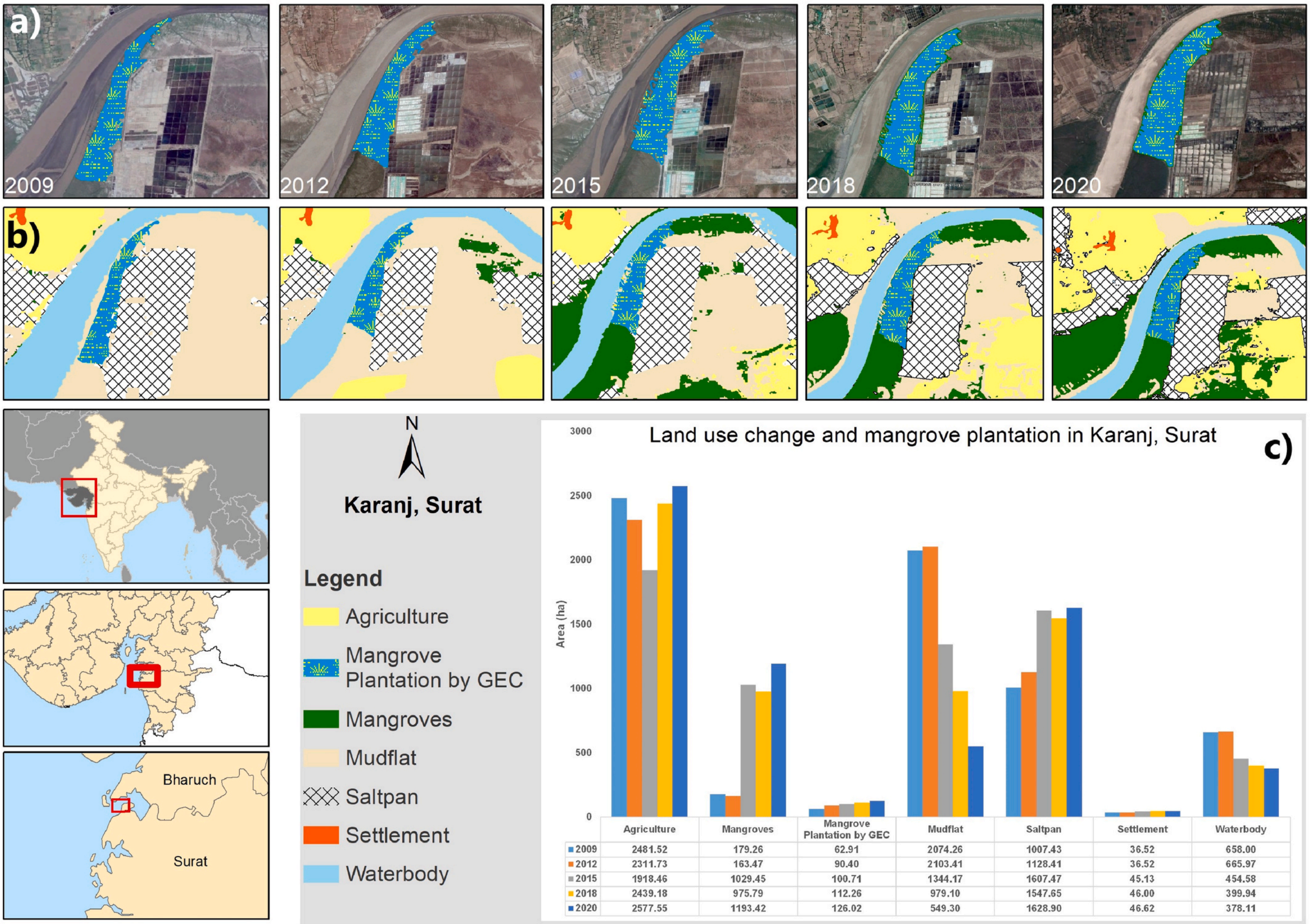

Fig. 9. Land use change and mangrove plantation in Karanj, Gujarat. (a) Year wise progress in mangrove restoration; (b) year wise change in major land use types (c) land use change statistics from 2009 to 2019 (ha: Hectares).

Technical support was also provided in transplantation of nursery raised saplings and systematic assessing their survival rate by developing skilled manpower within the local community. Between 2006-07 and 2017-18, the GEC funded 78 mangrove afforestation projects totaling 7530 ha with an average of 97 ha per project (JICA, 2020).

4. Adaptive management in Gujarat

Adaptive management necessitates regular monitoring of key indicators to determine if rehabilitation objectives and goals are being met, and to activate decision-points for appropriate intervention and action if the objectives or goals are not being met (Gann et al., 2019). In the case of mangrove plantation and restoration undertaken in Gujarat, adaptive management approaches have been extensively used for the identification of suitable plantation sites as described earlier. Local CBOs were used for undertaking the plantation efforts, monitoring and reporting. Adaptive management used in this entire process is an iterative process and the steady increase in the area under mangrove cover testifies the evolving processes followed by the state government over time.

4.1. Restoration methodologies adopted

The ecological goal of mangrove restoration is to increase mangrove cover to stabilize, strengthen and protect the shoreline, enhance biodiversity and, ensure continuity in the supply of goods and services. Between 1990 and 2013, planted mangroves contributed significantly to the net accretion of coastal land and to the inshore and offshore capture fisheries. Considering the major benefits provided by mangroves, the annual contribution of the planted mangroves to economy of the state is estimated to be INR 95 million/year or INR 1200/ha/year, despite various constraints such as single species dominance, stunted growth, lack of freshwater, etc. (Das, 2016).

Between 2005 and 2011, remote sensing studies revealed significant growth in mangrove area (166 ha–1414 ha) in the taluks of the Gulf of Kachchh (Upadhyay et al., 2015). It is attributed to extensive plantation measures and independent monitoring by coastal industries, which ensured strict adherence to the regulations laid by the Forest Department (Upadhyay et al., 2015). Based on the lessons learned from various restoration initiatives, a set of general conservation practices were proposed to help planted mangroves survive and grow into mature

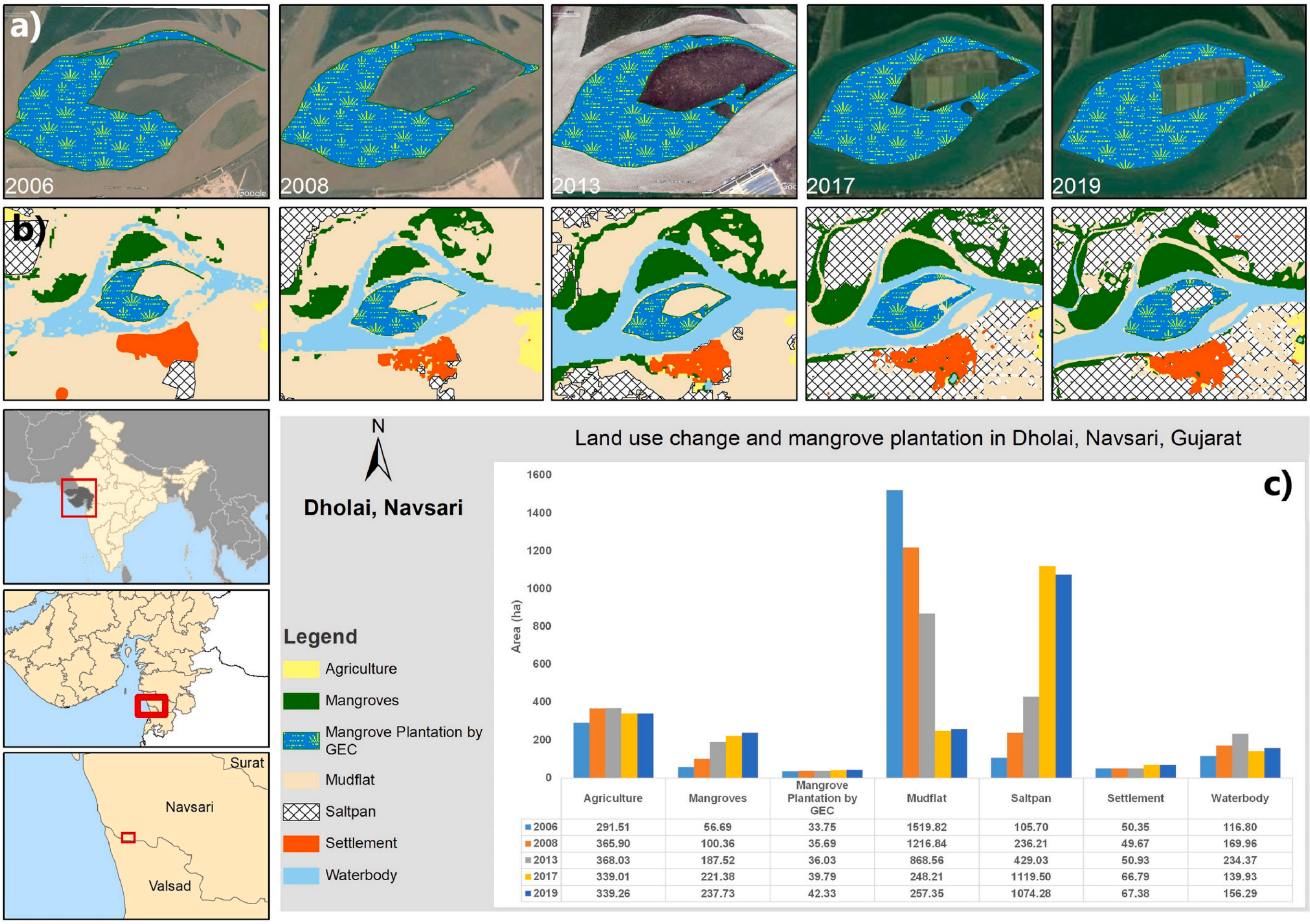

Fig. 10. Land use change and mangrove plantation in Navsari, Gujarat. (a) Year wise progress in mangrove restoration; (b) year wise change in major land use types (c) land use change statistics from 2009 to 2019 (ha: Hectares).

mangrove forests (GUIDE, 2018). This includes proper site selection and choosing a suitable plantation strategy requiring:

— avoidance of high mortality;
— regular watering of the nursery beds with fresh water (at appropriate intervals);
— regular tidal flushing and inundation;
— avoidance of algal infestation impact on mangrove recruitment and regeneration;
— monitoring of established mangrove plantations;
— regular check on grazing by livestock particularly the camels;
— limiting anthropogenic activities;
— mangrove plantation using seed from the closest available region;
— rehabilitation in mangrove-sparse areas rather than attempting new plantation sites;
— avoidance of introduction of a mangrove species that is not recorded in the identified plantation region (exotic to that region); and
— selection of indigenous species to undertake plantation.

5. Mangrove afforestation alongside coastal development in Gujarat

The coast of Gujarat includes multiple Special Economic Zones (SEZs), and the Sagarmala Project proposes three Coastal Economic Zones (CEZs) to promote port-led development. As a result, the state coast has become a hub for industrial and infrastructure development. Gujarat is dealing with this problem through multiple management strategies including compliance by industries towards allocating a stipulated land area for green belt development as a measure of keeping safe the ambient environment through community-based mangrove restoration (Viswanathan et al., 2011).

An example is corporate-funded community-based mangrove afforestation in Gujarat's Kantiyajal area, which was aided by GEC. When compared to the effort in 2013 which covered 13.25 ha, the mangrove plantation effort in 2019 was expanded by 252% covering 49.67 ha (Fig. 6). Between 2009 and 2019, the overall coverage of natural mangroves in the region increased by 257%. This increase has occurred despite the proliferation of saltpans in the region and settlements, indicating that coastal development and mangrove conservation can coexist. Settlement growth and mangrove cover increase have also been evident in the Mohandi region of the Gulf of Kachchh (Fig. 7).

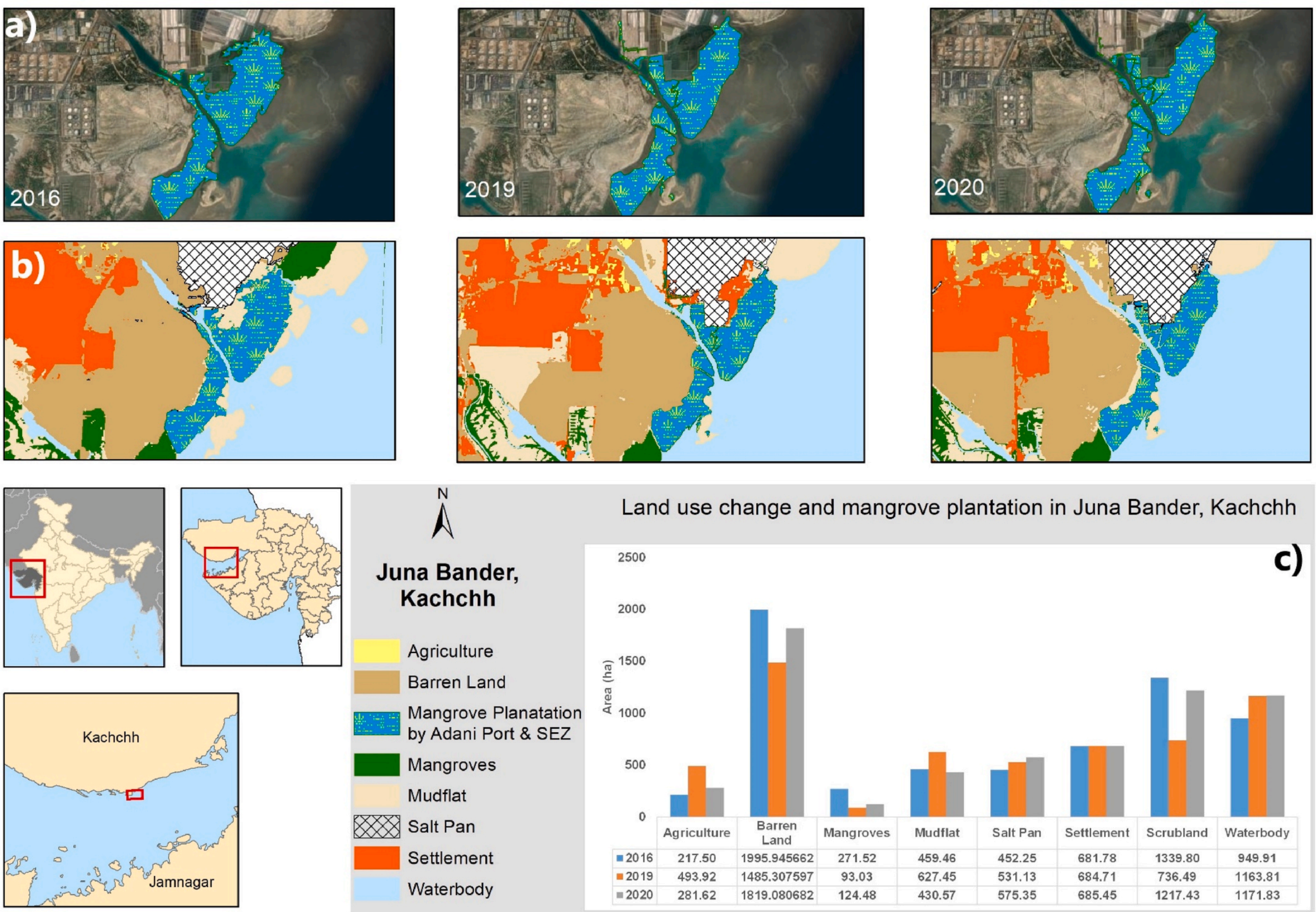

Fig. 11. Land use change and mangrove plantation in Juna Bander, Gujarat. (a) Year wise progress in mangrove restoration; (b) year wise change in major land use types (c) land use change statistics from 2009 to 2019 (ha: Hectares).

In Gujarat, expansion of salt production facilities and extension of mangrove cover have occurred concurrently with enhanced mangrove plantation activities. Spatial analysis of land-use changes using multi-temporal remote sensing data (from 2009 to 2020) in coastal regions, such as Mahavad Kotda, Karanj, and Navsari has shown such parallel expansion of salt pans and mangrove areas (Figs. 8–10). It is to be noted that both salt production and expansion of mangrove cover have occurred concurrently without any detrimental impacts. The local communities engaged in mangrove plantation, were paid directly on a daily wage basis from different state run projects. The extensive mangrove plantations established under these projects are geotagged. An increase of 35 sq. km in the area under mangrove cover across the coastline of Gujarat is recognized by the Forest Survey of India (2019) report, with a 20% increase in biodiversity (including seasonal avifaunal visitations), expanding fisheries-based livelihood opportunities. It is expected that these ecological benefits will improve the ecosystem function and the overall management of the coastal and marine environment in the coming years, and when the mangrove plantations reach maturity (in about 10 years), they will sequester carbon well into the future.

5.1. Coastal urban case study- Mundra town

Mundra is a town in Kachchh area of Gujarat where infrastructural modernization coexists with the region's abundant biodiversity. The Adani Ports and Special Economic Zone Limited (APSEZ) planted 2939 ha of mangroves along the Gujarat coast by engaging partners and knowledge support from local communities, public and corporate institutions, including the GEC, GUIDE, SAVE, and GFD (Adani Ports and Logistics, 2021). The APSEZ has planted 976 ha of mangroves in Juna Bander between 2016 and 2020, despite an increase in area of salt pans, dwellings, and agricultural activities in the area (Fig. 11). In addition, 7200 ha of mangrove afforestation is planned for the next five years. By expanding regions and enriching biodiversity hotspots, the Adani Foundation has implemented projects for both coastal and terrestrial biodiversity.

At Luni Bander, plantation of three mangrove species, *Rhizophora mucronata, Ceripos tagal,* and *C. decandra*, has been undertaken. The goal of the mangrove biodiversity enrichment project in and around APSEZ is to ascertain the viability of selected mangrove species in suitable coastal areas on a small scale. Two biodiversity parks are established in Mundra, one on a five-acre plot near Nandi Sarovar and the other in Luni, to

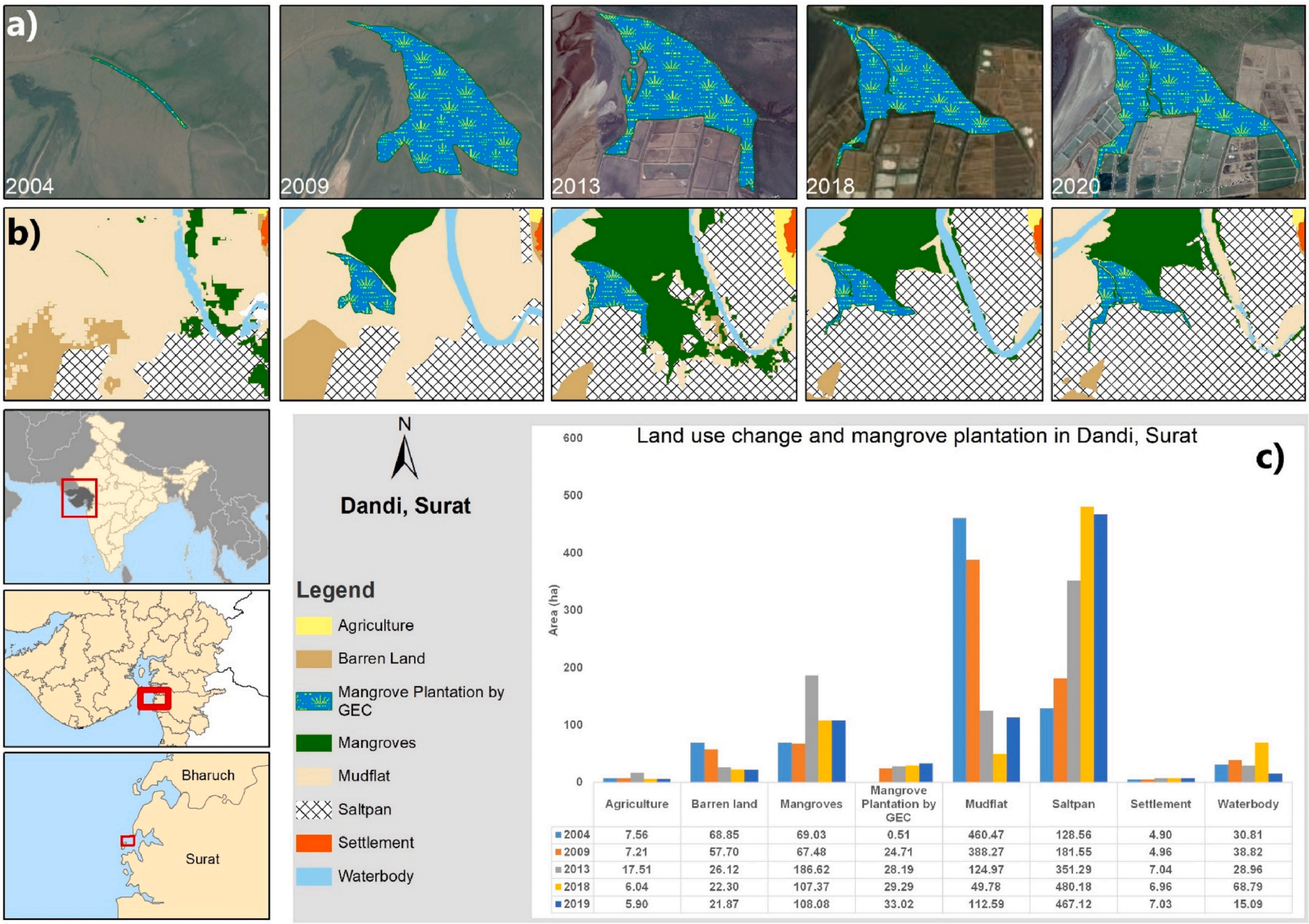

Fig. 12. Land use change and mangrove plantation in Dandi, Gujarat. (a) Year wise progress in mangrove restoration; (b) year wise change in major land use types (c) land use change statistics from 2009 to 2019 (ha: Hectares).

increase the biodiversity of the coastal region. By providing ideal habitats and breeding grounds with multispecies plantations of mangroves in a 10-ha coastal site, a significant increase in natural resources is expected to be achieved (Adani Ports and Logistics, 2021).

5.2. Coastal rural case study – Dandi village

The Dandi village is located in Olpad taluka of Surat district, where mangroves were restored with financial support from government and private agencies. The implementation of this programme was undertaken with the help of Dandi Kantha Tavar Vikas Samiti CBO (GEC, 2012), where mangrove plantations are undertaken in 30 ha area during the past 10 years. Adjacent to the plantation site, expansion of saltpans, aquaculture farms, agricultural fields, and settlement areas are observed. Salt pans increased from 128.56 ha in 2004 to 467.12 ha in 2021 with an increase of 264% within a span of 17 years (Fig. 13). Because of the port proximity (Hazira Port, 30 km from Dandi) to the restoration site, port-related activities have direct environmental impacts on the mangroves. Still, it is worth noting that the mangroves at the restoration site are thriving well and are continuously providing ecosystem benefits to the local fishing community. As a result of mangrove restoration, the fish catch in Dandi has increased by 143% compared to the pre-restoration levels, enhancing the revenue of fisherfolk (GEC, 2012). It is evident that the areas surrounding the mangrove plantation sites are simultaneously developed with multiple land-use, reflecting conservation-development synergies (Fig. 12).

6. Balancing conservation and development

One of the major regulating services of mangroves as being a shelterbelt against strong winds, storm surges, and cyclones has reinforced the need for these resilient natural barriers for their conservation value and socio-economic development. These have led to the “Public-private partnership (PPP)” project launched by in 2007 where, multiple business establishments had contributed almost INR 50 million for mangrove conservation (GEC, 2012). Mangrove conservation and development has been given very high importance in the state by involving all the stakeholders, be they coastal communities, commercial entities, or private and government agencies. Along with restoring mangrove patches, emphasis has been given to raising nurseries and continuing plantation. Between the years 2014 and 2021, the state has seen an expansion to a total of 40,480 ha of mangrove plantation (Table 5). The successful increase in mangrove cover can be attributed to the appropriate policies of the State Government and their effective implementation (Government of Gujarat, 2021).

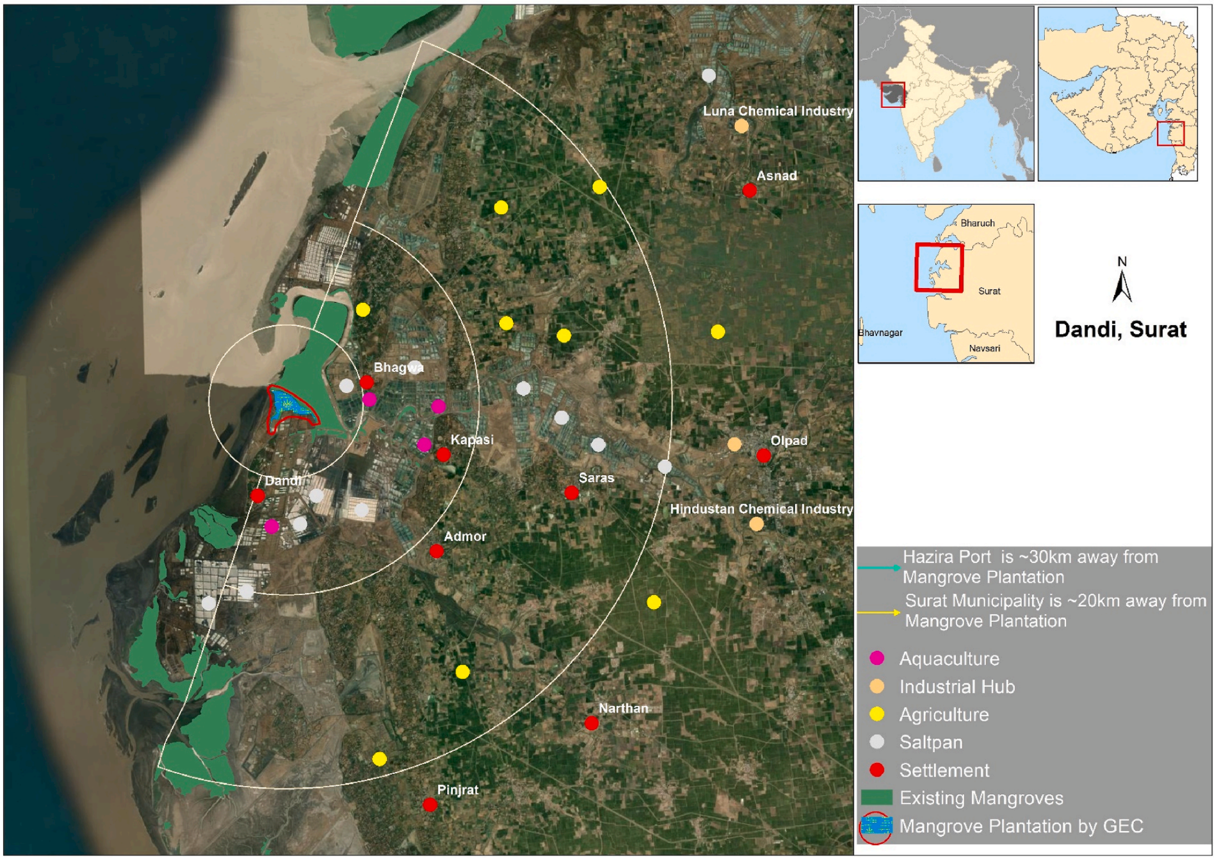

Fig. 13. Mangrove restoration site in Dandi and the surrounding land use.

Table 5
Mangrove plantation (ha) raised between 2014 and 2021 (Government of Gujarat).

Region	2014–15	2015–16	2016–17	2017–18	2018–19	2019–20	2020–21
Gulf of Kachchh	2910	1800	4920	3880	3020	4300	2950
Gulf of Khambhat	2250	200	3240	600	990	2820	3300
Surat	800	0	920	800	340	190	250
Total	5960	2000	9080	5280	4350	7310	6500
Grand total							40,480

7. Role of coastal communities

For the community, mangroves are an important common resource pool; therefore, conservation of these resources is beneficial to them. Through the PPP project initiatives, the communities have achieved plantation and preservation of an estimated 5000 ha of mangrove area. Gujarat Ecological Society, through community-based conservation of mangroves in Gujarat, has created three Biodiversity Management Committees to train and involve the fishing community to raise nurseries and care for saplings during the lean seasons (GED, 2018). Both the Mangrove Restoration Project (REMAG, 2002-07) and the PPP project have highlighted the success of community-based mangrove restoration efforts (Viswanathan, 2013) though participation may depend on the benefits from employment. Co-management rights to the mangrove ecosystem under national legislation and strong stakeholder participation including the local community, the administration, NGOs and research organisations have been key to the success of these restoration projects.

Among the communities too, there are different approaches towards the kind of benefit and services generated from mangrove ecosystems. These include trapping of coastal sediments, providing stability to coastal erosion, supporting unique breed of *Kharai* camels (livestock), protection of agricultural lands, recreational services, creating sinks of CO_2 and aquatic pollutants by the intertidal areas, etc. (Lakhmapurkar et al., 2022). Hence, the approach towards the conservation of mangroves is also different among various socio-economic groups (Viswanathan, 2016). While most of the projects and initiatives have been primarily the efforts of different government agencies so far, corporate commitments and mandates of NGO to educate and involve local communities and enthusiasts in conservation practices are also important. The coastal communities too have their own folk narratives and cultural heritage linked with mangrove forests. An increase in natural calamities and proof of the protection evidenced by intact mangrove ecosystems has further strengthened their connection with this coastal vegetation as natural safeguards for their life and livelihoods.

8. Conclusion

The dynamics of natural and social systems, as well as their interactions, are critical to the success of mangrove rehabilitation and restoration efforts. The successful mangrove restoration model of Gujarat has multi-stakeholder participation from the government, private corporations, local people, and non-governmental organisations. Long-term effective mangrove restoration can be attributed to three main factors; (a) community participation; (b) public-private partnerships and (c) good governance. Despite the current success, the state still has vast areas along the coast where mangrove regeneration is possible. Gujarat is predicted to have 258 to 1153 sq. km of mangrove regeneration potential scattered across the shores of ten districts (Upadhyay et al., 2015). The experience gathered through the successful projects indicates that state and/or national legislation on co-management rights to the forest along with strong collaboration between the communities, the government and industry partners are necessary for the better sustainability of the mangrove restoration activities. In addition, by considering their existing biological and social settings, such restoration approaches can be considered and replicated in other coastal states and Union Territories of India. There was immense commitment of State leadership for increasing the mangrove cover for larger benefits of coastal protection, ecological sustenance, livelihood development and in creating green jobs for sustainable fisheries. All these models were successfully implemented under the vision and guidance of the State leadership. Gujarat thus has set the model in the right direction for mangrove plantation initiatives alongside rapid coastal development.

CRediT authorship contribution statement

Hardik Shah: Writing – original draft, Investigation, Conceptualization. **R Ramesh:** Writing – review & editing, Visualization, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

Ramesh, R thanks the scientists Purvaja, R., Deepak Samuel, V., Muruganandam, R., Raghuraman, R., Hariharan, G., Ganguly, D., Joyson, JJJ., Gopi, M., Ahana Lakshmi and Soundararajan, R of NCSCM for their timely assistance in the preparation of maps, collection of secondary data, and for critically reviewing the manuscript.

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ARTICLES FOR FACULTY MEMBERS

MANGROVE RESTORATION TOWARDS SUSTAINABLE COASTAL ECOSYSTEM MANAGEMENT

Title/Author	**Emergy-based evaluation of world coastal ecosystem services / Liu, C., Liu, G., Yang, Q., Luo, T., He, P., Franzese, P. P., & Lombardi, G. V.**
Source	***Water Research*** **Volume 204 (2021) 117656 Pages 1-10 https://doi.org/10.1016/J.WATRES.2021.117656 (Database: ScienceDirect)**

Water Research 204 (2021) 117656

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

Emergy-based evaluation of world coastal ecosystem services

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ARTICLE INFO

Keywords:
Coastal ecosystem
Ecosystem service
Emergy analysis
Non-monetary accounting

ABSTRACT

The current lack of research on the evaluation of marine ecosystem services makes the value of marine protection, development and restoration underestimated during the decision-making process. Based on the non-monetary ecosystem service evaluation framework, a marine ecosystem service classification and accounting method has been established in this study, and the world's coastal ecosystem services have been measured as an example. The results show that (1) the world's coastal ecosystem service value is about 4.13E+23 sej/yr, of which Asia and North America contribute about 55% of the total service value; (2) the top ten countries in terms of the world's coastal ecosystem service values are Canada, Indonesia, Australia, the United States, Brazil, the Russian Federation, Norway, the Philippines, Mexico, and China, which contribute about 60% of the total service value; (3) estuaries have the highest ecosystem service values, followed by mangroves, seagrass beds, tidal flats, salt marshes, and warm water coral reefs; (4) developed countries can make better use of their coastal resources and pay more attention to the marine protection while the opposite is true in developing countries, which means that developed countries still occupy an advantageous position in the process of marine protection, development and utilization. This study assesses the coastal ecosystem service values in various coastal countries from the perspective of ecosystem contributors, emphasizes the importance of protecting them in marine management, and provides a certain reference basis and theoretical support for decision-makers in formulating marine-related protection and development strategies.

1. Introduction

Marine ecosystems have huge areas and complex structures, representing one of the most developed ecosystems in the world. It covers nearly three-quarters of the earth's surface and occupies 99% of the earth's bio-productive space (measured by volume) that sustains organisms' life. Not only can they regulate the ecological environment of the earth, but they also constitute a human life support system (Shen and Mao, 2019). Coastal areas only account for 4% of the earth's total land area and 11% of the world's ocean area, despite that, they carry more than one-third of the world's population and contribute about 90% of the global fisheries catchment and more than 60% of the total economic value provided by the global ecosystem (Barbier, 2017; Liquete et al., 2013). Coastal ecosystems can provide several services, such as habitat provision, pollution control, floods and storms mitigation, sediment maintaining, coastline stability maintaining, erosion control and carbon sequestration (Barbier, 2017). However, with the development of society and the continuous expansion of the scope of human activities, the abuse of marine areas and unregulated pollutant discharge have threatened the marine ecosystem. At present, 50% of the world's salt marshes, 35% of mangroves, 30% of coral reefs and 29% of seagrass beds have degraded or disappeared in recent decades (Barbier, 2017). In

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https://doi.org/10.1016/j.watres.2021.117656
Received 16 April 2021; Received in revised form 17 August 2021; Accepted 7 September 2021
Available online 11 September 2021

addition, the acceleration of urbanization and rapid economic development also affect the sustainable development of marine ecosystems (Dobson et al., 2006; Halpern et al., 2008). Although the public's awareness of marine ecosystems protection is constantly increasing, there is still a lack of plans and actions for marine protection. Compared with terrestrial ecosystems, the data and methods for marine ecosystem service evaluation are relatively lacking (Barbier, 2012) due to the complexity of the processes and functions of marine ecosystems and their highly dynamic characteristics (Galparsoro Iza et al., 2014). Therefore, the value of marine protection, development and restoration is often underestimated during the decision-making process (Camacho et al., 2014; Vassallo et al., 2018).

At present, the conceptual framework, indicators, and metrics of marine ecosystem services assessment are still missing or controversial (Liquete et al., 2013). Most studies only focus on the marine area at small scale, or only calculate the value of a single period and of a certain ecosystem services, which makes it difficult to reflect the overall marine ecosystem service values (Sun et al., 2018). The existing marine ecosystem service evaluation methods can be roughly divided into three categories: economic methods, InVEST model, and emergy analysis methods (Yang et al., 2019b). The economic method uses economic value to measure ecosystem services, which can be easily accepted by people and it is more suitable for accounting for values based on individual preferences and perceptions. However, when ecosystems provide some services that are not currently perceived by society, are ambiguous, or can only be expressed in the future, economic method shows its own limitations (Liu and Yang, 2018). Therefore, Costanza et al. (2017) recognized that there were certain limitations in using economic method to assess ecosystem services, and the calculated economic value was not equal to market value or transaction value. The InVEST model can be used to evaluate marine ecosystem services, spatial patterns and dynamics (Tallis and Polasky, 2009; Yang et al., 2018), but the model limitations consist in low simulation accuracy, no basis for parameter setting and unclear service trade-off mechanism (Wang et al., 2015). The emergy analysis method is based on the perspective of ecosystem contributors, considering that three renewable energy sources (solar energy, tidal energy and geothermal energy) are ensuring the material circulation, the energy flow, and the sustainable development of the earth's biosphere. Those sources of renewable energy can be used to account for the value of ecosystem services (Liu and Yang, 2018).

Emergy is the amount of solar energy (unit: solar joule, sej) that is directly or indirectly required to produce a service or to manufacture a commodity. It allows the measurement of different grades and types of substances and energy through a uniform scale, thus solving the current difficulties in comparing different ecosystem services (Odum, 1996). Based on the laws of thermodynamics, the emergy analysis method can minutely describe the resource flow (including matter and energy) in each system, and evaluate the environmental cost of any production from the perspective of contributors rather than from human preferences, thereby quantifying the cumulative available energy expenditure for the production and operation of any service or product (Odum, 1996). This method has been applied to forests (Campbell and Brown, 2012; Yang et al., 2018), wetlands (Yang et al., 2019a), grasslands (Yang et al., 2020), dams (Liu et al., 2019) and other ecosystem service evaluation process.

The current researches on marine ecosystem service evaluation still have the following deficiencies:

(1) The conceptual connotation and ecological process of marine ecosystem services are still unclear: the complexity of marine ecosystem structure makes it possible to provide a wide variety of services, and there may exist some services that have not yet been identified. Besides, some ecological process, operating mechanism, and dynamic evolution rules contained in them are still unclear, so in-depth research is needed.

(2) The current classification of marine ecosystem services is a little arbitrary: Millennium Ecosystem Assessment, Beaumont et al. (2007), The Economics of Ecosystems and Biodiversity (Kumar, 2010; (Haines-Young and Potschin-Young, 2010)), and Common International Classification for Ecosystem Services (Haines-Young and Potschin-Young, 2018), etc. classify marine ecosystem services, but these classifications still have some implementation problems, such as double counting problem and failure to measure various services in a reasonable and comprehensive manner. In addition, there has not been a unified conclusion about the specific services provided by different types of marine ecosystems, which also brings difficulties to the evaluation of marine ecosystem services.

(3) The theoretical framework and specific accounting methods for marine ecosystem service driven by ecological thermodynamics have not been fully established: traditional economic methods are widely used, but they mostly use substitute value. However, it is difficult to find alternative ways for the calculation of many services values (especially the services of non-marine fishery products). Therefore, the results obtained by these methods implementations show large deviations, so that new accounting methods need to be developed.

Therefore, based on the emergy analysis method, this study provides a theoretical framework and method for marine ecosystem services evaluation from the perspective of ecosystem contributors, focusing on the world's coastal wetlands case study, so as to provide a certain reference basis and theoretical support for the management, development and protection of the coastal and marine ecosystems. In addition, this study applies a regression model to verify the possible correlation between coastal ecosystem service and local socioeconomic growth of the region, clustering the countries on the basis of their tradeoff between the flow of ecosystems services and the socioeconomic conditions.

2. Methods

2.1. Description of study area

The world's coastal wetlands are the study areas for this evaluation. About half of the approximately 7 billion world population lives in coastal areas, and more than 3 billion people rely on marine and coastal resources for their livelihoods. For many coastal residents in developing countries, fishery is the main life and business activities. The market value of marine and coastal resources and industries is estimated to reach 3 trillion US dollars per year, accounting for about 5% of global GDP (Patil et al., 2016). In addition, coastal and marine areas provide a large number of employment opportunities for mankind, and marine fisheries directly or indirectly employ more than 200 million people. What's more, these areas not only have huge biodiversity, but they are also rich in resources. In fact, there are currently nearly 200,000 species of marine organisms known, but the actual number is assessed to be tens of millions. More than 70% of the world's oil and gas resources are stored in the seabed. At present, the proven offshore oil reserves on the global offshore shelf account for 45% of the world's total reserves, while the seabed natural gas reserves account for 1/3 of the world's total reserves. Besides, the vast coastline has made many countries rich in coastal tourism resources. Currently, the total number of international inbound and outbound tourism from major coastal countries in the world has exceeded 1 billion, and international tourism revenue has reached 1381.1 billion US dollars.

2.2. Marine ecosystems and their services classification

In function of specific characteristics of the environmental attributes, functions and human influence, marine ecosystems are divided into three main categories,: coastal ecosystems, offshore ecosystems and pelagic ecosystems. Coastal ecosystem is a transitional ecosystem between the open water and the land, which has the characteristics of both aquatic and terrestrial ecosystems. The unique structure and function of the coastal ecosystem plays an irreplaceable role in climate regulation, pollution control, environment stabilization and ecological balance maintaining. Based on the natural characteristics of different types of coastal ecosystems and on data availability, six types of natural coastal ecosystems are considered in this study (see Table 1), while artificial coastal wetlands are not considered.

The offshore ecosystem is the system between the outer boundary of the coastal ecosystems and the edge of the continental shelf of the 200 m isobath. Due to the varying degrees of interaction between continents and ocean circulations, the changes of hydrological, physical, chemical, and biological factors, the different offshore areas also show deep regional differences. In the offshore area close to the continent, the changes in hydrological, chemical, and physical process are complex due to the relatively large impact of the continent contributions. The offshore area, where the water depth is greater than 150 m and human activities have little impact, is mainly affected by various ocean circulations. It has the characteristics of ocean water that has high transparency, stable composition, high salinity and poor biological species.

The pelagic ecosystem refers to the ocean area with a water depth of more than 200 m, covering the entire body of water and the seabed beyond the continental shelf, including continental slopes, ocean ridges, ocean basins, trenches, and cold-water coral reefs. Compared with the offshore areas, the pelagic environment is relatively stable. Since the current understanding and research on the pelagic area is still poor, the pelagic ecosystems are not considered by this study as well as offshore ecosystem. Table 1

Based on the non-monetary ecosystem service evaluation framework, ecosystem services are grouped into three categories: direct, indirect and existing services. Direct services refer to the amount of flows and storages in the studied ecosystems. Among them, biomass increase refers to the total amount of living organic matter (dry weight) accounted per unit area at a certain moment, including land and sea external input; the carbon sequestration service includes the service of reducing CH_4 emission, as well as carbon fixation by photosynthesis. Soil/sediments organic matter building account for vegetation litter, underground dead roots and rhizomes. The groundwater recharge consists in preventing seawater intrusion. Indirect services refer to the additional services produced by the ecological process while producing direct services. Among indirect services, water purification deals with the absorption of water pollutants such as heavy mental and so on, while air purification deals with the absorption of air pollutants such as SO_2, fluoride, NOx, CO, O_3, and PM_{10}, $PM_{2.5}$ and other particulate pollutants interception. Microclimate regulation is due to evapotranspiration of vegetation and water bodies. Renewable power generation is the potential power generation services of the offshore ecosystems, comprising wind power generation and tidal power generation. Erosion control services are provided by the coverage of mangroves and salt marshes. Existing services are the local apportionment of global services and human preference-oriented services (Liu and Yang, 2018). Exiting services deal with global climate regulation services mitigating the impact of climate change. Biodiversity conservation services underline the role played by ecosystems in maintaining biodiversity richness. The cultural and education value comprises the esthetic and artistic value, as well as the pluralities of values inspiring and supporting the new knowledge development through scientific research. Despite the importance of this service value, their calculation is not included in our study given the lacks of their systematic definition and of a unified quantitative calculation method. The services provided by various types of marine ecosystems are shown in Table 2.

Table 1
Types and characteristics of coastal ecosystem.

Types	Characteristics
Mangroves	Intertidal swamp wetlands with main vegetation type being mangrove
Salt marshes	Salinized marsh wetlands with perennial water or excessive humidity, vegetation coverage ≥30%
Seagrass beds	Seagrass is a general term for submerged flowering plants that grow in the ocean or in a completely saline environment. Large areas of seagrass are connected to form a seagrass bed, and the vegetation coverage ≥30%
Warm water coral reefs	Aggregation formed by reefs which are accumulated of stony coral remains and calcareous algae as well as benthic organisms and algae living in them, mainly exist in tropical and subtropical oceans
Estuaries	Ecosystems formed at the mouth of a river, whose environmental factors (such as salinity, temperature, nutrient content, etc.) are often fluctuating due to the influence of both tides and rivers
Tidal flats	Including rocky coasts, sandy beaches and muddy beaches, vegetation coverage <30%

2.3. Marine ecosystem service accounting methods

Based on the emergy analysis method, this study establishes a theoretical framework and method for marine ecosystem services evaluation from the perspective of ecosystem contributors, applied to the world's coastal wetlands, in order to provide a certain reference basis and theoretical support for the management, development and protection of the coastal and marine ecosystems. The global emergy baseline (GEB) used in this study is 12.0E+24 seJ/yr (Brown and Ulgiati, 2016) and all the UEVs in this paper have been modified based on this GEB. The calculation process asses flows of services for direct, indirect and existing services through the total coastal ecosystem service value (*TESV*), that is, precisely, the sum of direct service value (Em_{DS}), indirect service value (Em_{IS}) and existing service value (Em_{ES}). The specific calculation formula is as follows:

$$TESV = Em_{DS} + Em_{IS} + Em_{ES} \tag{1}$$

$$Em_{DS} = MAX(Em_{Bio},\ Em_{CS}, Em_{SB}) + Em_{GR} \tag{2}$$

$$Em_{IS} = Em_{WP} + Em_{AP} + Em_{MR} + Em_{EG} + Em_{EC} \tag{3}$$

$$Em_{ES} = Em_{CR} + Em_{BC} \tag{4}$$

Of which, Em_{Bio} is the emergy (sej/yr) required for biomass increase; Em_{CS} is the emergy (sej/yr) required for carbon sequestration; Em_{SB} is the emergy (sej/yr) required for soil/sediment organic matter building; Em_{GR} is the emergy (sej/yr) required for groundwater recharge; Em_{WP} is the emergy (sej/yr) required for water purification; Em_{AP} is the emergy (sej/yr) required for air purification; Em_{MR} is the emergy (sej/yr) required for microclimate regulation; Em_{EG} is the emergy (sej/yr) required for renewable power generation; Em_{EC} is the emergy (sej/yr) required for erosion control; Em_{CR} is the emergy (sej/yr) required for global climate regulation; Em_{BC} is the emergy (sej/yr) required for biodiversity conservation.

Accounting methods for each ecosystem service are detailed in the supplementary material, and the coastal ecosystems evaluation in China enable us to understand the ecosystem services' calculation method clearly (also in the supplementary material).

2.4. Data source description

This study implements GIS (Geographical Information System) to evaluate ecosystems services by acquiring geospatial data. Data on the area covered by mangroves, salt marshes, tidal flats, seagrass beds, warm water coral reefs, and estuaries area are provided by the United Nations Environment Programme World Conservation Monitoring center (UNEP-WCMC) website, which provides the latest available spatial data on the global distribution of various ecosystems.

Data on the mangroves is from Giri et al. (2011): both the Global

Table 2
Types of services included in different marine ecosystems (excluding pelagic ecosystems).

