Ecological Genetics and Genomics 32 (2024) 100282

Contents lists available at ScienceDirect

Ecological Genetics and Genomics

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

A review of the mangrove ecosystem in Indonesia: Biodiversity, conservation, and challenges in sustainable management

Rizal M. Suhardi [a], Wira Rahardi [b], Huie-Chuan Shih [c], Junaldo A. Mantiquilla [d], Yi-Hui Wu [a], Meng-Shin Shiao [e,**], Yu-Chung Chiang [a,f,*]

[a] Department of Biological Sciences, National Sun Yat-sen University, Taiwan
[b] Department of Agricultural Technology, Khairun University, Indonesia
[c] Department of Nursing, Meiho University, Pingtung, Taiwan
[d] Department of Biological Sciences and Environmental Studies, University of the Philippines Mindanao, Davao City, Philippines
[e] Research Center, Faculty of Medicine Ramathibodi Hospital, Mahidol University, Bangkok, Thailand
[f] Department of Biomedical Science and Environment Biology, Kaohsiung Medical University, Kaohsiung, Taiwan

ARTICLE INFO

Keywords:
Mangrove
Biodiversity
Conservation
Management

ABSTRACT

Mangrove ecosystem in Indonesia, representing almost 1/5 of the world's mangroves, plays a pivotal role in biodiversity conservation, coastal protection, and the provision of ecosystem services. The diverse geographic landscapes of the country contribute to one of the largest mangrove forests in the world. However, the mangrove ecosystem in the country was damaged and reduced greatly in the past decades due to anthropogenic activities. To take a further step in the conservation of the ecosystem, it is important to understand the current status of the population distribution, species diversity, and conservation strategies. This article presents a comprehensive assessment of the status of Indonesia's mangrove ecosystems with a specific focus on biodiversity, ongoing conservation endeavors, and prevailing management practices. The principal objective of this review is to gain an in-depth understanding of the significance of these unique ecosystems and the challenges associated with sustaining their health.

1. Introduction

Mangrove ecosystems in tropical and subtropical regions function as crucial interfaces between terrestrial and marine environments [1,2]. It is typically situated along the shorelines of Africa, Asia, Oceania, and the Americas, thriving in areas marked by warm temperatures and high humidity. In addition, it is characterized by unique adaptations to saline and waterlogged conditions [3–5]. Mangroves are environmentally essential and economically valuable for the following three reasons: (1) They play a crucial role in coastal protection, acting as barriers against storm surges and preventing coastal erosion [6–8]. (2) They serve as biodiversity hotspots for vertebrate and invertebrate species [9,10]. (3) They function as significant carbon sinks sequestering vast amounts of carbon and thereby contributing considerably to mitigate climate change [11–14]. (4) They provide source of cultural services, mainly tourism, which assist local communities in both direct and indirect ways [15–17].

The centerpiece of the ecosystem is the mangrove trees and bushes, renowned for their distinctive traits enabling survival in harsh environments [18]. These plants have evolved specialized root systems and leaves. The trees have pneumatophores and prop roots to stabilize soft and unstable sediments and facilitate gas exchange in oxygen-poor soil. The aerial roots of mangrove trees promote gas exchange and water uptake. They play crucial roles in sustaining coastal populations with high socioeconomic impact on local communities and carbon sequestration from the atmosphere [19].

A complex symbiotic association is observed between arbuscular mycorrhizal fungi and the roots of the trees within the mangrove forest [20]. Fungi are of paramount importance in facilitating nutrient absorption of the plants, thereby augmenting biomass production. In the mangrove ecosystems, fungi play a crucial role in enabling plants to endure extremely high salinity, promoting their growth and ensuring survival under such challenging conditions. In addition, the mangrove trees are also characterized by salt-excreting leaves and viviparous

* Corresponding author. Department of Biological Sciences, National Sun Yat-sen University. Kaohsiung, 804, Taiwan.
** Corresponding author. Research Center, Faculty of Medicine Ramathibodi Hospital, Mahidol University, Bangkok, 10400, Thailand.
E-mail addresses: msshiao@gmail.com (M.-S. Shiao), yuchung@mail.nsysu.edu.tw (Y.-C. Chiang).

