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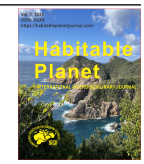

Sustainability challenges of mangrove ecosystems in the Anthropocene: Current perspectives and prospects

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ABSTRACT

Mangrove ecosystems, vital coastal habitats, face unprecedented challenges in the Anthropocene due to the interplay of natural and anthropogenic disturbances. Climate change-driven stressors, including sea level rise, altered precipitation regimes, and increased storm intensity, threaten mangrove survival by modifying hydrological and salinity conditions. Additionally, direct human activities such as land conversion, pollution, and unsustainable resource exploitation contribute to habitat degradation and biodiversity loss. These stressors impact mangroves' ability to provide crucial ecosystem services, including carbon sequestration, coastal protection, and habitat for diverse species. Understanding mangrove responses to these threats is essential for developing effective conservation and management strategies. This review synthesizes scientific literature, policy documents, and case studies to explore sustainability challenges in mangrove conservation. A holistic approach integrating ecological, social, and economic factors is necessary to enhance mangrove resilience. Collaborative efforts among scientists, policymakers, and local communities can drive sustainable management practices, ensuring the long-term health of mangrove ecosystems in the face of global environmental change.

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Research Highlights

- Challenges faced by mangrove ecosystems in the Anthropocene
- The various stressors impact mangroves' ability to provide crucial ecosystem services
- Exploring sustainability challenges in mangrove conservation
- Ensuring long-term health of mangrove ecosystems is important in the face of global environmental change

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1 Introduction

The Anthropocene is a proposed geological epoch characterized by significant human impact on Earth's geology and ecosystems. This era introduces novel disturbances to mangrove ecosystems, posing unique sustainability challenges (Lugo et al., 2014). Mangroves, which have historically thrived under natural disturbance regimes, now face a combination of these natural events and anthropogenic stressors, significantly impacting their survival and overall functionality (Choudhary et al., 2024). These stressors include climate change, pollution, and habitat destruction, which are altering the environmental conditions that mangroves depend on. Understanding these challenges is crucial for developing and implementing effective mangrove conservation and management strategies that can ensure the long-term health and resilience of these vital ecosystems (Akram et al., 2023).

The shift to the Anthropocene has brought about unprecedented changes in atmospheric gas composition, sea levels, and hydrological conditions, all of which directly affect mangrove ecosystems (Anu et al., 2024). Rising sea levels, for instance, can inundate mangrove forests, altering their salinity and sediment regimes. Changes in precipitation patterns can lead to both increased flooding and prolonged droughts, further stressing mangrove populations. Moreover, the increased frequency and intensity of extreme weather events, such as hurricanes and cyclones, can cause widespread damage to mangrove habitats. These environmental changes, coupled with direct human impacts like deforestation and pollution, create a complex web of challenges that mangroves must overcome to persist in the Anthropocene (Fig. 1).

The concept of the Anthropocene highlights the need for a more integrated and holistic approach to mangrove conservation (Lugo et al., 2014). Traditional conservation strategies, which often focus on protecting specific areas or species, may not be sufficient to address the broad-scale challenges posed by human activities. Instead, a more comprehensive approach is needed that considers the interactions between mangroves and the surrounding environment, as well as the social and economic factors that drive human impacts on these ecosystems. This requires collaboration between scientists, policymakers, and local communities to develop and implement sustainable management practices that can ensure the long-term health and resilience of mangrove forests.

This review examines the sustainability challenges facing mangrove ecosystems in the Anthropocene, focusing on the key threats to mangrove forests and identifying effective strategies for mitigating these threats and promoting mangrove conservation. The scope of this analysis includes a review of the scientific literature, policy documents, and case studies related to mangrove ecosystems worldwide. The aim is to identify effective strategies for promoting mangrove conservation and resilience in the face of global environmental change.

1.1 Importance of Mangrove Ecosystems

Mangrove ecosystems provide a wide array of essential services that are crucial for both the environment and human well-being. These services include carbon sequestration, which helps mitigate climate change, coastal protection from storms and erosion, and the provision of habitat for a diverse range of plant and animal species (MEA, 2005). Mangroves are highly effective at capturing and storing carbon dioxide from the atmosphere, making them important "blue carbon" ecosystems. They act as natural barriers against storms and coastal inundation by dissipating wave energy, reducing storm surge heights, and stabilizing shorelines through their dense root networks. For example, during the 2004 Indian Ocean tsunami, coastal areas in Malaysia, Thailand, India and Sri Lanka with intact mangrove belts experienced significantly less damage and loss of life, highlighting the protective value of mangroves in vulnerable coastal zones (Kathiresan and Rajendran, 2005; Alongi, 2008). Additionally, these ecosystems provide critical habitat for numerous species of fish, birds, and invertebrates, supporting biodiversity and maintaining ecological balance (Fig. 2).

Mangroves support local economies by providing timber, fuelwood, fisheries, and opportunities for tourism and recreation, all of which are vital sources of income (Nyangoko et al., 2022). The sustainable management of mangrove ecosystems is therefore essential for ensuring the long-term well-being of both the environment and the people who depend on them.

Globally, mangrove cover has experienced a steady decline over the past two decades due to the combined effects of aquaculture expansion, land-use change, and climate stressors (Fig. 3). Given the ecological and socioeconomic importance of mangroves, their conservation is vital for maintaining biodiversity and supporting human well-being in coastal regions (Samal and Dash, 2023). The loss of mangrove forests can have far-reaching consequences, including increased coastal erosion, reduced fisheries production, and loss of habitat for endangered species. Regional differences in carbon sequestration potential also underscore the global significance of mangrove conservation for climate mitigation (Fig. 4). Protecting and restoring mangrove ecosystems is therefore a critical priority for conservation efforts worldwide. This requires a multi-faceted approach that includes establishing protected areas, implementing sustainable management practices, and engaging local communities in conservation initiatives. Through the recognition of mangroves' ecological significance and coordinated conservation efforts, the sustained delivery of their vital ecosystem services can be secured for future generations.