Ecosystem service type	Mangroves	Salt marshes	Tidal flats	Seagrass beds	Coral reefs	Estuaries	Offshore ecosystems
Biomass increase	√	√	√	√	√	√	√
Carbon sequestration	√	√	√	√	√	√	√
Soil/sediment organic matter building	√	√		√		√	
Groundwater recharge	√	√	√			√	
Air purification	√	√				√	√
Water purification	√	√		√		√	√
Erosion control	√	√					
Renewable power generation							√
Microclimate regulation	√	√	√	√	√	√	√
Global climate regulation	√	√	√	√	√	√	√
Biodiversity conservation	√	√	√	√	√	√	√
Cultural and education value	√	√	√	√	√	√	√

Land Survey(GLS) data for 2000 and the Landsat imagery available from the US Geological Survey (USGS) are used to prepare this first global map of the mangrove forests of the world. The GLS 2000 mosaics were prepared using images acquired from 1997 to 2000. Landsat imagery is used if GLS data were cloudy. Secondary data such as national and local mangrove database were also collected.

Data on the salt marshes is from Mcowen et al. (2017) while that on the seagrass beds is from Short et al. (2007): both of the datasets were composed of data derived from peer-reviewed articles and gray literature, including reports and databases created by governmental and non-governmental organizations, universities, institutes and researchers globally. Actually, the dataset as a whole cannot be used for temporal analyses of change due to an incomplete systematic survey of ecosystems' extent globally over time, and they are just the combination of data from different sources. Overall, the survey time span of world's salt marshes is 1973–2015 while that of seagrass beds is 1934–2015, as we showed in Table 3.

The tidal flats data is from Murray et al. (2019): the dataset contains global maps of tidal flat ecosystems produced via a supervised classification of 707,528 Landsat Archive images. The map refers to a set of global training data and divides each pixel into tidal flats, permanent waters or others. The image collection started from 1984 to 2016, consisting of a time-series of 11 global maps, and only the 2014–2016 global extent data can be used directly. Therefore, the time span of tidal flat data is 2014–2016, as we showed in Table 3.

The Warm Water Coral Reef Database provides the global distribution of coral reefs in tropical and subtropical regions. The data set is compiled by UNEP-WCMC, the WorldFish center, World Resources Institute (WRI) and The Nature Conservancy (TNC). Data sources include the Millennium Coral Reef Mapping Project and the World Atlas of Coral Reefs. As in the case of salt marshes and seagrass beds data, this dataset is also a combination of data from different sources, and the survey time span is 1954–2018. Table 4

The estuaries data is provided by the Sea Around Us organization: this data is the 2003 global estuary data, showing the global distribution of more than 1300 estuaries in the world, including some lagoon systems and fjords.

In Table 4, physical data related to solar radiation comes from the Global Solar Atlas provided by the World Bank. The precipitation data comes from the global precipitation data set provided by NOAA. The wind speed data comes from the Global Wind Atlas (Global Wind Atlas) provided by the Technical University of Denmark (DTU). The evapotranspiration data comes from The Global High-Resolution Soil-Water Balance dataset provided by the Consultative Group for International Agricultural Research-Consortium for Spatial Information (CGIAR-CSI); other various coefficients come from relevant literatures (see supplementary material). The emergy transformity data mainly comes from the research results of Brown and Ulgiati (2016; 2018), Odum (1996) and others. The socioeconomic indicators comes from World Bank, Food and Agriculture Organization of the United Nations (FAO), UN ESD Database, and Organization for Economic Co-operation and Development (OECD) Database. The present study considers six kinds of socioeconomic indicators: (1) Seafood production is the sum of Crustaceans, Cephalopods, Demersal fish, Molluscs (other), and Marine fish (other) production(this seafood classification is defined by FAO); (2) Marine protected areas is the proportion of the territorial waters occupied by marine protected areas; (3) GDP is the gross domestic product of the coastal countries; (4) Offshore wind power generation is the wind power capacities of coastal countries; (5) inbound tourism is the number of tourists who travel to a country from a different country; (6) coastal population is population resident within 10 km from the coast.

Table 3
List of geospatial data sources for this study.

Types	Data sources	Data Format	Time span	Resolution/ scale
Mangroves	Giri et al. (2011)	Vectors	1997–2000	30m
Salt marshes	Mcowen et al. (2017)	Vectors	1973–2015	1:10,000
Tidal flats	Murray et al. (2019)	Grids	2014–2016	30m
Estuaries	Sea Around Us	Vectors	2003	–
Warm water coral reefs	UNEP-WCMC, the WorldFish center, WRI, TNC	Vectors	1954–2018	–
Seagrass beds	Short et al. (2007)	Vectors	1934–2015	1:1000,000

Table 4
List of physical data sources for this study.

Types	Data sources	Website
Solar radiation	Global Solar Atlas	https://globalsolaratlas.info/
Wind speed	Global Wind Atlas	https://globalwindatlas.info/
Precipitation	NOAA	https://psl.noaa.gov/data/gridded/tables/precipitation.html
Evapotranspiration	CGIAR-CSI	https://cgiarcsi.community/data/global-high-resolution-soil-water-balance/
Seafood production	FAO	http://www.fao.org/fishery/statistics/global-production/en
Marine protected areas	World Bank	https://datacatalog.worldbank.org/
GDP	World Bank	https://datacatalog.worldbank.org/
Offshore wind power generation	UN ESD Database	http://data.un.org/explorer.aspx
Inbound tourism	World Bank	https://datacatalog.worldbank.org/
Coastal population	OECD Database	https://stats.oecd.org/index.aspx?datasetcode=OCEAN

3. Results

3.1. Global ecosystems renewables input and services output

The emery-based evaluation allows us to evaluate the services provision by each different marine ecosystems. As shown in Fig. 1, the emergy of renewables that drives terrestrial and offshore & pelagic

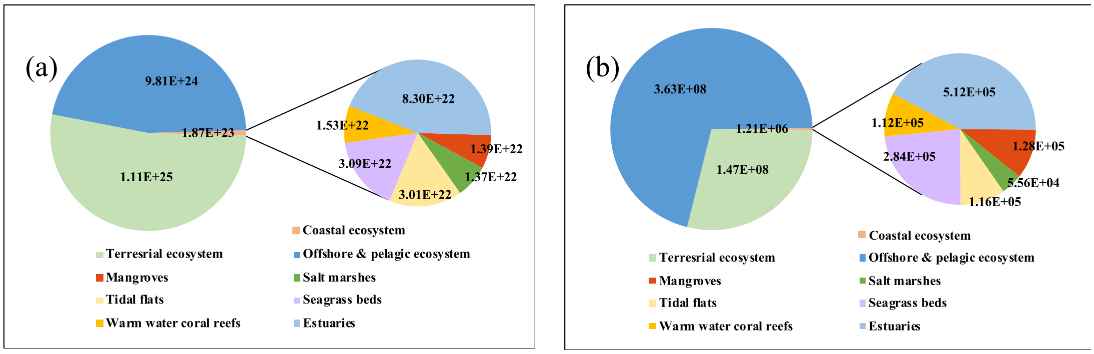

Fig. 1. Global ecosystems (a) renewables input (sej/yr) and (b) ecosystem areas (km^2). Note that the data of terrestrial ecosystem and offshore & pelagic ecosystem's renewable sources and areas is from (Lee and Brown, 2021).

ecosystems accounts for 52.54% and 46.57% of the global renewables respectively, while the emergy of renewables that drives coastal ecosystems only accounts for 0.89% of the global renewables. Among them, estuaries have the largest renewables emergy, which accounts for about 0.39% of the global renewables. The next are seagrass beds, tidal flats, warm water coral reefs, mangroves, and salt marshes, of which the renewables emergy accounts for 0.15%, 0.14%, 0.073%, 0.066%, and 0.065% of the global renewables.

As shown in Fig. 2, results on services provision by different types of coastal ecosystems indicates that estuaries have the highest total ecosystem services, followed by mangroves, seagrass beds, tidal flats, salt marshes, and warm water coral reefs. Besides, estuaries also have the largest local renewables input, while mangroves have the largest net external organic matter input. Considering the components of ecosystem services separately, estuaries have the largest direct services, followed by mangroves, seagrass beds, tidal flats, salt marshes, and warm water coral reefs. To be more specific, estuaries, mangroves, and seagrass beds have greater biomass increase services, while seagrass beds, warm-water coral reefs, and mangroves have greater carbon sequestration services. For soil/sediment organic matter building services, mangroves are the largest contributor, followed by seagrass beds. Estuaries, mangroves, and tidal flats show larger groundwater recharge services. However, for indirect services, estuaries are still the largest, followed by mangroves, salt marshes, seagrass beds, warm-water coral reefs and tidal flats. Among them, mangroves and estuaries play a major role in purifying air and water while mangroves and salt marshes contribute a lot to erosion control. For microclimate regulation services, seagrass beds and estuaries play a greater role. It has to be noted that, warm-water coral reefs play the biggest role in regulating global climate, followed by seagrass beds, estuaries, salt marshes, mangroves, and tidal flats.

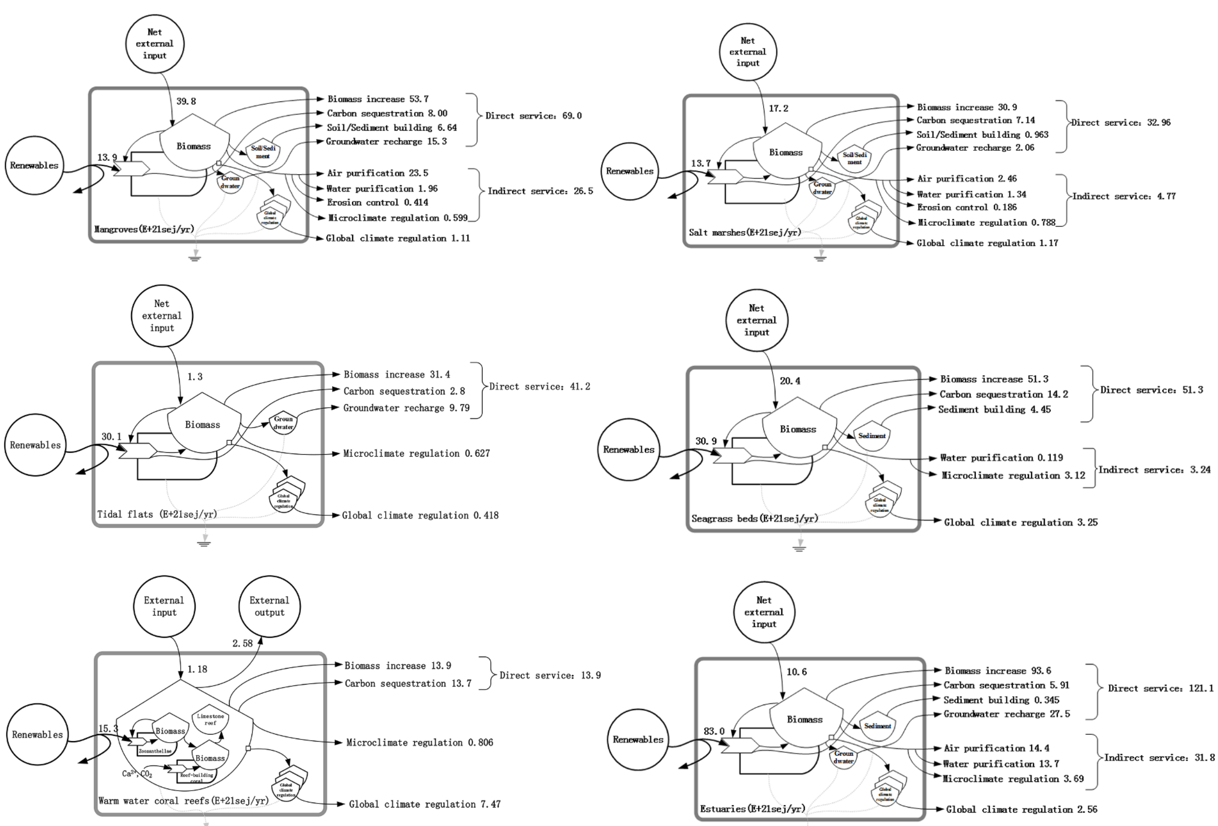

Fig. 2. Different kinds of global coastal ecosystems renewables input and services output.

3.2. Comparison of global coastal ecosystem services

The results show that global coastal ecosystem service value is about 4.13E+23sej/yr. To be more specific, Asia ranks first among all continents with a service value of 1.23E+23sej/yr, which contributes about 29.66% of the world's coastal ecosystem service value. North America ranks second, with a service value of 1.07E+23sej/yr, contributing about 25.82% of the world's coastal ecosystem service value. Next are Europe, Oceania, South America, and Africa, with the service value of 6.07E+22sej/yr, 4.90E+22sej/yr, 3.93E+22sej/yr, 3.50E+22sej/yr, of which the contribution is approximately 14.68%, 11.86%, 9.51%, and 8.48% respectively.

Although global and sub-global estimates of coastal ecosystem service values are important, it is at the national level that these results probably have the bigger utility. Among Asian countries, Indonesia has the largest coastal ecosystem service value, followed by Philippines, China, Bangladesh, India, Japan, Malaysia, Myanmar, Saudi Arabia, and Yemen. Among North American countries, Canada ranks first and the United States ranks second, followed by Mexico, Cuba, Panama, Nicaragua, Belize, Honduras, Haiti, and Jamaica. Comparing the coastal ecosystem service value in South American countries, Brazil ranks first, followed by Venezuela, Colombia, Chile, Ecuador, Argentina, Suriname, Uruguay, and Costa Rica. Among European countries, the coastal ecosystem service value of the Russian Federation is the largest, while Norway, Greece, the United Kingdom, Italy, Denmark, France, Ukraine, Spain, and Sweden rank second to tenth respectively. For African countries, Nigeria ranks first, followed by Guinea-Bissau, Guinea, Madagascar, Egypt, Mozambique, Cameroon, Gabon, Sierra Leone, and Angola. For Oceanian countries, Australia has the largest coastal ecosystem service value, followed by Papua New Guinea and New Zealand.

The coastal ecosystem service value in various countries worldwide shows that Canada has the largest service value of 5.77E+22sej/yr, while Indonesia, Australia, the United States, Brazil, the Russian Federation, Norway, Philippines, Mexico, and China rank second to tenth respectively, with the service value of 4.47E+22sej/yr, 3.77E+22sej/yr, 2.68E+22sej/yr, 1.98E+22sej/yr, 1.47E+22sej/yr, 1.39E+22sej/yr, 1.32E+22sej/yr, 9.93E+21sej/yr, 8.37E+21sej/yr. Indeed, the top 10 coastal countries contribute approximately 60% of the world's coastal ecosystem service values, and the top 26 countries just over 80%.

3.3. Correlation analysis of coastal ecosystem services and indicators

In order to explore the relationship between ecosystem services and some socioeconomic indicators (especially in coastal field), this study implements at country level the scatter plot of the ranking of coastal ecosystem service and the ranking of the key indicators, performs linear fitting, and analyzes the top 20 countries in both services and key indicators levels. The red dots represent the best top 20 countries in terms of both services and socio- economic indicators performances. The blue dots represent the countries that rank in the best top 20 in terms of ecosystem services provision while the socioeconomic indicators rank below the top 20. The green dots represent the top 20 countries in terms of socioeconomic indicators, while the services rank below 20 (see Fig. 3). Fig. 3

From Fig. 4(a), it can be found that for South Korea (KOR), Morocco (MAR), Peru (PER), Pakistan (PAK), etc., the coastal ecosystem service is relatively small, but a large number of people have gathered in the coastal area, which may bring greater pressure to the coastal environment to some extent. However, for Papua New Guinea (PNG), Norway (NOR), Cuba (CUB), Greece (GRC), etc., the situation is the opposite, which means that these countries have large coastal ecosystem service provision, while the coastal population is still small, indicating that there is a potential carrying capacity for increasing inhabitants in the coastal areas. For countries such as China (CHN), India (IND), Japan (JPN), and the United States (USA), etc., the coastal population is roughly positively correlated with the coastal ecosystem service

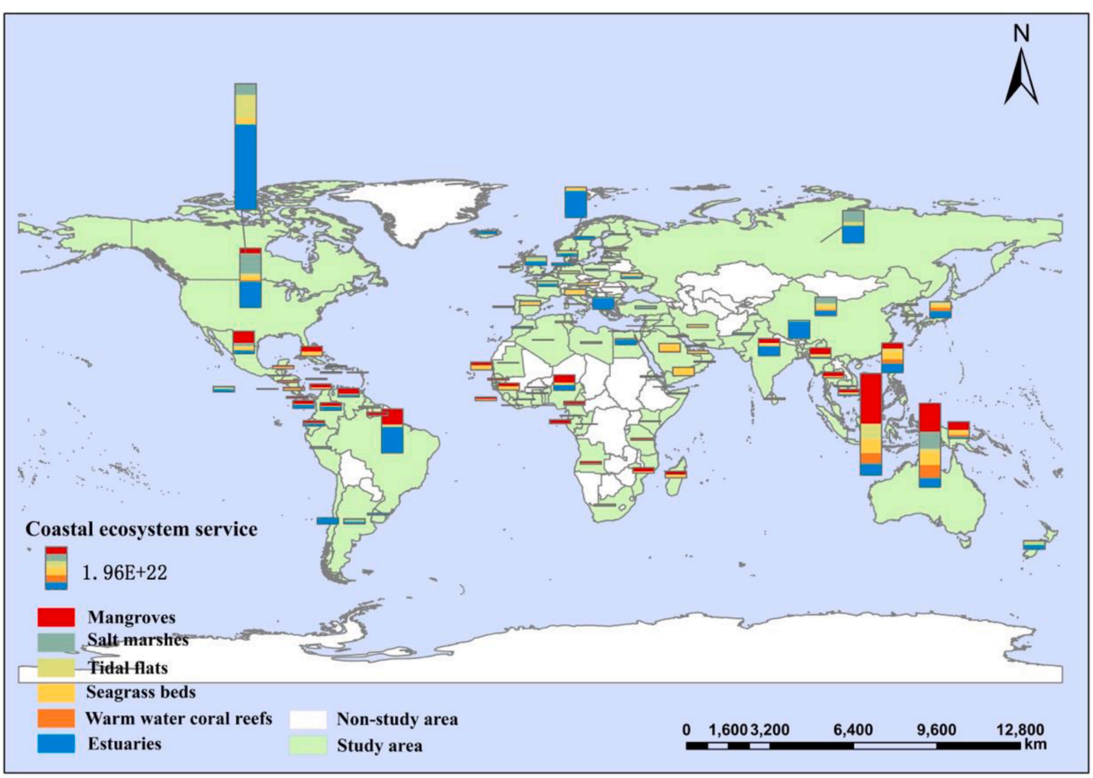

Fig. 3. Global coastal ecosystem services distribution (sej/yr). Note that some coastal states such as Greenland, Western Sahara, Namibia, etc., are not included in the study due to the lack of data.

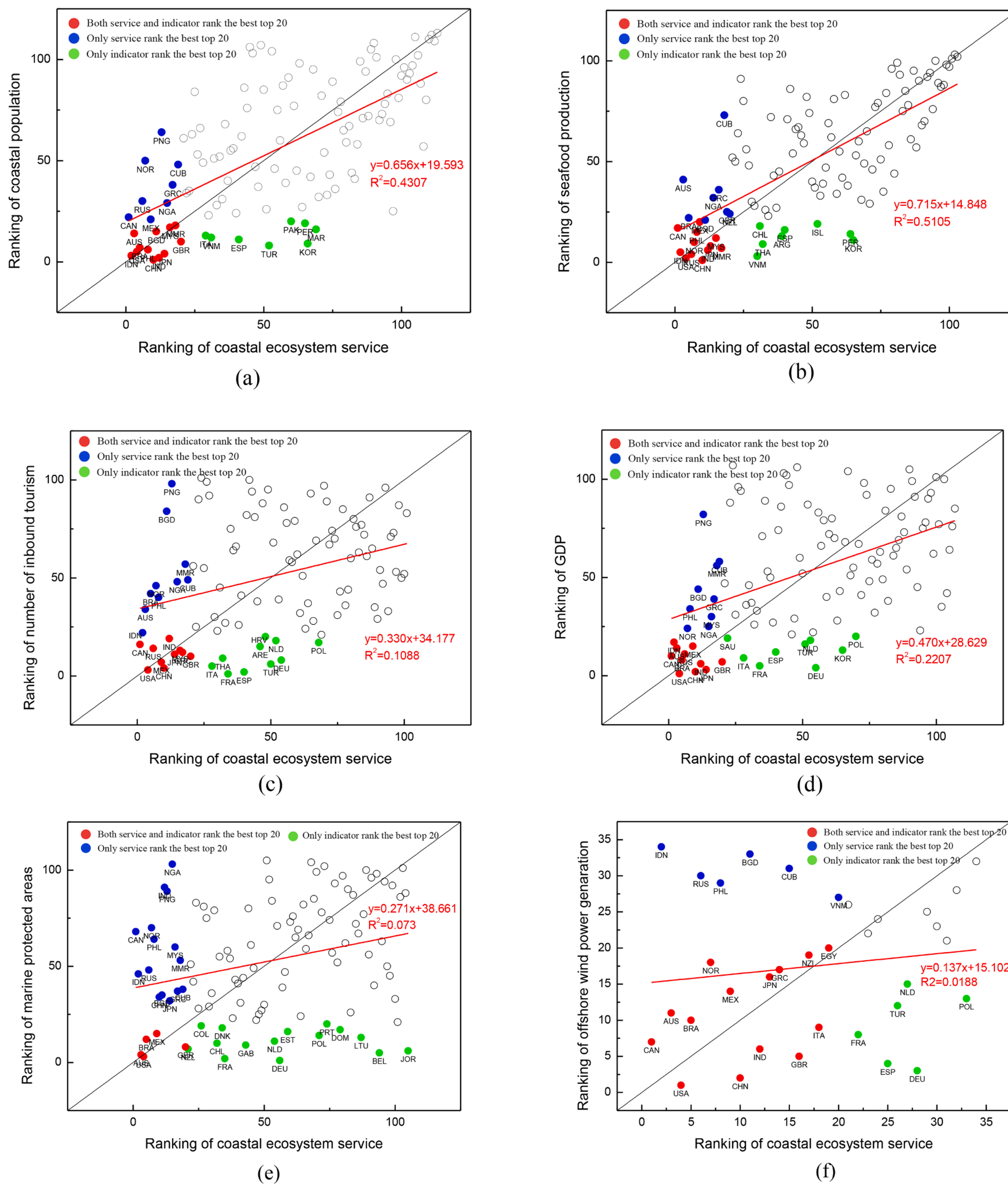

Fig. 4. The scatter plot of the ranking of coastal ecosystem service and the ranking of (a) Coastal population; (b) Seafood production; (c) Number of inbound tourism; (d) GDP; (e) marine protected areas (% of territorial waters); (f) offshore wind power generation. Note that countries are represented by ISO3 code.

provision, meaning that these countries have fully exploited the coastal area in terms of resident population without too much environmental load to the coastal area.

As shown in Fig. 4(b), for countries such as South Korea (KOR), Peru (PER), Iceland (ISL), and Spain (ESP), etc., although their coastal ecosystem services rank below 20, have fully utilized one of the most basic services of the ocean-seafood production services. In fact, the seafood catchments of these countries rank among the top 25 in the world. Countries such as Australia (AUS), Cuba (CUB), Greece (GRC), Nigeria (NGA), etc., have a higher rank of the coastal ecosystem services, while their seafood production ranks lower. China (CHN), the United States (USA), Russia (RUS), and Indonesia (IDN), etc., show both the coastal ecosystem service and the seafood production among the highest in the world.

Fig. 4(c) shows that countries such as Poland (POL), Croatia (HRV), the Netherlands (NLD), and Germany (DEU), although ranked below 20 for the coastal ecosystem service, have made full use of the tourism and leisure functions of the coastal areas, attracting a large number of foreign tourists. It has to be underlined that these countries are all European developed countries. However, for Papua New Guinea (PNG), Bangladesh (BGD), Myanmar (MMR), Cuba (CUB), etc., the situation is the opposite, accounting for a small number of tourists. In the United

States (USA), China (CHN), Mexico (MEX), the United Kingdom (GBR), coastal areas have played an important role in attracting international tourism and the coastal ecosystem services provision is relatively high. The Travel and Tourism Competitiveness Index (TTCI) (Calderwood and Soshkin, 2019) of these countries can help in explaining this situation. The index consists of three sub-indicators, namely human, cultural & natural resources, business environment & infrastructure, and regulatory framework. For countries corresponding to the green points, their TTCI rankings are among the top in the world, indicating that although these countries are not rich in coastal natural resources, their coastal tourism business environment & infrastructure and policies & regulations are well developed, and a safe and healthy tourism environment ensure competitiveness to such regions. For most countries represented by the blue dots, the TTCI ranks at the bottom of the world, meaning that although these countries have relatively rich coastal natural resources, their backward infrastructure, imperfect business environment & regulatory framework, and poor social security situations have hindered the development of the tourism sector.

As shown in Fig. 4(d), countries such as Poland (POL), Germany (DEU), Netherlands (NLD), South Korea (KOR), etc., with coastal ecosystem services ranked below 20, have a fully developed marine economy, enhancing domestic economic growth. According to The EU blue economy report 2019, the contribution of the Blue Economy Gross Value Added of EU countries to the Gross Value Added (GVA) in 2017 was: Poland (0.8%), Germany (0.8%), Netherlands (1.6%), while the contribution of South Korea's marine economy to its GDP growth in 2008 was 4.9% (Hwang, 2011). However, in countries such as Papua New Guinea (PNG), Cuba (CUB), Myanmar (MMR), and Bangladesh (BGD), etc., the coastal ecosystem services rank relatively high while their GDP ranks relatively low. Therefore, these countries should try to promote the development of the marine economy to stimulate domestic economic growth, making full use of coastal resources and vigorously developing marine industries. The United States (USA), China (CHN), Japan (JPN), the United Kingdom (GBR), etc. have made full use of the abundant domestic coastal resources to promote their national economic growth.

Fig. 4(e) shows that European and American countries such as Germany (DEU), France (FRA), Belgium (BEL), New Zealand (NZL), etc., are ranked below 20 for their coastal ecosystem service, even if their marine protected areas accounts for a large proportion of the territorial waters. The results indicate that awareness toward marine ecosystem protection is higher in those countries affected by ecosystem degradation and lower ecosystem service. However, in many Asian countries such as Japan (JPN), China (CHN), Bangladesh (BGD), Indonesia (IDN), etc., while having a greater coastal ecosystem service, the construction of marine protected areas has not received much attention. The cluster of countries including United States (USA), Australia (AUS), the United Kingdom (GBR), Brazil (BRA), Mexico (MEX), etc., not only has a large coastal ecosystem service, but also attaches great importance to the construction of marine protected areas. To sum up, European and American countries are more aware of marine protection and are in the forefront of the construction of marine protected areas. However, for most Asian, African, and Oceanian countries, their marine protection awareness still needs for improvement.

In relation to wind generation, as shown in Fig. 4(f), some European countries such as Germany (DEU), Spain (ESP), France (FRA), Turkey (TUR), etc., with coastal ecosystem service ranked below 20, have fully utilized the potential of offshore wind power generation. However, Indonesia (IDN), Bangladesh (BGD), the Russian Federation (RUS), Philippines (PHL), show an opposite situation. United States (USA), China (CHN), the United Kingdom (GBR), India (IND), etc., despite a greater coastal ecosystem service, they fully develop and utilize offshore wind resources. Generally speaking, European and American countries have a competitive advantage in the international market of offshore wind power generation for their advanced technology and economic strength, while the vast number of Asian, African, and Oceanian countries still have great unexplored potential in offshore wind power generation. Therefore, the experience of those countries that are at the forefront of offshore wind power generation is worth learning. The development of offshore wind power in the United Kingdom, Germany, the United States have some common features. Firstly, those countries attach great importance to the development of the offshore wind power industry, and some countries have listed it into the national strategy. They strongly support the development of new technologies and the research efforts on large-scale offshore wind power networking. Secondly, they actively promote the international cooperation plan for offshore wind power, and accelerate the strategic pace of the country's offshore wind power development. Finally, they vigorously seek to reduce the cost of offshore wind power. These experiences have enlightenment and reference significance for other countries to promote the full use of marine resources and the development of offshore wind power.

4. Discussion

4.1. Spatial variability of marine ecosystem services

Townsend et al. (2018) pointed out that due to the unique characteristics of marine ecosystems, the assignment of ecosystem services to specific map grids has become complicated. For marine ecosystems, sea water and components can be driven to other places by wind, tides and currents. Even for the relatively static submarine habitat, the movement of seawater over it and the transportation of carbon, oxygen, nutrients and pollutants also increase the complexity to the quantification and space allocation of marine ecosystem services. In addition, identifying and protecting areas where ecosystem services are provided does not necessarily ensure provision of those services over the time. Failure to integrate important processes and locations in service generation, the so-called "intermediate" services, may result in a loss of the "final" services generation (Haines-Young and Potschin-Young, 2018). For example, if spawning grounds and nurseries are not protected, the protection of fishing grounds alone may not be sufficient for the ecosystem service provision conservation. According to Börger et al. (2014), not all marine ecosystem services are location-specific. For example, although coral reefs are fixed in space, many marine resources, such as fish and mammal species and the ecosystem components which support them, such as plankton can move in different seasons and different regions. Therefore, some marine ecosystem services are not limited to single country, which means that people in one country can benefit from the services provided by other countries. This is an important factor for integrating the marine planning and policies of different country and needs to be further considered in subsequent studies.

4.2. Trade-off and synergy between different types of marine ecosystem services

Due to the diversity of marine ecosystem services, the heterogeneity of spatial distribution, and the selectivity of human use, there is a trade-off or synergy relationship between ecosystem services (Li et al., 2013). The trade-off relationship refers to the situation in which the supply of certain ecosystem services decreases due to the increase in the use of other ecosystem services (Rodríguez et al., 2006). The damage to marine biodiversity caused by excessive pursuit of seafood production services and the loss of biological habitat caused by the disorderly development of coastal tourism. The synergy relationship refers to a situation where two or more ecosystem services are enhanced at the same time (Li et al., 2013). For example, mangroves and seagrass beds are breeding and nursery grounds for some marine fisheries, and their existence greatly increases the organisms of coral reef fish communities. Mangroves and seagrass beds can absorb waste discharged into the ocean and serve as sinks of pollutants, sediments and other organic materials. This pollution and sediment control service can protect coral reefs and maintain their services. Coral reefs can protect coastal habitats by buffering waves and currents and slowing down periodic storm surges, thereby supporting the ability of seagrass beds and mangroves to attenuate waves and buffer winds (Barbier, 2017). Therefore, clarifying the trade-offs and synergies between different types of marine ecosystem services is crucial both in the calculation and evaluation of ecosystem services and in the policy design and needs to be included in future researches.

5. Conclusion

This research establishes a coastal ecosystem service evaluation framework and accounting method from the perspective of ecosystem contributors, and calculates the world's coastal ecosystem services. The results show that the total service value of coastal ecosystem in the world is about 4.13E+23sej/yr. To be more specific, Asia ranks first among all continents, and North America ranks second, followed by Europe, Oceania, South America, Africa. The top ten countries in terms of total coastal ecosystem services in the world are Canada, Indonesia, Australia, the United States, Brazil, the Russian Federation, Norway, Philippines, Mexico, and China. Among all types of coastal ecosystems, estuaries have the highest service value, followed by mangroves, seagrass beds, tidal flats, salt marshes, and warm water coral reefs. Furthermore, the scatter plots of the ranking of the coastal ecosystem service and of various indicators in different countries show that developed countries perform a better use of coastal resources and fully develop the coastal areas in terms of population carrying, seafood production, coastal tourism development, offshore wind power generation and blue economy promotion. Besides, they pay more attention to the marine protection. However, the vast number of developing countries may not make full use of their rich coastal resources, or only pay attention to the coastal resources usage but ignore the marine protection. Therefore, developed countries still occupy an advantageous position in the process of marine ecosystems protection, development and utilization.

Based on emergy analysis, this research provides an innovative method for calculating the coastal ecosystem services, which is different from the traditional monetary analysis. However, there are also some limitations in this study. Due to the lack of basic data and insufficient research on the ecological processes and operating mechanisms of some services, the coastal ecosystem service in some countries such as Singapore, Greenland, Namibia etc. and the value of specific services such as biodiversity conservation and cultural and education value have not been calculated. This may result in an underestimation of the global coastal ecosystem services. In addition, this study only calculates coastal ecosystem services involving only about 0.24% of the global area. Therefore, the offshore and pelagic ecosystem services of which the area accounts for approximately 70% of the global area needs further consideration. Due to the lack of global data on the dynamic changes of coastal wetlands on the time scale, only the multi-year average ecosystem service value is calculated, which may also lead to the deviation of accounting results to the real situation. What's more, the spatial variability of marine ecosystem services and the trade-off and synergy between different types of services need to be further investigated. Finally, dis-services such as storm surges, tsunamis, seawater intrusion, coastal ground subsidence, and marine oil spills should also be considered in the future if data becomes available.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (No. 52070021), special fund of State Key Joint Laboratory of Environment Simulation and Pollution Control (No. 21K01ESPCW) and the 111 Project (No. B17005).

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.watres.2021.117656.

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ARTICLES FOR FACULTY MEMBERS

MANGROVE RESTORATION TOWARDS SUSTAINABLE COASTAL ECOSYSTEM MANAGEMENT

Title/Author	**Mangroves as coastal bio-shield: A review of mangroves performance in wave attenuation / Kamil, E. A., Takaijudin, H., & Hashim, A. M.**
Source	***Civil Engineering Journal (Iran)*** **Volume 7 Issue 11 (2021)Pages 1964–1981** **https://doi.org/10.28991/cej-2021-03091772** **(Database: Civile Journal)**

Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 7, No. 11, November, 2021

Review Article

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

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Received 09 August 2021; Revised 13 October 2021; Accepted 22 October 2021; Published 01 November 2021

Abstract

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

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

1. Introduction

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

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http://dx.doi.org/10.28991/cej-2021-03091772

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

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

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

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

2. Research Methodology

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

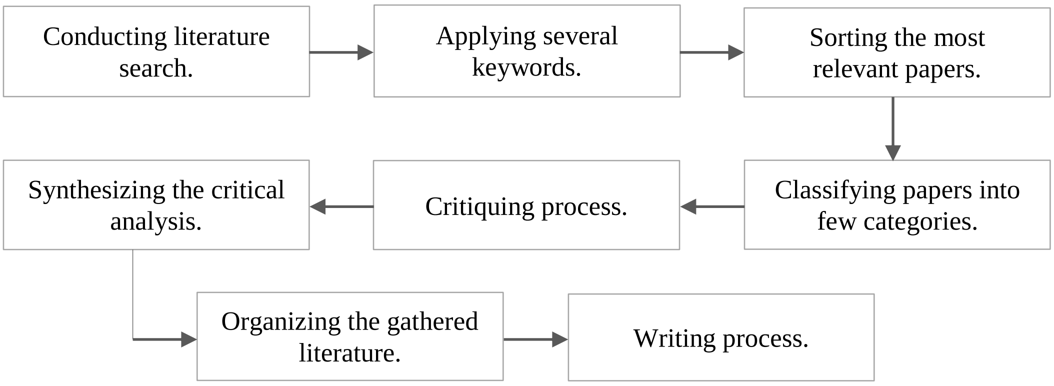

Figure 1. Research flowchart

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

3. Wave Dissipation by Mangroves

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

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

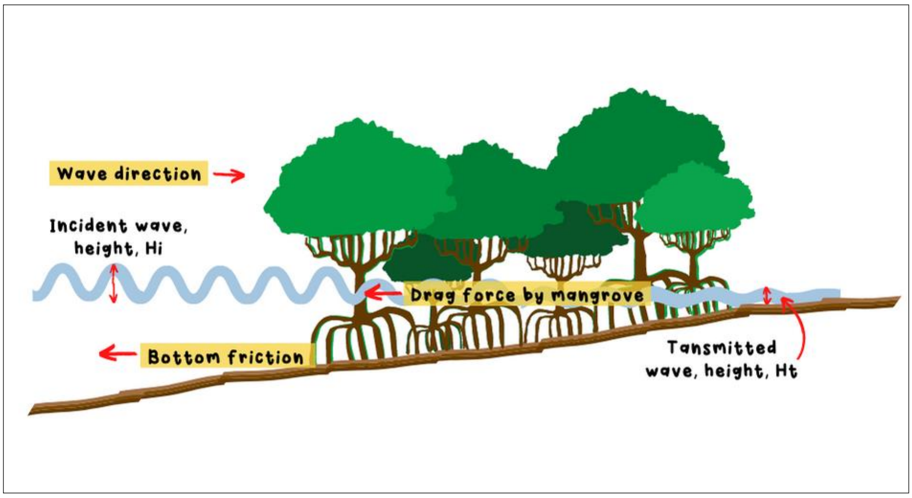

Figure 2. Wave attenuation by mangroves

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

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

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

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

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

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

4. Factors Governing Mangroves Performance in Dissipating Wave

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

4.1. Width

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

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

4.2. Species

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

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

4.3. Structure

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

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

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

4.4. Density

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

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

4.5. Age

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

4.6. Bathymetry

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

4.7. Water Depth

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

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

4.8. Incident Wave Height

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

5. Mangroves Dissipation Performance

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

5.1. Laboratory Experiments

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

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

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

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

5.2. Numerical Modeling

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

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

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

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

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

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

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

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

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

5.3. Field Studies

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

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

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

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

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

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

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

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

6. Effectiveness of Mangroves in Wave Dissipation

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

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

Table 1. Dissipation Effectiveness of Different Mangrove Species and Characteristics

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

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

7. Mangroves Rehabilitation and Conservation Efforts in Malaysia

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

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

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

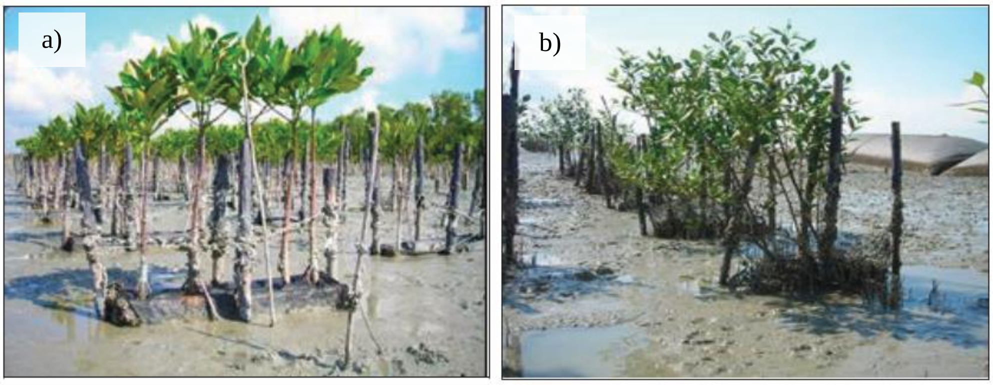

Figure 3. a) Comp-Matt technique for *Rhizophora apiculata* planting, b) Comp-Pillow technique for *Avicennia alba* planting [88]

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

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

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

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

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

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

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

8. Implementations of Mangroves as Coastal Bio-shield

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

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

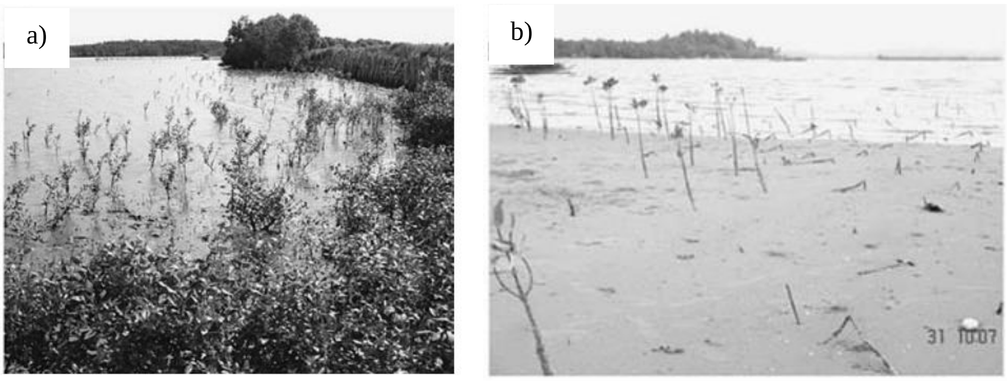

Figure 4. Colonization of a) *Avicennia marina* species, b) *Rhizophora* species at the similar habitat [99]

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

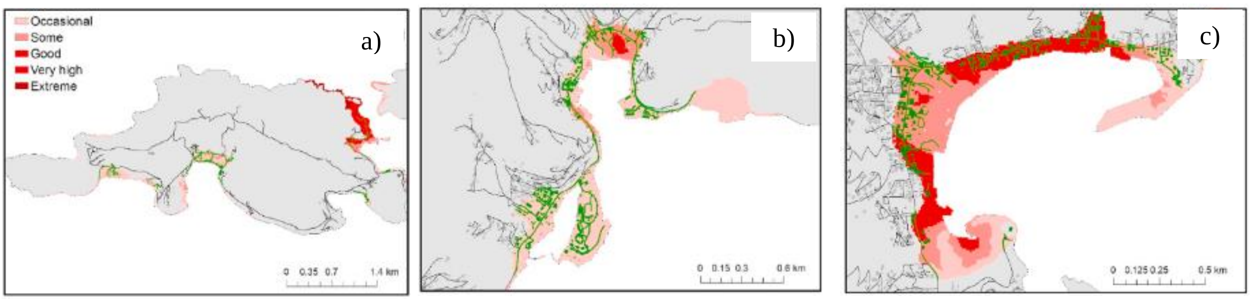

Figure 5. Level of protection as indicated by pink-red shades in coastal areas of (a) Jost Van Dyke, (b) Sea Cows Bay, and (c) East End [103]

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

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

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

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

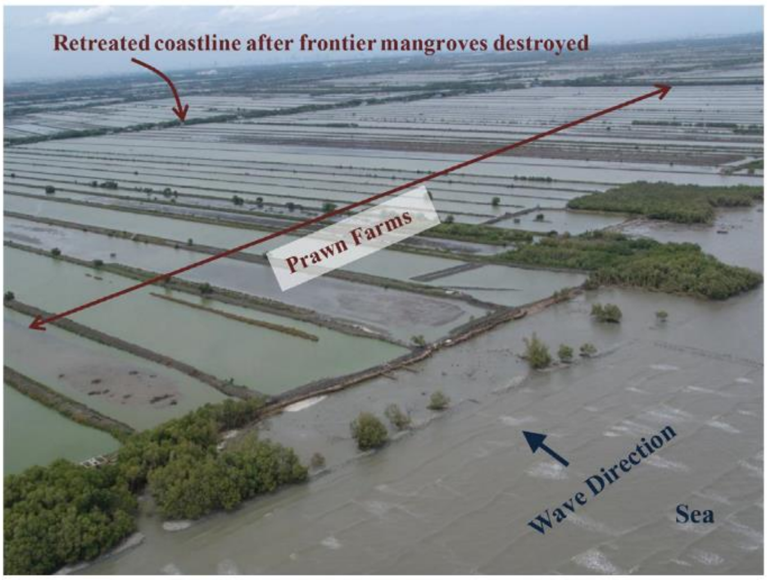

Figure 6. Conversion of previously planted mangroves area into shrimp ponding [29]

9. Conclusions

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

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

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

10. Declarations

10.1. Author Contributions

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

10.2. Data Availability Statement

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

10.3. Funding

This research is funded by Fundamental Research Grant Scheme (FRGS), FRGS/1/2010/TK01/UTP/02/7, Ministry of Higher Education Malaysia.

10.4. Acknowledgements

The authors would like to express their sincere gratitude to the Fundamental Research Grant Scheme (FRGS), FRGS/1/2010/TK01/UTP/02/7, Ministry of Higher Education Malaysia for funding this research paper. The authors would also like to thank the Centre for Graduate Studies and the Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS for their support and encouragement.

10.5. Conflicts of Interest

The authors declare no conflict of interest.

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ARTICLES FOR FACULTY MEMBERS

MANGROVE RESTORATION TOWARDS SUSTAINABLE COASTAL ECOSYSTEM MANAGEMENT

Title/Author	**Mangrove health: A review of functions, threats, and challenges associated with mangrove management practices / Akram, H., Hussain, S., Mazumdar, P., Chua, K. O., Butt, T. E., & Harikrishna, J. A.**
Source	***Forests*** **Volume 14 Issue 9 (2023)Pages 1-38** **https://doi.org/10.3390/f14091698** **(Database: MDPI)**

forests

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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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Citation: Akram, H.; Hussain, S.; Mazumdar, P.; Chua, K.O.; Butt, T.E.; Harikrishna, J.A. Mangrove Health: A Review of Functions, Threats, and Challenges Associated with Mangrove Management Practices. *Forests* **2023**, *14*, 1698. https://doi.org/10.3390/f14091698

Academic Editor: Bradley B. Walters

Received: 30 May 2023
Revised: 12 July 2023
Accepted: 17 July 2023
Published: 23 August 2023

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].

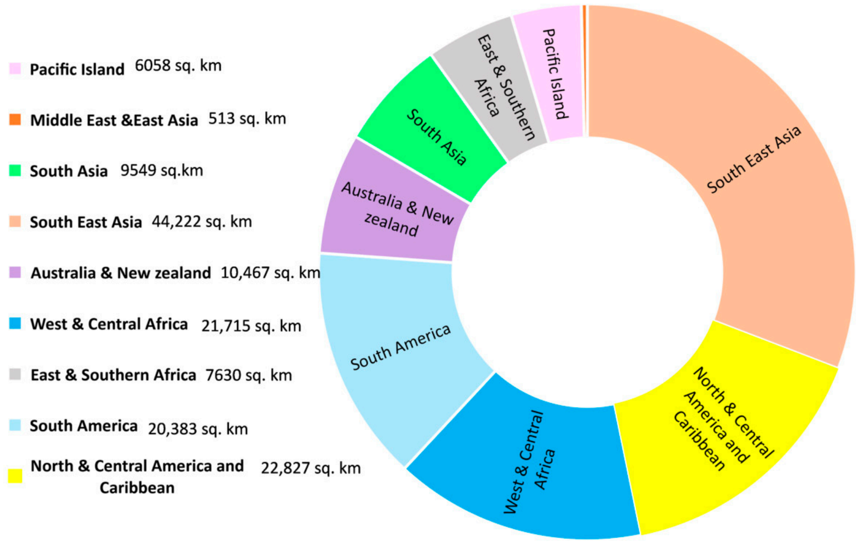

Figure 1. Percentage cover of mangrove forests in different parts of the world. (Data sourced from GMW, 2022).

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].