https://doi.org/10.1016/j.egg.2024.100282
Received 17 June 2024; Received in revised form 23 July 2024; Accepted 25 July 2024
Available online 26 July 2024

water-dispersed propagules. These specific modifications enable them to grow in strict environments and support a diverse range of terrestrial and aquatic species in the coastal area [21]. The intricate tangled roots serve as a nursery and sanctuary for marine life including fishes and crustaceans, which use mangrove forests as breeding and nursery habitats [22,23]. The economic fish and crustacean species benefit local fisheries and the livelihoods of fishing-dependent populations [24]. The daily ebb and flow of tides further contribute to the dynamic nature of these ecosystems [25].

Several studies of *Rhizophora* and *Avicennia* species indicated that the species can provide nourishment, wood-derived commodities, and local medicinal resources [26–28]. The ability to thrive in extreme conditions leads to the production of unique phytochemicals with therapeutic properties. These compounds include various phytochemicals like steroids, triterpenes, saponins, flavonoids, alkaloids, fatty acids, quinones, and tannins, which have medicinal benefits such as antibacterial and vermifuge actions [29,30]. The young roots of *Rhizophora* and the resin of *Avicennia* spp. have been utilized for treating infertility [28]. The bioactive compounds of *Rhizophora racemose, Nypa fruticans,* and *Avicennia africana* were proposed to have certain medicinal benefits [26]. Additionally, a study proposed that the crude extracts from *A. officinalis* and *R. mucronata* may contain antibacterial agents with potential therapeutic applications [27]. The studies underscore the diverse value of mangrove ecosystems, highlighting their environmental adaptability and potential medicinal applications.

Taken together, mangrove forests are not only valuable natural assets in a worldwide scale, but they are also critical for the survival of diverse human populations by providing essential resources. In addition, they also provide opportunities for tourism, which contribute to local economies. Nevertheless, these crucial ecosystems face perilous risks from human activities including deforestation, pollution, and land development, as well as natural adversities such as climate change [31, 32].

2. Flora of mangrove forests in Indonesia

The distribution of mangroves in Indonesia is comprised of seven primary islands. The greatest area is Papua, while the smallest is Bali and Nusa Tenggara (Fig. 1) [33]. Several studies reported the diverse species of mangroves in Indonesia. Soemodihardjo et al. [34] reported 157 species of mangroves, of which 52 species of trees (known as true mangroves), 21 species of shrubs, 13 species of lianas, 7 species of palms, 14 species of grasses, 8 species of herbs, 3 species of parasitic plants, 36 species of epiphytes, and 3 species of ferns. Furthermore, Basyuni et al. [35] reported that Indonesia has a total of 47 species of true mangrove plants. A most recent study reported a total of 240 species, of which 192 species were associated with mangroves and an additional species from Papua, *Ceriops australis,* bringing the total to 48 true mangroves [36]. This implies that Indonesia is home to the highest concentration of mangrove species in the world, with 53 true mangrove species (Table 1). It indicates that Indonesia has the highest concentration of these species globally, with a total of 77 species worldwide. The variation in numbers among the studies resulted from the decision to include saline marsh plants and mangrove associates, as well as from differing definitions of mangrove. Additionally, the taxonomic descriptions of some species may still remain incongruent [37].

In Bintuni Bay, 28 true mangrove species and 27 plant species were identified in Papua, and Bunaken National Park of Indonesia, Sulawesi [38,39]. Papua is home to one of the world's largest mangrove ecosystems and has high biodiversity. Furthermore, Papua's unique geological and geographical characteristics make it an appealing location for ecological research and conservation [38]. In contrast, the distribution and diversity of mangroves in the intertidal zone of the national park are believed to have been influenced by a combination of geophysical, geomorphic, and biological forces in Sulawesi [39]. Some commonly seen species include *Ceriops zippeliana, Lumnitzera racemosa, Lumnitzera littorea, Sonneratia ovata*, *Camptostemon philippinense, Acrostichum aureum, Aegiceras corniculatum, Allophylus cobbe*, *Avicennia marina*, *Bruguiera gymnorhiza*, *Ceriops tagal*, and *Rhizophora* spp [38–40].