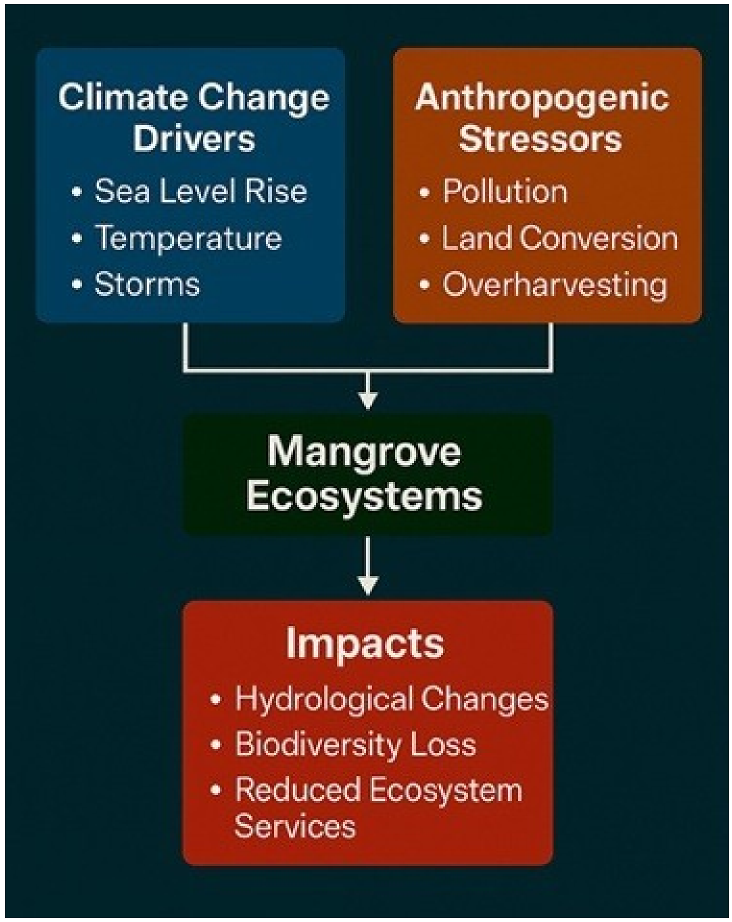

Fig. 1. Conceptual diagram of Mangrove Stressors.

2 Climate change impacts on mangroves

2.1 Sea level rise and inundation

Sea level rise (SLR) poses a profound and multifaceted threat to mangrove ecosystems, as illustrated in Fig. 1, by altering tidal regimes, increasing erosion, and driving salinity intrusions (Lovelock et al., 2017; Duke et al., 2022). Mangroves are finely adapted to narrow intertidal zones with species-specific tolerances to inundation duration and frequency (Ball, 1988; Friess et al., 2012). Disruptions to these tidal regimes can lead to prolonged waterlogging, which reduces oxygen availability in the root zone, causing hypoxic stress and mortality, particularly at the seaward edges (He et al., 2007). These changes can shift species composition, favoring flood-tolerant species and reducing overall ecosystem diversity and function (Gilman et al., 2007). For example, in the Gulf of Carpentaria, Australia, extensive dieback of *Avicennia marina* was observed after persistent inundation associated with SLR and extreme weather events (Duke et al., 2017).

Increased flooding also accelerates saltwater intrusion into upstream or groundwater-fed freshwater areas, disrupting soil and porewater salinity regimes that underpin mangrove physiological processes. Prolonged hypersalinity can inhibit seedling establishment and reduce primary productivity (Castañeda-Moya et al., 2013), ultimately leading to declines in biomass and carbon storage potential.

Despite these challenges, mangroves possess inherent resilience mechanisms, such as vertical surface elevation gain through sediment accretion and root production, and the capacity to migrate inland over time (Woodroffe and Grindrod, 1991; Krauss et al., 2014). However, in many regions this inland migration is constrained by human infrastructure and topographic barriers, leading to a "coastal squeeze" where mangroves are unable to shift landward and are gradually lost to the sea (Krauss et al., 2014). For instance, in parts of the Caribbean and Southeast Asia, studies have documented mangrove contraction due to urban encroachment and rising sea levels (Alongi, 2015).

Sea level rise also has implications for blue carbon dynamics, as shifting mangrove ranges and changing hydrology influence soil carbon processes. As mangroves colonize new substrates, carbon sequestration rates may vary depending on sediment type and nutrient availability

Fig. 2. Ecosystem services provided by mangroves.

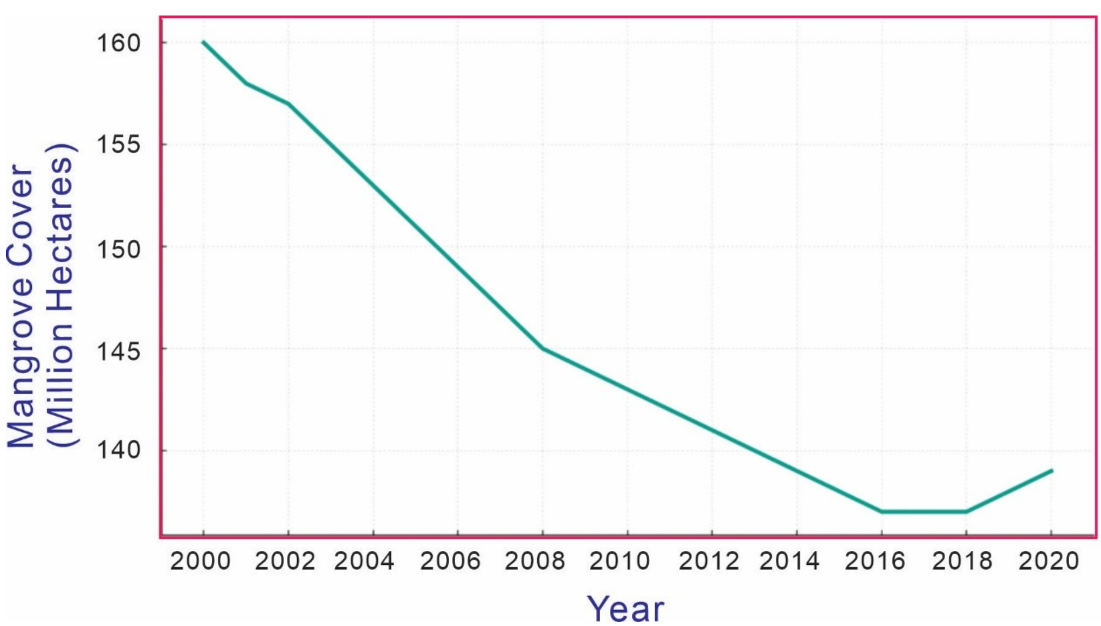

Fig. 3. Global Mangrove Cover Change (2000–2020) (Data Source: Global Mangrove Watch).