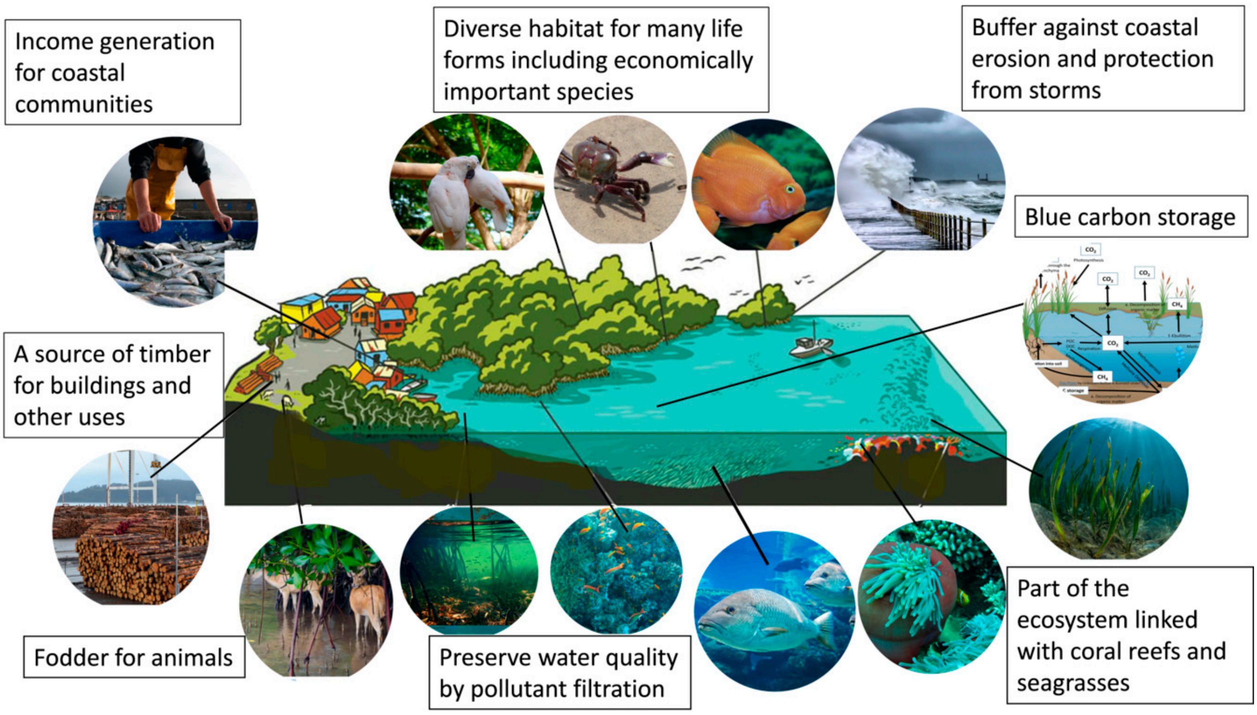

Figure 2. Functions and services of an intact mangrove ecosystem.

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.

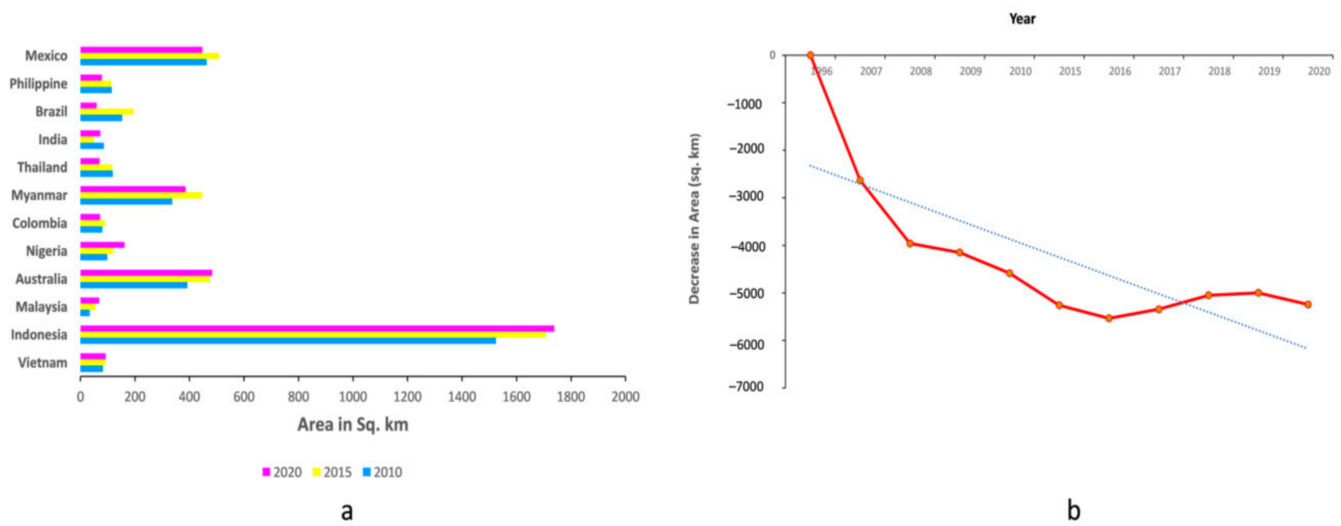

Figure 4. (**a**) Mangrove loss in different countries from 2010 to 2020; (**b**) global net mangrove area changes from 1996 to 2020. Red line represents the change in mangrove area in different years from 1996 to 2020, while blue dotted line reflects the trend of change in area, which is towards overall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

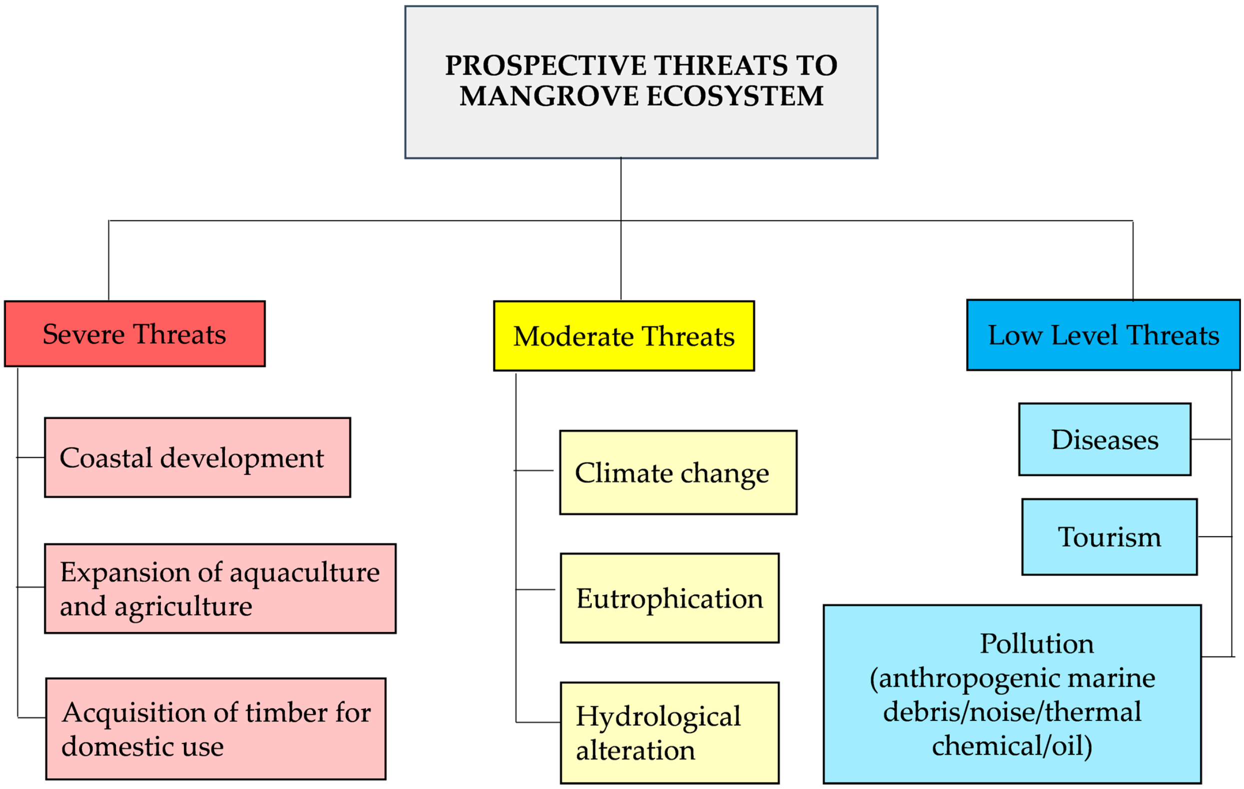

Figure 5. Prospective threats to mangrove ecosystem. (Adapted from D. Algoni, 2002 [209]).

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

Country	Total Species	Critically Endangered (CR)	Endangered (EN)	Vulnerable (VU)	Near Threatened (NT)	Data Deficient (DD)	Least Concern from All (LC)
Indonesia	47	*Sonneratia griffithii* *Bruguiera hainesii*	*Camptostemon philippinense* *Heritiera globose*	*Avicennia rumphiana*	*Aegialitis rotundifolia* *Aegiceras floridum* *Sonneratia ovata*	*Aglaia cucullata* *Excoecaria indica*	*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*
Malaysia	40	*Bruguiera hainesii* *Sonneratia griffithii*	*Heritiera fomes* *Heritiera globose*	*Avicennia rumphiana*	*Aegiceras floridum* *Ceriops decandra* *Sonneratia ovata*	*Aglaia cucullata* *Excoecaria indica*	
India	37	*Sonneratia griffithii*	*Heritiera fomes*		*Aegialitis rotundifolia* *Ceriops decandra*	*Aglaia cucullata* *Excoecaria indica*	
Myanmar	36	*Sonneratia griffithii*	*Heritiera fomes*		*Aegialitis rotundifolia* *Ceriops decandra*	*Aglaia cucullata* *Excoecaria indica*	
Thailand	35	*Sonneratia griffithii*	*Heritiera fomes*		*Aegialitis rotundifolia* *Ceriops decandra* *Sonneratia ovata*	*Aglaia cucullate*	
Australia	35			*Avicennia integra*	*Sonneratia ovata*		
Philippines	34		*Camptostemon philippinense*	*Avicennia rumphiana*	*Aegiceras floridum* *Sonneratia ovata*	*Aglaia cucullate*	
Vietnam	33				*Aegiceras floridum* *Sonneratia ovata*		
Colombia	12			*Avicennia bicolor* *Mora oleifera* *Pelliciera rhizophorae* *Tabebuia palustris*	*Rhizophora samoensis*		
Nigeria	7						

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.

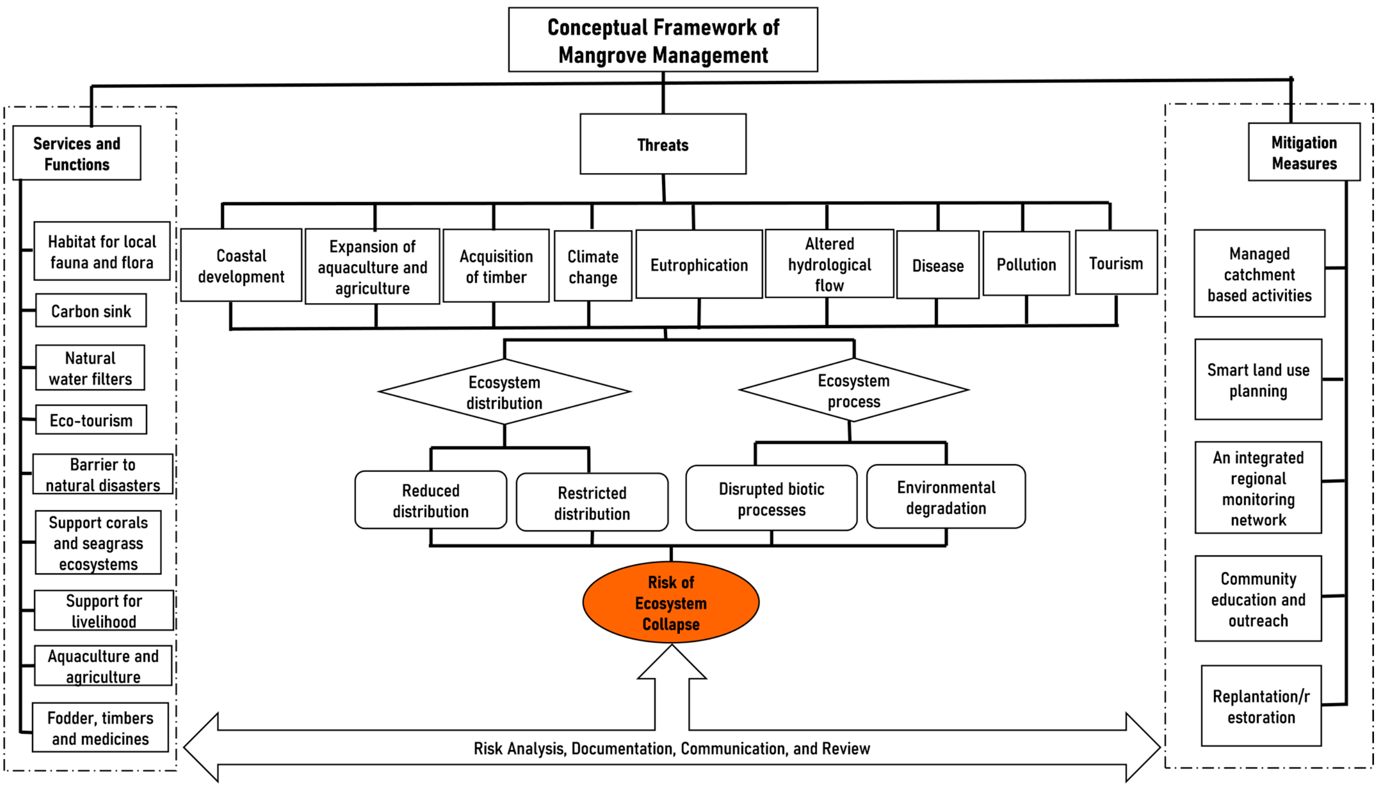

Figure 7. A conceptual framework of mangrove management.

Author Contributions: Conceptualization, J.A.H.; methodology, H.A., S.H. and P.M.; software, H.A. and K.O.C.; validation, H.A., P.M. and K.O.C.; formal analysis, H.A., S.H. and T.E.B.; investigation, H.A. and S.H.; resources, J.A.H.; data curation, H.A., P.M. and K.O.C.; writing—original draft preparation, H.A., S.H. and T.E.B.; writing—review and editing, P.M., K.O.C. and J.A.H.; visualization, H.A.; supervision, J.A.H. and P.M.; project administration, J.A.H.; funding acquisition, J.A.H. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Innovate at University of Malaya Research Grant Programme (PPSI-2020-HICOE-06).

Data Availability Statement: No new data were created for this study and all sources of data used in the review have been referenced.

Conflicts of Interest: The authors declare no conflict of interest.

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ARTICLES FOR FACULTY MEMBERS

MANGROVE RESTORATION TOWARDS SUSTAINABLE COASTAL ECOSYSTEM MANAGEMENT

Title/Author	**Mangroves in environmental engineering: Harnessing the multifunctional potential of nature's coastal architects for sustainable ecosystem management / K, A., Parveen K, H., V K, S., P, B., Muhammed, J., & Augustine, A.**
Source	***Results in Engineering*** **Volume 21 (2024) 101765 Pages 1-17** **https://doi.org/10.1016/j.rineng.2024.101765** **(Database: Science Direct)**

Results in Engineering 21 (2024) 101765

Contents lists available at ScienceDirect

Results in Engineering

journal homepage: www.sciencedirect.com/journal/results-in-engineering

Mangroves in environmental engineering: Harnessing the multifunctional potential of nature's coastal architects for sustainable ecosystem management

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ARTICLE INFO

Keywords:
Mangroves
Coastal protection
Carbon sequestration
Environmental engineering
Phytoremediation

ABSTRACT

Mangroves, the distinctive coastal ecosystems of the tropics and sub-tropics, serve as crucial intersections between terrestrial and marine environments. In this review, we delve into the manifold roles of mangroves, showcasing their significance in environmental engineering and sustainable ecosystem practices. Historically undervalued, mangroves have undergone a renaissance in perception, with increasing recognition of their indispensable ecological services, ranging from coastal protection and blue carbon sequestration to fostering biodiversity and supporting sustainable fisheries. As we explore their potential in phytoremediation, bioremediation, urban resilience, and ecosystem-based adaptation, the synergistic relationships between mangroves and their resident microorganisms are highlighted, offering innovative avenues for environmental restoration. Additionally, the review underscores the importance of collaborative partnerships for mangrove conservation, emphasizing the need for a harmonized approach between stakeholders. In an era marked by rapid environmental changes, this review accentuates the multifunctional capability of mangroves as nature's coastal architects, advocating for their conservation and integration into sustainable ecosystem management strategies.

1. Introduction

Mangroves, salt-tolerant forest ecosystems predominantly situated in tropical and sub-tropical intertidal regions, have long been subject to a shifting perception in the eyes of society. Up until the 1960s, these unique coastal habitats were often considered "economically unproductive areas" and, consequently, were systematically destroyed to make way for various economic endeavours. However, over time, a profound understanding of their economic and ecological significance has emerged, reshaping the way we perceive and value mangroves. These remarkable ecosystems have historically occupied a substantial 75 % of the world's tropical coastlines [1]. Yet, anthropogenic pressures and land development have encroached upon these vital ecosystems, reducing their global coverage to less than half of their original extent. Estimates suggest that mangrove cover dwindled from 18.8 million hectares in 1980 to less than 15 million hectares at present [2,3]. Despite their relatively small aerial coverage compared to other tropical forests, mangroves wield an outsized ecological influence due to their unique position at the interface between terrestrial and marine systems.

Mangroves play a multifaceted and indispensable role in supporting a multitude of ecosystem services. They contribute to soil formation, harness the power of photosynthesis for primary production, facilitate nutrient cycling, and regulate water movement within coastal regions. Beyond these ecological services, they serve as a vital source of natural products, providing proteins, tannins, and timbers to local communities. Additionally, mangroves actively participate in regulating crucial ecosystem processes, including biological control, nutrient cycling, air quality maintenance, and the preservation of biodiversity. In recent decades, there has been a growing appreciation for the value of mangrove wetlands. However, this newfound recognition has come hand in hand with an alarming realization of the magnitude of human interactions with these ecosystems [4–6]. The rapid expansion of human populations, coupled with an insatiable demand for mangrove resources, has led to overexploitation and ecosystem degradation on an unprecedented scale.

This review on environmental engineering harnessing the potential of mangroves will delve into the multifaceted world of these remarkable coastal ecosystems. It will explore the intricate balance between their

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https://doi.org/10.1016/j.rineng.2024.101765
Received 3 October 2023; Received in revised form 5 January 2024; Accepted 5 January 2024
Available online 7 January 2024

ecological significance and the pressing need for sustainable management in the face of increasing human pressures. In this review we explore the ecological services provided by mangroves, encompassing coastal protection, climate mitigation, biodiversity in mangrove habitats, mangroves' role in phytoremediation and bioremediation, their contribution to urban ecosystems and resilience, as well as potential threats faced by mangroves and the corresponding conservation and restoration strategies.

2. Ecological services of mangroves: foundations for environmental engineering

Within the realm of environmental engineering, the dynamic and resilient nature of mangroves has emerged as a topic of profound significance. These coastal ecosystems, found in tropical and subtropical regions worldwide, are both unique and highly productive [7]. Mangrove ecosystems are essential coastal environments situated in the transition zones between freshwater, saltwater, and terrestrial habitats [8]. The formation of mangrove ecosystems is characterized by distinct "zones" of tree species arranged in vertical patterns along the coastlines or riverbanks. Additionally, mangrove habitats are porous structures that facilitate the exchange of both matter and energy with offshore coastal ecosystems and terrestrial areas farther inland [9]. They provide a wide range of ecological services that are having ecological, direct and indirect utility values are foundational to environmental engineering and coastal management (Fig. 1). The value of their environmental contributions, assessed to range from several thousands to multiple tens of thousands of USD per hectare, makes them a focal point for governments and impact investors aiming to achieve both environmental and socioeconomic objectives [10].

2.1. Coastal protection and erosion control

Globally coastal communities have encountered substantial challenges in recent decades. Notably, the Indian Ocean Tsunami in 2004 left behind extensive destruction [11], followed by Hurricane Katrina's catastrophic effects on the Gulf of Mexico coast in 2005 [12,13], as well as Typhoon Haiyan's significant destruction in the Philippines and Southeast Asia in 2013. Moreover, in affluent nations, a significant concern centers on the depletion and conversion of mangrove areas to make way for industrial and residential expansion. In developing countries, this issue is increasingly gaining importance. The primary forms of conversion involve the establishment of industrial facilities, coastal tourism infrastructure such as the development of small ports, and the expansion of housing and residential areas [14]. In light of these concerns, there is an urgent necessity to establish effective and sustainable measures for coastal protection [15,16]. One particularly promising solution revolves around preserving, restoring, and establishing mangrove forests. Mangroves act as natural barriers against tsunamis. Firdaus et al. specifically studied how mangroves in Lampung, Indonesia, can reduce the impact of tsunami waves. Their research provides valuable insights into the effectiveness of mangroves in tsunami mitigation [17].

Mangroves have a dual function in reducing the impact of waves and surges, operating both directly and indirectly. In a direct sense, they serve as a protective barrier against wave energy, utilizing various physical components such as their trunks, leaves, root systems, and pneumatophores [18]. Indirectly, mangroves contribute to the stability and formation of coastal soil through their intricate root system [19,20]. These intricate root systems, similar to those of various coastal species, possess the capability to reduce coastal erosion by promoting the accumulation of sediment within their intricate structures. Mangroves exhibit the unique ability to thrive and adjust to their environment, strengthening coastlines through their intricate root systems and dense plant growth. It also diminishing turbulence and increasing friction, thereby facilitating sediment deposition [21]. Even a small number of mangroves had a significant impact on reducing erosion in intertidal habitats when compared to areas devoid of mangroves. Understanding the dynamics of mangrove ecosystems and their interaction with waves is essential for effective environmental engineering solutions in coastal areas [22]. Hybrid solutions that couple ecological systems with engineering infrastructure offer promising avenues for sustainable coastal management. For instance Takagi [23], proposes an 'adaptive mangrove hybrid platform' that leverages the natural protective functions of mangroves alongside engineered structures [23]. The adoption of mangrove-based solutions not only demonstrates their potential to provide cost-effective and sustainable coastal protection but also highlights the imperative of working in synergy with nature to enhance

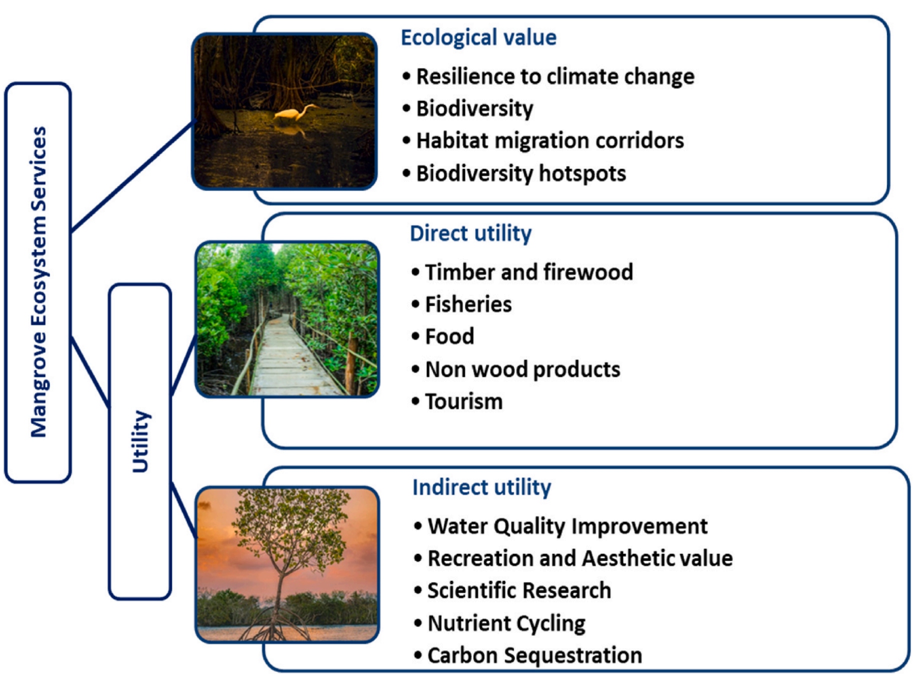

Fig. 1. Mangrove ecosystem services.

resilience against the increasing threats posed by climate change and rising sea levels [24].

Areas with healthy mangrove ecosystems reduced damage, as the dense root systems of these trees helped stabilize shorelines, minimizing erosion and providing critical protection to coastal communities. In an effort to combat severe coastal erosion and pollution in Samut Sakhon, Thailand, a successful mangrove rehabilitation project was undertaken, with 14,000 *Rhizophora mucronata* trees planted and significant survival rates achieved using NPK and coconut fiber as growth enhancers [25]. A study from Sri Lanka highlights their structural diversity, reforestation potential and vital role in protecting vulnerable coastal areas from erosion [26]. Inspired by mangroves, researchers in Florida are developing innovative coastal barriers that mimic the unique root structures of these trees, effectively combating coastal erosion and fostering marine biodiversity (Oscar Curet and Amirkhosro Kazemi, Florida Atlantic University). Mangroves demonstrated superior coastal erosion protection compared to salt marsh vegetation during Hurricane Harvey in Texas, USA, with erosion decreasing as mangrove cover increased [27]. A study conducted in northeast Brazil highlights the critical role of mangroves in coastal protection against hazards, with potential restoration costs of nearly USD 4 billion, emphasizing the importance of integrating mangrove conservation into environmental engineering strategies [28].

In conclusion, the vital role of mangroves in coastal protection is increasingly recognized not only for their inherent ability to mitigate erosion and buffer against extreme weather events but also as a cornerstone in Nature-based Solutions (NbS) for reducing coastal flood risks. Their integration into hybrid solutions, combining natural resilience with engineered structures, presents a forward-thinking approach to coastal defense.

2.2. Blue carbon initiatives: mangroves' role in climate change mitigation

Rising global temperatures, approaching a 1.5 °C increase, pose significant challenges to both ecosystems and human populations. Human activities, such as deforestation and fossil fuel combustion, have led to a 30 % increase in atmospheric CO_2 over the last century [29,30]. Notably, soil, which holds 75 % of terrestrial carbon, plays a stabilizing role in the global carbon cycle. Extreme events like wildfires, weather anomalies, and habitat declines have threatened ecosystems' ability to store carbon. Hence, the conservation of forests and wetlands is vital not just for biodiversity, but also as a mitigation strategy against climate change. Recently, as the global community confronts the pressing issues of global warming, the concept of carbon neutrality has become a focal point. Mangroves, notable for their role in the global carbon cycle, have attracted significant attention. These ecosystems, along with tidal marshes and seagrass meadows, are labelled as "blue carbon" habitats, given their pronounced role in climate change mitigation efforts [31]. While they occupy only about 0.2 % of the global ocean, they excel at sequestering and storing organic carbon in marine sediments. In particular, mangroves store up to five times more organic carbon than many terrestrial forests [32]. This capacity is attributed to their high productivity and rapid CO_2 capture via photosynthesis. Their waterlogged, anaerobic soils also inhibit organic matter decomposition, promoting long-term carbon storage [33].

The blue carbon concept, introduced in 2009 [34], underscores the carbon sequestration capabilities of coastal habitats, with mangroves at the forefront. Globally, the conservation and restoration of these ecosystems, including salt marshes and seagrasses, have been recognized as vital natural strategies to combat climate change [35]. Approximately 20 % of the global mangrove forests, or 2.6 million hectares, are particularly susceptible to threats and, hence, have the potential for carbon finance projects [36]. This vast swath of mangrove blue carbon can considerably aid in climate change mitigation by offsetting around 33.8 ± 5.1 million metric tons of CO_2 equivalent annually. To provide context, this deviation represents approximately 0.13 % of the world's yearly CO_2 emissions or about 1.02 % of the yearly emissions attributed to 'forestry and land-related activities' during the period 2002–2011, as cited by the SR15 report. During the UN Climate Change Conference in Glasgow (COP26), several strategies were proposed to enhance carbon sequestration, emphasizing the planet's soil as a major carbon sink, holding an astounding 2500 gigatons of carbon over thrice the atmospheric content [37]. As the world seeks solutions, choosing effective CO_2 capture and storage technologies, either abiotic or biotic, is essential. While abiotic methods leverage physical and chemical processes, biotic sequestration uses plants and microorganisms, with mangroves being prime examples, to draw CO_2 from the atmosphere [38,39].

2.2.1. Quantifying carbon storage potential of mangroves

Mangroves stand out as exceptional ecosystems when it comes to carbon storage and sequestration (Fig. 2 & Fig. 3). Influenced by various factors, including light intensity, salinity levels, tidal movements, and overarching climate conditions, the way carbon is allocated in trees varies significantly [40]. Mangroves, in particular, store an average around 1023 Mg of carbon per hectare, positioning them among the most productive and biologically significant ecosystems globally [32,41].

A remarkable evolutionary strategy of mangroves is their substantial investment in belowground carbon biomass. This adaptation counterbalances the loss of litter and carbon dissolved in the surrounding water, bolstering their resilience and carbon sequestration capacities [42]. Although below-ground roots constitute only 10–15 % of the total tree biomass, a significant amount of fixed carbon is dedicated to regenerating shed root hairs and fine roots [43,44]. Moreover, dead roots possess a higher carbon concentration than live roots, emphasizing their role in carbon retention [45,46]. Mangroves' intricate root systems trap organic litter and detritus, facilitating prolonged carbon storage in their soil, which can persist for millennia [33]. A comprehensive assessment of mangrove carbon stocks across 52 nations revealed that the average total ecosystem carbon organic stocks are approximately 738.9 Mg organic carbon per hectare [47]. Interestingly, a significant 76.5 % of these stocks are located in mangrove soils, extending to depths of at least 1 m (Table 1).

Challenges to the perceived carbon uptake from mangroves arise from two primary issues: the low nutritional value of mangrove litter and the lack of supportive data from stable isotope tracing. Yet, the effective carbon retention in these environments is attributed to several factors, including diminished decomposition rates, low nitrogen and phosphorous in plant tissues, and considerable allocation of biomass to roots embedded in the soil [48]. On the global stage, mangroves play a pivotal role in international climate policies like the UNFCCC and REDD+. With the potential to sequester vast amounts of CO_2, mangroves are globally recognized for their significant carbon stocks [48]. However, when compared to individual terrestrial ecosystems, mangroves account for only 1.6 % of carbon stocks. The threat of mangrove destruction, whether through human activities or natural disturbances, emphasizes the need for their conservation. If all mangroves were destroyed at a 0.16 % annual rate, it could lead to emissions of 0.088 Pg CO_2-eq a^{-1} [49].

Recent studies highlight the value of mangrove reforestation, especially in deforested regions. Reforestation has been found to offer a greater carbon storage potential per hectare compared to afforestation, mainly due to favorable tidal positions and reduced salinity in reforestation areas [48]. Research from southeastern China even emphasizes mangrove transplantation's role in enhancing carbon sequestration when replacing invasive species [50]. Furthermore, in the eastern Niger Delta, mangrove sediments were shown to contain an average organic carbon stock of 622.12 Mg C ha^{-1}, or 2283.18 Mg CO_2 ha^{-1} [51]. Although mangroves might play a marginal role in global carbon storage, their impact becomes pronounced at regional and national scales, particularly in areas grappling with deforestation [52]. As an example, a study on South African warm temperate mangroves at the Nxaxo Estuary

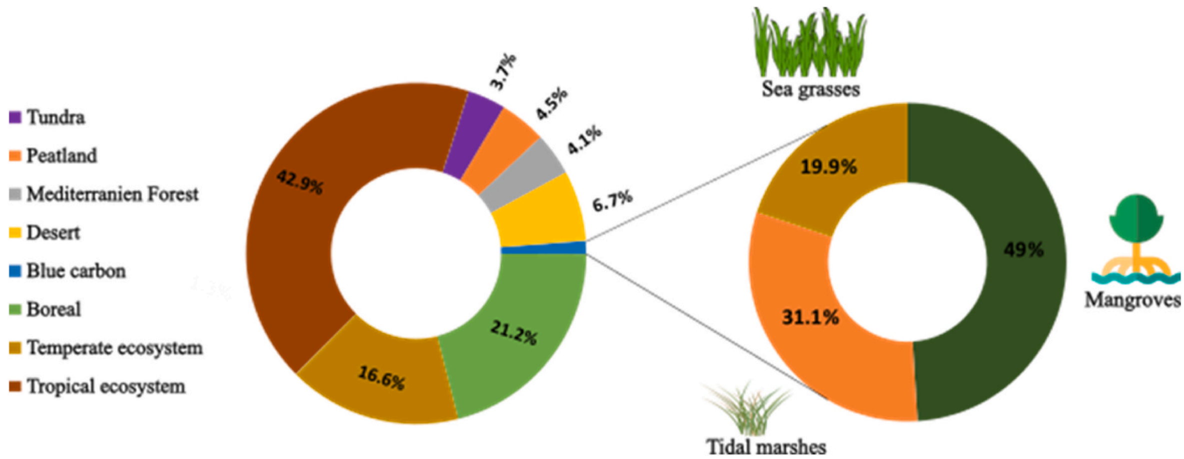

Fig. 2. Carbon sequestration: global and mangrove perspective.

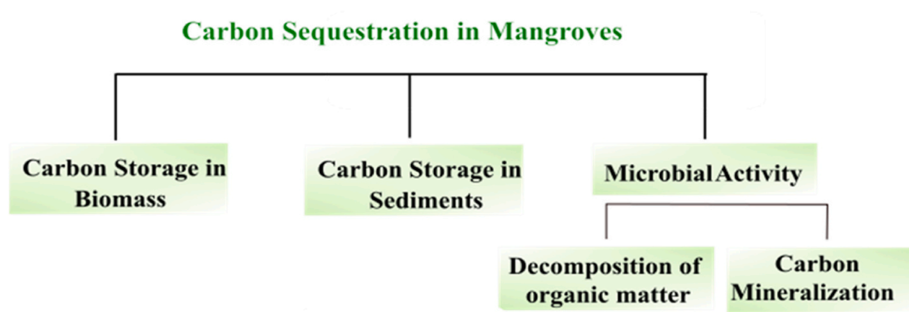

Fig. 3. Carbon sequestration strategies in mangrove ecosystem.

showed that soil carbon pools significantly contribute to the ecosystem's total carbon storage, averaging 234.9 Mg C ha^{-1} [53]. Mangroves are more than just carbon sinks. Manoj et al. found that undisturbed mangroves in Kerala (South India) have a higher carbon sequestration potential compared to disturbed areas, highlighting the need for preserving these natural habitats [54]. These data and studies underscore a resounding message in our quest to safeguard the future; mangroves are not a mere option, but a necessity [55]. Investing in their preservation is investing in a sustainable, resilient, and vibrant future for both the planet and its inhabitants.

2.3. *Mangrove ecosystems: a haven for diverse fauna*

Mangroves, the intricate coastal ecosystems of the tropics and subtropics, are indispensable reservoirs of biodiversity, supporting a plethora of life forms and delivering a suite of ecosystem services vital for the well-being of coastal communities. Their significance is underscored by their pivotal role in supporting fisheries, a primary income source for indigenous and marginalized populations in these areas [56]. These ecosystems craft distinct ecological niches that sustain a vast array of species (Fig. 4, graphictextile.blogspot.com). The muddy and sandy sediments of mangroves shelter diverse invertebrates, ranging from epibenthic species to the minuscule meiofauna. The web of channels within mangroves boosts populations of phytoplankton and zooplankton, which in turn lure a variety of fish species. Furthermore, mangroves are unparalleled in their role as nurturing grounds for juvenile fish, safeguarding them during their formative stages, even as their adult counterparts often inhabit different marine habitats, such as coral reefs and seagrass meadows [57]. Mangrove crabs, significant herbivores within this ecosystem, partake in vital nutrient cycling processes, feeding on the abundant detritus[58]. Simultaneously, shrimp and crustaceans find both shelter and sustenance among the intricate root systems of mangroves [20]. In addition, snails, frequent grazers of mangrove surfaces, assist in the cycling of nutrients [59], while mangrove oysters play a role in water purification through their filtration activities [60]. Many fish species, including the mangrove seabass and snapper, heavily rely on mangroves during various life stages [61]; [62].

Beyond the aquatic realm, mangroves are a sanctuary for diverse bird species. Birds like the Mangrove Kingfisher and Osprey are adept fishers within these regions [63]; [64], while the vibrant Mangrove Pitta adds a splash of colour to the landscape of Southeast Asian mangroves [65]. The reptilian inhabitants are no less fascinating, with the formidable Saltwater Crocodile marking its territory [66] and the agile Mangrove Monitor Lizard and venomous Mangrove Snake navigating the dense forests [67]; [68].

2.4. *Environmental cleanup through phytoremediation techniques: a mangrove-based perspective*

Phytoremediation emerges as a practical, environmentally sound, and cost-effective solution to counter environmental pollution using plant capacity to immobilize, absorb, reduce toxicity, stabilize, and even break down various compounds present in the environment due to different sources [69]. In comparison to traditional remediation techniques such as chemical treatments and excavation, phytoremediation boasts several advantages. Despite its decades-long practice, phytoremediation remains an evolving technology, adapting to meet the evolving challenges of environmental pollution [70]. As different plants utilize different strategies according to the contaminants present, the selection of the ideal plant for phytoremediation is crucial [71,72]. The ability of plants to perform phytoremediation is often evaluated by

Table 1
Above ground and underground carbon storage in mangroves and their extend and diversity in various countries (GMW, 2020).

Country	Above-ground in Mt CO_2e	Upper 1 m soil in Mt CO_2e	Species Distribution	Mangroves extend in Km^2
Indonesia	931.10	5008.47	47	29,533.98
Brazil	154.70	1334.74	8	11,414.71
Papua New Guinea	188.03	739.17	40	4524.74
Australia	186.61	1131.3	35	10,170.81
Malaysia	143.24	901.14	40	5245.75
Bangladesh	114	201.99	32	4483.86
Myanmar	100.71	532.55	36	5435.39
Nigeria	94.25	127.7	7	8442.43
Cameroon	62.97	256.57	7	1970.01
Madagascar	60.56	242.57	9	2775.67
Gabon	51.82	285.83	7	1747.01
Thailand	46.33	248.49	35	2527.99
Philippines	45.86	442.14	34	2847.98
India	43.15	275.45	37	4037.85
Mexico	40.58	1259.19	8	10,055.18
Mozambique	38.34	267.12	10	3027.35
United States	35.38	390.79	6	2329.12
Tanzania	31.42	121.19	10	1107.87
Vietnam	21.98	158.15	33	1871.47
Guinea	21.4	202.07	7	2211.45
Cuba	16.78	597	6	3596.94
Sierra Leone	12.89	127.7	7	1529.03
Angola	7.58	51.35	7	283.57
Kenya	3.68	73.64	9	544.3
Bahamas	1.98	224.29	6	1541.21
China	1.84	13.78	23	215.81
Pakistan	1.79	66.71	5	827.89
Sri Lanka	1.25	28.96	22	198.74
Iran	0.29	10.74	2	111.77

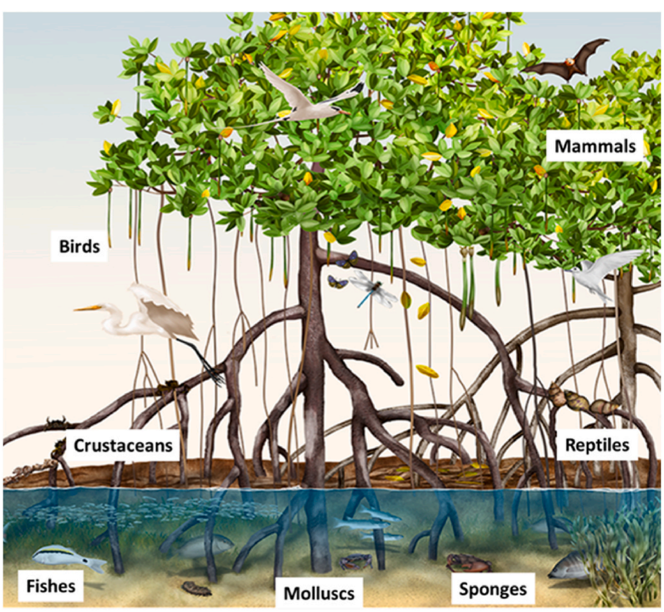

Fig. 4. Mangrove associated fauna.

measuring the Bioconcentration Factor (BCF) and Translocation Factor (TF). BCF represents the proportion of pollutant concentration in different plant sections compared to its concentration in the adjacent environment. On the other hand, TF refers to the ratio of the accumulation of specific elements in the aerial parts of the plant in comparison to its root system's accumulation [73]. Due to their inherent resilience in flourishing within challenging habitats, mangroves have garnered substantial attention as a promising avenue for phytoremediation. The technique encompasses four distinct methods: phytoextraction, phytostabilization, phytofiltration, and phytovolatilization (Fig. 5) [74]. While extensive research has been conducted on the phytoextraction and phytostabilization abilities of various mangrove species, studies on phytofiltration and phytovolatilization within mangroves remain limited.

The surge in industrial activities and population growth has introduced a significant influx of heavy metals, such as cadmium, mercury, arsenic, lead, and chromium, into both soil and water bodies [75–77]. The entry of these heavy metals into ecosystems initiates a substantial threat, stemming from their subsequent propagation through the food chain. The phytoextraction capacity of plants, involving the uptake of contaminants from their surroundings and subsequent translocation to distinct plant tissues, stands as an excellent technique for the eradication of metal pollutants from both terrestrial and aquatic environments [78, 79]. The phytoextraction potential of mangroves has been extensively explored across various regions globally, particularly in areas where there has been moderate to severe heavy metal contamination. Numerous studies have yielded diverse findings in response to the question of whether mangroves can serve as viable candidates for phytoextraction methodologies (Table 2). Phytoaccumulaltor plants are the most suitable plants for phytoextraction due to their high ability to accumulate large amounts of toxic metals. Even though there are no strict criteria for phytoaccumulators some literature identifies as one with BCF>1. According to Brooks and colleagues (1977), plants that accumulate more than 500 mg/kg of copper or 10,000 mg/kg of zinc in their tissues are defined as hyperaccumulators [80]. Although certain studies have indicated that mangroves possess a BCF below 1, labeling them as non-phytoaccumulators, a substantial consensus within the scientific community highlights the promising capacity of mangroves to serve as effective phytoremediation agents for heavy metals in estuarine ecosystems. Luthansa et al. reported BCF values of lead in *Avicennia marina, Sonneratia caseolaris, Avicennia lanata*, and *Rhizophora stylosa* from the Wonorejo River exceeded 1 and resulting in the characterization of these species as hyperaccumulator of lead [81]. Similarly, another study in the same location, documented that *Avicennia marina* is a hyperaccumulator of copper (Cu) and chromium (Cr), while *Avicennia alba* was identified as a potential hyperaccumulator of Cu and an accumulator of Cr [82]. Furthermore, another mangrove species, *Excoecaria agallocha*, stands out for its remarkable accumulation of cadmium, with a noteworthy maximum BCF value of 15.5 observed in the Sundarbans wetland [83]. While there are hyperaccumulators that can exhibit a BCF of several 100s like *Thlaspi caerulescens*, *Alyssum murale*, *Pteris vittata*, *Rinorea bengalensis*, *Phyllanthus balgooyi* their functionality in estuarine ecosystems can vary since phytoextraction potential depends on various factor [84–86]. Moreover, most of the mangroves are halophytes which can help in the desalinization thus making the region habitable for less salt-tolerant species [87,88].

Phytostabilization is another phytoremediation technique focused on mitigating the mobility of pollutants within the soil. This approach involves the accumulation of pollutants within plant roots and retention within the rhizosphere, effectively preventing their leaching into underground water sources and surrounding areas [102]; [103]. Numerous studies have explored the phytostabilization potential of various mangrove species in different locations. The grey mangrove *A. marina* has been extensively studied across different regions worldwide. For instance, a study conducted in the Sydney estuary of Australia investigated 15 locations and found that metal concentrations in the fine nutritive roots of *A. marina* consistently exceeded those in the underlying sediments. Moreover, the translocation of these metals to the leaves was minimal, indicating the species' ability to immobilize contaminants [104]. Similarly, another study by Gabriel and Salmo in 2014 identified *A. marina* as a potential phytostabilizer for copper (Cu) [105]. Additionally, elevated concentrations of lead (Pb) were reported in the roots of *A. marina* within the Sundarbans wetland [106]. Furthermore, an assessment of the accumulation of eight heavy metals in *A. marina*

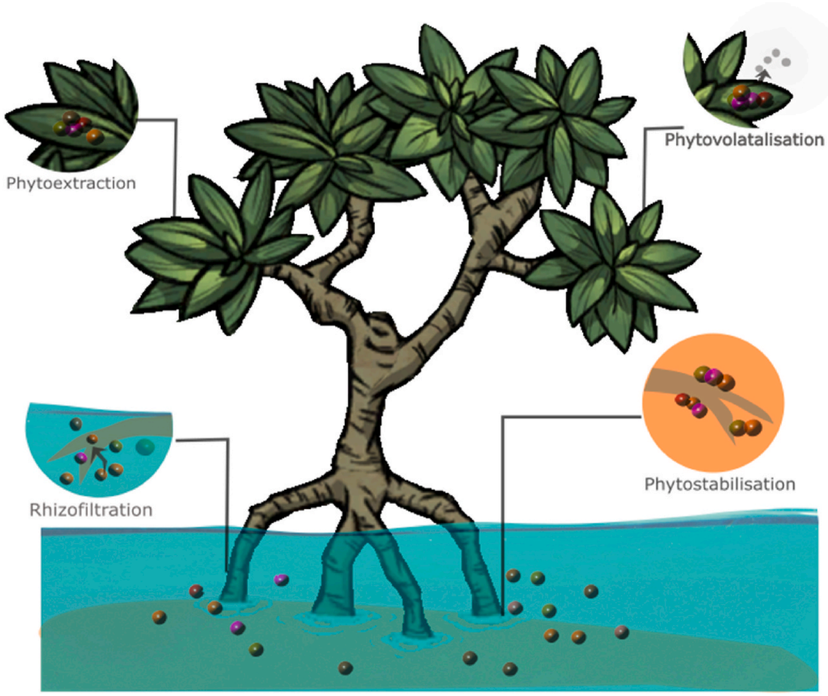

Fig. 5. Different aspects of phytoremediation through mangroves.

Table 2
Mangrove species and toxic metal that can accumulate.