The unique mangrove biodiversity in Papua, especially in Java and Kalimantan, is a high conservation priority due to the numerous species discovered in this ecosystem (Table 1) [35,36]. Papua's forests are a prime location for observation and ornithological research, boasting extensive avifauna that includes many endemic bird species. Additionally, Papua plays a crucial role in developing the region as an ideal habitat for gastropods and mussels by providing steady water, ample precipitation, and a diverse food source. Papua's maritime and coastal environments support a wide variety of mollusk species, enhancing the region's overall biodiversity [38,41]. This underscores the significant reliance of numerous species on mangrove ecosystems and the imperative to safeguard this ecosystem to sustain biodiversity.

Fig. 1. Map distribution of mangrove ecosystems in Indonesia with seven major regions.

Table 1
Distribution of true mangrove species across Indonesian Archipelago.

No.	Species	Papua	Maluku	Sulawesi	Bali & Nusa Tenggara	Kalimantan	Java	Sumatra
1	*Acanthus ebracteatus*	●	●	●	●	●	●	●
2	*Acanthus ilicifolius*	●	●	●	●	●	●	●
3	*Acrostichum aureum*	●	●	●	●	●	●	●
4	*Acrostichum speciosum*	●	●	●	●	●	●	●
5	*Aegialitis annulata*	●	●	●	●		●	
6	*Aegiceras corniculatum*	●	●	●	●	●	●	●
7	*Aegiceras floridum*	●	●	●	●	●	●	●
8	*Amyema anisomeres*	●		●	●	●	●	
9	*Amyema gravis*	●	●			●	●	
10	*Amyema mackayense*	●		●	●		●	●
11	*Avicennia alba*	●	●	●	●	●	●	●
12	*Avicennia eucalyptifolia*	●		●			●	●
13	*Avicennia lanata*			●	●	●		●
14	*Avicennia marina*	●	●	●	●	●	●	●
15	*Avicennia officinalis*	●	●	●	●	●	●	●
16	*Avicennia rumphiana*					●	●	●
17	*Bruguiera cylindrica*	●	●	●	●	●	●	●
18	*Bruguiera exaristata*	●	●	●			●	●
19	*Bruguiera gymnorrhiza*	●	●	●	●	●	●	●
20	*Bruguiera hainesii*	●	●	●	●	●	●	●
21	*Bruguiera parviflora*	●	●	●	●	●	●	●
22	*Bruguiera sexangula*	●	●	●	●	●	●	●
23	*Camptostemon philippinense*			●		●		
24	*Camptostemon schultzii*	●	●		●	●	●	
25	*Ceriops decandra*	●	●	●		●	●	●
26	*Ceriops australis*	●						
27	*Ceriops zippeliana*		●	●	●		●	●
28	*Ceriops tagal*	●	●	●	●	●	●	●
29	*Excoecaria agallocha*	●	●	●	●	●	●	●
30	*Finlaysonia maritima*	●	●	●	●	●	●	●
31	*Finlaysonia obovata*	●			●	●		●
32	*Gymnanthera paludosa*						●	
33	*Heritiera globosa*					●		
34	*Heritiera littoralis*	●	●	●	●	●	●	●
35	*Kandelia candel*	●			●	●		●
36	*Lumnitzera littorea*	●	●	●	●	●	●	●
37	*Lumnitzera racemosa*	●	●	●	●	●	●	●
38	*Nypa fruticans*	●	●	●	●	●	●	●
39	*Osbornia octodonta*	●	●	●	●	●	●	●
40	*Pemphis acidula*	●	●	●	●		●	
41	*Rhizophora apiculata*	●	●	●	●	●	●	●
42	*Rhizophora lamarckii*		●		●		●	
43	*Rhizophora mucronata*	●	●	●	●	●	●	●
44	*Rhizophora stylosa*	●	●	●	●	●	●	●
45	*Sarcolobus glabosa*						●	
46	*Scyphiphora hydrophyllacea*	●	●	●	●	●	●	●
47	*Sonneratia alba*	●	●	●	●	●	●	●
48	*Sonneratia caseolaris*	●	●	●	●	●	●	●
49	*Sonneratia ovata*	●	●	●	●	●	●	●
50	*Xylocarpus granatum*	●	●	●	●	●	●	●
51	*Xylocarpus mekongensis*	●	●			●	●	
52	*Xylocarpus moluccensis*	●	●	●	●	●	●	●
53	*Xylocarpus rumphii*	●	●		●		●	
	Total	**45**	**41**	**41**	**42**	**42**	**47**	**40**

Note: ● indicates occurrence of the species in the area.