(Alongi, 2022). Moreover, inundated, anoxic soils can enhance microbial production of greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O), although flux rates are highly dependent on redox conditions and microbial

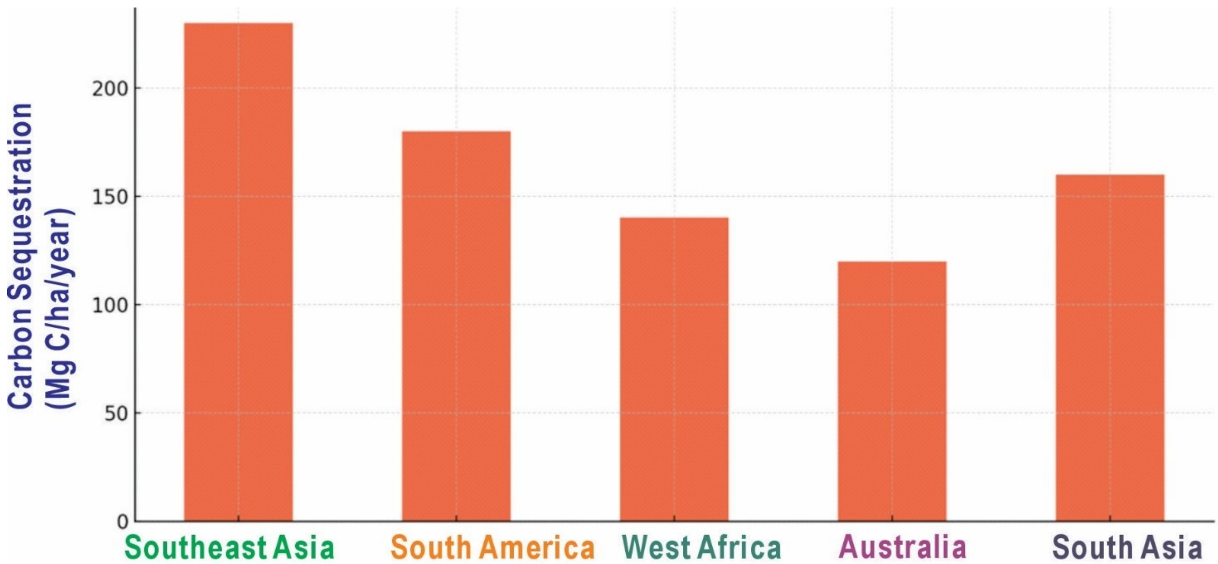

Fig. 4. Carbon Sequestration Potential of Mangrove Ecosystems by Region (Data Sources: Alongi, 2012; Choudhary et al., 2024).

community composition (Troxler et al., 2015). These feedbacks highlight the importance of preserving and restoring mangrove habitats in areas that allow for both vertical accretion and inland migration.

Therefore, understanding the ecological consequences of tidal disruption at species and landscape levels is critical for predicting mangrove response to SLR. Adaptive strategies should integrate sediment management, land-use planning, and blue carbon conservation to buffer against the cascading impacts of sea level rise.

2.2 Altered precipitation regimes and salinity stress

Altered rainfall regimes due to climate change, characterized by more frequent intense rainfall events and prolonged dry spells, are exerting complex pressures on mangrove ecosystems, with region-specific impacts. For instance, South Asia and parts of the Western Indian Ocean, including the Maldives, are expected to experience erratic monsoon patterns, with alternating flooding and drought conditions (IPCC, 2021). Intense rainfall can lead to increased freshwater runoff and reduced salinity in coastal zones, disrupting the osmotic balance vital for mangrove physiological functions. In contrast, extended dry periods reduce freshwater inputs and enhance evaporation, leading to hypersaline conditions that exceed the tolerance thresholds of many mangrove species (Sreelekshmi et al., 2025b).

Extreme salinity stress is particularly pronounced in semi-arid and low-lying island ecosystems such as the Maldives, where limited freshwater buffering capacity exacerbates the effects of drought and sea-level rise (Sreelekshmi et al., 2025a). Hypersalinity not only causes osmotic stress and tissue damage in mangrove trees but also alters soil chemistry, reducing nutrient availability and microbial activity essential for root function. Rising soil salinity can inhibit mangroves' water uptake and salt exclusion abilities, leading to symptoms of drought stress (Bompy et al., 2014), such as leaf loss, branch dieback, and eventually full tree mortality when salinity exceeds tolerance limits (Lovelock et al., 2009). Fig. 5 illustrates widespread mangrove dieback observed on Neykurendhoo Island, Maldives, where rising salinity, compounded by reduced precipitation and groundwater seepage, has led to large-scale mortality of *Bruguiera cylindrica*. These impacts are often more severe in areas already burdened by anthropogenic stressors, such as pollution or hydrological alterations.

Adaptive management strategies are critical to enhancing mangrove resilience under increasing salinity extremes. These include the restoration of tidal flow to prevent stagnation, conservation of freshwater inputs through watershed protection, and planting of salinity-tolerant mangrove species in high-risk zones. Long-term monitoring using salinity loggers and remote sensing can help detect early signs of dieback and guide intervention efforts. Integrating climate projections into local management plans is essential for anticipating salinity-related risks and ensuring the persistence of mangrove ecosystems in vulnerable regions.

2.3 Increased storm intensity and frequency

Tropical cyclones, hurricanes, and typhoons, collectively referred to as intense storm events, pose a significant threat to mangrove ecosystems, causing widespread structural damage and ecological disruption

Fig. 5. Mangrove dieback occurred in the Neykurendhoo island, Maldives, due to climate change (Source: Personal Collection).