Mangrove species	Toxic metal	Reference
Kandelia obovata	Cu, Cd, Zn, Pb, Hg, As	[89–93]
Rhizophora Apiculata Blume	Mn, Cu, Zn	[94]
Rhizophora mucronata lam.	Pb	[95]
Avicennia alba	Pb, Cu, Cr	[96,82]
Avicennia marina	Cu, Cr, As	[82,97]
Excoecaria. Agallocha	Mn, Cd, Zn	[83]
Avicennia officinalis	Cu, Pb, Ni,Zn,Fe	[98]
Nypa fruticans	Ni, Cd, Zn	[99]
Acanthus ilicifolius	Cu,Pb, Ni, Cr	[100,101]
Sonneratia caseolaris	Pb	[95]

from Tarut Bay, Saudi Arabia, suggests that this species has significant potential for phytostabilization [107]. This capacity for phytostabilization can be attributed to the presence of pneumatophores in *A. marina.* Pneumatophores, which absorb oxygen through lenticels, create an oxidized rhizosphere that assists in the stabilization and subsequent absorption of metals [108]. Likewise, many other mangrove species including *Acanthus ilicifolius*, *Aegiceras corniculatum* L., *Excoecaria agallocha*, *Bruguiera cylindrica* L. are reported as potential candidates for phytostabilisation [109]; [110–112].

Another phytoremediation strategy, phytofiltration or rhizofiltration, utilizes the roots ability to purify water from hazardous metals and chemicals. Mangroves, with their intricate root systems and unique vegetation, play a pivotal role in serving as natural water filtration systems along coastlines. The discussion surrounding their involvement in enhancing water quality through filtration underscores their vital contribution to maintaining the health of both terrestrial and marine ecosystems. As water flows through the dense network of mangrove roots, suspended particles and pollutants are trapped and filtered out, resulting in improved water clarity [113]. Moreover, mangroves exhibit remarkable capability in mitigating nutrient runoff from adjacent land areas, effectively reducing the influx of excess nutrients such as nitrogen and phosphorus into surrounding waters. This nutrient retention function not only prevents the deterioration of water quality but also contributes to the well-being of marine habitats downstream. By effectively reducing sediment transport and nutrient enrichment, mangroves contribute to the overall health and resilience of marine ecosystems, fostering the growth of diverse flora and fauna [114]. Despite several mangroves possessing an extensive root system that includes aerial silt roots and an underground root system, phytofiltration in mangroves is a relatively less explored approach in phytoremediation strategies. Therefore, further exploration in this regard is necessary. Similarly, the phytovolatilization capability, which involves the volatilization of absorbed metals, also remains relatively unexplored in mangroves. Being the crucial plant groups that can flourish between terrestrial and coastal boundary, mangrove stands as an exceptional candidate for preventing the exchange of hazardous heavy metals and chemical between terrestrial and coastal ecosystem. Thus, harnessing mangroves as a phytoremediation tool holds immense promise for a sustainable pollution removal strategy. Their potential can be further enhanced through genetic engineering and the introduction of chemical compounds and microorganisms [115].

2.5. Microorganisms in mangrove ecosystems and their potential for environmental restoration

Coastal ecosystems, especially mangrove habitats, offer unique environmental conditions that foster rich microbial diversity. These conditions, including fluctuating salinity levels, elevated redox potential values, and an abundance of organic matter, create an ideal environment for microbial colonization and proliferation [116,117]. Microbial communities in mangroves are incredibly diverse, occupying various niches, including sediments, water columns, mangrove root and leaf surfaces, and even as endophytes within plant tissues [118–120]; [121]; [122]; [123]. The mangrove microbiome is primarily comprised of bacteria and fungi, collectively accounting for a substantial proportion of 91 %, while algae and protozoa are present in smaller quantities, making up 7 % and 2 %, respectively [124–126]. These microorganisms play pivotal roles in shaping mangrove biogeochemistry and nutrient cycling (Fig. 6) [127,128]. Bacteria and fungi within this microbial community play a central role as primary decomposers responsible for ecosystem degradation. Bacterial diversity in mangrove ecosystems is

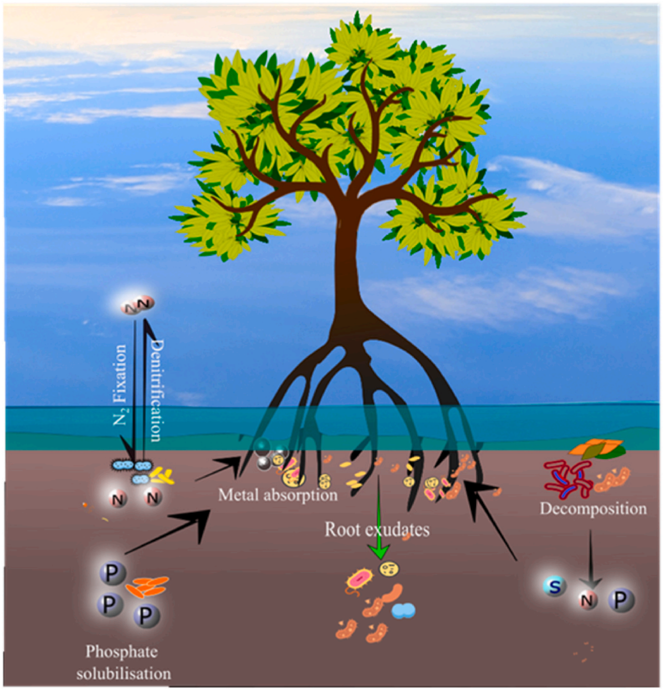

Fig. 6. Mangrove microbiome nutrient cycling.

highly variable and influenced by factors such as location, pollution levels, and vegetation [129]. Research has unveiled a diverse array of bacteria, with dominant phyla including Proteobacteria, Firmicutes, and Bacteroidetes, along with common classes like Gammaproteobacteria, Flavobacteriales, and Clostridiales [125,126]; [130]. Mangroves host a diverse range of fungal species, thriving in their unique intertidal environment. These manglicolous fungi, mainly belonging to Ascomycota, Deuteromycota, and Basidiomycota, are found in both terrestrial and marine niches within the mangrove ecosystem [131–133]. Phytoplankton diversity in mangrove ecosystems is characterized by a wide range of microalgae species, including diatoms, dinoflagellates, and cyanobacteria [134–136]. These microscopic organisms play a crucial role in the mangrove food web, contributing to primary production and serving as a vital food source for various aquatic species within these unique coastal habitats [137]; [138–141].

Microorganisms are central figures in the intricate web of nutrient cycling within mangrove ecosystems. They play vital roles in soil enrichment processes, including the mineralization of phosphate and sulfate, organic matter degradation, and nitrogen fixation [142,143]; [144]. They significantly contribute to phosphorus cycling by facilitating the remineralization and solubilization of otherwise inaccessible phosphorus sources [145,146]. They actively participate in processes such as nitrogen fixation and denitrification, which directly influence nitrogen cycling [128,147–149]. Various nitrogen-fixing bacteria, such as those belonging to the genera Rhizobium, Phyllobacterium, Devosia, Microvirga, and Clostridium, have previously been detected in the rhizosphere of mangrove ecosystems [150,151]. Mangrove sediments, rich in elements like iron (Fe) and manganese (Mn), are home to prevalent Fe and Mn reducers [152]. Microbes in mangrove sediments are key players in carbon turnover, orchestrating hydrocarbon degradation, sulfate reduction, and methane/nitrous oxide production [153]. These activities create chemical conditions that both decelerate organic matter decomposition and foster carbon sink formation [154].

Mangroves are vital exporters of plant detritus, which undergoes decomposition and remineralization, contributing to nutrient cycling. Falling plant parts, including leaves and branches, make up the extensive litter produced by mangrove ecosystems. This detritus undergoes leaching and microbial degradation, producing dissolved organic matter [135]. Saprophytic fungi and bacteria, with approximately 625 fungal species reported in mangroves globally [155,156], actively participate in litter decomposition. Decomposition is facilitated by several bacterial genera such as *Azotobacter, Pseudomonas, Flavobacterium, Staphylococcus, Acinetobacter, Enterobacter, Micrococcus, Bacillus, E. coli,* and *Klebsiella* [157,158]. This decomposition process supports dissolved organic matter production and nutrient recycling, enriching estuaries and coastal seas [159].

Microbes also play a significant role in maintaining mangrove soil properties, including the presence of the non-protein amino acid β-glutamic acid, which is distinctive to mangrove sediment [160,161]. Sulfate-reducing bacteria immobilize β-glutamic acid in mangrove soils unless the sediments are contaminated, leading to its release [162,163]. These microbial-driven processes collectively regulate nutrient availability in the mangrove environment, influencing the growth and health of mangrove vegetation and supporting diverse fauna [164,165]. Furthermore, these microbial communities are versatile in their metabolic activities across sediment redox gradients, initiating both the production and consumption of methane and nitrous oxide [166]. These activities can lead to net emissions of these greenhouse gases, adding an important dimension to the ecological role of mangrove microorganisms [167]. Microbes in the mangrove ecosystem are not limited to the sediments alone; they have a significant presence on the surfaces of roots and leaves. Here, they perform multifaceted roles, making micronutrients more accessible, offering defense mechanisms against pathogens, and initiating decay processes upon senescence [122,168].

It is noteworthy that the benefits of mangrove-health-promoting bacteria extend beyond environmental restoration. The bacterial strains isolated from mangrove environments exhibit promise in the realm of agricultural applications, particularly in adapting crops to saline conditions [169,170]; [171]; [172]; [173]. In a study conducted in the Sundarbans mangroves of India, halotolerant plant growth promoting rhizobacteria (PGPR), including Arthrobacter sp., *Pseudomonas plecoglossicida*, *Kocuria rosea*, and *Bacillus* genera, were isolated and characterized for their salt tolerance, PGP traits, and antagonistic activity against root rot pathogen *Macrophomina phaseolina*, demonstrating their potential as bioagents for saline soils [174]. Recent research exploring the microbiome associated with propagules of the *Avicennia marina* mangrove plant in the Red Sea has unveiled plant-growth-promoting bacteria. These microbes play a pivotal role in stimulating root development and aiding in the successful establishment of mangrove ecosystems [175].

In conclusion, the intricate and diverse microbial life within mangrove ecosystems not only plays a pivotal role in sustaining these unique habitats but also offers promising avenues for environmental restoration and sustainable ecosystem management, demonstrating the invaluable potential of nature's coastal architects in addressing contemporary ecological challenges.

2.5.1. Bioremediation potential of mangrove microbes

Mangrove ecosystems face numerous environmental challenges, with oil spills and pollution being particularly detrimental [176,177]. Oil spills, in particular, are of significant concern due to their lasting effects on coastal environments, including mangroves. To combat these challenges, it becomes imperative to harness the bioremediation potential residing within the microbial communities of mangrove ecosystems. Microbial bioremediation, a natural process orchestrated by microorganisms, involves the breakdown and transformation of pollutants, playing a pivotal role in mitigating environmental threats [178]. Bioremediation encompasses in situ and ex situ approaches, including bioattenuation, bioaugmentation, and biostimulation. Bioattenuation relies on natural processes, with contaminants being gradually degraded by native microbiota over time. Bioaugmentation entails the introduction of lab-grown microorganisms to enhance degradation when native microbiota is insufficient. Biostimulation involves the stimulation of indigenous microbial communities through nutrient provision and environmental condition adjustments [179,180]. Within mangrove ecosystems, microbial communities have evolved specific metabolic capabilities tailored for oil hydrocarbon degradation [181,182]. They produce essential enzymes such as alkane monooxygenases and dioxygenases, enabling the efficient breakdown of complex hydrocarbons into less harmful substances [183]. This approach offers a promising avenue to devise targeted microbiome manipulation strategies, serving as a valuable tool to prevent and mitigate the detrimental effects of oil spills on mangroves [117,182,184–186]. Of significant interest are microbial consortia with the unique ability to both degrade oil contaminants and promote the overall health of the ecosystem and mangrove plants, making them particularly intriguing [168]. These consortia offer a dual functionality by facilitating the breakdown of oil contaminants while simultaneously enhancing the well-being of the ecosystem and the mangrove plants themselves. In situ mesocosm study reveals the effectiveness of monitored natural attenuation for oil remediation in mangrove sediments, highlighting the role of microbial communities in environmental decontamination [186]. The diverse microbial community residing in mangrove sediments represents a valuable source of highly efficient hydrocarbon-degrading bacteria, which can be utilized as inoculants for bioremediation purposes [187].

Bioremediation has demonstrated its effectiveness in mitigating oil pollution, with notable success stories such as the Prince William Sound spill in 1989 and the Mexican Gulf spill in 2010 [188]; [189]. However, the primarily anaerobic nature of mangrove sediments presents unique challenges for bioremediation [116]. To advance bioremediation, it is crucial to explore syntrophic pollutant-degrading microorganisms and genes involved in the bioremediation process [168,190]; [191]. Research has demonstrated that bacteria isolated from mangrove ecosystems have exhibited potential in remediating hazardous industrial residues contaminated with cadmium and zinc, thereby highlighting the biotechnological advantages offered by mangrove-associated microbes in mitigating various environmental impacts [192]. In the study conducted by Sangale et al. it was found that polythene biodegradation by fungi isolated from mangrove rhizosphere soil along the West Coast of India holds significant promise as an ecofriendly approach [193]. The research identified elite polythene deteriorating fungi, particularly *Aspergillus terreus* strain MANGF1/WL and *Aspergillus sydowii* strain PNPF15/TS, which exhibited substantial reductions in weight and tensile strength of treated polythene. Harnessing the diverse microbial communities dwelling within mangrove sediments, particularly those endowed with oil-degrading and health-promoting properties, offers promising strategies for environmental restoration.

2.5.2. Enhancing mangrove ecosystems through rhizosphere engineering

The deliberate modification of the root-soil interface, known as rhizosphere engineering, offers innovative approaches for preserving and revitalizing mangrove ecosystems [194]. This concept revolves around optimizing interactions within the dynamic zone surrounding plant roots, where intricate relationships between plants and microorganisms unfold [195]. In mangrove conservation, rhizosphere engineering holds significant potential, providing strategies to enhance nutrient cycling, promote plant health, and bolster ecosystem resilience.

The significance of rhizosphere engineering in mangroves extends to various aspects (Fig. 7). Manipulating the rhizosphere can enhance nutrient cycling by fostering interactions between mangrove roots and beneficial microorganisms, contributing to the overall nutrient balance of the ecosystem [194]. Rhizosphere engineering might be employed in phytoremediation efforts to clean up polluted coastal areas by enhancing mangroves' pollutant-absorbing capabilities. In the context of diesel contamination, rhizospheric engineering with bacterial inoculation has shown promise in enhancing pollutant degradation while

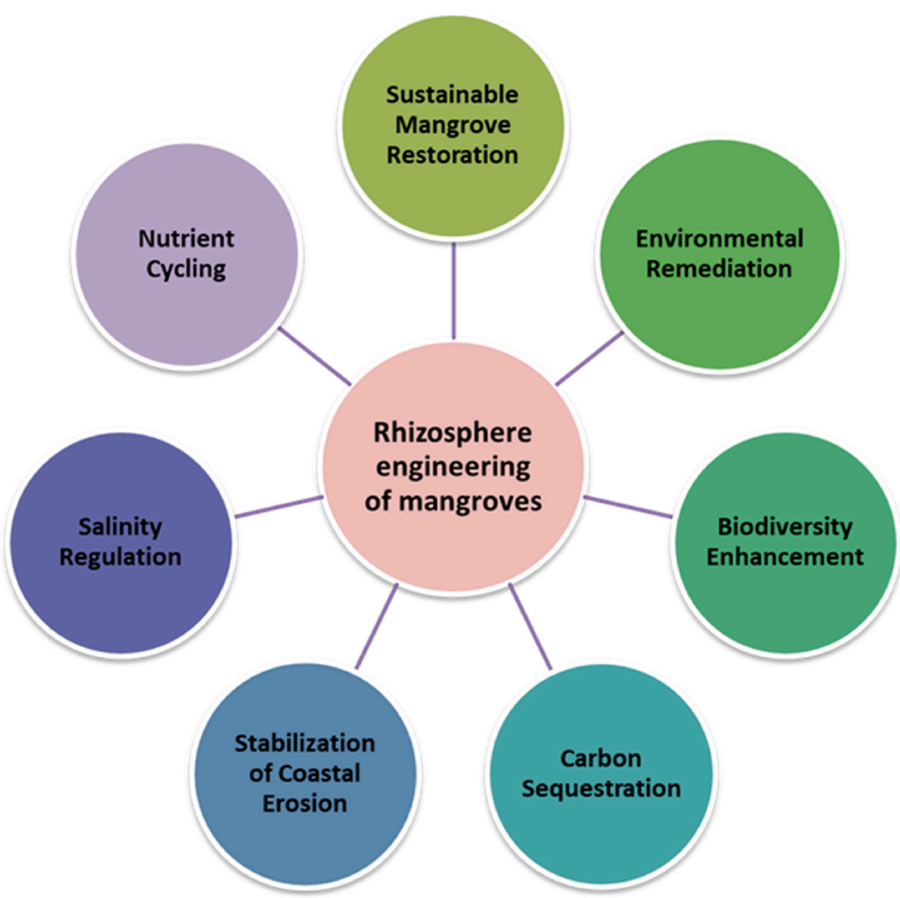

Fig. 7. Significance of rhizosphere engineering in mangroves.

improving mangrove seedling growth and antioxidant enzyme activities [196]. Several bacterial strains have been recognized for their ability to break down aromatic hydrocarbons found in diesel. These strains encompass *Rhodococcus, Sphingomonas, Pseudomonas, Mycobacterium, Burkholderia, Bacillus*, and *Arthrobacter* [117,168]. This approach highlights the potential of microbial-assisted rhizospheric engineering as an effective bioremediation strategy for mangrove environments contaminated with diesel spills [196]. Given the perpetual vulnerability of mangroves to oil contamination, leveraging native microbial species or consortia appears promising for their restoration. The deposition and adsorption of oil in underground layers pose a considerable problem. A novel method to address this is by using a consortium of bacteria that can thrive in both oxygen-rich and oxygen-deprived environments [182]. Furthermore, fungi isolated from mangrove rhizosphere soil have demonstrated the potential for eco-friendly polythene biodegradation, suggesting a viable approach to plastic waste management in mangrove environments [193].

In a case study focused on the impact of the rhizosphere on mangrove bacterial communities and its relevance to mangrove reforestation, researchers utilized barcoded pyrosequencing to analyse bacterial diversity in nursery-raised plants, native plants, and bulk sediment within the same mangrove habitat [151]. The research indicated a notable impact of mangrove roots on the abundance and variety of bacteria in the rhizosphere. Interestingly, they also observed that initial nursery conditions played a vital role in shaping the bacterial composition of transplanted mangrove trees' rhizosphere. This research highlights the significance of considering the conditions of nurseries and initial microbial colonization trends in projects aimed at replanting mangroves, shedding light on the rhizosphere's role as a habitat for bacteria from estuarine sediments. The rhizosphere engineering of mangroves holds promise for enhancing the resilience, productivity, and sustainability of mangrove ecosystems in the face of various environmental challenges. Research in this area would involve studying the interactions between mangrove roots, microorganisms, and soil properties, and understanding how these interactions can be manipulated to achieve specific ecological and environmental goals. It's important to note that any manipulation of natural systems should be approached with caution and a thorough understanding of the potential ecological consequences.

2.6. Mangroves in ecosystem-based adaptation and urban resilience

Mangroves represent nature's multifaceted defense mechanism, bolstering both environmental and community resilience. These unique ecosystems serve as robust buffers against coastal calamities, such as storm surges, tsunamis, and rising sea levels, reducing the energy of waves and preventing soil erosion [8,197]. Their dense root systems and canopies support a vibrant marine ecosystem, offering sustenance for local fisheries and other economic opportunities such as timber, honey, and traditional medicines [198,199]. Mangroves provide cost-effective alternatives to conventional infrastructure, mitigating impacts of storm surges and protecting urban spaces from potential flooding [8,197]. Their ecological significance is evident from their role in enhancing urban biodiversity, filtering pollutants, and functioning as significant carbon sinks [200]; [201]; [32].

Global initiatives have recognized the paramount role of mangroves in urban ecosystems and their resilience. For instance, the UN-REDD Programme in Myanmar launched a project, backed by Norway, to integrate mangrove conservation into urban frameworks, focusing on climate mitigation and community livelihoods. Studies from urban centers like Jakarta underscore the ecosystem benefits of urban mangroves, ranging from carbon storage to air purification [202]. The Green Coast project, in response to the 2004 tsunami, integrated mangrove restoration into urban planning, exemplifying their role in building resilient landscapes [42]. However, the coexistence of urbanization and mangrove conservation is not without challenges. Urban areas often target the coastal spaces vital for mangrove growth. Achieving harmony between urban expansion and mangrove preservation requires careful planning, stakeholder collaboration, and supportive policies [203]. In essence, the symbiotic relationship between mangroves and human communities, both rural and urban, underpins the need for holistic strategies. Such approaches not only safeguard our environment but also ensure that the associated communities remain resilient amidst escalating environmental uncertainties.

2.6.1. Synergies between mangroves and sustainable fisheries

Mangroves play an indispensable role in sustaining fisheries, acting as crucial nursery grounds for numerous significant fish species. These unique coastal ecosystems, with their complex root systems and nutrient-rich environments, provide optimal conditions for fish during their vulnerable early stages, safeguarding them from predators and adverse conditions [204,205]. The median mangrove fishing intensity, which reflects the frequency of fishing activity per unit area in mangrove regions globally, illustrates the reliance of local fisheries on these habitats (Fig. 8) [206]. As these juvenile fish mature, they bolster local fisheries, highlighting the mutual benefits of mangroves and fish (Fig. 8) [207]. The health of mangrove ecosystems is further maintained by fish, which regulate smaller invertebrate populations and contribute to nutrient cycling [208]. However, preserving this symbiotic relationship demands a balance between fisheries management and mangrove conservation. Strategies include regulated fishing practices, marine protected areas, and sustainable harvesting techniques, all rooted in scientific research [209]; [210,211]; [212]. Embracing these strategies ensures thriving fisheries and robust mangrove ecosystems, underscoring the profound interconnectedness of marine biodiversity, ecosystem health, and human well-being.

3. Threats to mangrove ecosystems

Mangrove ecosystems, which extend over approximately 147,359 square kilometers along the world's coastlines, are vital for biodiversity and environmental stability. These habitats, however, have experienced significant decline over the years. The global area of mangrove coverage has decreased from 152,604 km^2 in 1996 to 147,358.99 km^2 by 2020, according to the Global Mangrove Watch. This reduction marks a net loss of 3.4 % of mangrove forests, which corresponds to a reduction in the linear extent of mangroves to 14.93 % along the 2,139,308.93 km of coastlines where they previously existed (Fig. 9). These data highlight not only the fragility of mangrove ecosystems but also the alarming rate at which they are disappearing. This decline is largely attributed to a myriad of threats, both anthropogenic and natural, which have systematically undermined the integrity and sustainability of these ecosystems (Fig. 10) [203,213].

The primary human-driven threat to mangroves is deforestation for

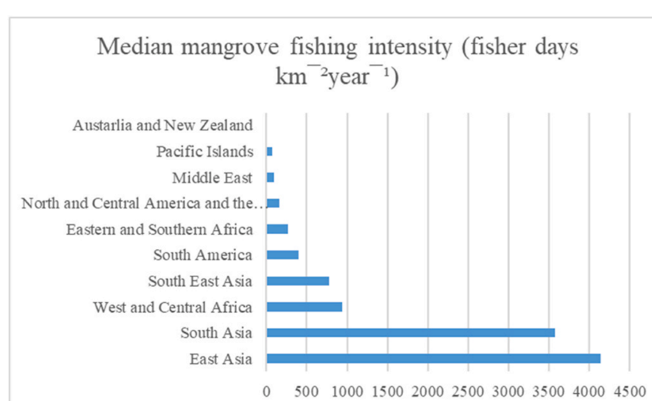

Fig. 8. Median mangrove fishing intensity (fisher days km^{-2} $year^{-1}$) across global mangrove regions [206].

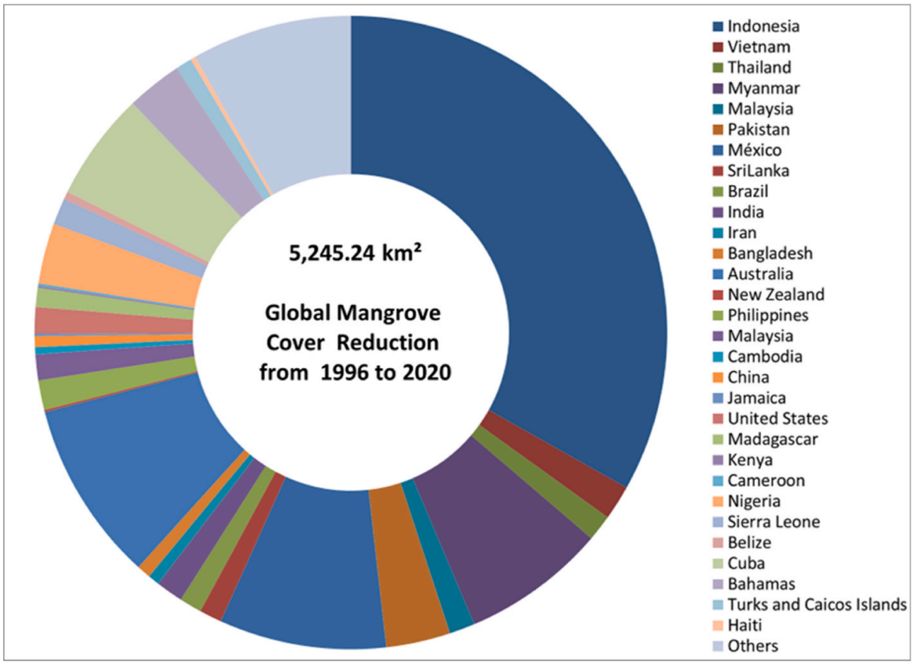

Fig. 9. Global mangrove cover reduction from 1996 to 2020 (Source: Global Mangrove Watch).

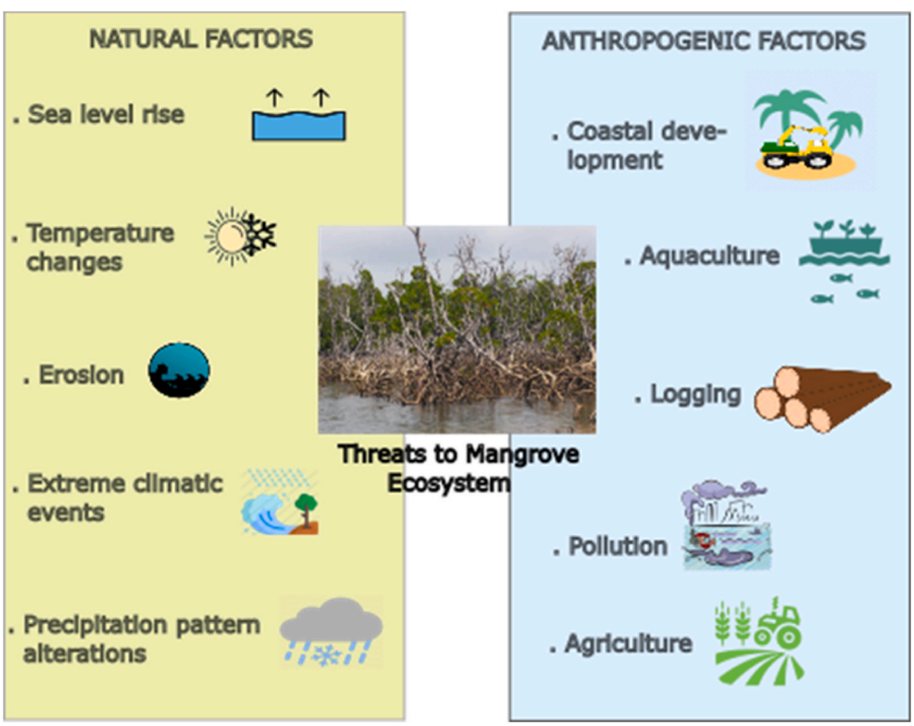

Fig. 10. Natural and anthropogenic threats of mangrove ecosystems.

commercial and residential development as coastal populations increase [214]. Conversion of mangrove areas to agricultural land, particularly for aquaculture such as shrimp farming, is a significant factor. Mangrove ecosystems are increasingly threatened by fragmentation and habitat loss, with Southeast Asia facing the most significant impact from activities such as aquaculture and rice plantation conversion, according to Brown et al. [215]. In countries like Indonesia, which holds about 23 % of the world's mangrove forests, mass conversion to shrimp ponds has led to substantial losses [216,217]. The Philippines, Myanmar, and Vietnam have also reported significant decreases due to similar land-use changes [218,219]. The repercussions of such activities are manifold, leading to habitat fragmentation, loss of biodiversity, and the disruption of the ecological services provided by these coastal forests. Moreover, pollution from various sources further exacerbates the stress on these ecosystems, with oil spills, industrial discharge, and urban runoff altering water quality and sediment composition, essential for mangrove health and productivity. In regions such as the Niger Delta, oil exploration has had disastrous impacts on mangrove forests, with repeated spills and leakages causing severe degradation of these ecosystems [220]. Furthermore, the overexploitation of mangroves for timber and fuelwood has led to forest degradation and loss, affecting the biodiversity and the structural integrity of these ecosystems. Climate change introduces additional stresses, including sea-level rise, increased storm intensity, and altered rainfall patterns. These changes can lead to mangrove dieback, as observed in parts of Australia and the Caribbean, where extreme weather events and tidal changes have caused significant damage [221]. Natural disturbances such as hurricanes, cyclones, and changes in sedimentation patterns due to river damming also significantly impact mangrove health and distribution. These events can cause profound structural damage to mangrove forests and alter the sediment and nutrient flows, further stressing these fragile ecosystems [222].

In light of these challenges, it becomes imperative to incorporate mangrove conservation into comprehensive environmental management strategies. Addressing both human-induced and natural threats is essential to safeguard the future of mangrove ecosystems. Recognizing the interdependence of mangroves with the well-being of coastal communities and the global environment is a step towards mitigating the threats they face and preserving their multifunctional roles.

4. Collaborative partnerships: stakeholders in mangrove conservation

Collaborative partnerships have become indispensable in the realm of mangrove conservation, weaving together the expertise and efforts of various stakeholders from governments, non-governmental organizations (NGOs), to local communities. Governments, with their policy-making machinery, are instrumental in formulating and enforcing regulations that ensure the sustainable management and protection of these vital coastal buffers [223]. They play a crucial role in creating the legal and administrative frameworks required for the sustainable utilization and conservation of mangrove ecosystems. On the other hand, NGOs, often armed with specialized knowledge and global outreach, amplify advocacy efforts and channel funds and resources to the grassroots. Their involvement often accelerates conservation initiatives, bridging the chasm between scientific discoveries and real-world applications [177]. Their role is crucial in raising awareness, mobilizing resources, and influencing policy decisions in favour of mangrove conservation.

The conservation tapestry is incomplete without the threads of local communities. Intimately connected with these ecosystems, local communities possess a trove of traditional wisdom and practices that have co-evolved with mangroves over generations. Their participation ensures that conservation strategies are grounded, culturally sensitive, and effective in the long run. Their knowledge, often overlooked in top-down approaches, provides a rich context, ensuring that conservation is not just ecologically sound but also socially equitable. The dynamic landscape of mangrove conservation demands cross-disciplinary collaboration. It's a space where environmental engineers and plant scientists meet ecologists, policymakers intersect with grassroots activists, and scientific insights resonate with indigenous wisdom. Such an integrated approach, as highlighted by Satyanarayana et al.,[224], ensures that conservation strategies are robust, adaptive, and holistic. By harnessing the collective strength of diverse stakeholders, these partnerships not only bolster the resilience of mangrove ecosystems but also sculpt a shared vision for their future. At its core, successful mangrove management hinges on collective effort. As climate change and urban growth continue to present increasing challenges, a web of joint efforts will be essential to drive future sustainable conservation measures.

5. Challenges and future directions: advancing mangrove-based engineering

Mangroves have been increasingly recognized for their multifaceted roles in environmental engineering. While several studies point out the importance of mangroves as Nature-based Solutions and hybrid systems including both mangroves and engineering structures for coastal protection, there is still a need to understand and quantify the site-specific factors that influence the effectiveness and resilience of mangrove ecosystems in attenuating flood events and adapting to a changing climate [24]. In this context, the study by et al.,[225] provides valuable insights into how the combination of breakwaters and mangroves can enhance coastal protection, demonstrating the potential of such hybrid systems in mitigating wave impacts. Similarly, the utilization of mangroves in phytoremediation necessitates the careful consideration of environmental conditions, a thorough evaluation of long-term effectiveness, the exploration of scalability, integration with complementary remediation methods, and the establishment of standardized monitoring and assessment protocols. Moreover, their potential is marred by a host of challenges that need urgent attention. One of the most pressing issues is the rapid loss of mangrove habitats. Factors such as deforestation, coastal development, aquaculture expansion, and pollution have led to significant reductions in mangrove coverage globally [2]. Climate change further exacerbates these threats, with rising sea levels, increased storm frequencies, and altered salinity patterns impacting mangrove health and distribution [221]. Harnessing advancements in technology has revolutionized mangrove restoration. Remote sensing tools, for instance, offer unprecedented capabilities in mapping and monitoring mangrove expanses. Such tools facilitate the identification of degraded areas, monitor the progress of restoration endeavours, and provide crucial insights into factors influencing mangrove health [226]. Despite the clear benefits of mangroves, from carbon sequestration to coastal protection, their integration into mainstream environmental engineering practices remains limited. Socioeconomic constraints, such as competing land-use priorities and a limited understanding of the multifunctional benefits of mangroves, hinder their widespread adoption [226].

Research in mangrove-based engineering also presents a myriad of opportunities. Advancements in restoration methodologies, understanding the complex rhizosphere dynamics for enhanced pollutant removal, and delving deeper into the symbiotic relationships between mangroves and their resident microbial communities are areas ripe for exploration [227]. Recent studies, such as those by Kayalvizhi and Kathiresan [228], emphasize the role of microbial communities in aiding mangroves in their pollutant removal capabilities. Furthermore, there's a treasure trove of traditional knowledge and practices associated with mangroves. Indigenous communities have coexisted with these ecosystems for centuries, and their practices, often rooted in sustainable principles, can offer valuable insights. Integrating such traditional knowledge with contemporary engineering practices can pave the way for innovative, holistic, and culturally sensitive solutions [229]. In conclusion, while the challenges faced by mangrove-based engineering are significant, they are not unsurmountable. By addressing the immediate threats, fostering interdisciplinary collaborations, leveraging traditional knowledge, and focusing on targeted research, the field can evolve to offer sustainable and resilient solutions for pressing environmental challenges. As urban areas globally grapple with the dual challenges of development and environmental conservation, mangroves emerge as nature's engineering marvels, waiting to be harnessed to their full potential.

6. Conclusion: the promise of mangroves in environmental engineering

Mangroves multifunctional role in supporting both terrestrial and marine life, while providing an array of ecological services, underscores their unparalleled importance in the domain of environmental engineering. As this review has illuminated, mangroves are not mere static entities on our coastlines; they are dynamic systems that offer solutions to some of the most pressing environmental challenges of our time, from climate change mitigation to bioremediation. Their intricate network of roots stabilizes shores, their leaves sequester carbon, and their unique biomes house myriad organisms that play pivotal roles in ecosystem health and restoration. As the world grapples with rapid urbanization and environmental degradation, it becomes paramount to recognize the potential of mangroves in fostering resilience, sustainability, and harmony between human settlements and natural systems. Collaborative efforts that bring together stakeholders from various sectors will be crucial in ensuring the conservation and sustainable utilization of these coastal treasures. As we move forward, it is essential that we integrate traditional knowledge, scientific insights, rapid multiplication strategies and innovative engineering techniques to safeguard and enhance mangrove ecosystems. Innovative engineering techniques such as fishbone and snake types of canals for mangrove reforestation in the Krishna Wildlife Sanctuary, India, has demonstrated significant success [230]. Unoccupied Aircraft Systems (UAS or drones), is another strategy which provide non-destructive, high-resolution, and cost-effective tools for planning and evaluating marine ecosystem restoration projects, including assessing population changes, species identification, habitat structure, water quality, and seed dispersal without disturbing the habitat [231]. Other innovative techniques such as Biodegradable Ecosystem Engineering Elements (BESE), automated hydraulic control gates, termed "SmartGates", also proved effectiveness in mangrove restoration [232]; [233]. In doing so, we not only protect these remarkable habitats but also invest in a future where nature and humanity coexist and thrive in synergy. Through concerted efforts and a commitment to sustainability, the promise of mangroves in environmental engineering can be fully realized, offering a beacon of hope for ecological restoration, climate resilience, and sustainable development in our rapidly changing world.

CRediT authorship contribution statement

Anu K: Conceptualization, Writing – original draft, Writing – review & editing. **Henna Parveen K:** Investigation, Writing – original draft, Writing – review & editing. **Sneha V K:** Writing – original draft. **Busheera P:** Writing – original draft. **Jumana Muhammed:** Writing – original draft. **Anu Augustine:** Writing – review & editing.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve readability and language. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

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

Acknowledgment

We sincerely acknowledge the fellowship and support provided by the Kerala State Higher Education Council (KSHEC), Council of Scientific & Industrial Research (CSIR), University Grants Commission (UGC), and the Research Development Cell of Kannur University.

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ARTICLES FOR FACULTY MEMBERS

MANGROVE RESTORATION TOWARDS SUSTAINABLE COASTAL ECOSYSTEM MANAGEMENT

Title/Author	**Plant–soil feedbacks in mangrove ecosystems: Establishing links between empirical and modelling studies / Wimmler, M. C., Bathmann, J., Peters, R., Jiang, J., Walther, M., Lovelock, C. E., & Berger, U.**
Source	***Trees*** **Volume 35 Issue 5 (2021) Pages 1423–1438** **https://doi.org/10.1007/S00468-021-02182-Z** **(Database: SpringerLink)**

Trees (2021) 35:1423–1438
https://doi.org/10.1007/s00468-021-02182-z

REVIEW

Plant–soil feedbacks in mangrove ecosystems: establishing links between empirical and modelling studies

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Received: 28 October 2020 / Accepted: 7 July 2021 / Published online: 22 July 2021

Abstract

Key message **Plant–soil feedbacks in mangrove ecosystems are important for ecosystem resilience and can be investigated by establishing links between empirical and modelling studies.**

Abstract Plant–soil feedbacks are important as they provide valuable insights into ecosystem dynamics and ecosystems stability and resilience against multiple stressors and disturbances, including global climate change. In mangroves, plant–soil feedbacks are important for ecosystem resilience in the face of sea level rise, carbon sequestration, and to support successful ecosystem restoration. Despite the recognition of the importance of plant–soil feedbacks in mangroves, there is limited empirical data available. We reviewed empirical studies from mangrove ecosystems and evaluate numerical models addressing plant–soil feedbacks. The empirical evidence suggests that plant–soil feedbacks strongly influence ecological processes (e.g. seedling recruitment and soil elevation change) and forest structure in mangrove ecosystems. Numerical models, which successfully describe plant–soil feedbacks in mangrove and other ecosystems, can be used in future empirical studies to test mechanistic understanding and project outcomes of environmental change. Moreover, the combination of both, modelling and empirical approaches, can improve mechanistic understanding of plant–soil feedbacks and thereby ecosystem dynamics in mangrove ecosystems. This combination will help to support sustainable coastal management and conservation.

Keywords Ecosystem stability · Ecosystem resilience · Ecosystem response · Climate change · Coastal forests · Wetland dynamics

Introduction

Mangroves are trees and scrubs that form extensive ecosystems that fringe sheltered coastlines, including shallow lagoons, river deltas and estuaries, in the tropics and subtropics. They cover a global area of approximately 137,000 km^2 (Spalding et al. 2010) and provide a wide range of ecosystem services (Walters et al. 2008; Barbier et al. 2013). In addition to supporting biodiversity, fisheries and providing other resources for coastal communities, they contribute to regulating water quality, provide coastal protection by reducing erosion and wave energy (Walters et al. 2008; Sánchez-Núñez et al. 2019), and are important for global carbon sequestration (Donato et al. 2011). Moreover, mangroves help in the maintenance of shorelines during sea level rise through vertical accretion of sediments (Krauss et al. 2014). However, mangrove forests vary in the range and level of ecosystem services that they provide due to variation in their position in the landscape, their species composition and structure (Gleason et al. 2003; Feller et al. 2010), which interacts with both human uses and physical environmental variables.

Despite the importance of mangroves to coastal communities, they are threatened by land-use change and global climate change (Gilman et al. 2008; Alongi 2018). This

Communicated by M. Buckeridge .

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includes anthropogenic interventions, such as the conversion to alternative land-uses (agriculture and aquaculture), overexploitation for timber, and pollution, for example, due to oil spills, sewerage and pesticides (Valiela et al. 1992; Ellison and Farnsworth 1996; Alongi 2018). Threats due to climate change include those associated with extreme drought (Duke et al. 2017), sea level fluctuations (Lovelock et al. 2017), increased frequency of intense storms (Krauss et al. 2009), and sea level rise (Lovelock et al. 2015). To maintain and restore mangroves in the face of this wide range of threats, conservation and restoration strategies could be supported by a profound understanding of mangrove ecosystem development (Lee et al. 2019). Yet, understanding of the mechanisms giving rise to long-term ecosystem development in mangroves is limited (Lugo 1980; Chen et al. 2015).

An emerging paradigm is that mangroves have the capacity to modify their environment through vertical accretion, which has been stimulated by the need to understand the impacts of rising sea levels and other disturbances, (Cahoon and Lynch 1997; Krauss et al. 2014). Additionally, there are observations that mangrove trees can alter the soil pore water salinity through their influence on water uptake and the interplay of salt excretion, salt exclusion and transpiration (Passioura et al. 1992; Lovelock and Feller 2003). However, there are very few research approaches that explicitly address such dynamics (Bathmann et al. 2020; Peters et al. 2020), yet these examples illustrate that mangrove habitat stability and habitat quality are influenced through plant–soil feedbacks, i.e. the interaction between the plant and its surrounding soil, which may be widespread (McKee et al. 2012). An enhanced understanding of mangrove plant–soil feedbacks in the context of ecosystem response to changing environmental conditions is important because plant–soil feedbacks may influence their role in climate change mitigation and adaptation (Mcleod et al. 2011) and the success of restoration and rehabilitation of degraded mangroves ecosystems to regain their ecosystem services (Lewis 2005).

Here, we describe and explore the nature of the plant–soil feedback mechanisms that have been proposed to occur in mangrove ecosystems. In doing so, we aim to gain insights into ecosystem responses to changing environmental conditions, including the potential for rehabilitating habitat degradation and loss as well as enhancing stability and expansion. Additionally, given that the potential to investigate ecosystem development and its responses to disturbances through empirical approaches are limited (e.g. by the time scales of measurements and spatial constraints on laboratory experiments), we assess how numerical modelling has been used as a tool to understand how mangrove ecosystems respond to changing environmental conditions. Specifically, we provide an overview of the theoretical background of feedback mechanisms and ecosystem stability, examine theoretical studies of positive and negative feedback mechanisms, and elaborate on empirical studies that provide evidence of plant–soil feedbacks in mangrove ecosystems. Finally, we list numerical approaches that are applicable to further investigate plant–soil feedbacks, highlighting shortcomings in the current simulation approaches and suggesting potential solutions.

For this literature review, we reviewed the available literature until June 2020 in the data bases 'Web of Science', 'Scopus' and 'Google Scholar', enabling the total timespan (i.e. 1900—present). First, we searched for empirical studies on plant–soil feedbacks in mangrove ecosystems (keywords listed in SI Table S1). As this search revealed a lack of studies, we additionally searched for specific plant–soil feedback mechanisms based on the feedback components listed by Ehrenfeld et al. (2005). Studies were retained if they describe a plant–soil feedback or a mechanism where either plants alter soil properties or vice versa. Second, we refined the search for models covering the found plant–soil feedbacks in mangroves. For model selection, we focussed on mangrove ecosystems. If no or too few models were found, we stepwise widened the search to coastal wetlands and later terrestrial forests. All models covering the feedback between mangroves and the surrounding soil were selected to be presented here. Non-mangrove models have been classified on their functionality and their popularity (i.e. high citations). Additionally, we aimed to select modelling studies with adaptability to mangrove ecosystems. An overview categorizing all selected studies by their plant–soil feedback is provided in Table 1. As we are interested in providing examples on empirical and numerical plant–soil feedbacks in mangroves, the presented selection provides an overview without the aspiration to be exhaustive.

Feedbacks as drivers for ecosystem dynamics

The interplay of positive and negative feedbacks is important for characterizing the dynamics of ecosystems and defining the response of ecosystems to changing environmental conditions, including those associated with global climate change (Chapin et al. 2009). Moreover, the effects of changing climate may influence the direction and intensity of plant–soil feedbacks which influences ecosystem behavior and development (Pugnaire et al. 2019).

Feedbacks are defined as the "[…] modification or control of a process or system by its results or effects […]" (Oxford University Press 2020). For example, in the context of plant–soil interactions, a change in plant community composition may lead to changes in soil conditions, which in turn affects the plant community, and vice versa.

Table 1 Overview of numerical and empirical studies on plant–soil feedbacks categorized by the soil component the plant interacts with

Plant interacts with	Numerical applications			Empirical evidence in mangrove ecosystem
	Terrestrial forests	Coastal wetlands	Mangrove forests	Mangrove forests
…Soil elevation	–	Fagherazzi et al. (2012) Kirwan and Murray (2007) Kirwan et al. (2008, 2010, 2016) Lago et al. (2010) Morris et al. (2002) Mudd et al. (2009) Rybczyk et al. (1998) Swanson et al. (2014)	Cahoon et al. (2002, 2003) Morris et al. (2019)	Brunier et al. (2019) Cahoon et al. (2003) Hurst et al. (2015) Huxham et al. (2010) Lang'at et al. (2014) Lovelock et al. (2017) Mazda et al. (2002) McKee (2011) McKee et al. (2007) Rogers et al. (2019)
… Porewater salinity	Chen et al. (2004) Janssen et al. (2008) Rietkerk & Koppel (1997)	Liu et al. (2019) Teh et al. (2015) Wang et al. (2007) Zhang et al. (2018)	Bathmann et al. (2020) Peters et al. (2014) Sternberg et al. (2007) Teh et al. (2008, 2013)	Ball (1988) Ball & Pidsley (1995) Cintron et al. (1978) Clough (1984) Hao et al. (2009) Lin et al. (1992) Naidoo (2006) Sherman et al. (2003)
… Chemical and biochemical soil components	Bever et al. (1997) Gbondo-Tugbawa et al. (2001) Herbert et al. (1999) Miki and Kondoh (2002) Miki et al. (2010) Rietkerk and Koppel (1997) Xiao et al. (2019)	Swanson et al. (2014)	Akamatsu and Ikeda (2016) Chen & Twilley (1999) Grueters et al. (2014, 2019)	Feller (1995) Feller et al. (2003, 2009) Liu et al. (2014) Lovelock and Feller (2003) Lovelock et al. (2004, 2009) McKee (1993) Naidoo (2006) Nickerson and Thibodeau (1985) Sherman et al. (1998)

The numerical studies are additionally classified by the ecosystem type (terrestrial, coastal wetland or mangrove)

Most feedbacks are directional. Their sign, i.e. direction is defined by the nature of the feedback mechanism itself, which is either self-decreasing (negative feedback, Fig. 1a) or self-amplifying (positive feedback, Fig. 1b) (Ramaprasad 1983). Since negative feedbacks tend to counteract perturbations, their presence in loop processes is required to stabilize an ecosystem in the presence of environmental noise (Zeng and Wang 2012). In contrast, positive feedbacks amplify or enhance changes that might move away a system from its dynamic equilibrium, destabilizing

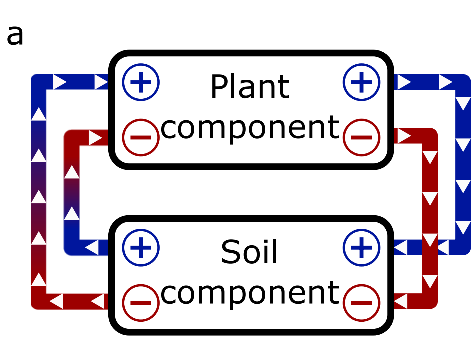

Fig. 1 Illustration for feedback types: **a** Increase in one plant component leads to increase in a soil component, which in turn decreases the plant component. This decreased plant component, in turn, leads to a reduction in the soil component (e.g. Fig. 3b–d). Thus, the negative feedback loop is stabilizing the system parameters. **b** In a dynamic ecosystem state, an increase of a plant component increases the corresponding soil component, which facilitates further increase of the plant component. This positive feedback eventually leads to ecosystem state change (e.g. Fig. 3a)

it which eventually may lead to state shifts (Suding et al. 2004). However, as multiple feedback processes can coexist, not only the presence of feedbacks but also their respective dominance are decisive for the direction. Overall, feedback strength specifies the importance of a feedback relative to other dynamic factors in the ecosystem (Ehrenfeld et al. 2005).