3. Status of mangrove forests in Indonesia

Indonesia plays an important role in conserving and overseeing mangrove habitats with its diverse geographic features and vast biodiversity. However, the mangrove forests in the country encounter substantial challenges and obstacles, mainly due to active human activities [42,43]. To ensure the long-term survival of these ecosystems and the priceless services they provide, it is critical to place a high priority on conservation and restoration efforts. The total area of mangrove forests in Indonesia was estimated to be 4.25 million hectares in 1990, representing 20 % of the world's mangroves [44]. However, according to the land cover maps published by Indonesia's Ministry of Environment and Forestry (Indonesian: Kementerian Lingkungan Hidup dan Kehutanan, KLHK), the mangrove area in the country declined by more than half a million hectares between 1990 and 2019 [45]. Between 2000 and 2020, mangrove areas of the country experienced significant declines in Bali

Table 2
Mangrove area and distribution in Indonesia from 2000 to 2020.

Main Island	Year 2000 (Hectares)	Year 2020 (Hectares)	Gap in 2000–2020 (%)
Bali & Nusa Tenggara	25,689.74	25,164.14	525.60 (0 %)
Java	44,808.21	44,098.24	709.97 (0 %)
Kalimantan	676,260.90	571,045.74	105,215.16 (54 %)
Maluku	234.816,87	232,525.04	2291.83 (1 %)
Papua	1,220,900.37	1,207,888.27	13,012.10 (7 %)
Sulawesi	155,474.63	138,675.72	16,798.91 (9 %)
Sumatra	572,402.18	517,588.72	54,813.46 (28 %)
Total	**2,930,352.90**	**2,736,985.87**	**193,367.03**

and Nusa Tenggara, Java, Kalimantan, Maluku, Papua, Sulawesi, and Sumatra (Table 2). One study estimated the mangrove forests had decreased by 193,367 ha, showing the widespread loss of the mangrove ecosystem in the country. All islands experienced a reduction in mangrove areas, with Kalimantan showing the greatest decrease of 5, 26075 ha yr^{-1} between 2000 and 2020 [35]. Additionally, 32,662 ha of mangroves located outside the officially designated forest estate have been reported as critically damaged, and restoration may not be feasible for these areas. In contrast, 6305 ha classified as critical, and yet have the potential to be restored [45]. This potential in successful restoration of the forest points to proper management and effort, such as taking species and genetic diversity into consideration.

Studies pointed out that there might be 30–40 % of coastal wetlands and functional decline of mangrove forests within the coming century if no further actions for preservation are taken [46,47]. Other studies proposed the challenges and importance of implementing sustainable mangrove management in the countries, which require practices and collaborative efforts [47,48].

In 2015, approximately 48 % of Indonesia's mangroves were classified as favorable, while the other half were degraded [49]. The major threat to mangrove forests in Indonesia is anthropogenic activities. They resulted in a great reduction of mangrove forest coverage, changes in species composition, and the introduction of pollutants. Additionally, the cumulative effects of these activities coupled with rising sea levels pose severe risks to the mangrove forests [50]. The primary cause of the mangrove area decline in Indonesia over the past decade has been the reduction in low vegetation, which includes shrub, savanna, and grasses. Infrastructure development, such as mining areas and residential has had the least impact (Fig. 2). Research underscores the critical need for enhanced mangrove management practices in Indonesia to curb the current rate of degradation and to maintain the unique biodiversity of these environments [51]. The reduction of mangrove forests resulted in the lack of buffering zones to climate change induced disasters, as well as in the loss of tropical and subtropical marine biodiversity [52,53]. Therefore, the conservation and sustainable management of mangroves transcend national boundaries and are pivotal for global environmental stability and social welfare.