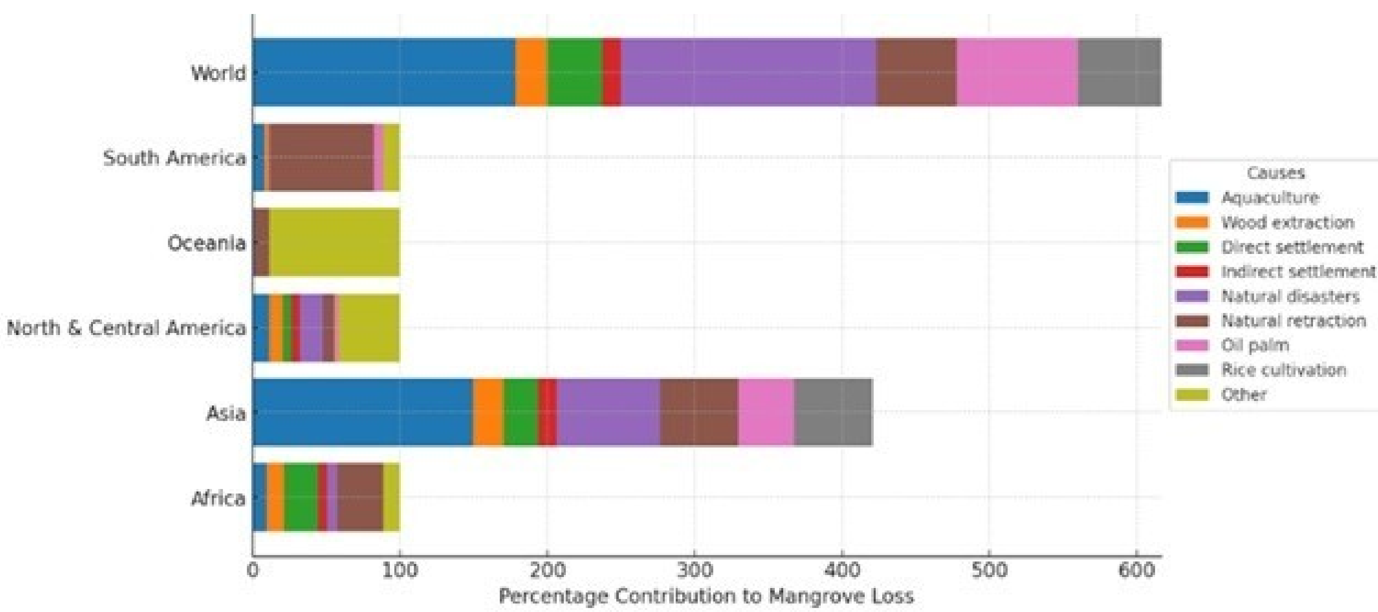

Fig. 6. Drivers of mangrove loss by region (Data Source: FAO, 2023).

(Cahoon et al., 2003). These storms can uproot trees, defoliate canopies, and erode sediment, leading to changes in species composition and forest structure. The degree of impact depends on multiple factors, including storm track, wind velocity, radius of maximum wind, and the timing of storm landfall relative to high tide (Krauss et al., 2005;

Piou et al., 2006; Zhang et al., 2008). While storm surges and winds are primarily destructive, storm-induced canopy gaps may also create opportunities for regeneration or, conversely, invasion by non-native species. The net ecological outcome often hinges on storm frequency and intensity, and the capacity of mangrove species to regenerate.

Recovery of mangrove forests following storm events is shaped by local environmental conditions. High groundwater conductivity, often indicative of hypersaline conditions, can inhibit seedling establishment by causing osmotic stress and reducing water uptake, whereas nutrient-rich sediments can promote recovery by supporting higher productivity and growth (Lagomasino et al., 2021). Additionally, extreme storms may contribute to mangrove resilience by depositing large volumes of allochthonous sediments, which enhance soil elevation and counterbalance sea-level rise (Smith et al., 2009; Smoak et al., 2013). For instance, Hurricane Wilma deposited up to 56 mm of sediment in Florida mangroves (Whelan et al., 2009). In arid coastal systems, storms can also deliver critical nutrient pulses that stimulate productivity (Castañeda-Moya et al., 2010; Lovelock et al., 2011). The presence of nearby seed sources and the absence of invasive species further influence regeneration dynamics.

Understanding the spatial and temporal patterns of mangrove regeneration is essential for predicting future responses and guiding conservation strategies. Remote sensing techniques, such as time-series analysis of satellite imagery, have been instrumental in tracking post-storm recovery trajectories across different mangrove regions (Mafi-Gholami et al., 2020). For example, Landsat and Sentinel data have been used to monitor canopy greenness and structural recovery over time, helping identify areas of persistent degradation versus successful regeneration. Incorporating such data into storm impact assessments allows for targeted interventions and enhances the effectiveness of resilience-building efforts in vulnerable coastal zones.

3 Anthropogenic drivers of mangrove degradation

3.1 Land conversion and habitat loss

Mangrove ecosystems face intense pressure from aquaculture, agriculture, and urban development, leading to widespread habitat loss, degradation, and fragmentation (Sabdaningsih et al., 2023). Among these drivers, aquaculture, particularly shrimp farming, stands out as the leading global cause of mangrove deforestation, accounting for a significant proportion of loss, especially in Asia (Fig. 6). In this region, aquaculture alone contributes over 35% of total mangrove loss, driven by the high economic value of shrimp exports (Richards and Friess, 2016). The conversion of mangroves into aquaculture ponds involves vegetation clearance, altered hydrology, and soil degradation, leading to habitat loss and reduced ecosystem services (Wu et al., 2022). Poorly managed shrimp farms often result in environmental degradation and eventual abandonment. However, sustainable alternatives like silvofisheries, which integrate mangrove conservation with low-impact aquaculture, offer a viable solution (Fitzgerald, 2002; Suyono and Fithor, 2025). By maintaining mangrove cover within aquaculture systems, silvofisheries support biodiversity, improve water quality, and provide long-term benefits to both ecosystems and local communities, encouraging mangrove protection through sustainable livelihoods.

Agricultural expansion, including rice cultivation, is another major cause, particularly prominent in Africa, Oceania, and parts of South America, where subsistence and commercial farming result in the clearance of mangrove lands (Hamilton and Casey, 2016). Urban development—such as port construction, road expansion, and settlement growth—also exerts pressure, especially in densely populated coastal regions of North and Central America, where infrastructure projects often override ecological concerns.

Fig. 6 illustrates the percentage contributions of various drivers across regions, highlighting the regional variation in mangrove threats. While aquaculture dominates in Asia, “other” drivers, including small-scale agriculture, tourism development, and sand mining, play a greater role in Oceania and South America. Natural retraction and natural disasters also account for a portion of losses, emphasizing the complex interplay of both anthropogenic and environmental factors (FAO, 2023).