The processes behind plant–soil feedbacks take place on various temporal and spatial scales (e.g. for mangrove see Feller et al. 2010), which can be categorized as short (hours-days, individual plant), intermediate (years to decades, plant population), or long (centuries to millennia, landscape). The number of components and interactions involved define the complexity of a particular feedback (Ehrenfeld et al. 2005).

As negative feedbacks tend to stabilize and positive feedbacks tend to destabilize ecosystem states, their interplay defines the ecosystem dynamics. The existence and implications of alternative quasi-steady states due to positive feedbacks in ecosystems have been well studied in the past (May 1977; Noy-Meir 1975). An ecosystem state is classified as either (i) a dynamic, rapidly changing state, where the individual components or the distribution of components of a system may change, or (ii) a quasi-steady state, where the average properties of components or the distribution of components remain relatively constant over time (Fig. 2). Additionally, various theoretical studies on the transition between alternative quasi-steady states show that state changes are a consequence of positive feedbacks (Scheffer et al. 2001; Scheffer and Carpenter 2003; Rietkerk et al. 2004). Assuming the maintenance of ecosystems in quasi-steady states are dominated by negative feedbacks, then after a disturbance, the system should return to a quasi-steady state configuration, which may be similar to or different from the configuration before the disturbance, depending on the direction and intensity of the feedbacks. Additionally, before reaching the quasi-steady state, the system's properties may be highly dynamic (Scheffer et al. 2009). In the quasi-steady state, the system or its components are providing sufficient levels of

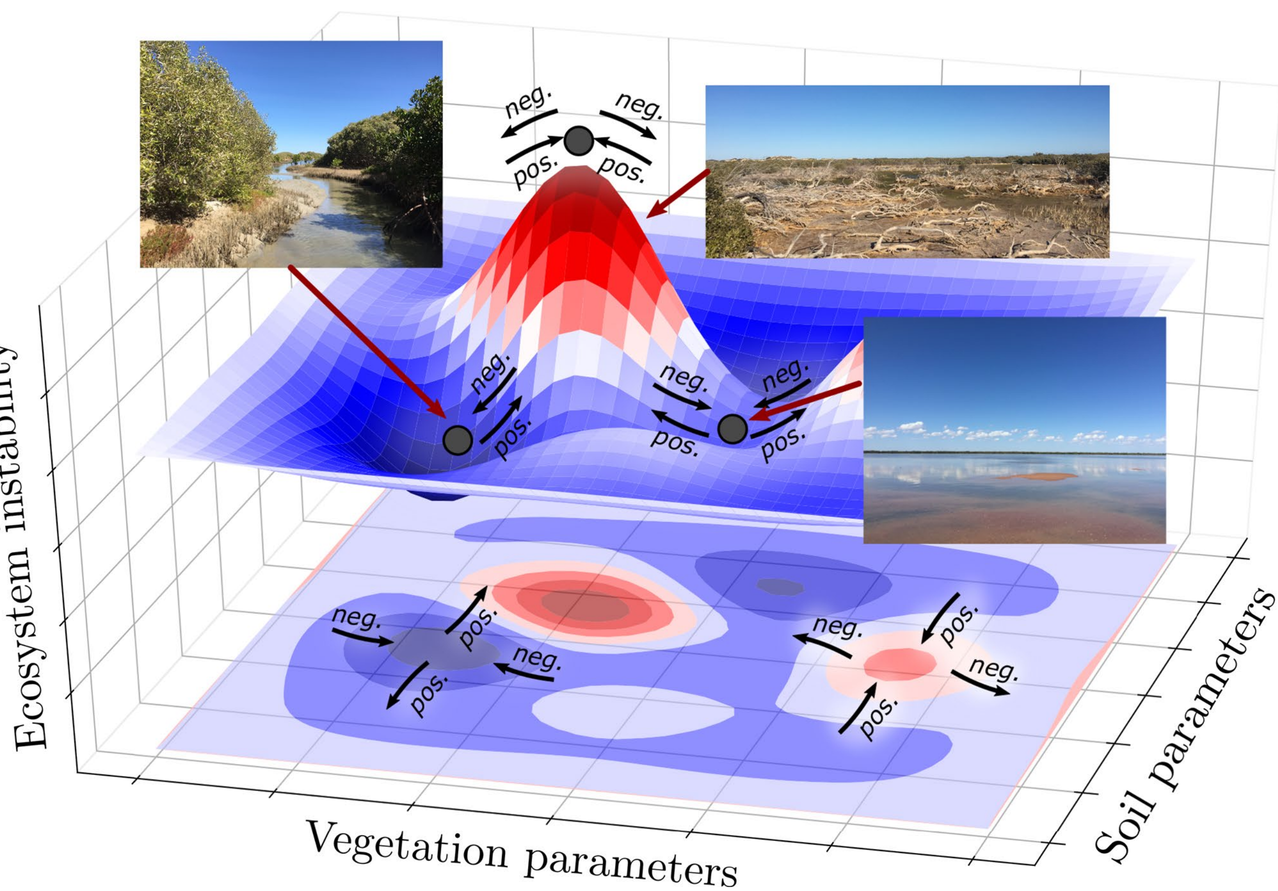

Fig. 2 Illustration of the role of positive and negative feedbacks for ecosystem stability: for each set of soil- and vegetation parameters, the ecosystem stability can be estimated. Negative feedbacks tend to change the parameter set until the system reaches a more stable state, whereas positive feedbacks do the opposite. The valleys in the potential landscape (blue areas) correspond to steady ecosystem configurations. The photographs illustrate mangrove ecosystems in different states, i.e. closed canopy, transitioning and salt flat (left to right), in arid zone mangroves of Northwest Australia

buffering or are able to adapt to perturbations rapidly enough to maintain system properties. The dynamic state, on the other hand, is the result of the intensity of all positive feedbacks and environmental noises overcoming the stabilizing effects of apparent negative feedbacks. Consequently, there is a direct link between the direction and intensity of feedbacks and the transitions between ecosystem states.

Scheffer and Carpenter (2003) highlighted that positive feedbacks are responsible for regime shifts in ecosystems. Over long temporal scales, where the intensity of all feedback effects is destabilizing, the system should eventually merge into a new quasi-steady state (Scheffer et al. 2009). The process is illustrated in Fig. 2: System instability defines a hyperplane within the parameter space, which can be interpreted as a potential landscape. Overall, positive feedbacks can drive the system out of one potential "well" (ecosystem state) into another. For example, extreme drought and altered inundation regimes can result in death of mangroves (Fig. 2). Within the new potential "well", the intensity of all feedback effects becomes stabilizing, e.g. seedling recruitment is inhibited by high levels of evaporation, highly saline conditions and lack of shade. The resulting changes in the environment can be less favourable for individuals of particular species (e.g. mangrove trees compared to cyanobacteria), but may stabilize the ecosystem in another configuration than before the transition (reduced mangrove cover and conditions on salt flats inhibit mangrove recruitment). At this point, negative feedbacks can prevent particular species from outcompeting all others, ultimately avoiding another system change. This in turn increases resilience for the whole ecosystem and provides stability against the effects of external perturbations and stressors (e.g. cyclones, flooding). However, the result of external perturbations and changes in environmental conditions (e.g. climate change effects) may not necessarily lead to a full transition, but might result in changes in habitat characteristics (e.g. scrub mangrove compared to taller mangroves).

An understanding of the nature of feedbacks is therefore crucial to predict the development of ecosystems in the face of climate change. In the past, analyses of feedbacks have identified early warning signals for regime shifts in other ecosystems. Identified early warning signals are, for example, changes in the variability, autocorrelation and recovery times in the response of ecosystems to small perturbations (Rietkerk and van de Koppel 2008; Scheffer et al. 2009; Carpenter et al. 2011). Scheffer et al. (2009) developed a theoretical framework to identify the nature of changes in feedbacks as they approached tipping points. These tipping points are critical turning points, where ecosystems change their states abruptly from one state (e.g. mangrove trees) to another (e.g. salt flat). This theoretical framework was corroborated by Carpenter et al. (2011) with empirical evidence obtained from experimental manipulation of an aquatic food web, which was destabilized by the addition of top predators to a lake over a 3-year period. The warning signals included nonlinear dynamics of zooplankton biomass. For mangrove ecosystems, such an empirical validation of the connection between feedbacks and regime shifts has not yet emerged, but the identification of feedback mechanisms and their understanding is a first step to predicting potential ecosystem state changes. Mangrove state changes of interest include those from mangroves to open water or tidal flats (Asbridge et al. 2019), or from saltmarsh or mud flats to mangrove (e.g. Whitt et al. 2020), or from high diversity mangrove to low diversity ecosystems (Polidoro et al. 2010).

The identification of plant–soil feedbacks in mangrove ecosystems is challenging. Past research on plant–soil interactions was conducted in artificial environments focussed on terrestrial forest species (Putten et al. 2016; De Long et al. 2019). In these studies, the performance of plants growing in their own soil is compared to growth in foreign soil, where their own and foreign soils are defined as soils cultured by the target species or another species, respectively (Pernilla Brinkman et al. 2010). During these experiments, abiotic drivers (De Long et al. 2019) and ecological factors (Ehrenfeld et al. 2005) are removed (or controlled), such that the transfer of findings to the field is challenging. Furthermore, different experimental designs and their statistical analysis to determine the direction and the strength of plant–soil feedbacks differ widely, leading to different interpretations of feedbacks and that studies are essentially not comparable (Pernilla Brinkman et al. 2010). Additionally, feedbacks may act over large spatial and temporal scales (Ehrenfeld et al. 2005), exceeding experimental capacities as well as usual project funding.

In general, it has been suggested that stressful environments have more facilitative interactions among components of ecosystems than competitive ones (Ehrenfeld et al. 2005; Halpern et al. 2007) and that these may underpin a range of stabilizing plant–soil feedbacks. The observation that particular species or groups of species can shape wetland topography to maintain favourable environments for themselves (Silvestri et al. 2005; D'Alpaos et al. 2012; Jiang and DeAngelis 2013) provides evidence that stabilizing feedbacks are important in maintaining coastal wetland communities. In mangrove and other wetland ecosystems, there are high levels of interest in increasing the effectiveness of restoration, for example with the use of facultative "foundation plants" (Yando et al. 2019; Renzi et al. 2019) and thus the exploration of plant–soil feedbacks is both theoretically interesting and of practical importance.

We conclude that the understanding of plant–soil feedbacks provides insights into ecosystem response to their environment. Below we consider plant–soil feedbacks in mangrove ecosystems. We explore how analysis of feedbacks in mangroves can be used to predict ecosystem responses to different disturbances and aid in developing strategies to manage the effects of disturbances and global climate change.

Plant–soil feedbacks in mangroves and applications of numerical modelling

We categorized plant–soil feedbacks in mangroves that are described in the literature as feedbacks between mangrove vegetation and (i) soil elevation, (ii) porewater salinity, or (iii) chemical and biochemical components of the soil. Many of the studies we examined included added complexities due to a wide range of interacting factors (e.g. bioturbation by burrowing animals). However, we focus on examples of feedbacks involving one soil compartment or property (e.g. porewater salinity), rather than a combination of multiple factors (Fig. 3). Where possible, we link the described plant–soil feedback to modelling approaches that have been applied to mangrove ecosystems, or link to appropriate approaches applied to other coastal wetlands or terrestrial habitats. An overview of the studies that have considered plant–soil feedbacks in mangroves, either empirical or modelling studies can be found in Table 1.

Mangrove vegetation and soil elevation

Empirical evidence

Changes in soil surface elevation have been investigated widely in mangroves (e.g. Sasmito et al. 2016 and references within). At the surface of the soil, accretion due to sedimentation and accumulation of organic matter are often the main drivers for elevation change, whereas root growth and decomposition make important contributions to subsurface changes in soil elevation (Fig. 3a; Cahoon et al. 2006; McKee 2011). Variation in soil surface elevation relative to sea level alters the frequency, depth and duration of inundation which influences nutrient and oxygen availability and other soil biogeochemical processes and therefore the growth and composition of the plant community (Twilley et al. 2019).

This process of surface elevation gain in mangroves can stabilize the mangrove ecosystem (negative feedback) as exemplified in Belize and in southwest Florida, where vertical accretion, mainly by root and leaf litter inputs, resulted in less frequently inundated soils (McKee 2011). Growth reduction and partial tree mortality, in turn, reduced surface elevation through decomposition of dead roots and sediment compaction (Lang'at et al. 2014). As a result, the frequency and duration of flooding can increase again which favour tree growth, thereby maintaining a stabilizing feedback loop (Woodroffe et al. 2016).

Mass mangrove tree mortality occurred in Honduras after Hurricane Mitch (Cahoon et al. 2003). In this case, positive feedback loops were observed where the loss in soil elevation due to peat collapse prevented the re-establishment of the same species and favoured the recruitment and growth of other mangrove species (Cahoon et al. 2003). The overall loss of mangrove cover can also lead to transitions to alternative ecosystem states, possibly through reducing suitability for recruitment (Balke et al. 2014; Hurst et al. 2015). Additionally, loss of mangrove cover enhances erosion, which can lead to a further decline in soil elevation (Mazda et al. 2002) and shoreline retreat (Brunier et al. 2019) where mangroves are replaced by mud flats.

Plant–soil feedbacks are also apparent over long time scales (centuries to thousands of years). Correlations of mangrove accretion rates with local mean sea-level rise suggest that mangroves kept pace with sea level rise for periods of the Holocene (Alongi 2008, 2015), which led to the development of large deposits of sediment carbon from mangrove

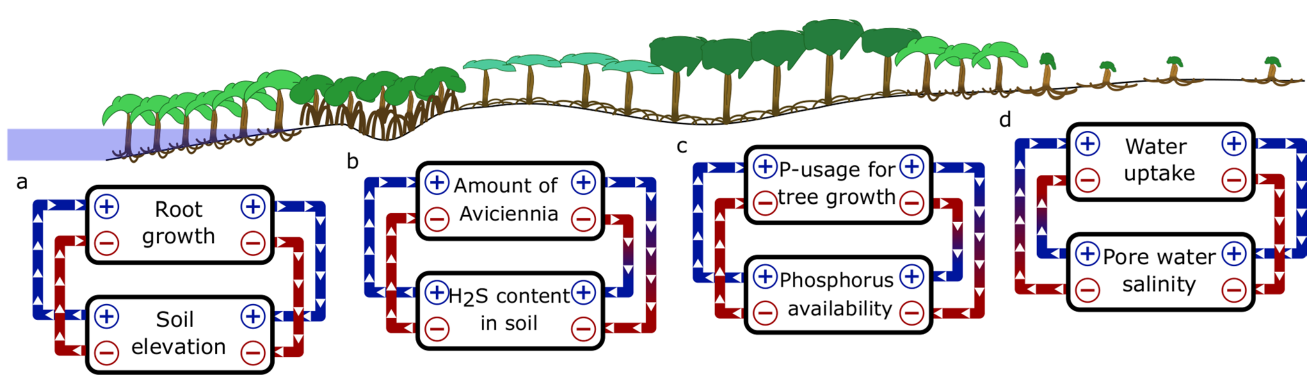

Fig. 3 Schematic representation of a mangrove transect with emerging zonation patterns parallel to the shoreline. Different colours represent different species. The transition between clusters of similar trees provides evidence for underlying plant–soil feedback. Position of the feedbacks in the intertidal cross section of the diagram does not imply that a particular plant–soil feedback is restricted to that position in the intertidal zone. Red and blue colours in the respective plant or soil component represent negative and positive increments, respectively

production (Rogers et al. 2019). However, sediment cores also revealed a decline in mangrove forests with sea level rise that exceeds 6–7 mm/year (Saintilan et al. 2020), unless they can migrate unimpeded onto coastal floodplains (Schuerch et al. 2018), suggesting positive feedbacks occur. The stability of feedback mechanisms, and thus the ability of mangroves to withstand sea level rise, also depends on site-specific conditions that contribute to soil surface elevation change. Sites factors that can influence the intensity and direction of plant–soil feedbacks include flooding intensity (influenced by subsidence associated with geological isostatic adjustments and extraction of oil, gas and water on coastal floodplains), geomorphology, storm frequency, sediment supply, groundwater and nutrients inputs and species composition (Gilman et al. 2008; Krauss et al. 2014; Lovelock et al. 2015; Sasmito et al. 2016). At Twin Cays (Belize), for example, root production is a major factor contributing to elevation change where interior flooded zones with scrub trees have five times lower accretion rates than fringe zones and are therefore more vulnerable to sea level rise (McKee et al. 2007). Both positive and negative plant–soil feedbacks are likely to contribute to the response of mangrove vegetation to climate change, although the relative importance of plant–soil feedbacks and their interactions with climate change factors and human modification of the coastal zone to the overall outcome is yet to be assessed.

Modelling approaches

The models reviewed here have not focussed on plant–soil interactions but have mainly been developed to investigate two objectives: (i) the ecosystem response of coastal wetland vegetation to rising sea levels (e.g. Rybczyk et al. 1998; Morris et al. 2002), and (ii) the spatiotemporal evolution of vegetation and surface topography patterns (e.g. Kirwan and Murray 2007). Predictive models of how coastal wetland ecosystems respond to sea level rise usually include the definition of drivers that describe changes in the modelled system components. Drivers for relative soil elevation changes are often categorized as either from abiotic- and biotic contributions (Fig. 4a). Examples of abiotic contributions are sediment erosion and deposition, whereas biological processes are exemplified by the production of organic matter by roots or the decomposition of leaf litter or peat.

For example, the influence of organic decomposition on relative elevation changes has been conceptualized using the coastal-wetland model of Rybczyk et al. (1998). The model was successfully applied in mangrove ecosystems, establishing the connection between peat collapse and mass tree mortality after Hurricane Mitch on the islands of Guanaja and Roatan, Honduras (Cahoon et al. 2002, 2003).

In 2007, a model to study the spatiotemporal development of tidal marsh platforms and the interwoven channel networks was introduced Kirwan and Murray (2007). The processes of sediment transport and the deposition and erosion of sediments were described in detail, which indicated there were threshold levels of sediment supply that supported the maintenance of marshes with sea level rise. This model considers the contribution of sediment trapping induced by the vegetation but omitted the contribution of other biomass-related processes (e.g. decomposition) to soil surface elevation change which was added later to the model as described below.

Models that considered both the abiotic and the biotic contributions to surface elevation dynamics in coastal wetlands have been developed. In 2002, a conceptual model of marsh elevation change (Marsh Equilibrium Model, MEM) was introduced and validated with field data from Goat Island (USA) (Morris et al. 2002) and which has subsequently been modified for mangroves (Morris et al. 2019). Further modelling work studied marsh stratigraphic response to sediment supply and the rate of sea-level rise (Mudd et al. 2009), the development of wetland topography (Lago et al. 2010), wetland ecosystem resilience to sea level rise (Swanson et al. 2014), and the development of marsh size in response to rising sea level (Kirwan et al. 2016).

Although these models partly rely on empirical relationships (Kirwan et al. 2010), they were able to show that the models qualitatively aligned in predicting the necessary conditions for marsh ecosystems to survive predicted rates of sea level rise. Most of the models above have not been explicitly applied to mangrove ecosystems. However, since the vegetation's response to variations in mean water depth is modelled as empirical relationships (Fig. 4a), a parametrization of the models for different mangrove ecosystems is possible (e.g. Morris et al. 2019).

Mangrove vegetation and porewater salinity

Empirical evidence

Observed patterns in species distribution and structure along salinity gradients provide evidence for feedbacks between porewater salinity and mangrove trees (Fig. 3d). Mangroves must exclude most of the salt in the porewater of the root zone from their transpiration stream to avoid the toxic effects of NaCl on metabolic components (Ball 1988). By excluding salt during their water uptake, mangroves salinize the surrounding soil (Passioura et al. 1992). With increasing soil salinity, photosynthetic rates and thus growth rates decline (Ball 1988). Prediction suggests that by salinizing the soil, trees may eventually limit water uptake and so soil salinity stabilize (Bathmann et al. 2020).

Mangroves in their scrub form are adapted to high salinities and they have higher root to shoot ratios than taller trees (Ball 1988; Hao et al. 2009). The water use efficiency

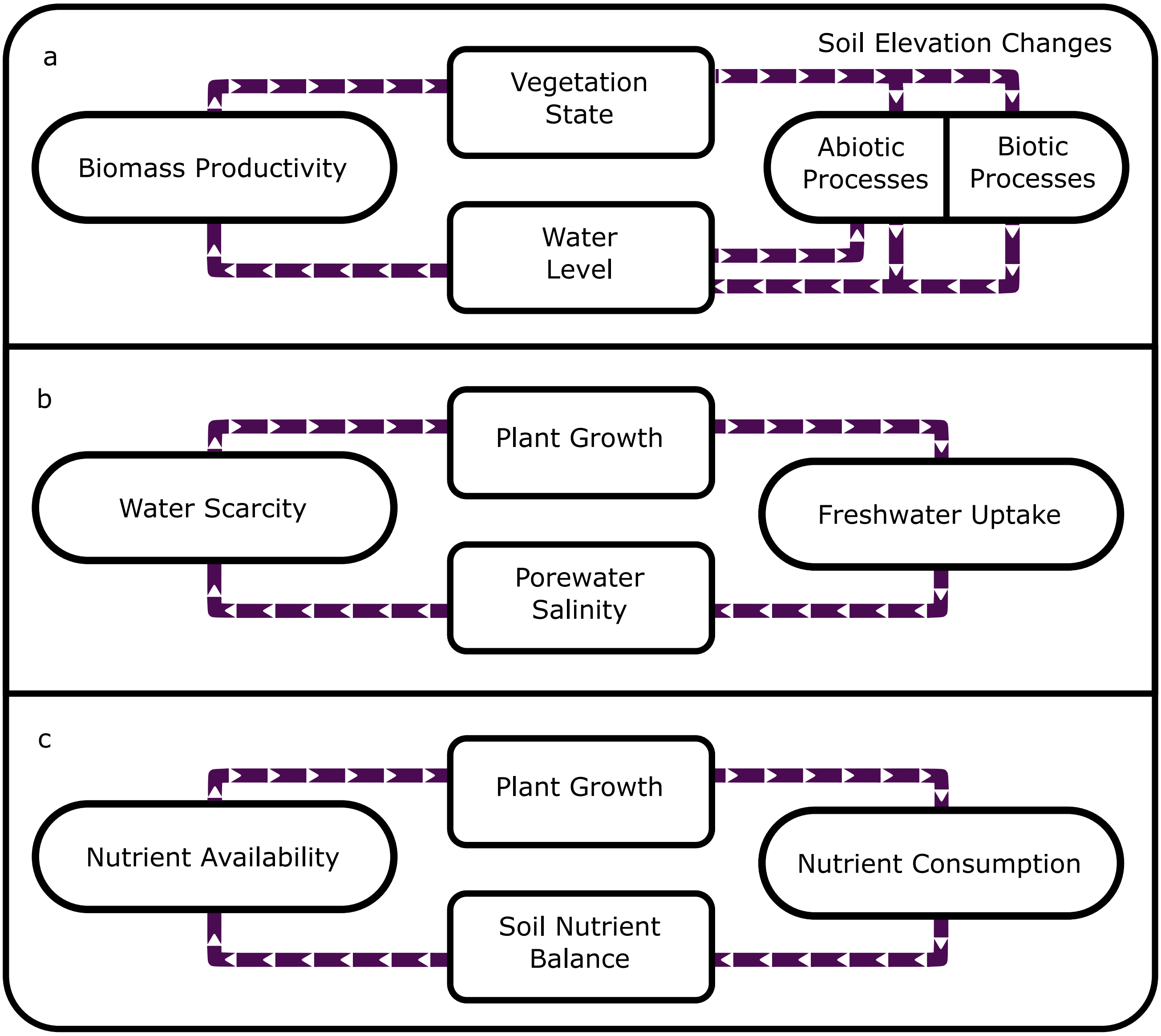

Fig. 4 A simplified schematic representation of modelled feedbacks between **a** vegetation and tidal water levels, **b** plant growth and soil water salinity, and c) plant growth and soil nutrient balance. The coupling of biomass production and soil parameters are often described with state variables that characterise the condition of the respective compartments. The direction of the arrows indicates which process (or status) influences which status (or process)

of scrub trees is higher than in taller mangroves (Lin et al. 1992), and their impact on porewater salinity is also smaller due to their lower water uptake. Therefore, the persistence of scrub (or dwarf) forms observed on the landward fringe of mangrove forests where hypersalinity (> 35 ppt) occurs due to limited tidal inundation and evapotranspiration, could be partially explained by a negative feedback between porewater salinity and tree growth (Fig. 3d, Naidoo (2006)).

However, from the perspective of inter-specific competition, the plant-porewater salinity feedback can be positive. Although mangroves tend to grow rapidly at about 25% seawater (Clough 1984), species vary in their range of salt tolerance (Ball and Pidsley 1995). Hence, a more salt-tolerant species can outcompete a less tolerant species by driving porewater salinity higher (withdrawing more water) and thereby its growth can be maintained at the expense of less salt-tolerant neighbouring species, although effects of canopy shading may also influence biomass and competitive outcomes (Kirui et al. 2012). If the soil salinity exceeds the maximum for mangrove growth high in the intertidal zone, halophytic herbaceous species or cyanobacterial mats eventually replace mangroves (Cintron et al. 1978; Duke et al. 1998).

Modelling approaches

Numerical models that investigate feedback mechanisms between vegetation and porewater salinity in mangrove ecosystems can be categorized by the spatial scale of the model and the level of detail incorporated within the models. There are regional models (Zhang et al. 2018; Liu et al. 2019), site-specific models (Sternberg et al. 2007; Teh et al. 2008, 2013, 2015) and models which describe the interactions on the scale of individual plants (Bathmann et al. 2020). Different scales of the models tend to incorporate different levels of detail. For example, at large scales, course-grained hydrological model tend to have no plant-specific details, mesoscale models often incorporate coarse-grained plant responses, while at small spatial scales high levels of detail can be included. For example, the fine-scale model of Bathmann et al. (2020) focusses on the plant's freshwater uptake, while the models of Liu et al. (2019) and Teh et al. (2015) focus on water scarcity in the soil (Fig. 4b).

The regional models of vegetation-porewater salinity feedbacks do not explicitly explore plant water use, but are used to predict the dynamics of porewater salinities on regional scales. This can help to understand the impacts of regional changes in water availability, which are predicted to vary as a consequence of climate change on ecosystem processes. For example, Zhang et al. (2018) used a detailed hydrological model to connect hydrological processes on the surface and the subsurface to inform how hydrological regimes in coastal wetlands influence the energy budgets and evapotranspiration of vegetated patches. The model developed by Liu et al. (2019) extended this idea through the incorporation of abiotic transport and accumulation processes to understand the dynamics of porewater salinity within the soil of coastal wetlands.

Site-specific models investigate the response of ecosystems within sites to changing environmental conditions. The Variable Water Table Salinity (VWTS) model coupled the transpiration rates of mangroves to variation in porewater salinity (Sternberg et al. 2007). Starting from a simplified model for both vegetation and soil water dynamics, the VWTS model has been extended to include horizontal diffusion of porewater (Teh et al. 2008). This idea was further developed by replacing this continuous vegetation model with an individual-based plant model, which was coupled with the United States Geological Survey groundwater model SUTRA (saturated–unsaturated transport), which describes the porewater salinity dynamics in a mechanistic manner (Teh et al. 2013). The resultant mangrove transport model (MANTRA) has been successfully applied to predict patterns of coastal vegetation zonation (patches of freshwater hammocks and mangrove trees) in the Everglades (Florida) caused by variation in porewater salinity resulting from sea level rise and storm surges (Teh et al. 2015).

Further improvements in the explicit incorporation of mangrove-porewater salinity feedbacks have been made through the introduction of a mechanistic feedback model (MANGA, Bathmann et al. 2020). MANGA coupled a process-based flow and transport groundwater model, which described porewater salinity changes (OpenGeoSys Version 6, www.opengeosys.org) to an individual-based mangrove model (BETTINA, Peters et al. 2014)) that incorporates plant water use. This coupled model suggested that plant–soil feedbacks contribute to maintaining mangrove tree forms (scrub vs. taller) and species zonation patterns (Bathmann et al. 2020, 2021).

Mangrove vegetation and the biogeochemistry of soils

Empirical evidence

There is evidence that altered nutrient levels and forms of nutrients can cause both negative and positive feedbacks on mangrove vegetation, as has been widely observed in terrestrial forests (Tilman 1987; Vitousek et al. 1997). Fertilization of mangroves with nutrients can have strong positive effects on their growth (Fig. 3c; Lovelock et al. 2004; Feller et al. 2009). In Belize, a gradient in nutrient availability from the seaward edge to inland parts of a mangrove island were observed, where nitrogen (N) limitations on growth tended to occur near the shoreline while in scrub mangroves in the landward position phosphorus (P) limited tree growth (Feller et al. 2003). In this case, a negative feedback loop maintains the small (<2 m tall) scrub form of these trees as available P is taken up and used for growth by fringing trees, which reduces P availability in soils which further feedbacks on growth (Feller 1995). Similar patterns of nutrient-limited scrub forests have been widely observed (Naidoo 2006; Feller et al. 2009; Lovelock et al. 2009) as well as differential sensitivity of mangrove species to nutrient availability (Lovelock and Feller 2003), which suggests widespread negative feedbacks that may influence the structure of mangroves and species composition. The addition of nutrients, either through human influences (Valiela et al. 1992; Valiela and Cole 2002), deposition during storms (Smoak et al. 2013) or through species-specific litter production and composition rates (Sherman et al. 1998; Liu et al. 2014) can alter the strength or direction of these feedbacks.

Microbial processes in soils can also contribute to plant–soil feedbacks. A "semi-cyclic succession" of *Rhizophora mangle* and *Avicennia germinans* has been hypothesized due to differences in species tolerance to hydrogen sulphide (H_2S), a natural phytotoxin that is produced by bacteria under anoxic soil conditions (Fig. 3b; Nickerson and Thibodeau 1985; McKee 1993). Although sulphide concentrations measured within the root systems of both species were low, the concentration of H_2S in the surrounding unvegetated soil was approximately five times higher for *A. germinans* than in *R. mangle*, and thus Nickerson and Thibodeau (1985) hypothesized that *A. germinans* releases oxygen from its roots which oxidizes the surrounding soil, thereby removing H_2S. As a result of this feedback, *A. germinans* can grow in areas with higher H_2S gas concentration but in doing so, they lower the concentration of H_2S in the soil. Consequently, as trees of *A. germinans* are established, the environmental conditions become more suitable for the establishment and growth of *R. mangle*.

Modelling approaches

Despite the empirical evidence of mangrove-soil biogeochemical feedbacks, the available models for vegetation-nutrient dynamics in mangrove ecosystems are limited. We therefore first discuss models that describe nutrient dynamics within mangrove soils (Fig. 4c, "Nutrient Consumption"). Secondly, models describing the effect of nutrient availability on mangrove plant growth are presented (Fig. 4c, "Nutrient Availability"). Finally, we discuss modelling approaches from the terrestrial ecosystem, where full feedback loops have been described (Fig. 4c).

In the late 1990s, Chen and Twilley (1999) developed the NUMAN (Nutrient in Mangroves) model which describes the nitrogen and phosphorus balance in a 60-cm-deep soil profile of mangrove ecosystems, but which does not include the effect of changing nutrient availability on plant growth. This model was used to describe the mechanisms that resulted in the observed accumulation of carbon and nutrient in mangrove soils along gradients of mangrove productivity. Recently, more detailed nutrient dynamic models have been developed that incorporated the coupling of groundwater flow and nutrient cycling (movement) in mangroves (Akamatsu and Ikeda 2016). While these models described the apparent development of nutrient and carbon concentrations within the soil, the explicit description of a feedback mechanism affecting mangrove growth was not included.

The individual-based mangrove forest model, mesoFON, considered the implications of nutrient availability within soils on mangrove growth dynamics (Grueters et al. 2014). In 2019, this model was calibrated and successfully parametrized for *Rhizophora apiculata* in Malaysia (Grueters et al. 2019). Although an effect of the available nutrients on tree growth was described within mesoFON, the description of the potential feedback of the plants' nutrient use on the soil nutrient balance was not included. However, the authors emphasized the importance of explicitly considering the interplay (i.e. feedbacks) between mangrove growth models and other biochemical processes within the ecosystem.

Some models of plant–soil feedbacks in terrestrial ecosystems are particularly relevant for application to modelling plant–soil feedbacks in mangrove ecosystems. The multi-element limitation model (MEL) couples biomass production rates to nitrogen availability in forests (Herbert et al. 1999) and could be adapted for use in mangrove ecosystems. A model that included the effects of the different microbial communities on the decomposition of leaf litter, nutrient availability and its subsequent effects on plant growth and plant community composition was developed by Miki and Kondoh (2002). Differences in communities of microbial decomposers and their effects on rates of plant litter decomposition have been added to this model further enhancing the detailed mechanisms by which microbial communities influence nutrient availability (Miki et al. 2010). Using this model, the authors were able to show the importance of microbial communities on plant–soil nutrient feedbacks. Another approach, which includes different vegetation types as well as microbial communities, suggested a mathematical framework to connect plant–soil nutrient feedbacks to competition among plant species (Bever et al. 1997). Bever et al.'s model has been further extended by a factor that describes interspecific plant–soil nutrient feedbacks (Xiao et al. 2019). Through the development of this detailed model, these authors were able to show the emergence of communities of different plant species compositions, which depended on the soil microbial communities. These terrestrial models for plant–soil feedbacks only account for a small amount of the studies available in the literature, but they provide an indication of the wide range of different plant–soil feedback models and their usability for further investigating plant–soil feedbacks in mangrove ecosystems in response to changing environmental conditions.

Implications for ecosystem resilience

Mangroves are threatened by a range of climate change effects and anthropogenic interventions (Friess et al. 2019) and therefore require management, including those focussed on conservation and restoration (Lewis et al. 2016). As these changes affect both, the composition of plant and soil communities (Pugnaire et al. 2019), the study of plant–soil feedback mechanisms and their relation to ecosystem stability may provide the means to explore tipping points in state transitions of mangroves and other coastal wetlands, even if empirical detection of tipping points is unlikely (Hillebrand et al. 2020).

There is evidence that plant–soil feedbacks shape mangrove ecosystems in both empirical and numerical studies. Knowledge of feedbacks is particularly developed and useful for understanding mangrove resilience in the face of sea level rise, which is of major global concern. Detailed descriptions of surface and subsurface processes involved in surface elevation changes are available for a wide range of sites (Lovelock et al. 2015), and theoretical outlines of the mechanisms involved in the feedback process of soil elevation changes in mangroves as a response to changing sea level are also available (McIvor et al. 2013). The development of models based on those for saltmarshes (e.g. Morris et al. 2002) that explicitly incorporate plant–soil feedbacks could be used to explore changes in variability, levels of autocorrelation among parameters and recovery times from small-scale disturbances with increasing rates of sea level rise, as they approach the proposed ~ 7 mm/year threshold (Saintilan et al. 2020). Assessing indicators of ecosystem transitions with sea level rise could help to build understandings of the processes operating prior to mangrove loss.

Incorporating plant–soil feedbacks associated with nutrient and carbon cycling within mangrove models could result in increases in understanding mangroves' role in carbon sequestration (blue carbon) and nutrient retention as well as the consequences of anthropogenic changes. Despite early progress in this field (Chen and Twilley 1999) and growing empirical data, models that incorporate plant–soil biogeochemical feedbacks are limited in their development and application, which given the growing knowledge of the role of mangroves to climate change mitigation (Mcleod et al. 2011) is a clear knowledge gap.

The proposed plant–soil porewater salinity and biogeochemistry feedbacks that we have examined (above) may interact with other environmental factors that could limit the strength of the feedbacks, which could be further explored using models. For example, hydrological processes may superimpose or reinforce single feedbacks in mangrove ecosystems. The strength of the interaction between porewater salinity and plant growth, for example, may be strongly influenced by the hydrological regime as nutrient delivery is altered or salt is diluted and leached (Hayes et al. 2019). The interplay of hydroperiod regime, salinity and vegetation has been observed in Colombia where the construction of a road led to the disturbance of the natural hydrological system (Röderstein et al. 2014): the reduced freshwater inflow led to a higher salinity and thus to a decline in mangrove cover. However, after the hydrological connection was restored, mangrove vegetation recovered. A process-based model built from such a priori knowledge (e.g. from existing empirical observations) would allow to test a variety of hypotheses with simulation experiments and to incorporate the findings in the experimental design. Subsequently, the model could be modified, such that the underlying mechanisms are disabled to investigate their impact (Bathmann et al. 2020, 2021). We hypothesize, that this approach would reveal the regimes, where specific feedbacks contribute to emerging ecosystem properties such as mangrove zonation. Additionally, ecosystem response to changing environmental conditions such as increased precipitation or periods of drought could be analysed by variation of the model setup according to predicted changes in environmental conditions. This includes, but is not limited to, cascading effects of single actions such as the installation of impoundments or the cutting of trees. This approach might even reveal yet unknown early warning signals for drastic ecosystem state changes (Scheffer et al. 2009) in mangroves such as mass tree mortality which has been observed in northern Australia (Duke et al. 2017; Lovelock et al. 2017).

Additionally, models can accommodate the investigation of complex interactions to focus on the implications of specific plant–soil feedbacks. Examples for a plant litter decomposition-nutrient availability feedback (Grueters et al. 2019) or a mechanistic plant water use-porewater salinity feedback (Bathmann et al. 2020) model are already available in the literature. Consequently, hypotheses on the mechanisms driving feedbacks derived from empirical findings could be tested using these numerical models. The combination of models and experiments allows assessment of the relative strength of different feedbacks, when multiple feedbacks are apparent in a system (Bathmann et al. 2020, 2021), which could further add to the knowledge of mangrove resilience in the face of environmental change.

Conclusions

The extent of the resilience of mangroves to climate change and other disturbances is important for the maintenance of ecosystem services that communities derive from mangroves. There is both empirical and theoretical evidence that plant–soil feedbacks play a crucial role in maintaining mangrove ecosystem stability. An enhanced understanding of the plant–soil feedbacks that underlie the stability of mangroves, as well as the characteristics that may indicate impending state transitions for mangroves will allow better prediction of the fate of mangroves in response to climate change and thus enhance the capacity to manage mangrove ecosystem dynamics in the future. Exploration of models that describe feedbacks between plants and soil elevation, porewater salinity and nutrient biogeochemistry will provide novel insights into mangrove ecosystem stability in the future.

Author contribution statement All authors contributed to the idea and the revision of the manuscript. JB and MCW performed the literature search and drafted the manuscript and thereby equally shared first-author responsibilities. CL, JJ, MW, RP and UB contributed to the discussion and revision of the manuscript.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00468-021-02182-z.

Acknowledgements This study was financed by the TU Dresden by fellowships for CL and JJ in the frame of the Winter School MARZIPAN 2018. JB was financed by German Research Foundation (DFG, Project Number 398759560) and MCW was financed by the Volkswagen Foundation (Volkswagen Stiftung, Project Number 94 844).

Funding Open Access funding enabled and organized by Projekt DEAL. See acknowledgements.

Availability of data and material Not applicable.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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ARTICLES FOR FACULTY MEMBERS

MANGROVE RESTORATION TOWARDS SUSTAINABLE COASTAL ECOSYSTEM MANAGEMENT

Title/Author	**Remote sensing-based assessment of mangrove ecosystems in the Gulf Cooperation Council countries: A systematic review / Rondon, M., Ewane, E. B., Abdullah, M. M., Watt, M. S., Blanton, A., Abulibdeh, A., Burt, J. A., Rogers, K., Ali, T., Reef, R., Mohtar, R., Sidik, F., Fahrenberg, M., de-Miguel, S., Galgamuwa, G. A. P., Charabi, Y. A. R., Arachchige, P. S. P., Velasquez-Camacho, L. F., Al-Awadhi, T., … Mohan, M.**
Source	***Frontiers in Marine Science*** **Volume 10 (2023) Pages 1-21** **https://doi.org/10.3389/fmars.2023.1241928** **(Database: Frontiers)**

TYPE Systematic Review
PUBLISHED 20 November 2023
DOI 10.3389/fmars.2023.1241928

Remote sensing-based assessment of mangrove ecosystems in the Gulf Cooperation Council countries: a systematic review

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RECEIVED 17 June 2023
ACCEPTED 23 October 2023
PUBLISHED 20 November 2023

CITATION
Rondon M, Ewane EB, Abdullah MM, Watt MS, Blanton A, Abulibdeh A, Burt JA, Rogers K, Ali T, Reef R, Mohtar R, Sidik F, Fahrenberg M, de-Miguel S, Galgamuwa GAP, Charabi YAR, Arachchige PSP, Velasquez-Camacho LF, Al-Awadhi T, King S, Srinivasan S, Jaafar WSWM, Montenegro JF, Karakasidou E, Pons J, Abbady MJ, Cardil A, Doaemo W and Mohan M (2023) Remote sensing-based assessment of mangrove ecosystems in the Gulf Cooperation Council countries: a systematic review. *Front. Mar. Sci.* 10:1241928. doi: 10.3389/fmars.2023.1241928

Mangrove forests in the Gulf Cooperation Council (GCC) countries are facing multiple threats from natural and anthropogenic-driven land use change stressors, contributing to altered ecosystem conditions. Remote sensing tools can be used to monitor mangroves, measure mangrove forest-and-tree-level attributes and vegetation indices at different spatial and temporal scales that allow a detailed and comprehensive understanding of these important ecosystems. Using a systematic literature approach, we reviewed 58 remote sensing-based mangrove assessment articles published from 2010 through 2022. The main objectives of the study were to examine the extent of mangrove distribution and cover, and the remotely sensed data sources used to assess mangrove forest/tree attributes. The key importance of and threats to mangroves that were specific to the region were also examined. Mangrove distribution and cover were mainly estimated from satellite images (75.2%), using NDVI (Normalized Difference Vegetation Index) derived from Landsat (73.3%), IKONOS (15%), Sentinel (11.7%), WorldView (10%), QuickBird (8.3%), SPOT-5 (6.7%), MODIS (5%) and others (5%) such as PlanetScope. Remotely sensed data from aerial photographs/images (6.7%), LiDAR (Light Detection and Ranging) (5%) and UAV (Unmanned Aerial Vehicles)/Drones (3.3%) were the least used. Mangrove cover decreased in Saudi Arabia, Oman, Bahrain, and Kuwait between 1996 and 2020. However, mangrove cover increased appreciably in Qatar and remained relatively stable for the United Arab Emirates (UAE) over the same period, which was attributed to government conservation initiatives toward expanding mangrove afforestation and restoration through direct seeding and seedling planting. The reported country-level mangrove distribution and cover change results varied between studies due to the lack of a standardized methodology, differences in satellite imagery resolution and classification approaches used. There is a need for UAV-LiDAR ground truthing to validate country-and-local-level satellite data. Urban development-driven coastal land reclamation and pollution, climate change-driven temperature and sea level rise, drought and hypersalinity from extreme evaporation are serious threats to mangrove ecosystems. Thus, we encourage the prioritization of mangrove conservation and restoration schemes to support the achievement of related UN Sustainable Development Goals (13 climate action, 14 life below water, and 15 life on land) in the GCC countries.

KEYWORDS

mangrove distribution and cover, mangrove forest classification, remote sensing, mangroves and climate change, mangrove afforestation, mangrove ecosystem services, machine learning, Arabian Gulf

Highlights

- Few remote sensing studies have focused on mangrove forests in GCC countries.
- A survey of 58 studies found that mangrove forest parameters were mainly estimated from Landsat images (75.9%).
- LiDAR (5.2%) and UAV (3.4%) imagery were the least used compared to other high resolution satellite remote sensing data sources.
- Mangrove cover in GCC countries decreased, remained stable or increased from 1996 and 2020, attributed to reforestation and afforestation efforts.
- Visual digitization and interpretation (46.6%) and machine learning (25.9%) techniques were the most commonly used mangrove classification approaches.

1 Introduction

Global mangrove forests provide important ecosystem services that are critical for the environment and human well-being. These include climate regulation through carbon sequestration, water purification through filtering and pollutant retention, nutrient cycling, provision of livelihoods, soil erosion control, coastal protection, and habitat provision (Bunting et al., 2022; Hagger et al., 2022). Global mangroves are recognized as carbon-rich tropical ecosystems (Donato et al., 2011), estimated to mitigate more than 25.5 million carbon tonnes annually and supply 10% of the vital liquefied carbon in the world's oceans (Khader, 2023). In general, healthy mangroves can store about 21 gigatons of carbon, the equivalent to three years of greenhouse gas (GHG) emissions from a nation like Australia, while restored degraded mangroves could lead to the sequestration of an additional 1.3 gigatons on a global scale (Spalding and Leal, 2021). Thus, mangrove ecosystems are now considered a high-priority conservation target for large scale international conservation initiatives such as the International Blue Carbon Initiative and the Global Mangrove Alliance. These ecosystems are increasingly incorporated into the Nationally Determined Contributions of countries to meet their pledges to the Paris Agreement of the United Nations Framework Convention on Climate Change (Friess et al., 2020).