Researchers are facing two primary obstacles in studying and preserving mangrove forests in Indonesia. First, there is a significant gap in extensive research on the diverse wildlife and plant species of mangrove forests in the country. The second challenge arises from the impact of human activities such as land development, resource extraction, and pollution, which play a considerable role in the degradation and destruction of mangrove habitats in the region [54].

4. Status of conservation and management of mangrove ecosystems in Indonesia

The conservation of mangrove ecosystems shows a positive correlation with carbon sequestration capabilities [55,56]. Implementation of effective strategies contributes to sustainable mangrove management. This supports the national blue carbon initiative agenda, which aims to utilize the capacity of marine and coastal ecosystems in the sequestration and storage of carbon dioxide [57].

To mitigate the loss of mangrove areas in Indonesia, it is imperative to implement sustainable and integrated management practices [57,58]. As emphasized by Carter et al. [59] effective mangrove management requires the integration of forestry, wetland, and Integrated Coastal Zone Management (ICZM) initiatives. The establishment and enforcement of protected areas and conservation zones are paramount in addressing the ongoing loss and degradation of habitats [60]. The foundation of sustainable management lies in the safeguarding and preservation of existing mangrove regions [61,62]. Enhancing the integration of mangroves within maritime protected zones holds the potential to effectively resolve certain policy conflicts [63].

Estimation of the sustainability of a mangrove forest is essential for establishing conservation regulations and policies. One study used the mangrove thickness, density and diversity of mangrove vegetation, tidal height, and animal biota as parameters to estimate the sustainability of ecotourism activities in the Idaman Mangrove Ecotourism area in South Sulawesi [64]. The researchers discovered that mangrove thickness (38 %), as well as density (25 %), have a significant impact on sustainability. The place scored an ecological dimension of 58.50, indicating that ecotourism is sustainable. However, effective management is still required.

The conservation status of mangrove ecosystems varies widely in the country. In Segara Anakan Cilacap, the mangrove ecosystem is relatively well-preserved but has limited biodiversity, with only a few species dominating the area [65]. The government also leased mangrove forests with ~85,000-ha in Bintuni, Papua, and ~28,000 ha in Batu Ampar,

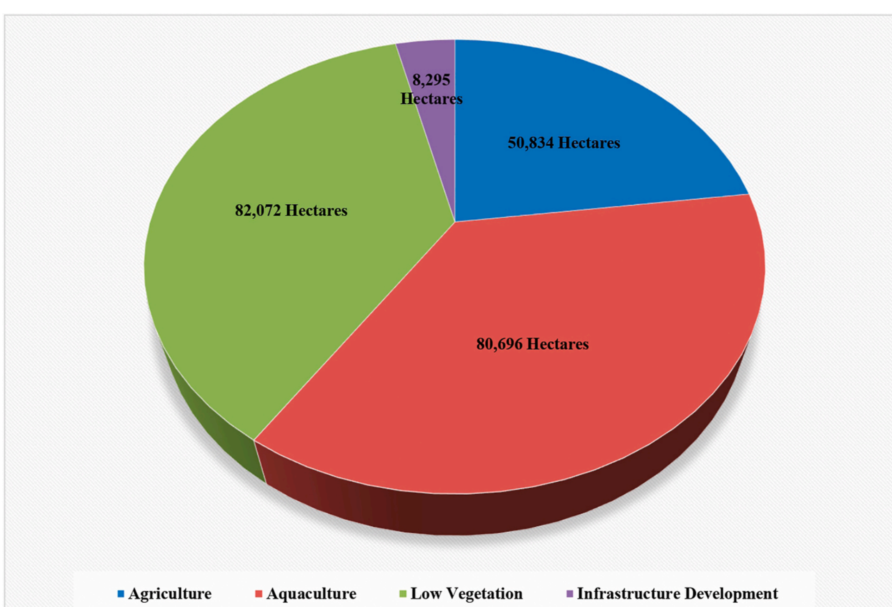

Fig. 2. Causes of Indonesian mangrove deforestation (2009–2019).