Historically, mangroves were perceived as “wastelands” in many regions. For example, during colonial and post-colonial periods in India and Southeast Asia, mangrove areas were actively drained and converted for paddy fields, salt pans, and settlement expansion (Muraleedharan et al., 2009; Alongi, 2002). Similarly, in parts of Latin America, mangroves were seen as obstacles to progress, resulting in policies that encouraged their conversion for commercial aquaculture (Valiela et al., 2001).

However, there is now growing recognition of the ecological and economic value of mangroves, leading to policy reforms and conservation-focused land-use planning. Initiatives such as Integrated Coastal Zone Management (ICZM) and Payment for Ecosystem Services (PES) are being implemented in countries like Indonesia, Bangladesh, and Brazil to balance development and conservation goals (Islam et al., 2009; Wever et al., 2012). Legal protections, community-based management schemes, and participatory restoration efforts are increasingly being adopted to curb further degradation and ensure sustainable use.

By contextualizing both the historical undervaluation and the emerging policy responses, it becomes clear that reversing mangrove loss requires a multifaceted approach—one that addresses regional drivers, shifts societal perceptions, and strengthens governance frameworks.

3.2 Pollution and contamination

Mangrove ecosystems are increasingly exposed to pollution from industrial, agricultural, and urban sources, especially in rapidly developing coastal regions such as Southeast Asia, West Africa, and India (Alongi, 2002). Industrial effluents introduce heavy metals, hydrocarbons, and synthetic chemicals, while agricultural runoff adds pesticides and fertilizers, and urban discharge contributes sewage and solid waste (Szafranski and Granek, 2023). These pollutants disrupt ecological balance, degrade habitat quality, and impair the ecosystem services mangroves provide. In the Cochin estuary (India), for instance, elevated levels of lead, cadmium, and zinc have been detected in mangrove sediments near industrial zones (Joseph et al., 2019; Sreelekshmi et al., 2023).

Non-degradable pollutants such as mercury, cadmium, and lead can persist in mangrove soils and interfere with biogeochemical processes, including nutrient cycling and microbial decomposition (Sivan et al., 2025). These metals may be taken up by mangrove flora and fauna, leading to bioaccumulation and biomagnification within food webs. Climate change further exacerbates these threats: sea level rise and saline intrusion alter redox conditions and ionic strength in soils, mobilizing bound metals and increasing their solubility and toxicity (Lacerda et al., 2022). Such processes have been observed in heavily polluted areas like the Niger Delta and Jakarta Bay, where sediment erosion and salinity changes intensify contaminant spread and ecological stress.

To mitigate these impacts, various management strategies are being adopted. These include source reduction through improved wastewater regulation, phytoremediation using metal-accumulating mangrove species, and the use of constructed wetlands to treat aquaculture effluents, as practiced in Vietnam (That and Hoang, 2024). However, further site-specific research is needed to understand pollutant dynamics and optimize interventions under changing climatic conditions.

3.3 Resource exploitation and unsustainable practices

Unsustainable timber harvesting and charcoal production are significant drivers of mangrove degradation, particularly in low- and middle-income countries where these resources are integral to local livelihoods (Nyangoko et al., 2022). Socio-economic factors such as poverty, lack of access to alternative energy sources, and limited livelihood options often drive overexploitation. In regions like West Africa and Southeast Asia, clear-cutting and selective logging are common due to weak enforcement of forestry regulations and high market demand (Walters et al., 2008). These practices disrupt forest structure, reduce biodiversity, and impair critical services such as shoreline stabilization and carbon sequestration.

Salt extraction and tourism also pose significant threats when not properly managed. In parts of South Asia and East Africa, traditional salt production involves converting mangrove wetlands into salt pans, altering hydrological and salinity regimes (Akram et al., 2023). Similarly, unregulated coastal tourism, marked by the construction of resorts and associated infrastructure, can lead to direct habitat loss and pollution. While sustainable alternatives such as community-based ecotourism and solar salt extraction exist, their implementation faces challenges, including limited technical capacity, insufficient incentives, and lack of institutional support (Alongi, 2002).

Effective governance plays a crucial role in mitigating these pressures. Community forestry programs in countries like Kenya and Bangladesh have shown promise by involving local stakeholders in mangrove stewardship (Fatoyinbo et al., 2017). However, many regions still suffer from inadequate regulatory frameworks, poor monitoring, and inconsistent law enforcement, allowing illegal harvesting and unregulated development to persist (Walters et al., 2008). Strengthening legal mechanisms, providing economic alternatives, and investing in education and community engagement are essential for promoting sustainable resource use and long-term mangrove conservation.

4 Social-ecological dynamics of Mangrove Ecosystems

4.1 Traditional knowledge and local communities

Indigenous and traditional communities across the globe, such as the Orang Laut in Southeast Asia, the Quilombola communities in Brazil, and coastal fisherfolk in India and Sri Lanka, have historically coexisted with mangrove ecosystems, developing sustainable practices that support both ecological integrity and human well-being. These groups have relied on mangroves for fisheries, medicinal plants, timber, and storm protection, while simultaneously managing these resources through customary practices, spiritual beliefs, and informal governance systems. Their deep ecological knowledge, passed orally through generations, encompasses species behavior, seasonal patterns, and sustainable harvesting techniques, forming an essential foundation for long-term ecosystem stewardship (Blaser, 2016; Chamberland-Fontaine et al., 2022).

In several regions, the integration of traditional knowledge into mangrove conservation has yielded tangible results. For example, in Micronesia, customary land tenure and traditional ecological practices have been incorporated into community-based mangrove restoration projects, leading to improved mangrove survival and enhanced community ownership (Falanruw, 1994; Shepherd et al., 2008). Similarly, in parts of Brazil, participatory mapping and co-management strategies involving Quilombola communities have helped to protect mangrove areas while securing land rights and cultural heritage (Ferreira et al., 2022). These cases demonstrate how blending traditional knowledge with scientific and policy frameworks can foster more resilient, culturally appropriate, and inclusive conservation outcomes.

However, traditional populations continue to face growing pressures from industrial-scale aquaculture, tourism expansion, agricultural conversion, and urban encroachment. These drivers not only lead to the degradation of mangrove habitats but also contribute to the displacement of traditional communities from their ancestral territories (Ferreira et al., 2022). Such displacement results in the erosion of cultural identity, traditional livelihoods, and ecological knowledge, factors that are critical for the continuity of sustainable mangrove use and management (Walters et al., 2008).