Mangroves exist in complex social-ecological systems around the world, and local economic pressures and biophysical drivers impact the condition of these mangrove forests (Goldberg et al., 2020; Hagger et al., 2022). Mangroves are disappearing three to five times faster than other forests, which is resulting in severe ecological and socio-economic challenges (Friess et al., 2020). From 1996 to 2020, more than 5, 245 km^2 (about 3.4%) of mangrove cover has been lost due to expansion of urban development, agriculture, and aquaculture in coastal environments (Bunting et al., 2022). Advances in remote sensing technologies have allowed us to quantify losses in mangrove cover due to anthropogenic stressors and characterize land use changes with high accuracy and precision (Goldberg et al., 2020; Bunting et al., 2022).

Mangroves in the Gulf Cooperation Council (GCC) countries are resilient evergreen forest ecosystems that are well adapted to the extreme environmental conditions of high temperatures and hypersalinity found in this region that make it hard for other forest ecosystems to thrive (Friis and Burt, 2020; Getzner and Islam, 2020). As a consequence of these environmental extremes, only two mangrove species - namely *Avicennia marina* and *Rhizophora mucronata* - commonly called gray and red mangrove, respectively, have been reported to flourish in the GCC countries (Almahasheer, 2018). They represent the dominant tree species resilient enough to grow and endure the extremely dry climates of the GCC countries, leading to the development of a unique vegetation habitat (Elsebaie et al., 2013; Almahasheer, 2018). Mangroves in the GCC countries tolerate temperatures of up to 47°C, water temperatures of up to 22-34°C, and water salinity of up to 44% (Elsebaie et al., 2013; Monsef et al., 2013). It was reported that *A. marina* grows naturally in all of the GCC countries, while *R. mucronata* was reported to grow over the Red Sea coast in Farasan Kabir and Kamaran Islands of Saudi Arabia (Kumar et al., 2010; Alwhibi, 2017). *R. mucronata* also grows in the waters of Ras Ghanada Island in the UAE, following a successful reintroduction effort by the Environment Agency-Abu Dhabi (Milani, 2018). In Qatar, mangrove height and tree density have been found to range between 0.6-6 meters and 1,000 to 2,600 trees/ha, respectively (Al-Khayat and Balakrishnan, 2014). Measurements obtained from the field and analyzes of leaves or sediments can complement remote sensing data in characterizing the status of mangrove communities within the GCC as shown by multiple studies (Al-Ali et al., 2015; Moore et al., 2015; Alwhibi, 2017).

Mangroves are the only naturally-occurring evergreen forest in the GCC countries and hold great importance because of the ecosystem services they provide (Friis and Burt, 2020). Mangroves in the GCC countries represent only a small fraction (0.11%, 147,359 km^2) of the total global mangrove area in 2020 (Bunting et al., 2022). They are found along the coastal shorelines of the Red Sea, Arabian Sea, Arabian Gulf, and Gulf of Oman, and these areas are located in Saudi Arabia, UAE, Qatar, Oman, Bahrain, and Kuwait. Among these countries, Saudi Arabia and the UAE have the largest mangrove forest area, which in combination constitute more than 95% of the total mangrove cover in the GCC countries (Bunting et al., 2022).

The importance of mangrove ecosystems for climate change mitigation is well documented as they sequester carbon more efficiently than other terrestrial forest ecosystems and consequently are considered important long-term carbon sinks (Alongi, 2020; Al-Nadabi and Sulaiman, 2021; Abd El-Hamid et al., 2022a; Aljenaid et al., 2022). Mangroves represent one of the most important 'blue carbon' ecosystems in this arid region (Schile et al., 2017; Cusack et al., 2018; Bukoski et al., 2020; Macreadie et al., 2021) and at the global level for climate change mitigation and adaptation (Duarte et al., 2013; Alongi, 2020). The carbon sequestration potential of mangroves is of particular importance for many countries within the GCC countries, which include some of the highest per capita greenhouse gas emitters in the world. During 2019, carbon emissions in metric tons (tCO_2e) per capita were very high for Qatar (32.47 tCO_2e), Kuwait (22.02 tCO_2e), Bahrain (20.26 tCO_2e), Saudi Arabia (15.28 tCO_2e), Oman (15.29 tCO_2e), and UAE (19.33 tCO_2e) (Climate Watch, 2022). This is tied to the socio-economic landscape of the GCC countries that has been progressively characterized by the development of the oil and gas industry and urban development at the detriment of mangrove conservation (Burt and Bartholomew, 2019; Vaughan et al., 2019).

Consequently, protection, conservation and restoration initiatives are of high interest for these countries as mangrove forests can be used to offset, for example, part of national oil and gas company emissions through carbon market mechanisms (Macreadie et al., 2021). Thus, progressive efforts have been made by the governments of Oman, United Arab Emirates (UAE), Qatar, Bahrain, and Saudi Arabia, especially post-2000 to expand and implement mangrove restoration and conservation programs (Milani, 2018). Most recently, the UAE through Abu Dhabi's Environment Agency and Abu Dhabi National Oil Company (ADNOC) began plans to plant up to 10 million mangrove seedlings in Abu Dhabi by 2030 (ADNOC, 2023). However, long-term sustenance and adaptive management of these restoration initiatives is important to ensure climate-related outcomes are realized.

Despite ongoing restoration since the 1980s, and more extensively in recent years, *A. marina* along the Qatar coastline (at Simaisma, Al Thakhira, Al Khor, and Fuwairit) are threatened due to the escalating scale of coastal development and an expanding tourism industry (Al-Khayat and Balakrishnan, 2014; Burt et al., 2017). Environmental hazards are exacerbated by climate change, including, but not limited to, sea-level rise, recurrent hypoxia, a shortage of fresh water, extreme storm surges, increasing wave energy, drought, flooding, inundation and erosion (Lincoln et al., 2021; Melville-Rea et al., 2021; Lachkar et al., 2022). It is important to assess the potential impacts of these threats so that management efforts can be undertaken to adapt and minimize their impacts (Babu et al., 2012; Bahrawi and Elhag, 2016; Hereher, 2016; Hereher and Al-Awadhi, 2019). Thus, developing a conceptual understanding of the extent and the severity of the impacts of the direct and indirect threats that lead to loss of mangrove cover, is important to develop strategies and actions (Rittenhouse, 2017). Because this mangrove ecosystem is very unique, there is a need to characterize its current status and the additional biophysical and anthropogenic pressures it endures.

Efforts to map, monitor and model mangrove restoration opportunities using remote sensing techniques can greatly improve the success of restoration programs (Monsef et al., 2013). Previous studies in the GCC region have used remote sensing data to quantify mangrove distribution and cover, temporal gain or loss of cover, ecological state of mangrove ecosystems (Elsebaie et al., 2013; Alsumaiti et al., 2019; Butler et al., 2020; Butler et al., 2021; Aljenaid et al., 2022), and the influence of physical and chemical properties of seawater, soil and geomorphology on the site suitability for mangrove restoration projects (Elsebaie et al., 2013; Alsumaiti, 2017; Butler et al., 2020; Butler et al., 2021; Aljenaid et al., 2022).

The Global Mangrove Watch (GMW) provides useful baseline data around current mangrove extent within the GCC. During 2020, GMW detected mangrove cover within five of the six GCC countries, but mangroves were not detected in Kuwait (Figure 1). Between these countries, Saudi Arabia (77.1 km^2) and the UAE (74.4 km^2) account for the largest areas, while Qatar (4.5 km^2), Bahrain (0.6 km^2) and Oman (1.4 km^2) have smaller mangrove areas (Bunting et al., 2022). Kuwait is the only country in the region that has no natural mangrove forest. Plantation establishment experiments have been undertaken in Kuwait since 1968 using *A. marina* and have reportedly been successful since 2001 (Milani, 2018), evidenced by a reported area of 0.58 km^2 of mangrove cover in 2017 (Almahasheer (2018). The discrepancy between mangrove cover in Kuwait, reported in various sources, is highlighted by (Guo et al., 2021) as their method provides results for 1990, 2000, 2010 and 2015 while FAO, GMW and WCMC (the Global Distribution of Mangroves study executed by USGS in 2011) do not.

Based on the data released by GMW (Bunting et al., 2022), Qatar is the only GCC country in which the mangrove forest extent increased between 1996 and 2020 (by 0.26 km^2). For Bahrain and Oman, estimated losses were 0.04 km^2 and 0.24 km^2, respectively, over this time period. Area changes in Saudi Arabia and UAE were similar, with area peaking in 2008, declining until 2016, and then slightly increasing until 2020. Over the period from 1996 to 2020, there were losses in mangrove extent in Saudi Arabia and UAE of 23 km^2 and a near-negligible 1.38 km^2, respectively (Figure 1).

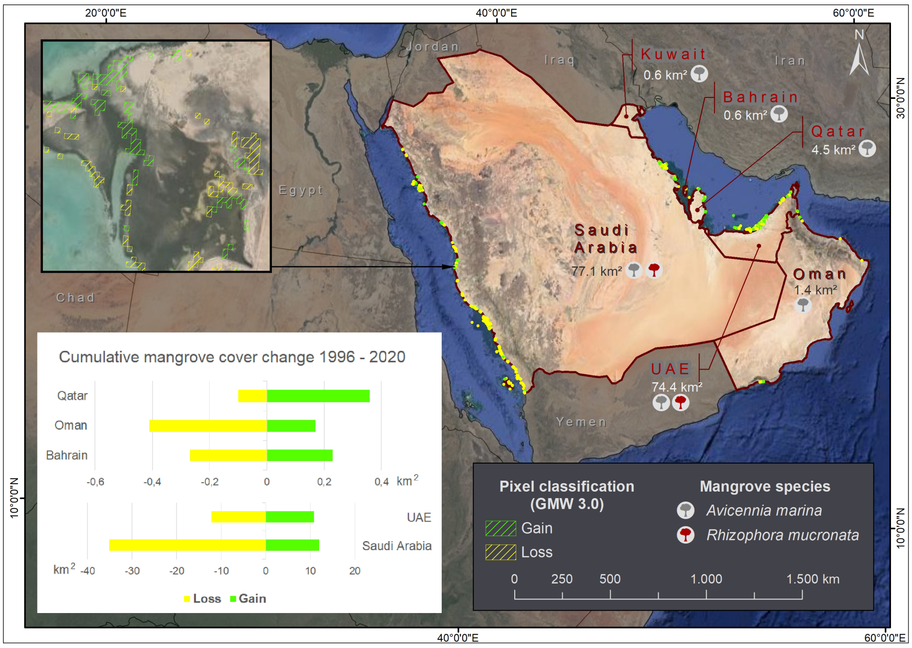

FIGURE 1
Location of mangrove forest and area determined by GMW 3.0. Green pixels represent gain in mangrove cover and yellow is used for loss in a comparison between 1996 and 2020. The cumulative change for Qatar, Oman and Bahrain is below 1 km^2 while UAE and Saudi Arabia are over 10 km^2. *A. marina* is present in all GCC countries while *R. mucronata* can only be found in Saudi Arabia and UAE.

While remote sensing has been increasingly used as the primary data source for delineating mangrove distribution, cover and habitat in the GCC countries, there are often variations in characteristics of these data (e.g. spectral, spatial and temporal resolution) that can influence estimates. Thus, the importance of fieldwork that provides ground truth data to validate satellite data and the opportunity to consult local and community experts cannot be overlooked, particularly for local scale studies (Mateos-Molina et al., 2020). Importantly, studies that combine field and remote sensing data are important to accurately represent mangrove ecosystems and their dynamics (Howari et al., 2009), including, for example, the sensitivity of range limits to climate variability, deforestation or regeneration rates and assessments of biomass and carbon stocks (Ximenes et al., 2023). However, no study has reviewed remote sensing-based assessments of mangrove ecosystems for the entire GCC region, advantages and limitations of different remotely sensed data types, and the measured mangrove characteristics that are important for climate change mitigation.

In this study, we undertook a comprehensive analysis of the remote sensing-based mangrove studies published from 2010 to 2022 in the GCC countries. Our objectives were to 1) examine the temporal and spatial distribution of the reviewed articles, 2) the most widely estimated mangrove forest parameters, 3) the vegetation indices/metrics that are used to classify mangrove forests, and 4) the remote sensing data types and classification methods used to assess and characterize mangrove forests in the GCC countries. We discuss the mangrove conservation initiatives implemented in the GCC countries, and how the fusion of remote sensing data can be used to increase the feasibility and accuracy of mapping and monitoring mangroves with reasonable cost and agility. Because data from UAV-LiDAR are very useful for detailed small scale studies that require high accuracy and ground validation of satellite data, we further discuss the UAV-based rules and regulations for operation in each GCC country. Lastly, we also highlight how high resolution LiDAR, UAVs and Google Earth Engine (GEE) data can be used to improve mangrove conservation and restoration planning in the GCC countries and describe current trends and progress in this area.

2 Methods

2.1 Data collection

This systematic review included only peer-reviewed scientific research papers with focus on mangroves in the GCC countries. The Preferred Reporting Items for Systematic Reviews and Meta-analysis statement (PRISMA) (Moher et al., 2009) was adopted for this purpose. The systematic literature review process also followed the population, intervention, comparators, outcomes and study type/design (PICOS) (Badzmierowski et al., 2021). Our review process used three different databases: Google Scholar, Scopus, and Web of Science. The search expression and workflow are presented in Figure 2. We used a combination of Python-based automated literature review and manual review to identify as many relevant articles as possible. Initially, the SerpAPI Google Scholar API (https://serpapi.com/search?engine=google_scholar) in Python was utilized to perform the Google Scholar search. Using this method, we examined the first ten Google Scholar pages of 100 results per page giving a total of 1000 articles. We limited the search to the first 1000 articles in the Google Scholar search after a pre-test screening of the literature search results. This screening showed only five articles were included after reviewing 1000 articles, but none were retrieved through examining 500 more articles (Ewane et al., 2023a). Similarly, in the case of the manual literature review, we examined the first 1000 results in Google Scholar and all the obtained results for Scopus and Web of Science for the publication period from January 2010 through December 2022. Relevant articles were identified by reading the title, abstract, and methods section first and these articles were later verified by reading the entire paper.

The primary list of returned articles - from the combination of automated and manual review - included 807 results, of which 79 were removed after filtering for duplicates. We also excluded non-English articles. Subsequently, we applied a secondary filtering phase, where we excluded multiple versions of blog posts and global articles that were not directly related to the GCC countries. We excluded gray literature from blogs, online newspaper articles, press releases, etc. We included published articles in journals and gray literature from conference proceedings, book chapters and institutional reports. The eligibility criteria for inclusion or exclusion of the searched articles is included under the search criteria in Figure 2. We continued with supplementary searches by identifying relevant articles in the reference list of included articles in a backward and forward snowballing approach (Badzmierowski et al., 2021). The final list included 58 peer-reviewed articles from different journals, conference proceedings, book chapters and institutional reports (Figure 2).

2.2 Data analysis

We extracted information on the country and location of the studies in the GCC region, the journal and year of publications, sensors/platforms, classification approaches, vegetation indices, and mangrove parameters estimated. We developed frequencies for the extracted data, analyzed and presented as maps, figures, and tables. We analyzed the remote sensing data used to derive the vegetation indices to estimate mangrove cover, distribution, and related mangrove forest characteristics to provide an understanding on spatiotemporal dynamics of mangrove ecosystems. We compiled the provided ecosystem services, threats, and ongoing mangrove conservation initiatives to guide future research endeavors and inform policy and practice on mangrove conservation in the region.

The final list of 58 included papers were published across 49 different journals, conference proceedings, book chapters and institutional reports. The five main journals where more than one article was published include Marine Pollution Bulletin (4), Environmental Monitoring and Assessment (3), Arabian Journal of Geosciences (3), Remote Sensing (MDPI) (2), and Journal of Ecosystem and Ecography (2). All the other journals and publication outlets published just one article (See Supplementary Table 1).

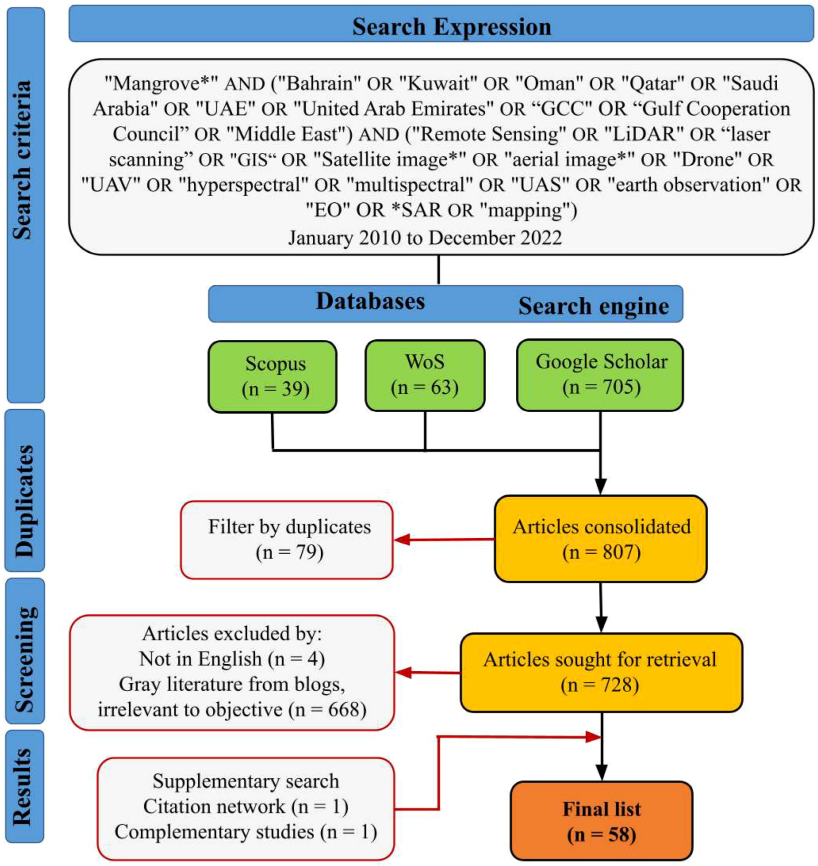

FIGURE 2
Workflow representing the systematic literature review process.

3 Results

3.1 Temporal and spatial distribution of the reviewed articles

A clear trend in the number of papers (remote sensing-based) published from 2010 to 2022 was not established. The number of papers published was highly variable over time, with publications peaking in 2022 (17.2%), followed by 2013/2020 (12.1%), and 2016/2021 (8.6%), as shown in Figure 3. The remote sensing-based mangrove papers varied in geographic scale of focus with some global (e.g., Bunting et al., 2022) and regional (e.g., Kumar, 2011) studies assessing mangroves in more than one GCC country. This increased the total number of times that a particular GCC country was mentioned in the 58 articles to 74 times. Most of the remote sensing-based papers focused on mangroves in Saudi Arabia (38.7%), followed by UAE (26.7%), Qatar (16%), Oman (8%), Bahrain (8%) and Kuwait (2.7%) as shown in Figure 4A. Figure 4B shows the proportion of studies we categorized as local, national, regional and global for each GCC country.

The spatial distribution of the study areas in each paper showed that some locations have multiple overlapping local studies (yellow polygons) while others were only included in the broader scale of national, regional or global studies (white polygons) (Figure 5). It was found that the 12 studies for Saudi Arabia include large extensions over the Red Sea but there are also five studies covering the mangroves over the Arabian Gulf in Al-Khair, Jubail and Tarut Bay. The UAE has ten overlapping local studies that include the mangroves near Abu Dhabi, while only one targeted the mangroves located toward the northern coast. Qatar has four studies and we categorize them as national and the other five studies are in the vicinity of AI-Dhakira, northwest near Khasooma and moving southeast near Hamad Container Terminal Port. For Oman, the studies were at the national level and included the shoreline over the Gulf of Oman and the Arabian Sea. In the case of Bahrain, the local studies overlapped over Muharraq Island and Tubli Bay while Kuwait was only included in the regional and global studies. Since the GMW is a global study and the spatial data is available to the general public, it can be used as a base for regional analysis. The mangrove cover for the GCC countries (excluding Kuwait) determined by Bunting et al. (2022) for the year 2020 is presented as a spatial reference in relation to the study areas.

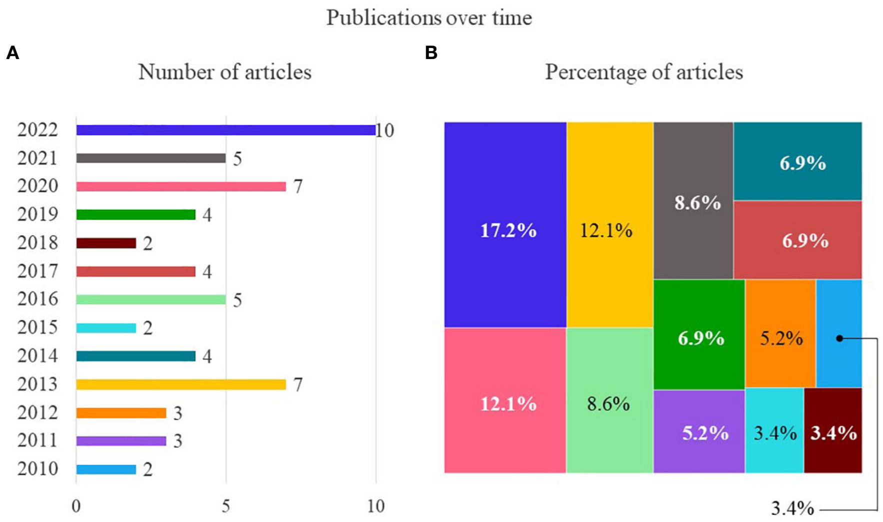

FIGURE 3
Number **(A)** and percentage **(B)** of articles published over time (January 2010 to December 2022).

3.2 Measured mangrove characteristics and vegetation indices using remote sensing data

All the reviewed studies measured mangrove cover change (100%) and mangrove distribution mapping (100%) as the main mangrove characteristics using remote sensing data. Studies also included the estimation of mangrove health/greenness (41.4%), biomass (10.3%), height (8.6%), density (8.6%), carbon stock (8.6%), species type (5.2%), restoration assessment (5.2%), sensitivity mapping (5.2%), and chlorophyll content (1.7%). A total of 33.9% of the studies examined more than one parameter, that is, mangrove cover and one or more other mangrove-related parameters (Figure 6).

The main vegetation index used to classify mangrove forest/tree stands in the reviewed papers was the Normalized Difference Vegetation Index (NDVI) (24 papers, 41%). Some of the reviewed papers used the multi-indices method to detect and classify

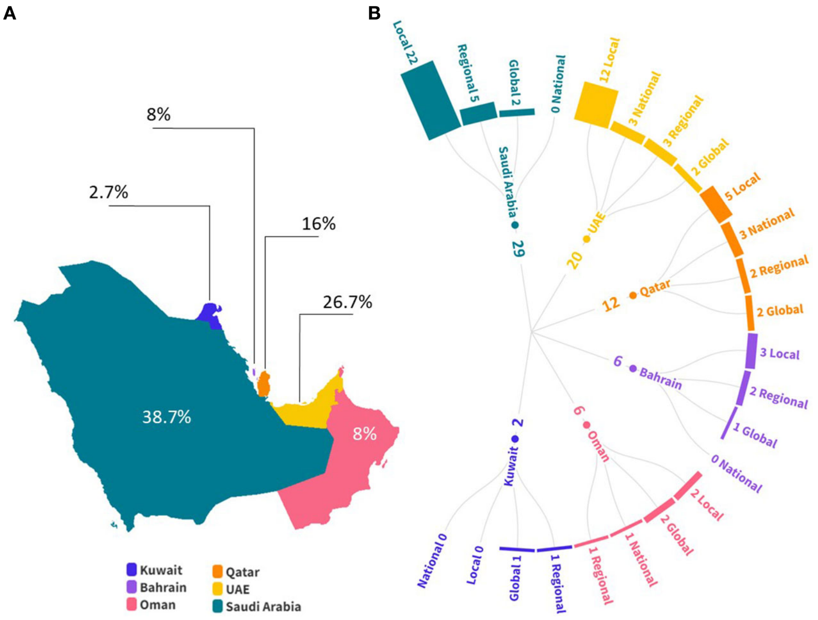

FIGURE 4
Location and scale of the studies that illustrate **(A)** percentage of articles that mentioned each GCC country, and **(B)** number and scale of the articles that included each GCC country. Studies that included countries in multiple continents were considered global, the studies that included multiple neighboring countries were considered regional, and the studies covering more than 70% of a country's shoreline were considered national. Regional and global studies were taken into account for each country included.

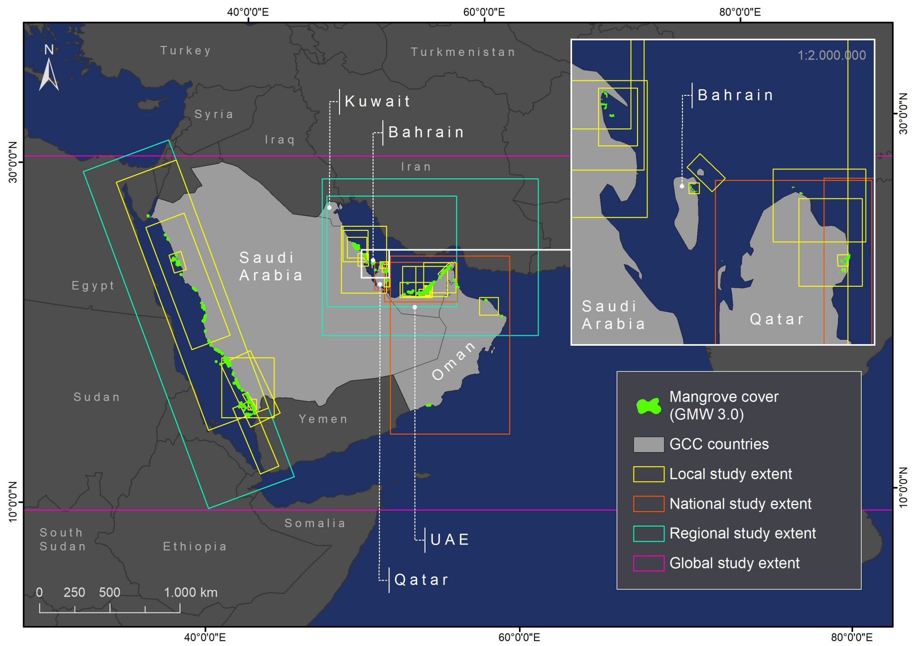

FIGURE 5
Study area extent for the reviewed papers in relation to the mangrove cover determined by GMW 3.0.

mangrove cover, distribution and health. Five of the reviewed remote sensing-based papers (8.6%) used NDVI in combination with other vegetation indices such as 1) Leaf Area Index (LAI) and Optimized Soil Adjusted Vegetation Index (OSAVI) to study mangrove health (Arshad et al., 2020); 2) Enhanced Vegetation Index (EVI), Modified Soil-Adjusted Vegetation Index (MSAVI) and Normalized Difference Moisture Index (NDMI) to study mangrove forest degradation and regeneration (Aljahdali et al., 2021); 3) Normalized Difference Built-up Index (NDBI) and Urban Thermal Field Variance Index (UTFVI) to study the effects of coastal development on mangrove ecosystems (Abd El-Hamid et al., 2022b); 4) Modified Normalized Difference Water Index (MNDWI), Normalized Difference Water Index (NDWI) and Ratio Index for Bright Soil (RIBS) for mangrove cover and distribution mapping (Hereher and Al-Awadhi, 2019); and 5) Submerged Mangrove Recognition Index (SMRI) to quantify mangrove changes during tidal inundation (Li et al., 2019) (Figure 7). A total of 34 (59%) out of the 58 reviewed papers did not explicitly indicate that NDVI or other vegetation indices were used for the detection and delineation of mangrove cover.

The multi-indices approach to map mangrove cover change was important to overcome the challenge of detecting submerged

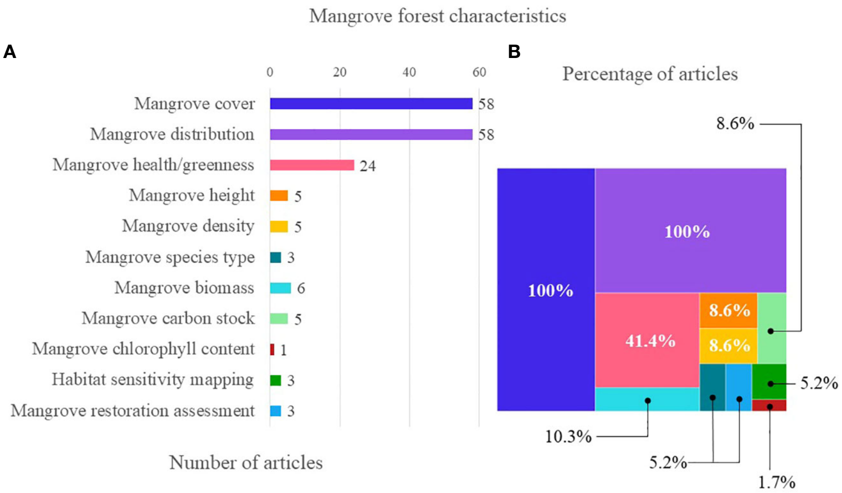

FIGURE 6
Mangrove forest characteristics estimated using remote sensing data in relation to **(A)** number and **(B)** percentage of articles.

mangroves and differentiating mangrove forests from water during tidal inundation. NDVI and SMRI values showed agreement for predicting mangrove cover and distribution and in the differentiating submerged mangroves from water in tidal flats during conditions of low and high tides (Li et al., 2019). In particular, the SMRI was reported as an effective indicator to detect submerged mangroves in both high and medium spatial resolution WorldView-2 and Landsat satellite images, respectively, over the western Arabian Gulf along the Saudi Arabian coastline. Thus, values of SMRI obtained from high resolution satellite imageries efficiently differentiates spectral signatures of mangrove forests under high and low tides with high accuracy (94%), and is usually preferred for mangrove cover classifications and distribution mapping during tidal inundation (Li et al., 2019; Xia et al., 2018; Xia et al., 2020).

3.3 Overview of remote sensing-based studies data sources

Remote sensing data derived from the instruments onboard Landsat satellites (multispectral scanner (MSS) thematic mapper (TM), enhanced thematic mapper plus (ETM+), operational land imager (OLI), and thermal infrared sensor (TIRS)) were the most widely used to map and monitor mangroves. These data featured in three-quarters (75.9%) of the reviewed papers that measured mangrove forest characteristics such as distribution and cover. This datasource was used solely or in combination with other satellite imageries from IKONOS (12.1%), Sentinel (8.6%), Worldview (8.6%), GeoEye (6.9%), SPOT-5 (6.9%), QuickBird (5.2%), MODIS (5.2%), SAR - JERS-1 SAR, ALOS PALSAR and ALOS-2 PALSAR-2 (3.4%) and IRISS LISS-3 (3.4%). Remote sensing data from Google Earth Pro imagery (10.3%), SRTM/ASTER - DEM imagery (13.8%), aerial photographs/imagery (6.9%), airborne terrestrial LIDAR (5.2%) and UAV imagery (3.4%) were also used. The satellite imageries from Pleiades-1A, PlanetScope, Mapper (ALTM) 3100 EA system, Earth Observing-1 (EO-1), DubaiSat-2 and AVHRR, and JAI AD-080GE multi-spectral 2-channel CCD scan camera imagery from close-range sensing of mangroves are also featured in some studies and presented as Others (12.1%) in Figure 8A.

One third (27.9%) of the reviewed papers used data fusion methods, integrating one or two medium-resolution Landsat, Sentinel or SPOT-5 imageries and one or two high-resolution data from Worldview, Quick Bird, aerial photographs and LiDAR. Satellite imagery of various types were documented 82 times in the 58 remote sensing-based mangrove papers, accounting for over three-quarters (75.9%) of the data types. From 2019, high spatial resolution imageries from UAVs and LiDAR and medium to high-resolution remote sensing data from Sentinel, Worldview, Quickbird, PlanetScope, SAR (JERS-1 SAR, ALOS PALSAR and ALOS-2 PALSAR-2) were increasingly used in the remote sensing-based mangrove studies (Figure 8B).

3.4 Classification methods used to detect mangrove forests cover and their accuracies

The reviewed studies used a variety of classification approaches to detect mangrove forest cover and changes over time from the remote sensing imagery. These included manual identification of changes based on visual digitization and interpretation - onscreen vector-based digitization methods (27 studies, 46.6%), machine learning algorithms (15 studies, 25.9%), and statistical modeling techniques (2 studies, 3.4%). A total of 7 studies (12.1%) used

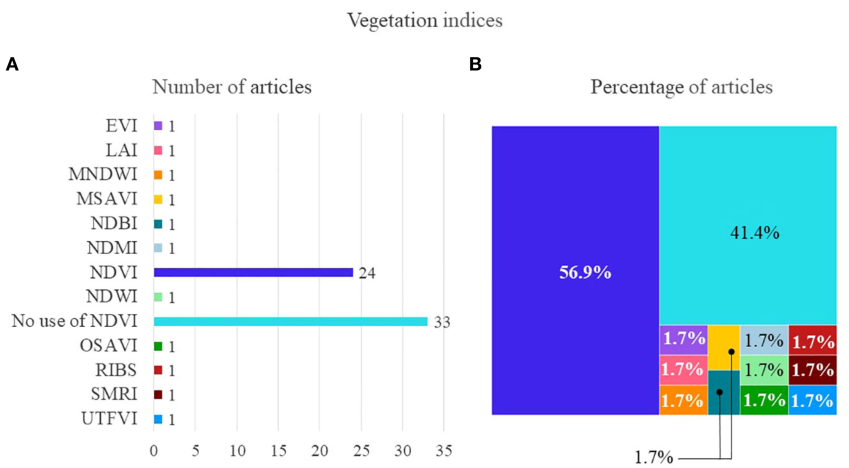

FIGURE 7
Vegetation indices used for mangrove classifications in the reviewed remote sensing studies focused on GCC region (2010-2022) in relation to **(A)** number and **(B)** percentage of articles: NDVI, Normalized Difference Vegetation Index; SMRI, Submerged Mangrove Recognition Index; EVI, Enhanced Vegetation Index; MSAVI, Modified Soil-Adjusted Vegetation Index; NDMI, Normalized Difference Moisture Index; NDBI, Normalized Difference Built-up Index; UTFVI, Urban Thermal Field Variance Index; MNDWI, Modified Normalized Difference Water Index; NDWI, Normalized Difference Water Index; RIBS, Ratio Index for Bright Soil; LAI, Leaf Area Index; OSAVI, Optimized Soil Adjusted Vegetation Index.

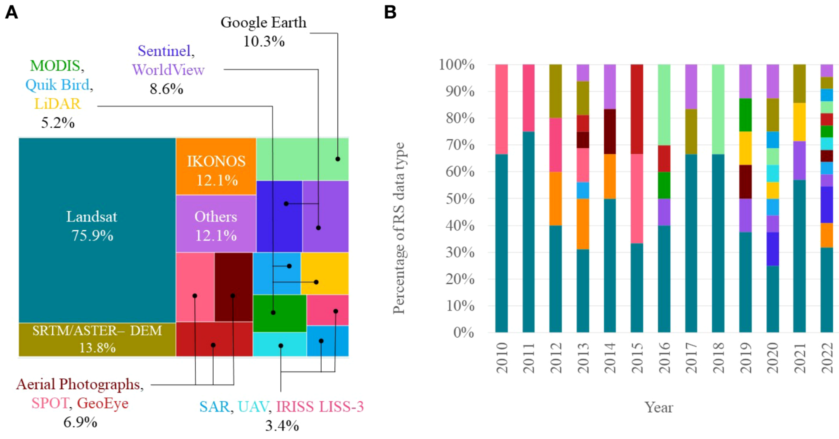

FIGURE 8
Remote sensing data types used in the reviewed papers as an overall percentage and for each year of the considered timeframe. **(A)** Remote sensing data type usage (percentage) between January 2010 and December 2022. Percentages do not sum to 100% as more than one remote sensing data source was used in a single reviewed article. **(B)** Percentage of remote sensing data type used for each year over the time period.

supervised and unsupervised classification approaches while the remaining 7 studies (12.1%) did not provide any specific information on the classification approaches used (Figure 9A). The reviewed remote sensing studies mostly used ENVI, ArcGIS and ERDAS for image processing and segmentation. Google Earth Engine was less used, mainly for global and regional studies, using multi-temporal and multi-sensor satellite imageries.

Data on the accuracy of the classification methods used to detect mangrove cover and distribution in the GCC countries was provided only in 13 (22.4%) of the reviewed studies. The most common machine learning techniques (accuracy given in brackets) used in 9 reviewed studies to detect and classify mangrove forest cover and changes over time included: random forest (95%), super vector machine (96%), decision tree or classification and regression tree (CART) algorithm (>95%), iterative self-organizing data analysis technique algorithm (ISODATA) (80%) and maximum likelihood (91%). Others included the canonical correlation forest models (96.2%), kernel logistic regression (95%), eCognition with contextual editing (94%), fuzzy logic model (90%) and deep learning (Capsules-Unet) (86%). Minimum distance (77%), naive bayes tree model (75%), deep learning (U-net) (74%), eCognition no contextual editing (72%) and ENVI FX algorithm (52%) classifiers were less accurate (Figure 9B). The 4 reviewed studies that used visual digitisation and interpretation techniques also reported classification accuracies of greater than 90%. Overall, the classification accuracies and estimation of vegetation greenness and health, based on NDVI, was relatively invariant to the classification method and remote sensing data used.

The specific classification method and accuracies used in the detection of mangrove forest cover were described more in the reviewed studies that used machine learning algorithm techniques than those that used visual digitisation and interpretation and other classification techniques. Details of the classification methods and accuracies of the models used to predict key attributes are provided in Supplementary Tables 2, 3.

4 Discussion

4.1 Contribution of remote sensing studies

For mangrove studies based in GCC countries over the past 30 years, satellite remote sensing data sources were particularly useful in determining mangrove cover, distribution, density, tree height, biomass and carbon stock, and potential areas for future afforestation initiatives (Elsebaie et al., 2013; Monsef et al., 2013; Alwhibi, 2017; Blanco-Sacristán et al., 2022). The majority of the studies used medium-resolution Landsat imageries from MSS, TM, ETM, ETM+, OLI and TIRS instruments/sensors solely or in combination with high-resolution satellite data from WorldView, QuickBird, Sentinel, Ikonos and SPOT to study the spatiotemporal dynamics of mangrove cover and distribution in the GCC countries. Data fusion methods involving the combination and integration of satellite imageries, LiDAR, and UAV (for ground truthing) images provided significant progress in efficiently and accurately detecting and mapping mangrove habitat and their sensitivity to natural and anthropogenic stressors (Butler et al., 2020; Jiang et al., 2022).

Estimates of mangrove cover and distribution for the GCC countries showed an appreciable decrease in dense mangrove cover, particularly post-2007, except for Qatar and the UAE (Bunting et al., 2022). For example, Bahrain and Saudi Arabia lost about 25.9% (21 ha) and 30.6% (3,396 ha) of their natural mangrove cover from 2007 to 2020, respectively. Similarly, Oman lost 14.3% (24 ha) of natural mangroves from 1996 to 2020 (Bunting et al., 2022). This was mainly due to the growth of urban development activities related to coastal infrastructure and industrial expansion (Milani, 2018; Arshad et al., 2020; Aljenaid et al., 2022; AlQahtany et al., 2022), in addition to climate change impacts (Al-Naimi et al., 2016; Almahasheer, 2018; Blanco-Sacristán et al., 2022). However, some studies reported stable to slight increases in mangrove cover over the same period in the GCC countries (Almahasheer et al., 2016; Almahasheer, 2018; Milani, 2018). This was particularly evident by

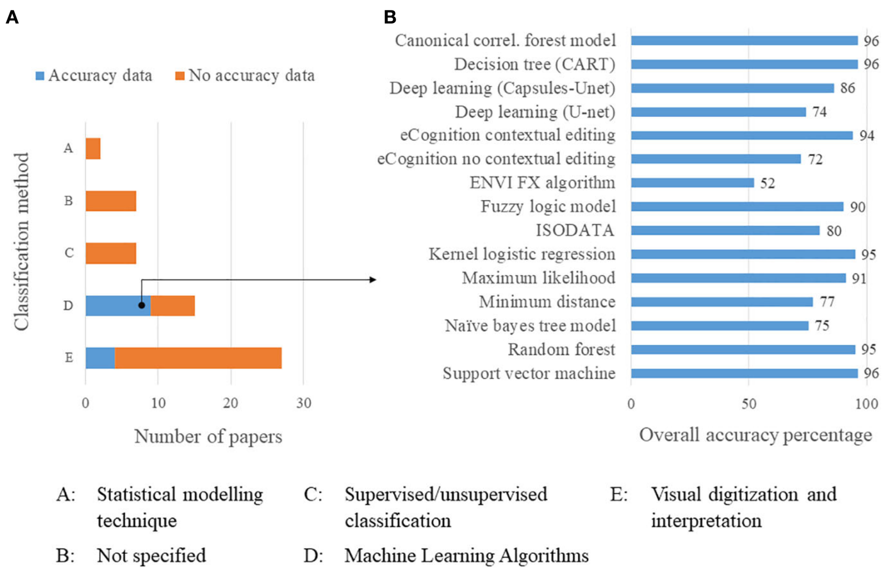

FIGURE 9
(A) Frequency of papers by mangrove classification methods, further broken down into those that included or did not have accuracy data, and **(B)** overall accuracy of the various machine learning algorithm (Classification method D) used in the studies.

appreciable increases and relatively stable mangrove cover in the post-2000s in Qatar and UAE, respectively, where government efforts toward mangrove reforestation and afforestation projects had likely played a significant role in increasing mangrove cover post-2000. This is compared to pre-2000 records when most loss in mangrove extent generally occurred (Almahasheer et al., 2016; Alsumaiti, 2017; Almahasheer, 2018; Bunting et al., 2022).

The limitations of the remote sensing-based mangrove studies that were identified mainly focused on disparities in mangrove distribution and cover data within each GCC country. The observed disparity in the statistics in mangrove distribution and cover change (loss/decrease or gain/increase) was attributed to the differences in mapping methods, classification approaches, and spatial resolution of the satellite remotely sensed data used between different studies (See Supplementary Table 2). For example, the remote sensing method and data (JERS-1 SAR, ALOS PALSAR and ALOS-2 PALSAR-2) used in the GMW (Bunting et al., 2022) were different from most of the other studies, where Landsat and WorldView, QuickBird, Sentinel, Ikonos and SPOT satellite imageries were mainly used (See Supplementary Table 3). Guo et al. (2021) found that factors such as the spatial resolution of the remote sensing images, tidal inundation, and information extraction strategy can account for inconsistencies in mangrove cover estimates.

The classification methods used in the various remote sensing studies in the GCC countries vary widely - for instance, supervised/unsupervised, visual interpretation by experts and/or machine learning algorithms - and the scope of the studies can range from global to local. The scale of a study influences some of the decisions regarding sources of remote sensing data and the classification approach used. For example, the scope of the study, such as the question the mapping is intended to address, will also modify the type of data and classification approach used. As a result, studies could use high temporal resolution data to track dynamics, versus low temporal resolution data to quantify changes at specific time steps such as pre- and post-restoration. Global scale studies such as the World Atlas of Mangroves (WAM-1, WAM-2), the Global Distribution of Mangroves (GDM) and the GMW rely on the use of larger scale mostly lower temporal resolution remote sensing data. Local scale studies mostly used a combination of high and low temporal resolution remote sensing and field data, with less use of LiDAR and UAV data.

4.2 Major findings

Mangrove ecosystems in the GCC countries provide diverse ecosystem services that are of critical importance to the ecological, social and economic well-being of the region (Vaughan et al., 2019). However, the main mangrove ecosystem service that was reported to be directly measured using remote sensing data sources was carbon sequestration and storage (Al-Nadabi and Sulaiman, 2021; Abd El-Hamid et al., 2022a; Aljenaid et al., 2022). Globally, mangroves are recognized as an important asset for blue carbon sequestration (Friess et al., 2019), thus its conservation provides optimism for climate change mitigation and adaptation efforts (Friess et al., 2020). The reviewed studies did not explicitly use remote sensing data or technology to investigate other important benefits of mangrove ecosystems to the environment and society of the GCC countries.

Despite the well-known importance of mangroves in the GCC region, these highly complex, vulnerable and fragile forest ecosystems are facing a wide variety of threats, including stressors driven by climate change and anthropogenic land use change activities (Burt, 2014; Al-Naimi et al., 2016; Almahasheer, 2018; Blanco-Sacristán et al., 2022). Specific threats to mangrove ecosystems are important to understand and can be identified through the use of remotely sensed data. In particular, climate change-induced sea-level rise, erosion and flooding, changes in precipitation, increases in temperature and salinity, and decreases in dissolved oxygen in submerged mangrove aerial roots are expected to significantly increase mortality of mangrove trees in the GCC countries (Al-Khayat and Balakrishnan, 2014; Al-Naimi et al., 2016; Almahasheer, 2018; Samara et al., 2020; Blanco-Sacristán et al., 2022; Subraelu et al., 2022). Rapid urbanization, land reclamation and dredging operations for infrastructural and industrial development and sewage disposal constitute important threats to the sustainability of mangrove ecosystems (Al-Naimi et al., 2016; Almahasheer, 2018; Milani, 2018; Aljenaid et al., 2022; Blanco-Sacristán et al., 2022).

Increased timber exploitation, camel grazing associated with local livelihood sustenance activities, and unsustainable tourism development are also threatening the conditions of mangroves in the GCC countries (Kumar et al., 2010; Al-Ali et al., 2015; Alsumaiti, 2017; Alwhibi, 2017; Milani, 2018). A lack of awareness about the importance of mangroves among local people was reported to have negatively impacted the conservation of mangrove ecosystems in Saudi Arabia (Al-Ali et al., 2015; Alwhibi, 2017). However, anthropogenic pressures are not always considered entirely negative for mangrove ecosystem health. Evidence suggested that treated sewage could enhance mangrove growth due to its low salinity and high nutrient concentrations. Similarly, dredging of channels, particularly in lagoon areas characterized by hypersalinity/extreme temperatures, can result in increased mixing with less extreme coastal waters, enhancing mangrove growth (Burt et al., 2021).

Most of the reviewed studies used open source (free access) and time series Landsat imageries to map mangrove distribution and cover. The low spatial (30 m) and temporal (16 days) resolutions of Landsat imageries limited the ability to extract detailed tree- and forest-level characteristics, which are important for monitoring biomass and estimating carbon sequestration. Only a few of the reviewed studies used moderate to high spatial (10 m or less) and temporal (4 days or less) resolution remote sensing data to study mangrove ecosystems in the GCC region. High spatial resolution sensors offer the opportunity to obtain more detailed ecological information of forest ecosystems and are increasingly being used for monitoring mangroves although they can be costly (Goldblatt et al., 2017; Psomiadis et al., 2017; Xian et al., 2019).