West Kalimantan to three forest concessioner companies to be harvested using seed tree method silvicultural systems [47]. The conservation of mangrove forests still requires more efforts from government departments and private parties in Indonesia. Additionally, the diversity of the species restored and preserved is a key point to maintain biodiversity and balance of the diverse and strict coastal environment.

Mangrove ecosystem management in Indonesia is a multidimensional activity that requires combining conservation with sustainable development and incorporating a variety of environmental, economic, and social considerations [66–68]. Important considerations should include management aims, ecosystem features, and indicators for ecosystem services [69]. Efforts are also being made to improve the function and value of mangrove forests, as well as to enhance political commitments involving stakeholders, and advance research and innovation [57]. Selective cutting and sustainable logging practices are also necessary for the preservation of biodiversity, ecosystem carbon stores, and other ecosystem services [70,71].

The restoration of mangroves in Indonesia involves complex processes and varying costs based on different settings. For one setting, the estimated economic impact of commercial mangrove harvesting is approximately Rp40 billion (about $20 million USD) annually with research methods include household surveys to obtain primary data, economic correlation studies, and cost-benefit analysis to evaluate mangrove forest management. This approach helps understand traditional activities' economic and ecological contributions and determine optimal management strategies [71], which is significantly higher than the costs of restoration. The estimated restoration costs range from ~ $3000 to $510,000 USD per hectare depending on different settings [72]. However, Marlianingrum et al. [73] highlighted the substantial ecological and economic value of intact mangrove ecosystems could be $189,027.25 USD per hectare. This underscores the critical need for establishing the most cost-effective plan for restoration to reach the long-term ecological and economic benefits as well as the sustainability of healthy mangrove ecosystems. This study uses benefit transfer and InVEST (Integrated Evaluation of Environmental Services Trade-Offs) to assess mangrove habitat resilience and sensitivity. Additionally, benefit transfer is used to estimate biodiversity per hectare as part of mangrove ecosystem services' total economic value (TEV). This method provides valuable land for economic assessment and mangrove ecosystem management.

The Indonesian government has launched ambitious initiatives to restore and conserve mangrove ecosystems. This includes plans to restore 600,000 ha of mangroves from 2021 to 2024 [74] and restore at least 5000 ha annually from 2025 to 2030, as outlined in the 2020–2024 Mid-Term Development Plan [75]. Moreover, guidelines have been issued to encourage community participation in mangrove management. These efforts are supported by the "Mangroves for Coastal Resilience Project", which is the largest mangrove restoration endeavor globally. The integrated conservation, restoration, and livelihood development method might be replicated across the country after being tested in major mangrove regions in North Kalimantan, East Kalimantan, Riau and North Sumatra. The project also contributes to Climate Action Plan and Gender Strategy, notably the strategic goals of economic opportunity and women's voice and agency [76]. In the Philippines, community-based management programmes have been implemented, which underscore the importance of local communities in conservation efforts. These initiatives have demonstrated effectiveness in enhancing livelihoods and expanding mangrove coverage [77]. Additionally, in Singapore, it is becoming more prevalent to implement a mangrove rehabilitation programme on tropical urban coastlines that features ecologically sensitive design and community-based initiatives. It is anticipated that the successful resolve of barriers through financial incentives and innovation will serve as a model for other urban tropical areas [78].

Many local residents depend on mangrove forests for their daily sustenance, which presents a challenge for these populations when it comes to conservation initiatives. The primary challenge is the lengthy process of obtaining government permits and complying with regulations, which needs alternative sources of revenue [79]. To effectively protect and restore mangroves at the national level, improved policies and practices based on scientific knowledge must be considered [35].

Regarding the purpose of providing an objective evaluation, it is essential to take consideration the challenges and potential drawbacks of mangrove conservation, despite the fact that the benefits of mangrove protection are enormous. It is necessary to make substantial financial commitments as part of conservation efforts. The lack of available funds is a barrier to the implementation of conservation efforts [80]. Furthermore, the absence of fair land management decisions might lead to conflicts between society interests and individual interests [77]. Additionally, significant challenges that the preservation of mangrove forests faces, including weak regulatory enforcement, technical limitations, poor coordination among stakeholders, and institutional barriers [81]. These obstacles can be particularly difficult to overcome.