The marginalization and loss of traditional knowledge can severely undermine conservation efforts, as it removes locally adapted practices and weakens community engagement. To counter this, it is vital to recognize traditional rights, support community land tenure, and actively involve local knowledge holders in conservation planning and restoration activities (Ferreira et al., 2022). Bridging traditional and scientific knowledge systems can strengthen the social foundations of mangrove governance and contribute to more effective, equitable, and enduring conservation strategies.

4.2 Governance and management challenges

Unclear property rights and overlapping authority among government agencies, communities, and private stakeholders can create governance vacuums, leading to conflicts and poor enforcement of conservation measures. This fragmentation hinders effective mangrove management, as it reduces accountability and diminishes incentives for long-term stewardship (Lugo et al., 2014). When land tenure is ambiguous, communities are less likely to invest in sustainable practices or resist encroachment, resulting in unchecked degradation of mangrove ecosystems.

As illustrated in Fig. 7, mangrove conservation is embedded within a complex socio-ecological system where economic drivers, social pressures, and environmental feedbacks interact dynamically. For example, economic activities can exert anthropogenic pressures on mangroves, while the degradation of mangrove ecosystems undermines the ecosystem services, such as coastal protection and fisheries support, that society and the economy rely upon (Bhowmik et al., 2022). Governance structures that fail to account for these interlinkages are unlikely to achieve lasting conservation outcomes.

Effective governance, therefore, must be inclusive and adaptive, incorporating the perspectives of local communities, government institutions, and civil society organizations. Participatory approaches foster legitimacy and ensure that conservation policies align with local realities (Reed, 2008). Adaptive decision-making mechanisms, based on continuous learning and feedback, are essential to respond to dynamic environmental and socio-economic conditions.

Market-based instruments such as payments for ecosystem services (PES) and carbon credit schemes have been proposed to align economic incentives with conservation goals. These tools can help correct market failures that arise when the ecological value of mangroves, such as carbon storage, flood protection, or biodiversity habitat, is not reflected in economic decisions (Pham et al., 2022). For instance, PES schemes can reward landowners or communities for conserving mangrove cover, while participation in voluntary or regulated carbon markets allows them to monetize carbon sequestration benefits (Wylie et al., 2016).

However, these approaches come with challenges. Verification of ecological outcomes, such as carbon storage or biodiversity gains, can be technically demanding and costly. Additionally, there is a risk of inequitable benefit distribution, where more powerful actors capture a disproportionate share of economic rewards, marginalizing the very communities responsible for on-the-ground conservation. Furthermore, the commodification of ecosystem services may shift the focus from intrinsic ecological and cultural values toward purely economic metrics, potentially undermining long-term sustainability and social equity (López-Maldonado and Sánchez-Delgado, 2021).

In summary, while economic incentives and market-based mechanisms can play a valuable role in mangrove conservation, their design and implementation must be accompanied by robust governance frameworks that ensure equity, accountability, and ecological integrity.

4.3 Social pressures and community-level impacts

Mangrove degradation exerts a wide range of tangible impacts on local communities, including loss of livelihoods, declining fishery resources, food insecurity, increased vulnerability to coastal hazards, and erosion of cultural and traditional practices. These socio-economic and cultural effects are not merely abstract concerns, they are lived experiences that can galvanize local and global support for mangrove conservation. Narratives that document these community-level impacts provide critical insights into the human dimensions of mangrove degradation, helping to foster a sense of urgency and engagement among policymakers, practitioners, and the public (Hagger et al., 2022). For instance, in coastal regions of Indonesia and

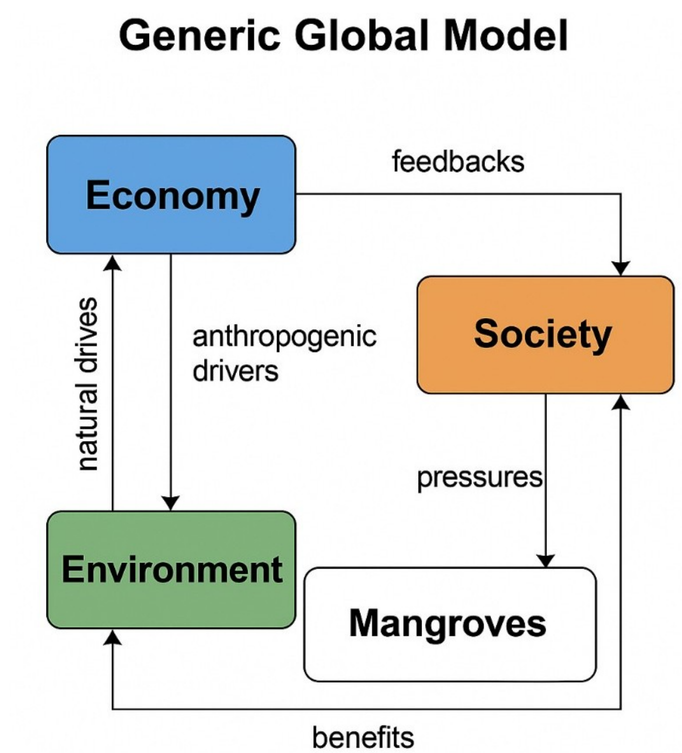

Fig. 7. Vulnerability-Resilience Framework.