Field-based measurements of mangrove forest characteristics are usually expensive, time-consuming and difficult to undertake due to the challenging physical conditions and remoteness of mangrove habitats. As an alternative to field-based assessments, LiDAR data were used in three of the reviewed studies to measure mangrove aboveground biomass (AGB) and tree height inventory in UAE (Alsumaiti et al., 2019), and for benthic habitat (including mangrove forests) mapping and benthic habitat sensitivity analysis of mangrove forests in Qatar (Butler et al., 2020). The inclusion of LiDAR data improved the accuracy and efficiency of mangrove detection when compared to pixel-based classifiers alone (Butler et al., 2021). A high-resolution centimeter-scale UAV-mounted MicaSense RedEdge-MX sensor was used for validating data from satellite imageries in Saudi Arabia (Jiang et al., 2022) and to obtain georeferenced photographs of mangroves for interpretation in UAE (Mateos-Molina et al., 2020). UAVs allow the collection of high-resolution, time series imagery over small spatial scales, with the advantages of lowering costs and the risks of human involvement, which can be considerable in mangrove ecosystems. Such UAV-derived high-resolution data improves the accuracy of mangrove forest classification and the estimation of tree-level growth characteristics, and early detection of any ecological changes (Meyer et al., 2019; Ewane et al., 2023b).

4.3 Integration of UAVs in mangrove forests monitoring and assessment

Satellite imagery has been the primary resource used to map mangrove forests in GCC countries. In contrast, UAVs are yet to be widely used due to issues related to accessibility, local laws and regulations, logistics, privacy and ethics in GCC countries. Despite the technical and logistic limitations associated with UAV-based endeavors, there is a potential for greater use of UAVs in forest resource management schemes, as the use of UAVs is becoming increasingly cost-competitive to bridge the data limitation gap between field measurements and satellite remote sensing (Ewane et al., 2023b). High-resolution UAV imagery provides detailed data with high accuracy that can be sufficient to validate satellite data. As UAVs can collect a wide array of useful data including LiDAR, multi and hyperspectral, infrared, accelerometers, pressure gauges and temperature sensors (Nitoslawski et al., 2021), they can be used for high-accuracy mangrove mapping and present opportunities for monitoring, evaluation, and reporting (Jiang et al., 2022).

UAVs have been used to monitor mangrove ecosystems and provide detailed tree-level information over small to large areas in a fast, repeatable, cost-effective, and accurate way (Ruwaimana et al., 2018; Castellanos-Galindo et al., 2019; Jones et al., 2020; Navarro et al., 2020). This highly detailed tree-level information of mangrove ecosystems can be integrated as a complementary data source to cover low data frequency gap from field surveys. UAV based imagery makes it possible to map mangrove cover with higher accuracy than satellite-based imagery since the latter has been found to overestimate mangrove cover in semi-arid dwarf mangroves in Mexico (Hsu et al., 2020). UAVs provide one of the best remote sensing options to rapidly acquire accurate monitoring data to evaluate progress and validate satellite data to support mangrove restoration and conservation initiatives for increased carbon sequestration.

UAVs offer the best option to monitor and assess mangrove ecosystems in GCC countries since mangrove extent are relatively small and are mostly discontinuous in their distribution. Because the operational costs of using UAVs reduces over time, its use becomes advantageous over satellite data and field surveys for long-term monitoring over small to large areas (Ewane et al., 2023b). Although the application of UAVs in mangrove monitoring and assessment is highly feasible in the GCC countries, their deployment does require in-depth knowledge of the regulations governing their use and required authorisations in the various GCC countries. In addition, the processing time for UAV imageries can be ten times greater than that of satellite images due to the larger data size of UAV images particularly when revisit times are very frequent (Ruwaimana et al., 2018).

4.4 UAV-based rules and regulations initiatives in the GCC countries

The rules and regulations for the use of UAVs are generally strict in the GCC countries, and differ in their requirements among the countries. In particular, the use of UAVs in most of the GCC countries (Bahrain, Oman, Saudi Arabia, Qatar and UAE) is subject to a prior acquisition of an authorization or permit. In Qatar, UAE and Oman, obtaining this permit can be quite challenging and time consuming (OZYRPAS, 2022; UAV Coach, 2023).

In the UAE, for instance, a two-step application process must be followed. Firstly, the operator (person or group) needs to register for, and obtain, a drone operator's license which usually takes from one to three weeks. Secondly, an application for a permit to fly over a specific area is required in order to be able to capture images, and this permit is only valid for 14 days (General Civil Aviation Authority - GCAA of UAE, 2023). Even after gaining the permit, there may still be specific rules that surround the flight. These include awareness of safety measures such as - not flying UAVs in the vicinity of people, airports, or governmental facilities, - flying UAVs only in daylight and good weather - and limiting flight height to a maximum of 120 meters, among other practices (General Civil Aviation Authority - GCAA of UAE, 2023; UAV Systems International, 2023). These restrictions and time delays also apply for research-related flight permits.

Similarly in Bahrain, the UAV type needs to be specified based on its weight in order to register at Bahrain Civil Aviation Affairs (BCAA) where the submission should take place prior to its importation by the owner or the intended owner (Ministry of Transportation and Telecommunication, 2023). The user/owner may be requested to prove a certain level of skills and proficiency to the authority to fly UAVs.

In Saudi Arabia, the government has launched an awareness and outreach initiative to facilitate the registration and issuing of licenses to operate UAVs. The initiative will also promote the issuance of operating licenses to practitioners by the General Authority of Civil Aviation (GACA) as a fundamental prerequisite for their activities. This is part of the country's efforts to develop a more efficient and organized drone operation in line with Saudi Arabia's Vision 2030 (Drone Laws, 2022). The application and status tracking is fully online via the governmental website (https://eaviation.gaca.gov.sa/uas/login.xvw).

In Kuwait, the user only needs a permit if the UAV is being used for commercial purposes (Markert, 2020; UAV Systems International, 2023), and it must also have insurance and registration (Markert, 2020). Once the permit is obtained, there are restrictions regarding proximity to crowds or airports and only daylight flights are allowed (Markert, 2020; UAV Systems International, 2023).

4.5 Importance of mangroves

The reviewed studies implicitly and explicitly evaluated and documented five important mangrove ecosystem services, which included habitat for fish and fauna species, carbon storage and sequestration, coastal protection, provision of livelihood opportunities, and water purification and filtration closely related to nutrient cycling (Figure 10). Based on the reviewed remote sensing studies, mangroves in the GCC countries filter and trap sediments that further improve anchorage to their roots (Butler et al., 2020), and sequester and store high quantities of carbon in soil and trees (Alwhibi, 2017; Butler et al., 2020; Aljenaid et al., 2022; Blanco-Sacristán et al., 2022). They filter pollutants and purify water (Al-Naimi et al., 2016; Alwhibi, 2017; Alsumaiti et al., 2019), and help protect coastal shorelines from tsunamis, tropical cyclones, storm surges, erosion and flooding (Elmahdy and Mohamed, 2013; Al-Ali et al., 2015; Alwhibi, 2017; Milani, 2018; Subraelu et al., 2022). In addition, mangrove ecosystems provide habitats for diverse fisheries and fauna species (Alwhibi, 2017; Milani, 2018; Mateos-Molina et al., 2020; Elmahdy and Ali, 2022). Mangrove ecosystems are important recreation areas for tourists (Alsumaiti, 2017). Their leaves, stems and roots are important medicinal resources and fodder for domestic animals (Alwhibi, 2017). Lastly, mangrove trees also offer livelihood benefits to some communities such as seafood, fuelwood, timber and wood for housing materials (Al-Ali et al., 2015; Alsumaiti, 2017; Alwhibi, 2017).

Mangrove carbon stocks and sequestration capacity was estimated using remote sensing data in previous studies. For example, an average above-ground carbon sequestration of 6.3 Mg C/m^2 was estimated using NDVI derived from above ground biomass using Landsat OLI imagery. Higher above ground and below ground biomass and carbon stocks were reported in landward than seaward areas (Al-Nadabi and Sulaiman, 2021). Mangrove forests of about 328 ha and 48 ha were estimated to store up to 34,932 Mg C ha^{-1} and 5,112 Mg C ha^{-1} of carbon, respectively, in 1967 and 2020, with the decrease due to land reclamation associated with coastal development. This was estimated using multi-sensor high resolution satellite images from Worldview-3, Worldview-2, IKONOS, and QuickBird, coupled with true-color orthorectified aerial photographs, and GIS-based spatial analysis of mangroves in Bahrain from 1967 to 2020 (Aljenaid et al., 2022). Using the Carbon Sequestration Storage Model in the InVEST software program, above ground biomass estimated using NDVI from moderate resolution Landsat TM, ETM and OLI stored a total carbon stock of 3,772,968 Mg C along 13,500 km^2 of the Jazan biome coastline in Saudi Arabia partly covered by mangroves in 2021 (Abd El-Hamid et al., 2022a).

4.6 Major threats to mangroves

Mangrove forest ecosystems in the GCC countries are concurrently stressed by the combination of five natural and anthropogenic threats/pressures, which include coastal industrial and infrastructural development, pollution, climate change, erosion

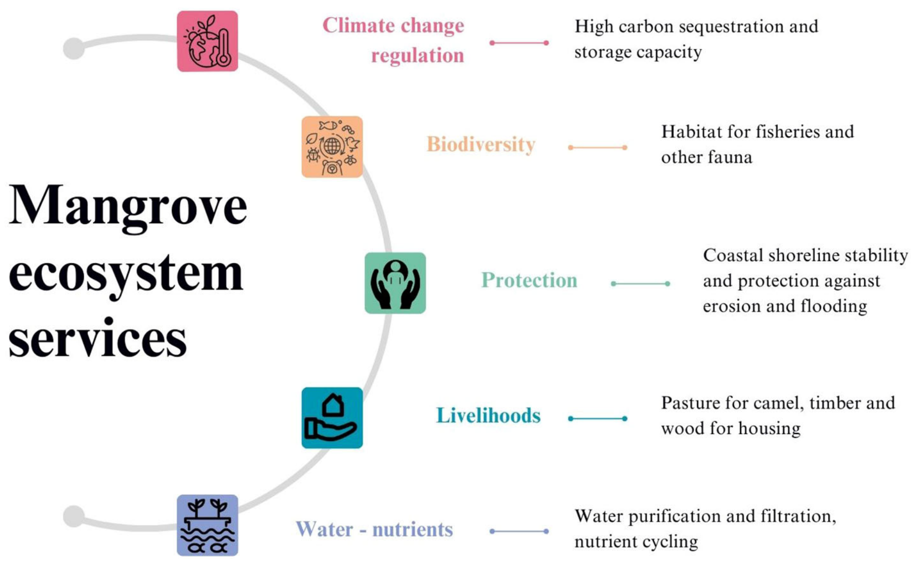

FIGURE 10
Important ecosystem services of mangroves in the GCC countries identified in the reviewed papers.

and flooding, and unsustainable extraction of timber/wood (Figure 11). Mangrove loss associated with rapid urban development activities such as development of crude oil refinery and petroleum industries, road and housing, seaports and harbors infrastructures are by far the primary threats to mangrove forest ecosystems in all GCC countries (Al-Khayat and Balakrishnan, 2014; Arshad et al., 2020; Abd El-Hamid et al., 2022b). The loss in mangrove cover reduces its carbon stock and sequestration and storage capacity due to a reduction in above ground biomass and loss of sediments (Al-Nadabi and Sulaiman, 2021; Aljenaid et al., 2022; Abd El-Hamid et al., 2022a).

Pollution due to oil spills from pipeline leakage and heavy metal are threatening mangrove ecosystem health and species survival in the GCC (Aljamali et al., 2014; Al-Khayat and Balakrishnan, 2014; Al-Ali et al., 2015; Warren et al., 2016). Mangrove ecosystems are also threatened by climate change-driven sea level rise and associated flash flooding and inundation risks and coastal shoreline erosion (Aljamali et al., 2014; Hereher, 2016; Alsumaiti, 2017; Subraelu et al., 2022). Sea-level rise driven flooding and inundation is expected to submerge and destroy mangrove trees and modify the supply of propagules as mangroves reach a maximum of 6 m tall (Al-Khayat and Balakrishnan, 2014; Al-Awadhi et al., 2020). Climate change driven rising temperatures and excessive evaporation causes droughts and hypersalinity in mangrove lagoons. Uncontrolled cattle grazing by camels and wood exploitation are also important threats to mangroves in Saudi Arabia (Alwhibi, 2017).

4.7 Some examples of hotspots of mangrove loss in the GCC countries

Spatial and temporal changes that characterize loss and gain in mangrove forest cover in the GCC countries are provided in Figure 1 and specific locations of high mangrove cover loss and gain are provided in Supplementary Tables 2, 3. In Bahrain hotspots of mangrove loss were detected mainly in Tubli bay in the northeast region at locations in Ras Tubli, Ras Sanad and Sitra Island, where mangrove cover decreased from 170.78 ha to 4.17 ha, 96.75 ha to 33.90 ha and 60.47 ha to 9.93 ha, respectively, from 1967 to 2020. In total, mangrove cover decreased from 328 ha to 48 ha in the three locations from 1967 to 2020, with these changes derived from aerial photographs and multi-sensor satellite imagery (Aljenaid et al., 2022).

In Qatar hotspots of mangrove loss were detected in six locations, including planted mangrove areas at Al Mafjar and Fuwairit in the north, natural mangrove areas at Al Thakira and Al Khor, and planted mangroves at Simaisma in the east, and planted mangroves at Zekreet in the west using Landsat imagery. Zekreet is the main hotspot of declining and stunted plantations of *A.marina* with just 1.11 ha remaining, with losses caused by climate change-driven rising seawater temperature, hyper salinity and lowered dissolved oxygen while Al Thakira (65.2%) and Al Khor (38.8%) coast boost luxuriant stands of natural mangroves (Al-Khayat and Balakrishnan, 2014).

In Saudi Arabia hotspots of mangrove loss were originally detected at locations in the Tarut Bay in the eastern province (Almahasheer, 2018) and along the Jazan shoreline in the Red Sea (Abd El-Hamid et al., 2022b) of Saudi Arabia. Mangroves in these areas were exposed to many environmental and human pressures such as urban encroachment, pollutants, and land reclamation (Almahasheer, 2018).

In the UAE hotspots of mangrove loss were detected in locations in Umm AnNar and Mosaffah, Khor Ra's al-Khaimah mangal and Khor Kalba communities due to urban development in the coastal shoreline of Abu Dhabi (Almahasheer, 2018). Mangroves decreased slightly at locations in Khor Kalba natural reserve, RAK natural reserve, Umm Al Quwain estuarine, Ajman-Hammriah and Ras Al Khor in Dubai, from 1990 to 2019, especially

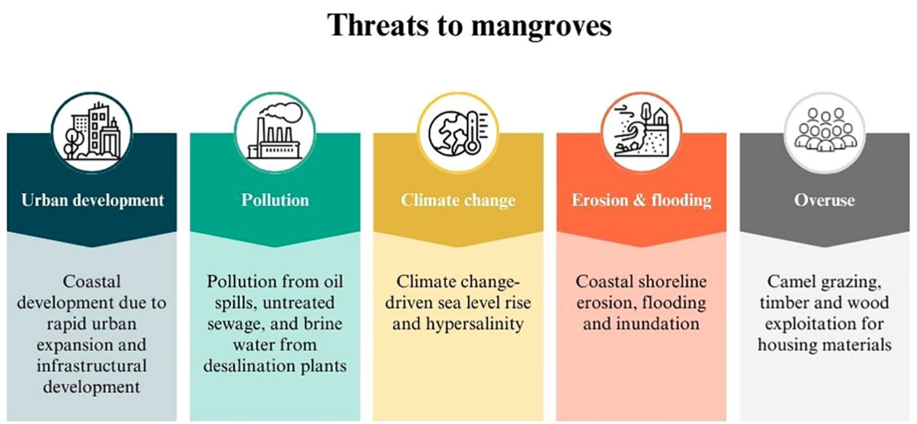

FIGURE 11
Major threats to mangroves in the GCC countries identified in the reviewed papers.

in the RAK and Umm Al Quwain areas facing the Arabian Gulf (Elmahdy et al., 2020).

Kuwait does not have any natural mangrove forests (FAO, 2005), while planted mangrove areas of about 0.58 km^2 were detected at 29° N in 2017 (Almahasheer, 2018; Guo et al., 2021). It is thought that mangroves in Kuwait were completely destroyed during the Kuwait war. There is increasing afforestation of mangroves from nursery reared propagules of *A. marina* that were successfully transplanted in the artificial islands of Sabah Al-Ahmad Sea City of Kuwait (Loughland et al., 2020).

4.8 Ongoing mangrove conservation initiatives

Most governments in the GCC countries have implemented coastal environmental management and planning initiatives that include mangrove protection and restoration (Milani, 2018). Restoration of *A. marina* along the coast of Al-Sharifa Island, Al-lith Red Sea in Saudi Arabia was carried out in the mid-2000s, and these mangrove saplings had a 39% survival rate (Chithambaran, 2019). Mangrove conservation has been studied in Oman (Al-Afifi, 2018). Since 2000, Oman has partnered with the government of Japan to work on conservation and restoration of mangroves, planting saplings in 7 of the 11 governorates (UNEP, 2018). In 2022, “the Environment Authority of Oman launched an action plan to plant 1,500,000 mangrove seeds in Khor Ghawi in the Wilayat of Al Jazir and the Wetland Reserve in the Wilayat of Mahout in the Al Wusta Governorate during the months of July and August of 2022, as part of the national initiative to plant 10 million trees (EA, 2022).” Also, in the UAE, 12% of the country’s marine and coastal areas are designated as protected areas, and the government is continuing to expand marine protected areas to conserve important habitats such as that of mangroves (Lamine et al., 2020). Recent efforts are underway in the UAE to restore marine ecosystems, and the Aquaculture and Marine Studies (AMSC) has planted 5,026 hectares of *A. marina* in Abu Dhabi Emirate (Yosef et al., 2022). Research is underway in the UAE to utilize treated sewage effluent as a water-source to enhance the growth of mangrove seedlings in nurseries (Erftemeijer et al., 2021). This research was linked to the growing evidence that treated sewage enhances mangrove growth due to the lower salinity and the high nutrient concentration of this media (Burt et al., 2021).

There are a few current and ongoing conservation initiatives in the GCC region. Saudi Arabia plans to plant over 300 million mangrove trees by 2030 (Al-Sinan et al., 2023). The UAE has prioritized the importance of mangrove conservation and preservation, citing it as a defining and important characteristic of their ecosystems during public events. On July 26th, 2022, the UAE Pavilion celebrated “International Day for Conservation of Mangrove Ecosystems” at the Floriade expo 2022 by highlighting mangroves in their exhibition (Ismail and Alghoul, 2022). An alliance between the UAE and Indonesia was announced at United Nations Climate Change Conference or Conference of the Parties (COP27) of the UNFCCC in 2022 in Egypt, in which the two nations plan to accelerate mangrove restoration and support mangrove conservation globally (Ministry of Climate Change and Environment, 2022; The National, 2022). Also in 2020, 1,000 mangrove saplings were planted in the Al Wusta governorate of Oman (Oman Observer, 2020; Times News Service, 2022).

Overall, there is a lack of literature on community-based mangrove conservation and restoration initiatives in the GCC countries. The increases in mangrove cover that have occurred post-2000, for example, in UAE and Qatar are attributable to government efforts toward promoting mangrove plantation reforestation and afforestation projects for improved and sustainable coastal environmental management and planning. This played a significant role in increasing mangrove cover over this century, compared to pre-2000 records when much of the loss in mangrove extent generally occurred (Almahasheer et al., 2016; Alsumaiti, 2017; Almahasheer, 2018; Bunting et al., 2022).

Kuwait engaged in the planting of *A. marina* in the artificial islands of Sabah Al- Ahmad Sea City along the southern coast of Kuwait over the last two decades and reports suggest that the germination of the nursery reared propagules and transplantation of the mangrove seedlings was successful during 2006-2008. A decade after transplantation, successful seed production and self-germination indicated establishment of a sustainable *A. marina* population, which enhances biodiversity and offers valuable ecosystem goods and services (Loughland et al., 2020).

4.9 Mangrove conservation in relation to United Nations Sustainable Development Goals (UN SDGs)

Mangrove forests in the GCC countries, though comparatively smaller in spatial extent and shorter in height (mostly less than 6 meters tall), provide a range of environmental, social and economic benefits in the form of ecosystem services (Figure 10). For example, mangrove ecosystems foster rich biodiversity and nurturing flora and fauna of diverse microorganisms indispensable for basic chemical and biological processes. These benefits, including carbon sequestration, water purification, nutrient cycling, erosion and flooding control are critical to enhancing the region's effort toward achieving progress with several of the UN Sustainable Development Goals (SDGs), particularly related to climate action (SDG 13), life below water (SDG 14) and life on land (SDG15). Considering that the GCC countries are among the highest carbon emitters per capita from oil and gas industries and the mangrove cover has generally declined over the past three decades, expanding mangrove conservation and restoration initiatives is very important for the well-being of the environment and society.

Mangrove restoration can be enhanced with the use of specifically designed UAVs through direct seeding to expand mangrove cover as recently demonstrated in the UAE (Mohan et al., 2021; ADNOC Uses Innovative Drone Technology to Plant Mangroves, 2023). Mangroves will play a key role (as the only evergreen forest and the most important carbon sink in this arid region) in achieving the recent climate change mitigation initiative in the UAE (Net Zero 2050 and COP-28) (ADNOC Uses Innovative Drone Technology to Plant Mangroves, 2023). Such mangrove restoration initiatives are invaluable for the GCC countries to increase mangrove carbon sequestration for climate change mitigation, and storm, flooding, erosion, and marine habitat and biodiversity protection. This is important for achieving sustainable development and sustainability in coastal environmental management in the region.

4.10 Existing research gaps

This review of remote sensing-based studies enabled the identification of considerable research, management and policy gaps on remote sensing-based mangrove data collection, use and interpretation, and data management and availability to the public. In particular, these largely focus on the use and integration of LiDAR and UAV data, and the application of emerging classification approaches that rely on machine learning and artificial intelligence.

- There is a need to explore further the integration of multiple remote sensing data sources with different resolutions and scales. This should include the integration of high-resolution long-term data from satellite sources and large scale LiDAR and UAV data that is frequently acquired. Adoption of this data fusion approach will improve accuracy and efficiency for long-term area-based monitoring of mangrove forests over large spatial scales and tree-level characteristics over small spatial scales.
- Similarly, generation of more remotely sensed data from LiDAR and UAVs and development of new applications that can use small-scale data from this platform and data source is required. These data should be compiled into a user-friendly interface that incorporates rigorous quality assurance and quality control protocols that support automation and standardization.
- Tree-level data acquisition is almost non-existent due to the minimal usage of UAVs and LiDAR data. Thus, enhanced LiDAR and UAV applications could facilitate the detection and measurement of individual tree-level growth characteristics and conditions. These acquisition techniques can provide useful data on tree stress allowing mortality to be identified and be associated with the various threats to mangrove ecosystems in the GCC countries for upscaling and validation of satellite-derived data.
- Standard protocols for data measurement, reporting, analysis, validation, etc. are required for comparison and quality assessment purposes. Thus, increased accessibility to high-resolution satellite, LiDAR and UAV data at lower cost using standardized methodologies that produce comparable results for different periods of time and locations is needed. Results from these analyses should be freely available to the public.
- Baseline estimation of mangrove cover change needs to be robust and different kinds of machine learning algorithms should be explored and compared to locate the best option. This application would capitalize on the high level of detail that can be extracted from fine-resolution images and 3D point clouds.
- Long-term data monitoring and collection should be prioritized, and more attention is especially needed for newly planted sites.
- Remote sensing-based studies that can estimate mangrove forest greenness and moisture content using different combinations of vegetation indices obtained from multispectral or hyperspectral imagery would be invaluable to accurately detect and classify mangrove forest.
- The need for hardware/software for processing data can be mitigated by using platforms such as GEE or similar data cube platforms such as Digital Earth Australia that provide remotely sensed data. The GEE platform offers opportunities for coding, neural networks, deep learning, and machine learning that would help to improve data and geographic accuracy and streamline predictions within mangrove ecosystems.

4.11 Recommendations for future research

- GCC-wide LiDAR and UAV data collection campaigns are recommended for the provision of long-term data for estimating mangrove forests and tree-level characteristics and valuation of mangrove ecosystem services in real time for inclusion in various models to improve model reliability. Analysis of such data could be used to guide coastal planning and development policy reforms and practices, which support sustainable mangrove management and protection.
- In particular, GCC countries such as Kuwait, Bahrain and Oman with limited studies and spatial data and discrepancy in mangrove cover and distribution results would benefit immensely from the use of advanced UAV and LiDAR remote sensing technologies to gather high resolution data to provide validation options for moderate and high resolution satellite data. This will help bridge the observed regional gap in remote sensing-based mangrove assessment studies between the other GCC countries such as Saudi Arabia, UAE and Qatar.
- The moderate and high resolution remote sensing data for large and small spatial scales should be combined with machine learning algorithms to increase the accuracy and efficiency of detecting and classifying mangrove cover. Very high spatial resolution images such as QuickBird (0.6 m) and WorldView (0.3 m) or 1-m resolution DEM derived from Airborne Laser Scanning (ALS) LIDAR data integrated with machine learning approaches and validated with fieldwork are recommended for future studies to map and monitor changes in mangroves (Elmahdy and Ali, 2022). Results show that non-parametric models such as random forest provided high predictive accuracy in detecting and classifying mangrove forests in the GCC countries as has been shown previously (Elmahdy et al., 2020). Deep learning using Capsules-Unet method performed more accurately and efficiently in processing detailed information on mangrove cover change and extracting tiny features over 25 years than using the U-net method (Guo et al., 2021). The Object-based eCognition with contextual editing was more accurate and efficient than the Object-based: eCognition no contextual editing, Pixel-based ISODATA and Object-based ENVI FX in their ability to detect and classify mangrove habitats (Butler et al., 2020).
- A recommended mapping protocol is to fuse moderate to high spatial resolution time series datasets and preprocess and train models from these datasets using ensemble advanced machine learning techniques in GEE (Pham et al., 2019; Elmahdy et al., 2020). GEE provides a better web platform to model mangrove cover change and carbon stock and sequestration for global, regional and national studies using multi-temporal and multi-sensor medium and high resolution satellite imageries (Blanco-Sacristán et al., 2022). This approach could provide benchmark datasets to guide current and future mangrove afforestation and conservation initiatives as part of each GCC country's net zero CO_2 emission inventory and climate change mitigation efforts (Aljenaid et al., 2022).
- Very high spatial resolution images such as QuickBird (0.6 m) and WorldView (0.3 m) or 1-m resolution DEM derived from Airborne Laser Scanning (ALS) LIDAR data integrated with deep learning approaches and validated with fieldwork are recommended for future studies to map and monitor changes in mangroves (Elmahdy and Ali, 2022).
- Remote sensing-based mangrove forest carbon stocks estimation should integrate field measurements since model estimates can be significantly different from those obtained using comprehensive field inventories (Bukoski et al., 2020).
- In general, studies of mangroves, combining very high resolution remote sensing data with machine learning and deep learning techniques is likely to greatly advance our ability to map mangrove area, identify species and quantify biomass and carbon stocks.

4.12 Potential opportunities and policy implications

As technology advances, there are increasing opportunities for the use of UAVs for mangrove monitoring and assessment over small areas in GCC countries. The often small and dispersed distribution of mangroves is well suited to the use of terrestrial LiDAR and UAV remote sensing technologies. These emerging remote sensing technologies provide opportunities for the acquisition of high-resolution forest-level and tree-level data at small spatial scales that are often needed for the validation and upscaling of satellite data over larger spatial scales (Ewane et al., 2023b). There are also opportunities for training and evaluation of remote sensing tools and integration of machine learning algorithms to improve on the accuracy of assessment of mangrove distribution and cover and specific characteristics.

There are great opportunities for the expansion of mangrove regeneration and restoration initiatives. Government efforts to promote improved coastal environmental management and planning through expanding mangrove plantations have been laudable. This serves as part of the growing movement toward using nature-based solutions and ecological engineering approaches to respond to looming climate change challenges for coastal communities (Burt and Bartholomew, 2019; Pittman et al., 2022). These efforts can be further enhanced by involving local community stakeholders in mangrove conservation and restoration initiatives for increased success as a nature-based solution to climate change mitigation efforts in the GCC countries. There are also opportunities for involving local experts through participatory mapping exercises and the integration of local ecological knowledge to support secondary ground-truthing and post-classification improvement and accuracy assessment of mangrove data in the GCC region (Mateos-Molina et al., 2020).

Mangrove forest conservation and restoration provide viable opportunities for carbon offset programs for the industries contributing to GHG emissions in the GCC countries through compliance and/or voluntary carbon markets. Governments in the GCC countries have the opportunity to develop well-structured mechanisms and legal frameworks for compliance and voluntary carbon markets for companies in individual countries and the region. Expansion of remote sensing-based studies that estimate biomass and blue carbon for integration into carbon markets for mangrove forests ecosystem is invaluable. This nature-based carbon offset credits initiative in the compliance and voluntary carbon markets may encourage more oil and gas companies to fund mangrove restoration programmes as a nature-based solution to climate change in the GCC countries. Predictive models are useful in designing national and regional scale policy programs and strategies for mangrove forest biomass carbon estimation and monitoring, but less so at local scales.

There are opportunities to develop Mangrove Monitoring, Evaluation, and Reporting (MMER) programs and to establish an open-source benchmark mangrove distribution, cover and forest characteristics dataset for individual GCC countries, as part of a national forest inventory. These initiatives would support mangrove conservation and climate change mitigation efforts by the government, international organizations, and oil and petrochemical industries. It will also foster the movement toward using ecosystem-based approaches to coastal management that are growing in the GCC region (Fanning et al., 2021; Mateos-Molina et al., 2021).

There are opportunities for understanding the impact of climate change and environmental variables on mangrove cover and distribution. This can be achieved by automating mangrove forest monitoring using integrated high-resolution data with machine learning techniques (Alsumaiti et al., 2019; Elmahdy et al., 2020; Guo et al., 2021). This will improve on mangrove classification, biomass estimation and carbon sequestration accuracy assessment under different climate change scenarios. There are opportunities for the use of UAVs and LiDAR technologies to help support research on afforestation and reforestation best practices, including aspects such as seedling density, substrate slope and inundation and related parameters in order to enhance the growth and survivorship of seedlings in future planting efforts. Also, development of a novel mangrove-soil-climate nexus approach to improve our understanding of the interconnections and factors influencing the growth of mangroves in the region would be invaluable.

5 Conclusions

Mangrove species *A. marina* and *R. mucronata* are the two most resilient evergreen forests along the coastlines of the GCC countries that provide critical ecosystem services crucial to the environment and human-well-being. Remote sensing tools can be used to monitor and measure a wide range of mangrove forest characteristics at different spatial and temporal scales that allow for a more detailed and better understanding of mangrove ecosystems. Based on a systematic literature review, the largest expanse of mangrove forests was reported in Saudi Arabia, followed by the UAE, Qatar, Oman, Bahrain and Kuwait, respectively, with this area mainly estimated from satellite images. Mangrove cover in the GCC countries, from 1996 to 2020, decreased in Saudi Arabia, Bahrain, Oman and Kuwait, remained relatively stable in the UAE but increased appreciably in Qatar. However, reported changes in area varied highly between studies due to the lack of a standardization methodology, differences in satellite imagery resolutions and classification approaches used in different studies. Mangrove ecosystems in the GCC countries are threatened by climate change, but more so by progressive anthropogenic land use change stressors. GCC countries such as UAE and Qatar are investing tremendously toward expanding mangrove plantations through various large scale reforestation and afforestation projects.

The overall paucity of studies that used remotely sensed data in the GCC countries, particularly in Kuwait, Bahrain, Oman, and Qatar highlights the urgent need for more research in this area. In particular, the lack of LiDAR and UAV data and the relative complexities around flying UAVs in the GCC countries explains why only a few mangrove forest tree-level characteristics were measured in the reviewed remote sensing studies. Studies should capitalize on recent developments that use high-resolution remote sensing data at different spatial scales and in real-time for the sustainable management of the mangrove forests. The reforestation and conservation of mangrove forests should be prioritized to sustain key mangrove ecosystem services. Community involvement should also be encouraged to increase local awareness of mangrove conservation and support global UN Sustainable Development Goals related to climate change actions, life below water, and life on land.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

MR: Writing - original draft, Review & editing, Methodology, Data curation, Formal analysis. EBE: Writing - original draft, Review & editing, Methodology, Data curation, Formal analysis, Supervision, Project administration. MMA: Writing - original draft, Review & editing, Supervision, Project administration. MSW: Review & Editing. AB: Writing - original draft, Review & Editing. AA: Review & Editing. JAB: Review & Editing. KR: Review & Editing. TA: Review & Editing. RR: Review & Editing; RM: Review & Editing. FS: Review & Editing. MF: Writing - original draft, Review & Editing. Sd-M: Review & Editing. GAPG: Review & Editing. YARC: Review & Editing. PSPA: Review & Editing. LFV-C: Review & Editing. TA-A: Review & Editing. SK: Writing - original draft. SS: Review & Editing. WSWMJ: Review & Editing. JFM: Review & Editing. EK: Writing - original draft. JP: Writing – original draft. MJA: Review & Editing. AC: Review & Editing. WD: Review & Editing. MM: Conceptualization, Writing - original draft, Review & editing, Methodology, Supervision, Project administration, Data curation, Formal analysis. All authors contributed to the article and approved the submitted version.

Funding

This project and publication was made possible by a High-Impact Grant Award [211] from Qatar University, Qatar. The publication was also funded by the Internal Grant Award No. IG/ART/GEOG/23/01 from Sultan Qaboos University of Oman, entitled "Managing Ecosystem Services and Natural Resources for Water and Food Resilience in a Changing Climate".

Acknowledgments

The authors would like to thank the following people for their support during the literature review: Daniel A. Friess, Esmaeel Adrah, Shaurya Bajaj, Gabby Richardson and Dhouha Elouerfelli. EBE was supported by the University of Buea Research Grants (Decision No. 2023/0546/UB/DFinA/DFSMS/FO/FIN/AA). RR would like to thank Australian Research Council Discovery Award DP180103444. JAB was supported by the NYUAD Center for Interacting Urban Networks (CITIES) and the Arabian Center for Climate and Environmental Sciences (ACCESS), funded by Tamkeen under the NYUAD Research Institute Award CG001 and CG009, respectively. TA acknowledges the support of the ORGS at the American University of Sharjah (UAE) through grant # FRG21-E77. The statements made herein are solely the responsibility of the authors.

Conflict of interest

Authors MR, EBE, JFM, JP, and MM were employed by Ecoresolve. Authors MMA, AB, GAPG, PSPA, LFV-C, SK, SS and WSWMJ were volunteers (unpaid) with Ecoresolve at the scientific research and advisory roles. Authors EBE, JFM, and MM were employed by BlueForests. Author AC was employed by Tecnosylva.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2023.1241928/full#supplementary-material

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ARTICLES FOR FACULTY MEMBERS

MANGROVE RESTORATION TOWARDS SUSTAINABLE COASTAL ECOSYSTEM MANAGEMENT

Title/Author	**Restoration of coastal ecosystems as an approach to the integrated mangrove ecosystem management and mitigation and adaptation to climate changes in north coast of East Java / Rudianto, R., Darmawan, V., Isdianto, A., & Bintoro, G.**
Source	***Journal of Coastal Conservation*** **Volume 26 Issue 4 (2022) Article No. 37 Pages 1-17 https://doi.org/10.1007/s11852-022-00865-4 (Database: SpringerLink)**

Journal of Coastal Conservation (2022) 26: 37
https://doi.org/10.1007/s11852-022-00865-4

Restoration of coastal ecosystems as an approach to the integrated mangrove ecosystem management and mitigation and adaptation to climate changes in north coast of East Java

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Received: 8 November 2021 / Revised: 20 January 2022 / Accepted: 20 April 2022 / Published online: 27 July 2022

Abstract
Climate change is very basic and appears on earth. Climate change has become an issue that must be faced by humans today and in the future. One of the impacts of climate change can be found in coastal areas. Tsunamis and tidal floods repeatedly occur in coastal areas. One of the efforts to overcome sea level rise that causes tsunamis, erosion, and tidal flooding is mangrove forests. This study aims to determine public awareness of the occurrence of tidal flooding and tsunami and to find an easy and inexpensive way to overcome it. This research is integrated using the partial least square (PLS) approach and the coastal vulnerability index (CVI) approach to mangrove forests. The results showed that the awareness and assessment of the community to carry out mangrove forest restoration to overcome disasters caused by climate change must be managed and handled with a co-management approach..

Keywords Climate Changes · Mangrove Restoration · PLS · CVI · Mitigation · Adaptation

Introduction

Climate changes due to global warming have changed rain intensity and duration, temperature fluctuations, wind, and tropical storm frequency, and other climatic phenomena (Seneviratne et al. 2012; Sofian and Nahib 2010; Trenberth 2011). Climate change has altered nature, and the future risks for humans are prolonged suffer (Otto et al. 2017; McMichael 2012). Therefore, we need immediate, quick, and large-scale actions to reduce emissions because the average global temperatures are predicted to reach or pass the warming threshold to 1.5 Celsius degrees within 20 years (Frölicher et al. 2018;King and Karoly 2017). The impacts of global warming on human life are increasing and expanding drought, widespread diseases like malaria, increasing the frequency of storms, sea level rise, effects on agricultural production, heat waves, forest fires, destruction of marine ecosystems, and animal extinction (Ortiz-Bobea et al. 2021; Alig et al. 2011; Wents 2016).

The coastal region is a vulnerable region to sea level rise. Sea level rise potentially endangers coastal regions (Mcleod et al., 2010). This condition will bring social, economic, and cultural impacts (Stephens et al. 2018; Yan et al. 2016). Climate change affects manufactured infrastructures and coastal ecosystems in coastal areas and causes catastrophes, such as coastline erosions, coastal flooding, and water pollution.

These issues have become a concern in many countries. Coping with additional pressures of climate change may require a new approach to manage land, water, waste, and coastal ecosystems (Mandal et al. 2021; Toimil et al. 2020). Therefore, many countries create innovations to cope with

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the impacts of climate change in coastal areas (Hsin-Ning et al. 2017; Kaspersen et al. 2016).

The ICCSR (2010) reports that Indonesia's sea level will increase by 10 to 50 cm with an average increase of 25 to 30 cm by 2050. Meanwhile, the IPCC (2019) reports that the height above sea levels increases by an average of 0.86 cm per year. The leading causes of rising sea levels are thermal expansion of the ocean and iceberg melting in polar regions (ICCSR 2010).

Oceans absorb 90% of greenhouse gases trapped in the atmosphere, and this condition increases and expands seawater temperature. Consequently, seawater volumes increase. Greenhouse gases will melt the glaciers and ice sheets in the arctic; thus, the amount of water in oceans will increase (Lindsey 2021). Sea level rise (SLR) escalates and worsens the frequency of extreme sea levels (ESLs), leading to beach flooding. The global mean surface level (GMSL) is a function of the global mean surface temperature (GMST). Therefore, targets of temperature stabilization have essential implications for the risks of coastal flooding; for example, 1.5 C and 2.0 C of warming above pre-industrial level as mentioned in the Paris Agreement (Rasmussen et al. 2018). To date, few studies have investigated the impacts of climate change on shoreline change. First, the shoreline data is inadequate or cannot be solved temporally to analyze the dynamics of coastlines. Second, relative sea levels along the coastlines are generally known in an area that has a tide gauge. These two challenges can be solved due to the increasing number of mutually complementing observations of shoreline change and geodetic engineering. Different interpretations regarding the sea level rise in the coastline change recently highlight the need to conduct specific studies that rely on local observations and applicable models in the local geomorphology context. Cozanneta et al. (2014) state that understanding the dynamics of coastlines requires shoreline data that are frequently insufficient or cannot be solved temporally. Besides, data of sea levels along the coast is generally unknown because there are only a few tide gauges. Moreover, this problem can be solved because the observations of shoreline changes have increased; thus, they mutually complement.

Various interpretations regarding the sea level rise in the coastline change recently highlight the need to conduct specific studies that rely on local observations and applicable models in the local geomorphology context. Zacharioudaki and Reeve (2011) state that the current climate scenario and future projections report there statistically significant changes to wave climate conditions. For the scenario of future emissions, the most notable change occurs during the late summer from medium to high fluctuations and during the late winter from medium to low fluctuations. Finally, the critical points to manage coastal are observing the significant shoreline changes in the future wave direction and comparing them with wave height fluctuations.

Sofian (2010) explain that the increasing sea surface temperature (SST) in the Indonesian sea varies from -0.01°C/year to +0.04°C/year, and the highest increase trend occurs in the north coast of Papua Island and the lowest occurs in the south coast of Java Island. The decrease of SST on the south coast of Java Island does not happen in the long term. This decline is probably caused by growing upwelling in the southern coast of Java Island due to the increasing frequency of El Nino (Sofian 2010). The sea level rise changes current patterns, increases erosion, changes shorelines, and reduces wetland areas along the coast. In the end, wetland ecosystems in coastal areas may be damaged if the sea level rise and the sea surface temperature exceed the maximum limit of the adaptation capacity of marine biotas.

The SST is predicted to increase from 0.6° C to 0.7° C by 2030, and will reach 1° C to 1.2° C by 2050; these numbers are relative to the average SST in 2000. Meanwhile, the SST will rise from 1.6° C to 1.8° C by 2080 and will reach 2° C to 2.3° C by 2100. Compared to the data of SST paleoclimate in the Western Pacific Ocean, this phenomenon indicates that the SST will reach the highest rise in 2050 since 150,000 years ago. In addition, the sea level rise increased along with the increasing SST due to thermal processes and the increasing water from melted ice glaciers in Greenland or Antarctica. The potential increase in SST follows the expanding temperature and the melted ice (Sofian 2010).

Climate change brings impacts to Indonesian cities and potentially sinks coastal areas due to the declining land surface. Land subsidence or land subsidence often occurs in the coastal lowlands of Indonesia. The Road Map research (2019) revealed that 21 provinces and 132 districts or cities in Indonesia are indicated to encounter subsidence, particularly in coastal areas. Therefore, coastal lowlands need mitigation and adaptation subsidence. Dobben et al. (2012) state that the vegetation in coastal areas is expected to change due to sea level rise; these changes can be interpreted as the loss of diversity that will decline common species but increase rare species in extreme habitats. However, Dobben et al. (2012) did not discuss the existence of mangrove vegetation to prevent sea level rise towards the mainland. Mangrove vegetation is currently shrinking due to an anthropogenic process. In fact, the density of mangrove vegetation is necessarily improved to protect coastal areas from abrasion. Whidayanti et al. (2021) support this opinion and state that the more extensive and densed the mangrove vegetation in a region is, the lower the abrasion rate will be. However, if the region's area and density levels are low, the abrasion will possibly become greater.

Xiaoxu et al. (2016) argues that community' awareness and human vulnerability to potential health impacts due to climate change are active agents. Humans can control the effective use of technology and resources, community awareness, and health effects by adopting proactive measures, including a better understanding of climate change patterns and their effects on health.

Based on research by Brown et al (2020) stated that global mangrove forests have experienced fragmentation and Indonesia is one of the countries with high rates of deforestation due to land conversion. For this reason, Cinco-Castro and Herrera-Silveira (2020) states that Cinco-Castro and Herrera-Silveira (2020) states that well-conserved mangroves have low vulnerability and are in good health because of their high sensitivity. Meanwhile, mangroves that are affected by human activities are more vulnerable in terms of sensitivity and adaptive capacity. In the research area, the mangrove forest is degraded because it is heavily influenced by human activities. Thus, mangrove restoration is an option to improve a healthier coastal environment.

Research on mapping public awareness of disaster was conducted to more comprehensively observe public perception and appraisal of disasters and analyze shoreline change. Thus, the research could cope with the impacts of climate change by restoring coastal and mangrove forests as a "bodyguard" and integrated effort to manage coastal ecosystems, draft mitigation, and adapt to climate change. This study was conducted on the south coast of East Java Province, an area constantly inundated by water due to tidal flooding and tsunami. BMKG (2020) also reported a similar recurring condition and predicted that coastal flooding or rob would occur on May 27-28, 2020. Sea tides, high waves, and high rainfall can affect the dynamics of coastal regions in Indonesia, such as the south coastal region of East Java, and trigger coastal flooding (rob). BMKG explains that these conditions can disrupt transportation around the harbor and coastal, activities of salt farmers and inland fisheries, as well as loading and unloading activities in ports. The south coastal area of Java experiences a more severe impact of tidal waves and flooding. Hundreds of buildings, such as houses, gazebos, stalls, beach slopes, and buildings on the coast are damaged. In Lumajang, 300 children and women were displaced.

This study aimed to determine public awareness of disasters and map the vulnerability of coastal areas that required immediate, simple, and inexpensive management due to climate change. The results will be used to develop mitigation strategies and adaptation utilizing an approach of mangrove forest restoration.

Coastal ecosystem restoration is a comprehensive concept and approach to overcome the degradation of coastal ecosystems with interconnected ecosystems. This approach is the basis for restoring damaged (micro) mangrove forests. Integrated restoration of mangrove ecosystems is the method of restoring mangrove forests using the principles of scientific integration which include the PLS model, CVI model by assessing variables of geology, geomorphology, elevation/altitude, shoreline change, relative sea level rise, the average tidal wave, and significant wave height. While the results of the combination of the two models above produce a mitigation and adaptation model adapted to the Regulation of the Minister of Environment and Forestry of the Republic of Indonesia Number P.33/Menlhk/Secretariat/Kum.1/3/2016 concerning the Guidelines for the Preparation of Climate Change Adaptation.

Therefore, this study necessarily composed mitigation and adaptation models using a co- management-based cooperation approach in coastal areas of Lamongan and Gresik Regencies with a coastal length of 187 Km. These areas are prone to tidal flooding and tsunami. CNN Indonesia (2021) and kompas.com (2020) report that flood frequently submerges coastal areas of Lamongan and Gresik, and flood puddles have increasingly widespread. Therefore, this study mapped public appraisal and awareness of disasters due to tidal flooding as well as classified and identified the susceptibility of coastal areas.

Materials and methods

This research was conducted in coastal areas of Lamongan and Gresik Regencies, as shown in Fig. 1.

Central Bureau of Statistics of Lamongan Regency (2020) mentions that astronomically, Lamongan Regency is located 6 ° 51’54’ to 7º23’6’ south latitude and between 112º4’41’ to 112º33’12’ east longitude. Geographically, Lamongan shares borders with other areas: the Java Sea in the north, Gresik Regency in the east, Jombang and Mojokerto regencies in the south, and Bojonegoro and Tuban Regencies in the west. Lamongan Regency covers 1,812.8 km2 or 3.78% of the area of East Java Province. Lamongan Regency consists of 47 miles of coastline and 902.4 km2 of marine area calculated 12 miles from the sea surface Tables 1 and 2.