Mangrove ecosystem conservation varies greatly across Indonesia, revealing regional difficulties and opportunities. These vital ecosystems need localised strategies for conservation and management. These initiatives are recommended for long-term management and sustainability of the mangrove forests:

a. Mangrove conservation policies should be in line with international climate-change adaptation actions

Efforts to incorporate mangrove conservation and restoration into national climate change adaptation and mitigation programmes are critical for maximising their benefits [82]. Several directions have been suggested to reach the goals such as prioritizing the implementation of climate change abatement actions to reduce greenhouse gas [83,84]. More details were address in the working paper published by World Resource Institute [84]. It is also suggested to incorporate mangrove targets in its Paris Agreement NDC to secure funding and support for mangrove conservation and restoration projects [85]. Furthermore, incorporating mangrove conservation into larger climate policies can encourage cross-sectoral collaboration and guarantee that mangrove protection is prioritised in national and international climate initiatives [86].

b. Developing community-based conservation economy

Engaging local communities in mangrove conservation is essential for the success of conservation efforts [87]. Community-based mangrove management programs empower local residents to take an active role in protecting and restoring mangrove forests [88]. One interesting breakthrough is to create a payment for ecosystem services (PES) scheme and provide financial rewards for conserving mangrove forests. This can motivate communities to conserve and restore mangrove areas. This scheme recognizes the value of services provided by mangrove forests, such as carbon sequestration, water purification, and coastal protection, and offers compensation for conservation efforts. These programs must be well-structured and transparent, ensuring that payments are based on measurable conservation outcomes [89–91]. Collaboration between governments, NGOs and private companies can help secure the necessary funding and support for these schemes, creating a sustainable financial model for mangrove conservation [63].

c. Strengthen research and monitoring

Increased research and monitoring contribute to a better understanding of mangrove ecosystem dynamics, which can influence effective management strategies and decisions [63]. Comprehensive study on mangroves gives insights into their ecological functions, responses to environmental change, and best approaches for conservation and recovery [92]. Long-term monitoring also aids in tracking the health of mangrove ecosystems and evaluating the impact of conservation initiatives [93]. Furthermore, it can aid in the identification of emerging dangers and opportunities, enabling timely and adaptive management actions. The hope is that reliable scientific data will help guide conservation measures [94]. Field data-driven decisions can be more effective and sustainable since they are based on a thorough understanding of ecological processes and patterns [95]. It is essential to assist universities and research institutes that perform ecological studies and monitoring programmes. This type of assistance may include funding, technical resources, and collaborative possibilities [96]. Building a sound research infrastructure allows for the generation of high-quality data that may inform and improve conservation efforts [97].

5. Conclusion

The continuous research and conservation efforts dedicated to Indonesian mangrove ecosystems are vital in securing their long-term survival and benefiting the communities and environments reliant upon them. These endeavours bear significance within the local sphere and make substantial contributions to global goals concerning biodiversity preservation and climate change mitigation. In light of these ecosystems' significant challenges, research and conservation initiatives must remain at the forefront to ensure their sustainable preservation. Financial diversity and complexity are inherent in mangrove rehabilitation initiatives highlighting the need for approaches addressing ecological sustainability and economic feasibility.

Funding

This research was funded by the National Science and Technology Council, Taiwan [MOST 108-2621-B-110-003-MY3, MOST 109-2313-B-110-005, MOST 111-2621-B-110-001 and NSTC 112-2621-B-110-001-MY3] to Y.C.C. and by partial financing (the Higher Education Sprout Project) of NSYSU.

CRediT authorship contribution statement

Rizal M. Suhardi: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Wira Rahardi:** Validation, Software, Formal analysis. **Huie-Chuan Shih:** Writing – original draft, Software. **Junaldo A. Mantiquilla:** Validation, Investigation. **Yi-Hui Wu:** Validation. **Meng-Shin Shiao:** Writing – review & editing, Validation, Supervision, Conceptualization. **Yu-Chung Chiang:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization.

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.

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