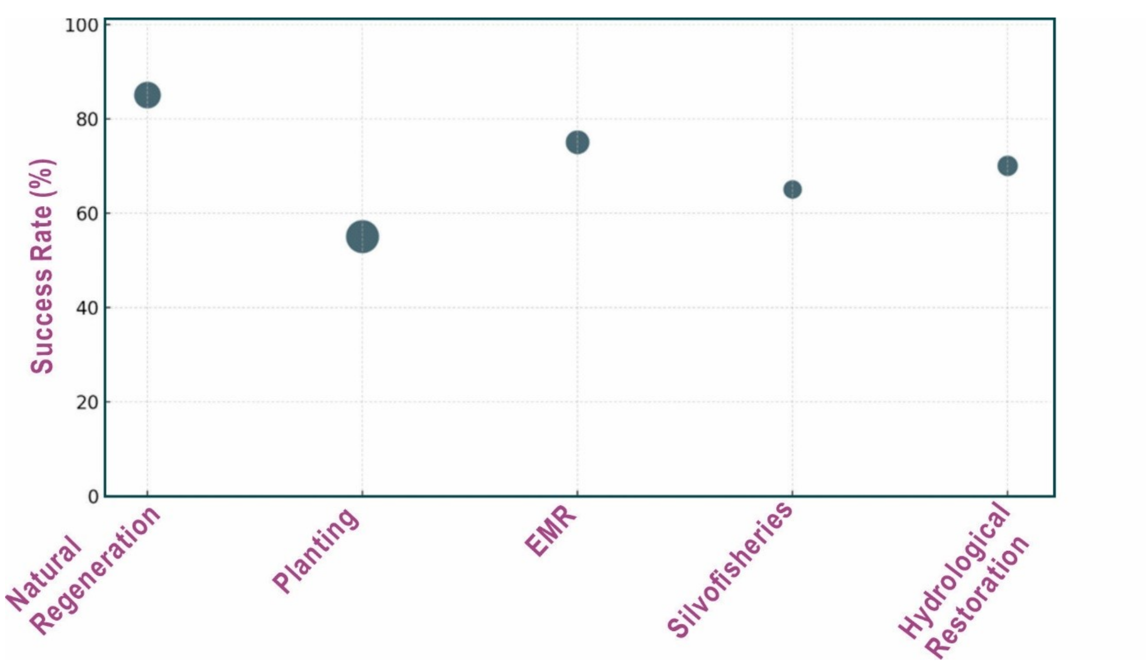

Fig. 8. Restoration Strategies by Success Rate and Area Restored (Data Sources: Kairo et al., 2001; Lewis, 2005; Romañach et al., 2018).

Bangladesh, studies have shown that mangrove loss has led to reduced availability of timber and fish, directly affecting subsistence livelihoods and traditional resource-use patterns (Iftekhar and Takama, 2008).

Despite their importance, such community-based accounts are often underrepresented in mangrove research. Only a few studies have explicitly explored the social pressures that contribute to mangrove degradation, such as land tenure insecurity, migration pressures, and weak enforcement of conservation regulations. Moreover, the concept of critical thresholds, points beyond which ecosystem degradation leads to irreversible damage, is rarely examined in relation to the socio-economic resilience of mangrove-dependent communities (Cruz Portorreal et al., 2024). This knowledge gap constrains our ability to design integrative conservation strategies that are both ecologically and socially sustainable.

Addressing these social dimensions requires a participatory approach to conservation, one that actively involves local communities in planning, monitoring, and decision-making processes. Successful examples include community-based mangrove management in Micronesia, where customary land ownership and traditional knowledge have been integrated into restoration planning, leading to higher survival rates of planted mangroves and improved community buy-in (Wylie et al., 2016). Similarly, alternative livelihood programs, such as eco-tourism in Thailand or sustainable crab farming in India, have shown potential in reducing dependence on mangrove resources while providing economic resilience (Walton and Wood, 2019). Mangrove ecosystems offer unique opportunities for ecotourism, such as guided boat tours, bird watching, and educational trails that showcase biodiversity and ecosystem services. Promoting sustainable mangrove tourism can generate income for local communities while incentivizing conservation efforts by both residents and government authorities. However, the success of such initiatives depends heavily on local context, governance structures, and long-term support mechanisms (Moussa et al., 2024).

Incorporating local voices and addressing the socioeconomic drivers of mangrove degradation are essential for crafting effective and equitable conservation strategies (Zimmer et al., 2022). A deeper understanding of these pressures, and how they intersect with ecological change, will help safeguard both mangrove ecosystems and the communities whose well-being is intricately tied to them.

5 Restoration and conservation

5.1 Challenges in mangrove restoration efforts

Despite notable successes in mangrove restoration, failure rates in some regions have remained alarmingly high, up to 80% in certain parts of Southeast Asia and East Africa, primarily due to inadequate understanding and implementation of ecological best practices (Lewis, 2005). For instance, restoration efforts in parts of the Philippines and Kenya have failed when mangroves were planted on mudflats or seagrass beds that lacked suitable hydrological conditions (Kairo et al., 2001). Common pitfalls include unrealistic project goals, insufficient site assessments, limited stakeholder engagement, and planting in ecologically unsuitable areas without addressing foundational factors such as tidal hydrology, sediment stability, and nutrient availability.

Mangrove restoration holds enormous potential as a nature-based solution for climate change mitigation, biodiversity conservation, and coastal resilience (Table 1). Projects like the Mikoko Pamoja initiative in Kenya and large-scale efforts in the Mekong Delta demonstrate how community-led, science-based restoration can deliver both ecological and social benefits (Wylie et al., 2016). However, despite these promising examples, large-scale investments and expansion remain limited due to concerns over cost-effectiveness, long-term success, and governance risks. The effectiveness of restoration efforts varies considerably by strategy, with natural regeneration and hydrological restoration often achieving higher success rates than conventional planting (Fig. 8).

The encouraging reality is that, scientifically grounded and equitable restoration strategies, such as Ecological Mangrove Restoration (EMR), have existed for decades. These approaches emphasize natural regeneration through hydrological restoration and stakeholder participation (Ellison et al., 2020). Yet, broader adoption is hampered by persistent gaps in technical capacity, funding, and cross-sectoral knowledge sharing. Bridging these gaps is critical to unlocking the full potential of mangrove restoration as a transformative climate and conservation solution.

5.2 Global collaborations and initiatives for mangrove conservation

In recent years, there has been an unprecedented increase in public and private sector efforts to restore degraded mangrove ecosystems and protect remaining stands. A growing coalition of governments, NGOs, and private actors is aligning under initiatives such as the Mangrove Breakthrough, which aims to secure the restoration of 15 million hectares and the protection of existing mangroves by 2030 through coordinated policy advocacy and investment mobilization. This initiative builds on the momentum generated by the Global Mangrove Alliance (GMA), launched in 2018 by leading conservation organizations including the IUCN, WWF, Conservation International, Wetlands International, and The Nature Conservancy (Jia et al., 2023). While the Mangrove Breakthrough emphasizes high-level policy commitments and financing frameworks, the GMA focuses on data-driven restoration, cross-sector collaboration, and country-level implementation strategies.

These efforts are supported by multilateral environmental agreements such as the Ramsar Convention, the Convention on Biological Diversity (CBD), and the World

Component	Key elements	Examples
Ecological	Species diversity, hydrological connectivity, sediment dynamics	Restoring tidal flows, species mix planting
Social	Community involvement, traditional knowledge, land tenure	Co-management, participatory monitoring
Economic	Sustainable livelihoods, blue carbon markets, eco-tourism	Carbon credits, mangrove ecotourism ventures
Institutional	Policies, governance frameworks, enforcement mechanisms	Coastal zone acts, marine protected areas
Technological	Monitoring tools, GIS, early warning systems	Remote sensing, AI-based risk prediction

Table 1. Integrated Framework for Enhancing Mangrove Resilience.