The Central Bureau of Statistics of Gresik Regency (2020) describes that Gresik Regency is located between 112^0-113^0 East longitude and 7^0 – 8^0 South Latitude. It shares borders with several areas: the Java Sea in the north, Sidoarjo Regency in the south, Lamongan Regency in the west, and Madura Strait in the east. Almost one-third of Gresik's territory is coastal, consisting of along Kebomas District and some parts of Gresik, Manyar, Bungah, and Ujungpangkah Districts.

This study focused on excavating public opinions and judgment on coastal areas in Lamongan and Gresik Regencies. These areas are exposed to tidal flooding and inundation every year. Public opinion and appraisal were employed as the basis of cooperation among stakeholders. It is necessary to map vulnerable coastal areas using the coastal vulnerability index (CVI) to facilitate and direct stakeholders on areas requiring direct handling. This research interviewed several respondents in two regencies, as follows Table 3:

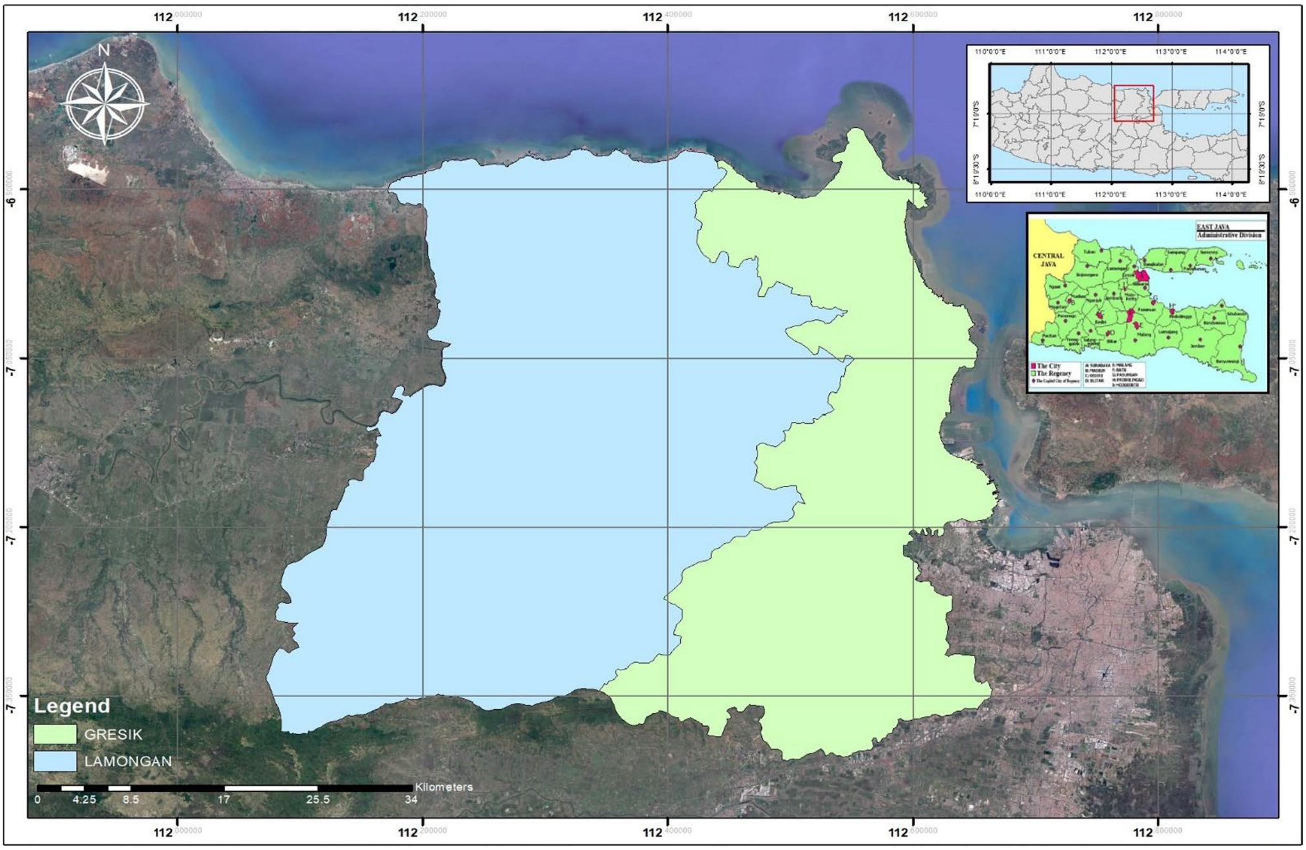

Fig. 1 Map of the research sites

Table 1 Flood in Lamongan in 2015–2020

Year	Flooded areas	Number of families	Flooded agricultural land (Ha)	Flooded pond land (Ha)
2015	6 Districts (39 Villages)	2,159	182	3,790
2016	11 Districts (83 Villages)	8,670	4,373	1,522
2017	12 Districts (88 Villages)	4,006	-	4,384
2018	9 Districts (40 Villages)	3,921	1,710	2,350
2019	6 Districts (35 Villages)	3,391	100	3,325
2020	17 Districts (115 Villages)	9,610	1,120	6,513

Source: BPPD Lamongan in 2015–2020

Table 2 Flood in Gresik in 2015—2021

Year	Flooded areas	Height of flood	Flooded settlements (Families)	Number of people dead
2015	Benjeng District	30 -100 cm	1,245	9,857
	Cerme District		655	
	Menagnti District		581	
2021	Cerme Districts comprises of Gurang Anyar, Dungus, Morowudi, Iker-Iker, Cerme Kidul, Pandu, Jono, Tambak Beras, and Banjarsari Villages	5 – 45 cm	760 families	Not found

Table 3 Location samples in two regencies in East Java

No	Type of respondents	Coastal areas	
		Lamongan regency	Gresik regency
1 2	Village government Local communities (including small employers)	10 people 55 people	10 people 54 people

This study mapped 129 respondents' opinions and appraisal using the PLS method with a list of questions referring to five goals: the hazards or natural disaster assessment, vulnerability assessment, capacity assessment, resource management in a disaster situation, and risk analysis. Table 4 shows the list of questions answered by one respondent.

Based on the above questions, this research composed the PLS structural model of Lamongan and Gresik coastal areas, as presented in Fig. 2.

Structural model that emerged from the results of SEM modeling using SmartPLS 3.0. This is in accordance with the INNER MODEL which is a structural model used to predict causality relationships between latent variables or variables that cannot be measured directly. The structural model (inner model) describes the causal relationship between latent variables that has been built based on the substance of the theory.

The software used is SmartPLS 3.

The coastal vulnerability index (CVI) method was done by assessing variables of geology, geomorphology, elevation/altitude, shoreline change, relative sea level rise, the average tidal wave, and significant wave height. These variables strongly affected coastal region changes. Determining the CVI parameters was necessary to overcome threats of damaging coastal areas and formulate strategies and action plan mitigation to minimize the impacts of coastal damage (Pendleton et al. (2005), Thieler and Hammar-Klose (1999), Gornitz et al, (1994), Shah et al. (2013). Data to analyze CVI included CVI of Lamongan and Gresik Regencies (Fig. 3 and Tables 5 and 6).

Results and discussion

Results of the PLS analysis

The PLS software operation revealed that the construct correlation between the assessment of hazards or natural disasters and its indicators is higher than the correlation between assessment indicators of hazards/natural disasters and other indicators. The construct correlation between vulnerability assessment and its indicators is higher than that between vulnerability assessment indicators with other indicators. The construct correlation between capacity assessment and its indicators is higher than the correlation between capacity assessment indicators and other indicators. The construct correlation between source management in a disaster condition and its indicators is higher than that between vulnerability assessment indicators and other indicators. Similarly, the construct correlation between the risk analysis and its indicators is higher than the correlation between risk analysis indicators and the other indicators. These findings show that latent constructs predict that indicators on their blocks are better than those on other blocks.

Based on Table 7, this concludes several points.

1. The output results show the AVE value of each construct is greater than 0.5. The constructs of hazards/natural disaster assessment, vulnerability assessment, capacity assessment, risk analysis, and resource management in a disaster situation were good models. Therefore, it was estimated that all constructs in the model met the discriminant validity criteria.
2. Composite reliability is considered significant if its value is above 0.70. Table 7 signifies the composite reliability value of the risk analysis variable by 0.946, resource management in a disaster situation by 0.988, capacity assessment by 0.988, vulnerability assessment by 0.985, and hazards/natural disaster assessment by 0.976. The composite reliability values of the five constructs in the model are greater than 0.70. Therefore, the measurement or outer models with reflexive indicators show a very high validation rate. In other words, the indicators of the hazards/natural disaster assessment, vulnerability assessment, capacity assessment, risk analysis, and resource management in a disaster situation completely reinforced or could measure their latent variables. Moreover, the model in this research met the composite reliability.
3. The R-squared for the risk analysis variables was 0.413. This number denoted that the capacity assessment influenced the risk analysis by 41.3%. Meanwhile, other factors influenced the other 58.7%. The R-squared value of the resource management variable in a disaster situation was 0.801. This number denoted that the risk analysis and vulnerability assessment influenced the resource management in a disaster situation by 80.1%. Meanwhile, other factors influenced the other 19.9%. The R-squared value of the capacity assessment variable was 0.415. This number interpreted that the assessment of dangers or natural disasters influenced the capacity assessment by 41.5%. Meanwhile, other factors influenced the other 58.8%.
4. The R-squared value of the vulnerability assessment variable was 0.511. This number indicated that the assessment of dangers or natural disasters influenced the vulnerability assessment by 51.5%. Meanwhile, other

Table 4 List of questions referring to five goals

No	List of Questions
1.	A. Assessment Variables of Hazards or Natural Disasters A.1.1 Disasters occurring in these areas are combined effects between natural disasters (e.g., landslides of soil slopes due to heavy rains) and disasters due to human activities (e.g., logging of mangrove trees, reclamation, agricultural planting, and mining). A.1.2 Conflicts in these areas are due to human activities, such as pond development, mining excavation, and other activities destructing mangrove forests in coastal areas. A.1.3 Natural disasters in coastal areas, such as flood puddles, flash floods, or flooding, are due to high rainfall. A.1.4 Flood hazards cause many people to suffer from diarrhea, skin diseases, and other diseases. A.1.5 The local government institutions dealing with disasters have documented floods. A.1.6 The officers record the danger of floods and directly observe the field. A.1.7 The local authorities identify causes of floods by explaining the frequency, seasons, geographical regions of disasters, and cyclical or seasonal weather systems. A.1.8 Flood with the quick or slow flow will spoil any flooded objects. A.1.9 Flood in the past was more severe than that today. A.1.10 Recent floods have much greater physical impacts on infrastructures. A.1.11 It is necessary to create a trend to identify the occurrence of floods. Therefore, changes in frequency, season, location, and intensity patterns are identifiable and well-informed decisions on programming can be applied. A.1.12 Local government necessarily estimates the frequency and probability of rain and floods considering return periods. A.1.13 Flood in the past was more severe than that today. A.1.14 Earthquakes will probably increase due to releasing energy or climate change.
2.	Vulnerability Assessment Variables B.1.1 Individual or family vulnerability refers to a condition caused by inadequate basic necessities of life, such as basic needs, clean water, etc. B.1.2 the Impacts of floods will reduce the government's asset values. B.1.3 Intervention from the government or NGOs aimed to protect and enhance communities' assets and livelihoods affected by natural disasters. B.1.4 Society's economic vulnerability is caused by debt and the absence of savings, access to credit, and insurance. B.1.5 Natural disasters damage physical conditions and infrastructure in coastal areas. B.1.6 Society's social conditions do not guarantee security levels or access to education. B.1.7 The local government provides minimal access to assistance. B.1.8 The government still upholds human rights in addressing flood damage. B.1.9 When a disaster occurs, traditional values, such as cooperation, are still upheld as guidelines to overcome the vulnerable community. B.1.10 The local government disregards ethnic groups, tribes, religions, or political choices when distributing assistance to disaster victims. B.1.11 During the disaster, women in a family play an essential role in protecting children and the elderly and maintaining health, nutrition, and physically disabled family members. B.1.12 When a disaster occurs, people outside the disaster area assist. B.1.13 When a disaster occurs, each individual receives different impacts. B.1.14 When a disaster occurs, the poor usually are affected the most.
3.	Assessment Capacity Variables C.1.1 Disasters do not cause significant damage to life or property because they occur in an area without inhabitants. C.1.2 Before a disaster occurs, the government informs the community to leave a disaster area. C.1.3 Before a disaster occurs, the community has taken actions to prevent or reduce the damaging impacts of disasters. C.1.4 When a disaster occurs, not all people in a disaster area have identical suffering. C.1.5 People who have known the emergence of disaster can immediately save themselves and their property. C.1.6 The local government has the policy to determine a policy for the community during a disaster to reduce the damaging effects of dangers and secure sustainable livelihoods. C.1.7 The government could handle the previous disasters by counseling the community before a disaster occurs (the local government's reduction strategy). C.1.8 The local government is experienced in analyzing which resources will be affected by a disaster to reduce the risks. C.1.9 The local government anticipates a disaster by providing various needs required by the affected community and determining which institution will be responsible for delivering and controlling food. C.1.10 The local government has a policy and strategy to reduce disaster risks on the community and increase their ability to cope with disasters. C.1.11 The local government anticipates a disaster by training and providing counseling to the community. Therefore, the community can adjust themselves to disasters occurring in the future. C.1.12 The government trains the community by providing information about disaster prevention or mitigation. C.1.13 The local government gives aid, such as rice, social cash assistance, equipment, employment, etc. C.1.14 The community can handle or control all types of emerging threats, live normally, have adequate food and clean water, and receive better health services to prevent any disease. C.1.15 After the disaster, the community was assisted by the police, army, and local government officials to buy materials and equipment to rebuild their house destroyed by the disaster. C.1.16 Social organizations help communities confront, resist, and deal with possible threats in the future. C.1.17 Many social organizations or NGOs help the community during the disaster. C.1.18 Local social institutions that care about disaster provide much physical and non-physical assistance to the community. C.1.19 These social Institutions support people affected by disasters to realize their abilities and have the self-confidence to deal with the crisis more significantly. Therefore, they can have control over an event and the power to change their conditions and become invulnerable to any threat.

Table 4 (continued)

No	List of Questions
4.	Resource Management Variables in a Disaster Situation D.1.1 The community has strategies to solve food shortages when a disaster occurs. D.1.2 The community experiences short-term changes in meal patterns when a disaster occurs. D.1.3 The community change agricultural and diversified practices and patterns. D.1.4 The community performs various efforts to find other income sources. D.1.5 The community temporarily migrates to find work during the dry and flood seasons. D.1.6 The community survives by selling properties that they do not need. D.1.7 The community sells livestock to survive. D.1.8 The society prepares the seeds for the next planting season. D.1.9 The society faces disasters to survive and sell farm equipment. D.1.10 The society affected by disasters does not borrow money. D.1.11 The society affected by disasters sells their land. D.1.12 The society affected by disasters goes to a shelter. D.1.13 The society affected by disasters sells their valuable household properties. D.1.14 The society affected by disasters becomes beggars. D.1.15 The society affected by disasters raids the government's warehouse where food is stockpiled. D.1.16 The society affected by disasters migrates permanently, and all families live in relief camps to get emergency food.
5.	Risk Analysis Variables E.1.1 The government has a policy on handling areas frequently affected by disasters in the future. E.1.2 The government anticipates the reemergence of disasters in a prone area by preparing food, health, and education. E.1.3 The government has disaster data, mitigation efforts, and adaptation for communities affected by disasters. E.1.4 The government can calculate and estimate economic and social impacts if a disaster occurs.

factors influenced the other 48.9%. The variable of the danger or natural disaster assessment was an independent variable affecting the dependent variables. Therefore, it did not have an R-squared value.

The outer loading for the variable of the danger or natural disaster assessment confirmed that the 14 indicators had outer loading greater than 0.7 with P-values <0.05. This finding concluded that 14 indicators of the variable of the danger or natural disaster assessment met the convergent validity and significantly measured the variable of the danger or natural disaster assessment. Indicator A1.13 had an outer loading of 0.907, and indicator A1.2 had outer loading of 0.803.

The outer loading for the vulnerability assessment variable confirmed that 14 indicators had outer loading greater than 0.7 with P-values <0.05. This finding concluded that 14 indicators of the vulnerability assessment variable met the convergent validity and significantly measured the vulnerability assessment variable. Indicator B1.8 had an outer loading of 0.935, and indicator B1.1 had an outer loading of 0.895 Table 8.

The above table summarizes several points of the respondents in Lamongan and Gresik.

1. the assessment of hazards or natural disasters was very high.
2. The vulnerability assessment was very high.
3. The capacity assessment was very high.
4. The resource management in a disaster situation was very high.
5. The risk analysis was very high.

Results of the CVI analysis

The results of the CVI analysis were divided into the CVI of Lamongan Regency and the CVI of Gresik Regency. This division aimed to determine the vulnerability of coastal areas in each regency. The grid was necessarily created to determine the CVI values of two districts. The grid was created with a size of 5x5 km; thus, 21 grids were formed in the two regencies. This step was done to simplify the analysis of vulnerability levels in coastal areas of Lamongan and Gresik Regencies. The following table summarizes vulnerability categories and the weight of scores of the CVI variable.

Based on the above table, the CVI map was compiled and shown in Fig. 4 with cell divisions of G1 – G7 for coastal regions of Lamongan and G8 – G21 for coastal regions of Gresik.

Figure 5 shows that each cell measured CVI based on six criteria following Table 9. These criteria included aspects of geomorphology, erosion/accretion, the average wave height, coastal slopes, tidal range, and sea level rise. The result is presented in maps shown in Figs. 6, 7, 8, 9, 10, and 11. The figures indicated that the results of calculating the CVI then grouped the regions into three vulnerability levels: vulnerable, moderate, and very vulnerable. The coastal areas of Lamongan and Gresik had a moderate vulnerability level. Meanwhile, the calculation results (Tables 8, 10)revealed that 16 coastal areas of Gresik had a high vulnerability level. Almost all coastlines of Gresik and Lamongan had a moderate vulnerability level. Although the majority of areas of

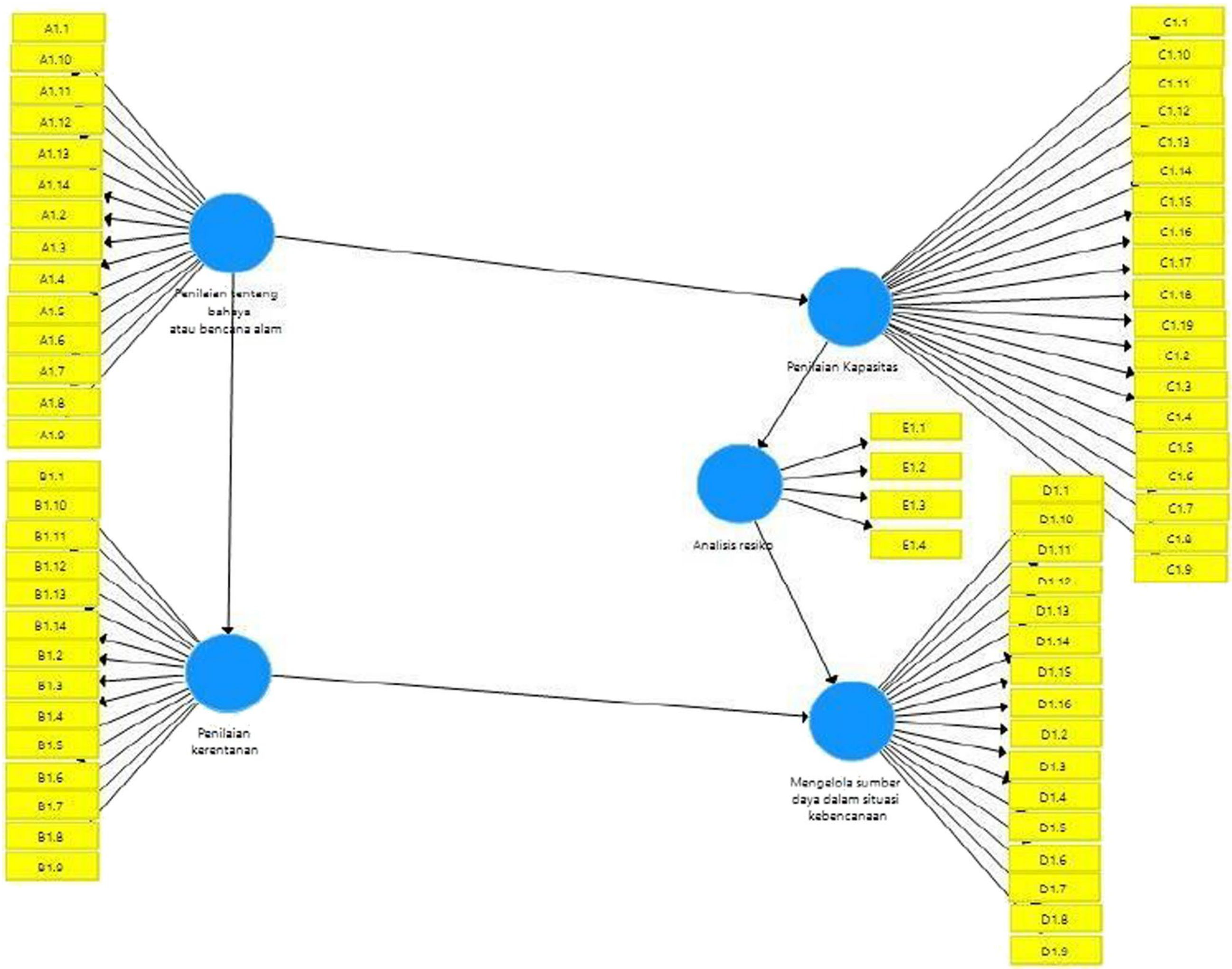

Fig. 2 The PLS Structural Model of Lamongan and Gresik Coastal Areas

Gresik and Lamongan showed a moderate category, disasters occurred sporadically there.

Adaptation and mitigation strategies

The adaptation and mitigation strategies in the coastal areas of Lamongan and Gresik were prepared by considering local wisdom and referring to the Regulation of the Minister of Environment and Forestry of the Republic of Indonesia Number P.33/Menlhk/Secretariat/Kum.1/3/2016 concerning the Guidelines for the Preparation of Climate Change Adaptation. Article 9, point 2 of the Regulation of the Minister of Environment

Number P.33/Menlhk/Secretariat/Kum.1/3/2016 states that the determination of priority actions for climate change adaptation referring to paragraph (1) must consider the following points:

1. Coverage of regions and/or sectors associated with climate risks,
2. The area of regions and/or sectors affected by climate change,
3. Resources needed,
4. Potential constraints in implementing climate change adaptation,
5. Benefits from implementing climate change adaptation,
6. Period of the benefits of climate change adaptation,
7. Acquiring investment benefits of climate change adaptation, and
8. Institutional capacity to implement climate change adaptation.

Table 10 summarizes several occurrences in the coastal areas of Lamongan and Gresik. 1. The changing situation

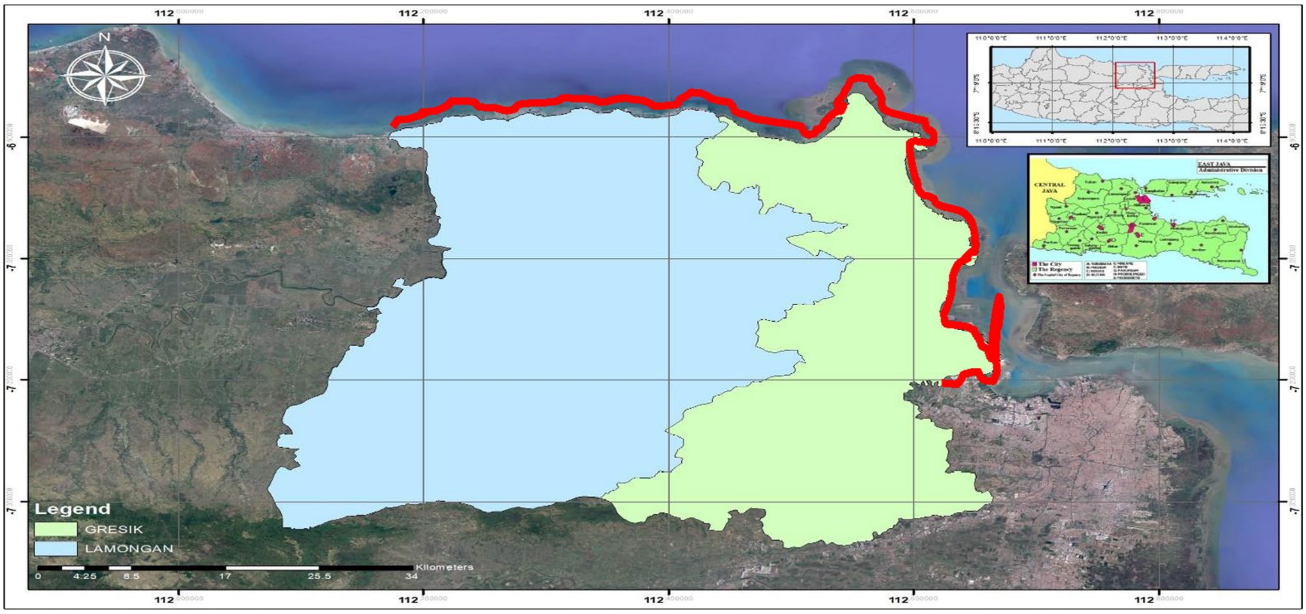

Fig. 3 Coast line Lamongan Gresik

Table 5 Data of CVI measurement of Lamongan

Cell s	Parameters					
	Coastal geomorphology	Coastal slopes	Abrasion (-)/ Accretion (+)	Tidal ranges	Significant wave height	Sea level rise
G1	Mangroves, Coral Reefs, Muddy	0.15	8.36	0.4776	0.5846	3.5853
G2	Mangrove, Muddy	0.11	9.66	0.4938	0.5846	3.5853
G3	Muddy	0.06	3.31	0.53	0.5846	3.5853
G4	Muddy	0.06	12.42	0.56	0.5846	3.5853
G5	Muddy	0.15	2.70	0.559	0.5846	3.5853
G6	Muddy	0.10	21.80	0.6206	0.5846	3.5853
G7	Muddy, Seagrass	0.12	26.06	0.6374	0.6115	3.5575

Table 6 Data of CVI measurement of Gresik Regency

Cell s	Parameters					
	Coastal geomorphology	Coastal slopes	asion (- etion (+)	Tidal ranges	Significant wave height	Sea level rise
G8	Muddy	0.35	7.80	0.7358	0.6115	3.5575
G9	Muddy	0.07	6.20	0.8124	0.6115	3.5575
G10	Brackish Marsh	0.01	26.48	0.7962	0.6115	3.5575
G11	Brackish Marsh	0.05	23.08	0.698	0.6115	3.5575
G12	Brackish Marsh	0.00	39.12	0.8374	0.6115	3.5575
G13	Muddy	0.01	21.16	1.043	0.6115	3.5575
G14	Muddy	0.03	15.61	1.1232	0.6115	3.5575
G15	Muddy	0.06	-9.32	1.2398	0.6115	3.5575
G16	Delta	0.27	-12.52	1.3772	0.6115	3.5575
G17	Delta	0.27	23.81	1.4852	0.6115	3.5575
G18	Delta	0.21	19.22	1.6324	0.6115	3.5575
G19	Muddy	0.27	17.01	1.6966	0.6115	3.5575
G20	Muddy	0.38	-0.38	1.8102	0.6115	3.5575
G21	Muddy	0.45	22.66	1.9378	0.6115	3.5575

Table 7 Values of AVE, composite reliability, Cronbachs Alpha, and R-square

construct variables	Average variance extracted (AVE)	Composite reliability	Construct reliability (Cronbach's Alpha)	R-squared
Risk Analysis	0.815	0.946	0.924	0.413
Resource Management in a Disaster Situation	0.837	0.988	0.987	0.801
Capacity Assessment	0.818	0.988	0.988	0.415
Vulnerability Assessment	0.829	0.985	0.984	0.415
Assessment of Hazards or	0.741	0.976	0.973	-

Table 8 The outer loading assessment

No	Variables	Outer loading values > 0.7, p < 0.5	
		The biggest indicators	The smallest indicators
1	Assessment of Hazards or Natural Disasters	A.1.13 (0.907)	A.1.2 (803)
2	Vulnerability Assessment	B.1.8 (0.935)	B.1.1 (0.895)
3	Capacity Assessment	C.1.15 (0.933)	C.1.7 (0.864)
4	Resource Management in a Disaster Situation	D.1.14 (0.946)	D.1.4 (to 0.883)
5	Risk Analysis	E.1.1 (0.924)	E.1.3 (0.866)

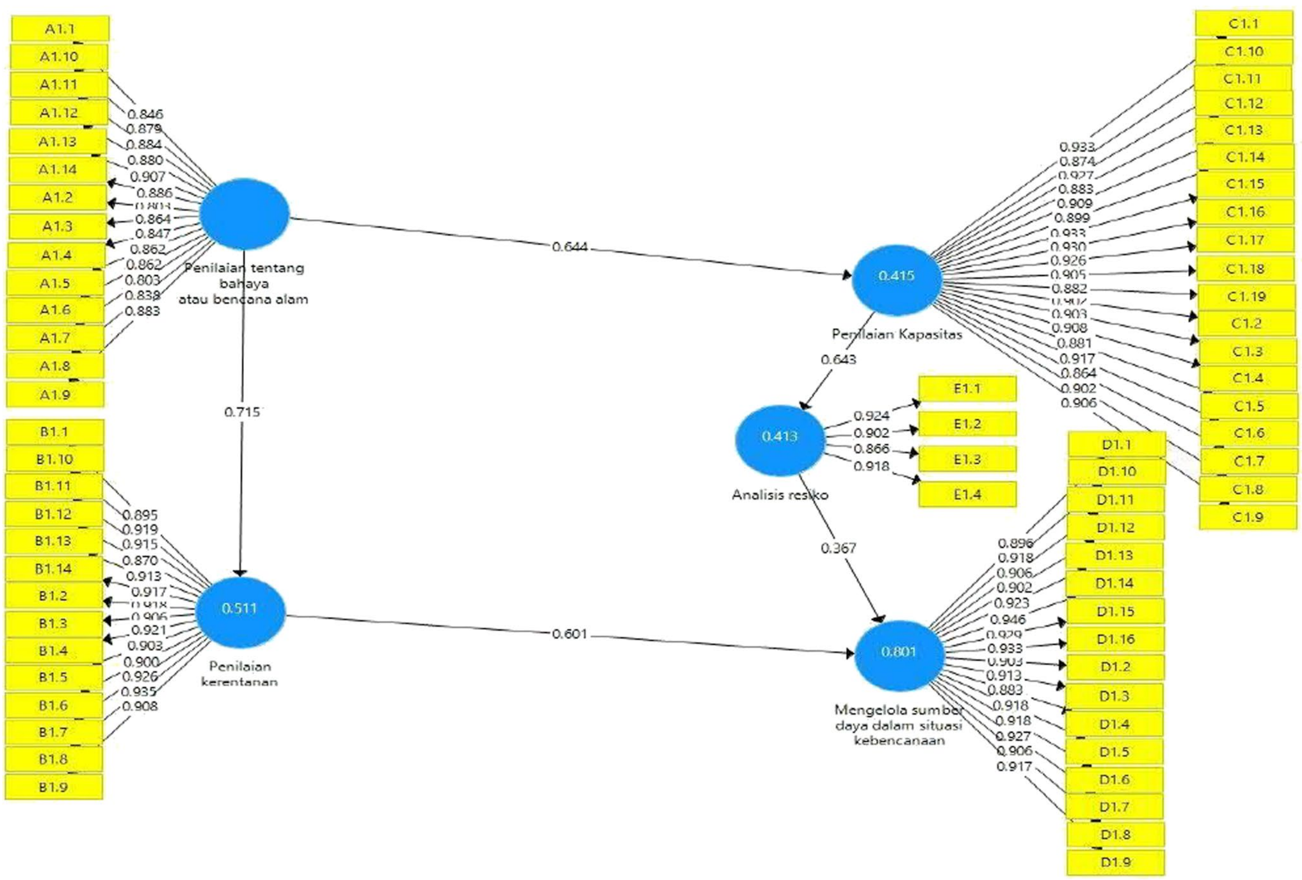

Fig. 4 Diagram of the Structural Equation Modeling (from Running PLS) with a Partial Least Square Approach Using the Smartpls Software (Measurement Model Specification)

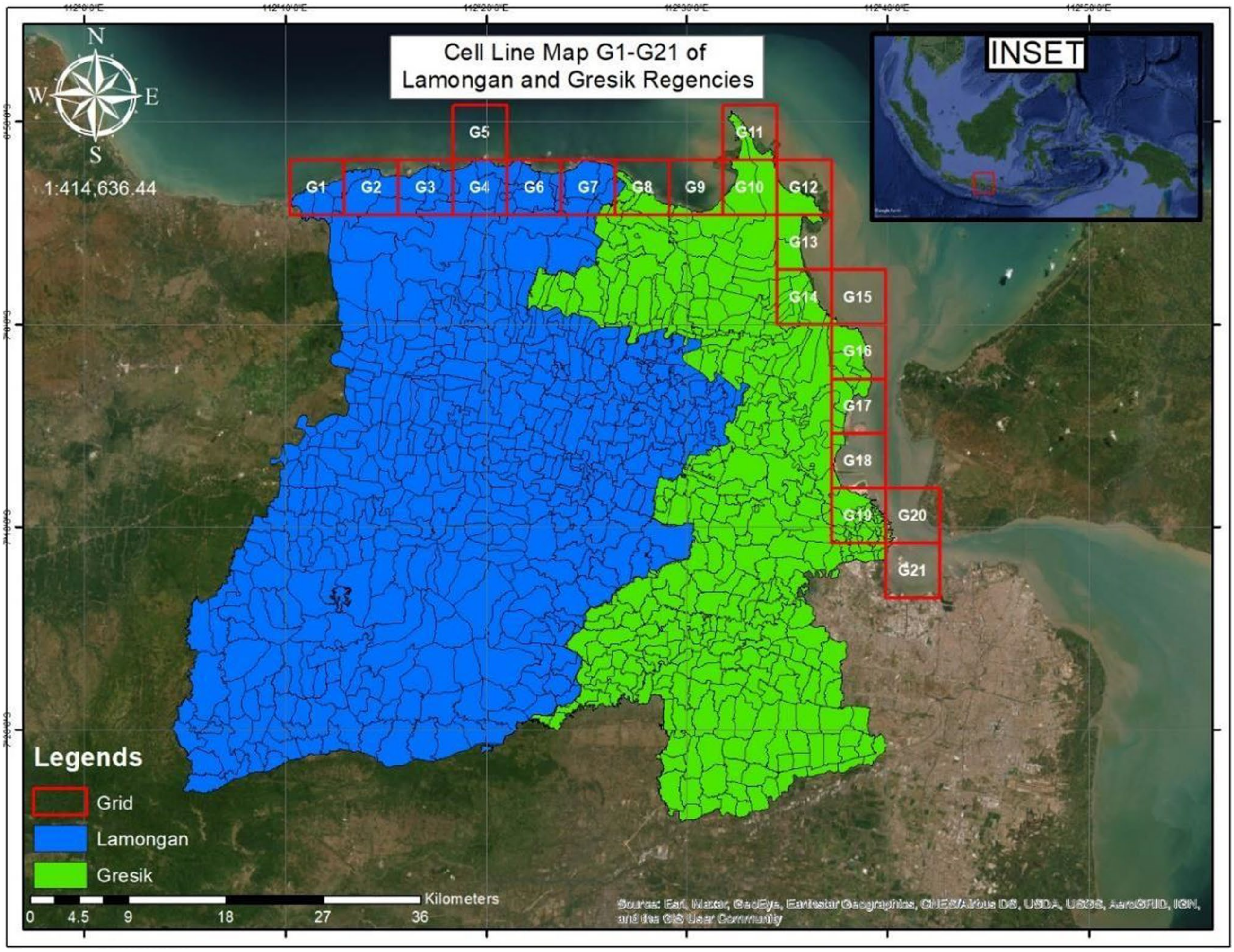

Fig. 5 The Map of G1—G21 Cell Lines of Lamongan and Gresik

Table 9 Categories and weight of scores of the CVI variable

Score categories					
Variables	Very Low	Low	Moderate	High	Very High
	1	2	3	4	5
Coastal Geomorphology	Craggy rocky beach	Medium- sized craggy and rocky beach	Lowly craggy and rocky beach with alluvial plains	Pebble, estuarine, and lagoon beach	Sandy beach with brackish marsh, mangrove, coral reef, delta, mud, and seagrass
Abrasion (-)/ Accretion (+) (m/Yr)	> 2.00	1.00—2.00	-1.00—1.00	-2.00—1.00	< -2.00
The average wave height (m)	< 0.55	0.55—0.85	0.85—1.05	1.05—1.25	> 1.25
Coastal slopes (%)	> 1.2	1.2—0.9	0.9—0.6	0.6—0.3	< 0.3
Tidal range (m/yr)	< 1.00	1.00—1.90	2.00—4.00	4.10—6.00	> 6.00
Sea level rise (m/year)	< 1.8	1.8—2.5	2.5—3.0	3.0—3.4	> 3.4

Fig. 6 CVI map based on beach geomorphology

Fig. 7 CVI map based on coastal slope

Fig. 8 CVI map based on shoreline change

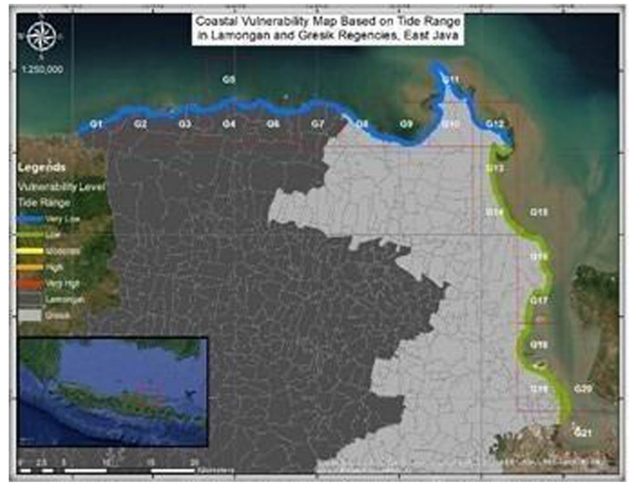

Fig. 9 CVI map based on tide range

Fig. 10 CVI map based on significant wave height

Fig. 11 CVI map based on sea level rise

Table 10 Composing actions for climate change adaptation

No	Parameters of determining action priorities	Climate change			
		Increasing air temperature	Increasing precipitation	Sea level rise	Increased incidence of extreme
1	Coverage of regions and/or sectors associated with climate risks	a) The climate systems in Lamongan and Gresik have changed and affected the quality and quantity of water, habitats, forests, health, agricultural land, and ecosystems of coastal regions b) The climate has become hotter in Lamongan and Gresik	a) Inundation and flooding occur in Lamongan and Gresik and have lowered the quality of water sources b) The temperature rise also increases chlorine levels in the water	Fish stock in Lamongan and Gresik has declined sharply, and this condition affected fishermen's daily income	a) Harvest is possibly failed due to drought b) The dry season prolongs c) The distance of fishermen catching fish gets further
2	The area of regions and/or sectors affected by climate change	a) The primary productivity rates are hampered b) This condition affects the habitat and fauna life and	a) Sectors of food security and fisheries are disturbed b) Drought has changed cropping patterns that result in crop failure	a) Changes in air pressure, temperature, wind speed, and wind direction alter the ocean currents. These phenomena can affect fish migration b) Ocean acidification occurs	a) Seasons become unpredictabl e b) Changes in habitat allow changes in the life resistance of larvae and their growth
3	Resources needed	a) The sea becomes warm due to the declining nutrient levels in the mesopelagic zone. Therefore, thegrowth of diatoms, not phytoplankton, is restricted b) The above condition affects marine biodiversities and is very harmful to coral reefs	High rainfall results in a high inundation and possibly brings water directly to the sea without storing it in the basin used as a clean water source	Sea level rise, tide, and uncertain rainy seasons increase the frequency and intensity of floods and inundation	a) Animal habitats change due to changes in temperature, humidity, and primary productivity. Therefore, several animals migrate to find a new and appropriate habitat b) Bird migration will change because seasons, wind speed, wind direction, and ocean currents bringing nutrients and fish migration also change
4	Implementing the climate change adaptation potentially faces constraints	a) Increasing the capacity of carbon absorption b) Reducing gas emissions of greenhouse c) Maintaining sustainable forests d) Exceeding climate change rates beyond the adaptation ability	a) The frequency and intensity of floods increase b) The long rainy season raises the seawater and floods human settlements and ponds	a) Food production is affected b) Tsunami and tidal flooding potentially occur	c) The agricultural sector and food security are disrupted d) The land is fired e) Coastal areas are damaged f) The need for energy increases
5	Benefits from implementing climate change adaptation	a) Preventing the increasing microclimate heat b) Preventing the decreasing water availability c) Preventing the loss of biodiversity	a) Preventing the increasing tidal flood and tsunami b) Preventing health impacts for the society c) Preventing puddles in residential areas, offices, fields, and yards	a) Preventing the intrusion of seawater b) Restoring mangrove c) Building coastal protection structures d) Elevating road constructio ns e) Dumping the beach	a) Reducing social and economic vulnerability of the community b) Reducing the declining fish and rice production
6	Period of the benefits of climate change adaptation	A long-term period (25 years)	A medium-term period (10 Years)	A medium- term period (5 Years)	A short-term period (1 year)

Table 10 (continued)

No	Parameters of determining action priorities	Climate change			
		Increasing air temperature	Increasing precipitation	Sea level rise	Increased incidence of extreme
7	Acquiring investment benefits of climate change adaptation	a) Food security b) Energy independence c) Health d) Settlements e) Infrastructures	a) Food security b) Energy independence c) Health d) Settlements e) Infrastructures	a) Food security b) Energy independence c) Health d)Settlements e) Infrastructure	a) Food security b) Energy independenc e c) Health d) Settlements e) Infrastructure s
8	Institutional capacity to implement climate change adaptation	a) A plan for environment protectionand management, specifically the increasing temperature, is necessary b) The environmental aspect of the temperature rise is investigated c) The involved institutions are government agencies, universities, and representatives of the local society	a) A plan for environmental protection and management, specifically the increasing rainfall, is necessary b) The environmental aspect of the rainfall rise is investigated c) The involved institutions are government agencies, universities, and representatives of the local society	a) A plan for environmental protection and management, specifically the sea level rise, is necessary b) The environmental aspect of the sea level rise is investigated c) The involved institutions are government agencies, universities, and representatives of the local society	a) A plan for environment al protection and management, specifically the rise in extreme weather events, is necessary b) The environment al aspect of the surge in extreme weather events is investigated c) The involved institutions are government agencies, universities, and representatives of the local society

will threaten human life and the survival of flora and fauna. 2. Public health is disturbed. 3. The seawater intrusion pollutes the quality and quantity of water supply for the community. 4. The micro-climate difficultly predicts climate change. 5. The quality and quantity of water supply for coastal communities decline due to seawater intrusion. 6. Coastal ecosystem Habitats on land and in the sea are endangered due to sea level rise. 7. Flooding and inundation frequently emerge due to high rainfall. 8. The coastal land subsidence occurs. 9. Fish stocks are impaired due to seawater acidification. 10. Ocean currents change due to changes in air pressure and an increase in temperature.

Therefore, public, local governments, and private parties must mutually cooperate to protect the beach naturally. The beach protection by building jetty, groin, breakwater, seawalls is necessarily reconsidered because their development and operation cost highly. Therefore, this study proposed a natural and cheap approach mutually performed by all parties, namely the restoration of mangrove ecosystems as a "bodyguard" to protect the beach from changing conditions due to climate change.

The results of research, mitigation, adaptation to climate change show that mangrove forests are essential coastal ecosystems and play a major role in human life. Mangrove forests maintain biodiversity and a nursery for many marine and coastal species and support fisheries. Mangrove forests play an important role in supporting coastal communities against extreme weather events, such as hurricanes, stabilizing the shoreline, and slowing down or reducing soil erosion.

Newton et al. (2011) discovered that the mangrove forest restoration could cope with climate change. Thus, mangrove ecosystems closely relate to climate change. Moreover, healthy mangroves in coastal areas can increase coastal communities' resilience to climate change and minimize the impacts of natural disasters, such as tsunami, storms, and waves (adaptive function).

It is recommended that the restoration plan should initially examine potential pressures, such as blocked tidal waves to prevent secondary succession, and plan to eliminate the stress before trying the restoration (Hamilton and Snedaker 1984; Cintron-Molero 1992).

First, the government necessarily addresses mangrove forests in a damaged coastal village as a key of the coastal restoration. Second, the village government then forms a team consisting of society, government, and private sectors. Finally, stakeholders work using the co- management approach (Priyono et al. 2017). Thus, the village government forms institutional aspects by considering the village's characters and using the co-management approach.

The CVI data signify that mangrove forests in the entire coastal areas in Lamongan- Gresik should be restored although these areas are currently categorized as lowly and highly vulnerable areas. The mangrove forest is absolutely restored as a solution to protect coastal and critical areas. Coastal land conservation is easily done by the society in cooperation with the local government and private sectors.

Conclusion

The impacts of climate change in the coastal areas of Lamongan and Gresik are solved by adaptation and mitigation efforts using mangrove forest restoration. The PLS analysis concluded several points. a) The assessment of hazards/natural disasters was classified very high. b) The vulnerability assessment was classified very high. c) The community's capacity assessment was very high. d) The management resource in a disaster situation was very high. The risk analysis was very high. This research implies that people living in the coastal areas of Lamongan and Gresik are highly aware of the dangers of disasters due to climate change. The awareness and assessment of communities and local government are pivotal to coping with disasters in the future. To date, society still "surrender" to emerging disasters. Moreover, the local government will act to overcome a disaster after it occurs. The local government's ability to anticipate and face a disaster is necessarily improved using the available data; priority areas require particular attention.

The CVI results discover that the coastal areas in Lamongan and Gresik that need attention are along with the 129 Ha, and a high priority of flooding is in cell 16 in Gresik. However, due to limited funds and personnel, this research did not investigate the next categories. Therefore, further research necessarily sharpens the utmost priority and priority categories based on the results of village discussion. The local government should initiate this discussion to prevent disaster areas.

The approach is applied as a solution to protect coastal areas, critical land, and land conservation by restoring mangrove forest ecosystems. Types, structures, and autecology of mangroves should consider their original vegetation adjusted with the coastal land structures and textures.

Acknowledgements The corresponding authors are grateful to thank the Rector of Universitas Brawijaya, Professor Dr., Ir. Nuhfil Hanani A. R., who provided a chance to conduct this research. We also thank the head of Research institutes and the devotion community of Universitas Brawijaya, Dr., Ir. Bambang Susilo, M.Sc., Agr., who helped us accelerate the research.

Any grants / equipment / drugs, and/ or other support that facilitated the conduct of research / writing of the manuscript (including AFMRC project details, if applicable) None

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