Heritage Convention, which have helped mainstream mangrove conservation into national planning and created legal protections across 302 Ramsar sites and 23 World Heritage sites as of March 2023 (Friess et al., 2019). However, the effectiveness of these frameworks varies widely by region. While some countries have successfully integrated mangrove targets into their National Biodiversity Strategies and Action Plans (NBSAPs), others face difficulties due to limited capacity, funding constraints, and governance fragmentation.

Despite these advances, global mangrove conservation is not without challenges. Many initiatives still struggle with coordination among stakeholders, long-term financing mechanisms, and the equitable inclusion of Indigenous peoples and local communities in decision-making processes. Additionally, the monitoring of restoration outcomes remains inconsistent, with gaps in evaluating long-term ecological success and social benefits (Friess et al., 2016). While mangroves are now among the most formally protected ecosystems globally, their continued survival depends not just on the number of policies or protected areas, but on sustained, inclusive, and adaptive management at local and regional scales (`https://www.mangrovealliance.org/mangrove-forests/`).

5.3 Technological innovations in mangrove restoration

Mangrove restoration is undergoing a transformation through the integration of emerging technologies, including drones, AI-powered software, and automated seeding mechanisms, which complement and, in some cases, enhance traditional labor-intensive methods. When combined with ecological expertise, these technologies enable scalable, data-driven interventions that support efficient and targeted restoration efforts. For example, AI-driven tools and robotics facilitate high-resolution mapping, site-specific seed dispersal, and continuous ecosystem monitoring, helping minimize disturbance while maximizing restoration success. During the mapping phase, drones and remote sensors collect extensive environmental data, such as topography, hydrology, soil salinity, and canopy density, to guide precision interventions. Advanced drones equipped with adaptive trajectory algorithms can deploy propagules or seeds with remarkable accuracy, optimizing resource use and labor (`https://www.dendra.io/mangrove-restoration`).

Moreover, sensor networks including weather stations, camera traps, and drone-based imagery are increasingly being used to monitor mangrove health and environmental conditions. These tools capture dynamic parameters like air and sea surface temperatures, salinity, tidal variations, and faunal presence. AI can analyze these datasets to identify long-term patterns related to carbon sequestration, post-disturbance recovery, and species resilience, thereby informing adaptive management strategies and improving restoration outcomes. Despite these advances, challenges remain. The high cost of deploying and maintaining such technologies, potential ecological disturbance caused by drones (e.g., noise affecting wildlife), and the risk of overreliance on automated systems without sufficient local involvement must be carefully managed (Getzin et al., 2012). Furthermore, while promising pilot programs have been implemented in countries like the UAE, Indonesia, and Mexico, large-scale adoption of these technologies is still limited, and success often hinges on local context, technical capacity, and community engagement. Thus, while technology holds great potential as a tool for mangrove restoration, it should complement, not replace, community-based and ecologically grounded approaches.

5.4 Remote sensing and global policy integration for conservation

Recent advancements in remote sensing technologies have significantly enhanced mangrove conservation efforts by enabling precise monitoring of forest health, detecting deforestation or degradation, and evaluating the success of restoration initiatives (Wang et al., 2023). These data products, such as high-resolution satellite imagery, LIDAR, and synthetic aperture radar, support evidence-based decision-making and provide critical spatial insights for national reporting and policy design. For instance, remote sensing datasets contribute to global initiatives by tracking changes in mangrove cover, assessing carbon stocks, and identifying areas of high conservation value. This information directly feeds into the implementation and monitoring of international frameworks, including the UN Sustainable Development Goals (SDGs 1, 2, 6, 13, 14, and 15), the UN Framework Convention on Climate Change, the Convention on Biological Diversity, the Ramsar Convention, the Sendai Framework for Disaster Risk Reduction, and the Bonn Challenge, among others (Worthington et al., 2020).

Effective mangrove management and restoration require coordinated efforts among national, regional, and local governments, alongside the meaningful participation of local communities (Romañach et al., 2018). Yet, persistent challenges, such as limited financial resources and weak enforcement mechanisms, often hinder community engagement in co-management (Friess et al., 2019). Incentive-based approaches, including payment for ecosystem services and livelihood diversification through micro-enterprises, especially those led by women, have demonstrated positive outcomes for both conservation and socioeconomic development (Begum et al., 2021).

6 Conclusions and prospects for mangrove sustainability

The sustainability of mangrove ecosystems in the Anthropocene hinges not only on understanding the individual impacts of climate change, pollution, and land-use change, as discussed in previous sections, but on addressing their cumulative and interconnected nature. Mangroves face layered and regionally varied threats, yet they also exhibit remarkable ecological resilience when supported by appropriate social, economic, and governance frameworks. Ensuring their long-term sustainability requires integrating these diverse dimensions into a cohesive management and restoration strategy.

A key opportunity lies in the growing global recognition of mangroves' value as nature-based solutions for climate mitigation, disaster risk reduction, and livelihood security. Advances in ecological restoration science, traditional knowledge integration, technological tools (e.g., remote sensing, AI-assisted monitoring), and community-based governance models have already demonstrated success across multiple regions. These innovations must now be scaled, adapted to local contexts, and supported by cross-sectoral partnerships. Initiatives such as the Mangrove Breakthrough and Global Mangrove Alliance offer promising platforms to unify political will, scientific evidence, and financial investment toward this goal.

Looking ahead, the path to mangrove sustainability lies in coupling ecological restoration with socioeconomic equity, empowering frontline communities, and embedding adaptive management into coastal governance. Sustained success will depend on translating research into action, securing inclusive policy frameworks, and reinforcing mangrove conservation as both an ecological imperative and a societal investment.

Declaration of Competing Interests

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.

Credit Author statement

S. Sreelekshmi: Writing—original draft, Data curation, Formal analysis, Methodology, Investigation, Conceptualization.

S. Bijoy Nandan: Conceptualization, Data curation, Funding acquisition, Investigation, Supervision, Validation, Writing—review and editing

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

During the preparation of this work, the authors used Chat GPT to improve the manuscript's 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 published article.

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