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Mangroves' role in supporting ecosystem-based techniques to reduce disaster risk and adapt to climate change: A review

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ABSTRACT

Variations due to climate change like rising sea levels, recurring storm surges and changing wave conditions coupled with unsustainable development along the coast are exacerbating coastal populations' vulnerability to coastal dangers globally. The ecosystem based solution to achieve sustainable development is increasingly advocated in the last two decades to leverage nature's robust adaptive capacity to change and protect people against its negative consequences. Mangroves protect and maintain a rich marine biodiversity in the tropics and subtropics and are crucial carbon sinks. The present study thus analyses mangroves' role as ecosystem-based technique to reduce disaster risk and adapt to climate change using Mauritius, a small island state, as case study, particularly the coastal protective and climate change adaptive capacities of the two local species *Rhizophora mucronata* Lam. and *Bruguiera gymnorrhiza* (L.) Lam. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines were used to retrieve resources from Google Scholar, Web of Science and ScienceDirect for the 2002 to 2022 period. A total of 41,789 records were identified and through a robust screening and filtering process only 50 studies were deemed relevant to the present study. In this context, key attributes of mangrove forests were found to be in reducing coastal flood risk, sheltering coastal regions during storms and stabilizing the coast. This study lays the foundation to consider *Rhizophora* and *Brugueira* as robust nature based solutions for Mauritius which will be of key importance to decision makers, researchers and the public at large to consider restoring degraded mangrove sites and promote ecosystem-based approaches to reduce disaster risk, adapt to climate change, enhance marine spatial planning and better coastal zone management.

1. Introduction

Climate change is transforming disaster risk globally. Changes in global climate together with unsustainable ecosystem management are exacerbating coastal populations' vulnerability to coastal dangers (Dada et al., 2021; Zhang et al., 2020; Rizvi et al., 2015). Today, approximately 75% of the global citizens live within a range of 50 km from the coastline (Broom, 2022) with over 1 billion people, particularly in Asia, inhabiting low-lying coastal regions. The large density of human population near the coasts can be attributed to the richness and diversity of resources along estuaries and coastal strips throughout the world which is expected to remain a key asset for future generations (Melet et al., 2020; Crossland et al., 2005). Kantamaneni et al. (2019) remark that environmental processes that are being affected by climate change and human activities are also becoming significant factors in exacerbating coastal vulnerability. Concurrently, climate change induced variations in the form of rising sea levels, recurring storm surges and changing wave conditions will not only affect coastal zones in numerous ways (Zhang et al., 2020; Ranasinghe, 2016) but also increase communities' vulnerability to climate-related disasters which have only been intensifying especially in coastal urban areas with disastrous consequences on environments and populaces (Busayo and Kalumba, 2021). When it comes to the SIDS (Small Island Developing States), climate change is typically superimposed on existing vulnerabilities including their remoteness, limited land area, dependency on foreign resources, declining biodiversity and unprecedented impacts due to climate change (Robinson, 2020; UN-OHRLLS, 2017). Since the 1992 Rio Conference of the United Nations, SIDS have been recognized to be particular due to

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their fragile environment and limited economic development capacity. Most of their settlements, infrastructure, agricultural lands and economic centers are located on the coast thus increasing their vulnerability to coastal threats as well as climate change induced impacts. For flat atolls such as the Maldives where almost all of the coastal nation live within a few meters from the sea, climate change impacts can be quite significant (Duvat et al., 2021; UN-OHRLLS, 2017).

Recently, ecosystem based solutions to achieve sustainable development has become a hot topic around the world leading to the genesis of several concepts such as nature-based solutions, green infrastructures, ecosystem-based adaptation, working with nature and ecosystem based management amongst others (Stefanakis et al., 2021; O'Higgins et al., 2020; Seddon et al., 2020; Renaud et al., 2016). While all of these concepts are founded on the use of natural resources, their purposes are quite different and thus it is worth to differentiate between the definitions at this stage. According to Estrella and Saalismaa (2013), ecosystem based disaster risk reduction (Eco-DRR) aims at achieving sustainable development by sustainably managing, conserving and restoring ecosystems to reduce the risk of disasters. The CBD (Lo, 2016) defines ecosystem based adaptation (EbA) as using biodiversity and its additional ecosystem services within the broader framework of adaptation so as to aid nations adjust to anticipated changes in the climate system. As Renaud et al. (2016) point out, very often, nature provides solutions to both reduce the risk of disasters and to adapt to adverse impacts of climate change thus coining the two concepts into a single approach called ecosystem based disaster risk reduction and climate change adaptation (Eco-DRR/CCA) defined as sustainably managing, conserving and restoring natural ecosystems to reduce risks associated with disasters and adjust to changes in the climate regime for green development. In line with this, mangrove ecosystems are sentinels to reduce the risk of disasters and adapt to a changing climate due to their particular geographical position within the coastal region, a place which is geologically and physically dynamic and highly affected by climatic and environmental conditions (Akbar et al., 2021; Wang and Gu, 2021; Alongi, 2015). The Global Mangrove Alliance (2018) declares that mangrove ecosystems are an underutilized natural climate solution as they are an important carbon sink, supply food resources, offer coastal protection and manage pollution. Nonetheless, their position along the coast with rising human populations and clashing coastal management priorities threaten their existence across their range (Friess et al., 2019). While the role that mangroves play in protecting coastal shores in the continental context is well established, very few studies have been conducted in the island-wise context. The rationale behind this research was thus to explore the benefits associated with mangroves as ecosystem-based solution to reduce the risk of coastal disaster and adapt to climate change within the context of Mauritius. As there is a scarcity of studies on nature-based solutions to reduce the risk of disasters and adapt to a changing climate, the present study's objectives were to find answers to the following research questions:

RQ1. Can mangroves be used as nature-based solution to reduce the risk of disasters and adapt to climate change?

RQ2. Which mangrove forests' attributes can be effective to reduce the risk of disasters and adapt to climate change for Mauritius Island?

RQ3. Are the mangrove species found in Mauritius resilient enough to reduce the risk of disasters and adapt to climate change?

We believe this research is the first study on the potential of the mangrove forests of Mauritius as ecosystem-based solution to reduce the risk of disasters and adapt to climate change which will be of key importance to decision makers, researchers and the public at large to consider restoring degraded mangrove sites and promote ecosystem-based approaches to reduce disaster risk, adapt to climate change, enhance marine spatial planning and better coastal zone management. In addition, this study lays the groundwork for climate change modeling on the mangroves of Mauritius to quantify their potential as assets to reduce disaster risk and adapt to climate change in the coastal zones.

2. Materials and methods

2.1. Case study area

The Republic of Mauritius includes Mauritius and adjacent islands Rodrigues, Cargados Carajos, Agalega and the Chagos Archipelago. This study considers only the main island Mauritius. Mauritius is an 8 million years old volcanic island located in south west Indian Ocean centered on coordinates 20°15′ S and 57°35′. The area of Mauritius is 1865km^2 with highest elevation of 828 m and gentle slopes on the northern and eastern coastlines. Mauritius has one of the largest Exclusive Economic Zones in the world that covers an extent of 2.3 million km^2, with 400,000km^2 managed with Seychelles. Mauritius' coastline is 322 km and fringing coral reefs surround the island except near estuaries, river mouths and the south thus enclosing a 243km^2 lagoon area. The coastal zone of Mauritius refers to any region within the range of 1 km from the high water mark on either the land or sea side according to Section 49 of the Environment Protection Act 2002 of Mauritius (Government of Mauritius, 2002).

Several weather systems affect Mauritius thereby creating a yearly mild tropical maritime climate. The sub-tropical high pressure belt at the south of Mauritius causes the South East Trade Winds to blow over the island almost all year round, gaining strength in winter months. Summer generally span from the months November to March while winter months last from June to October. Tropical cyclones can cause considerable damage to the shoreline through the impacts of strong gusts which initiate high swells and leading to beach erosion. For example, cyclone Hollanda in 1994, damaged a large portion of the coast of Mauritius; coastal structures like sea walls, jetties and groynes were destroyed and where there were vertical seawalls, deflecting waves caused rip currents leading to scour. Mauritius has a semi-diurnal tide system in the range of 0.7 m (spring tides) with subtle variations in magnitudes of neap tides.

2.2. Mangroves in Mauritius

Mauritius' mangroves typically grow in coastal wetlands (Fig. 1) near river mouths and generally cover a spatial extent of 14 km^2 (JICA, 2016). They occur in small patches of tens of square meters very rarely reaching large sizes up to two thousand square meters (NWFS Consultancy, 2009). There are two species of mangroves in Mauritius: *Rhizophora mucronata* Lam. and *Bruguiera gymnorrhiza* (L.) Lam. (Appadoo, 2003; Sauer, 1962). *Rhizophora* stands are more abundant (Fagoonee, 1990) occurring in almost pure stands in most swamps (Poonyth, 1998; Appadoo, 2003). It grows mainly along the northeastern, eastern and southwestern coast often in narrow belts due to topographical features and low tidal range of 0.5 m (Appadoo, 2003). *Bruguiera* is less common occurring in small patches in the east and south east of Mauritius. Mangroves provide a range of benefits to the Mauritian community including protection against storm surges, high waves and swells, trapping sediment and pollutants, preventing erosion, capturing carbon from the air, acting as nursery grounds for marine creatures, as ecotourism sites, as traditional medicine to cure wounds and ailments and as livelihood and food source. However, mangrove extent has considerately decreased within the last decades mainly due to coastal development, infrastructural development, to provide passage for boats and as acts of vandalism (Abib and Appadoo, 2021; Gopala, 1980). Large expanses of mangroves have been removed in the past for hotel construction and coastal tourism amenities. Even though the Fisheries and Marine Resources Act 1998 prohibited mangrove trees cut down, illegal deforestation continued until 2008 when the government recognized the importance of mangroves and prohibited mangrove cut down for development under the coastal zone management policy (Baird and associates, 2003). Natural changes have also impacted on mangrove

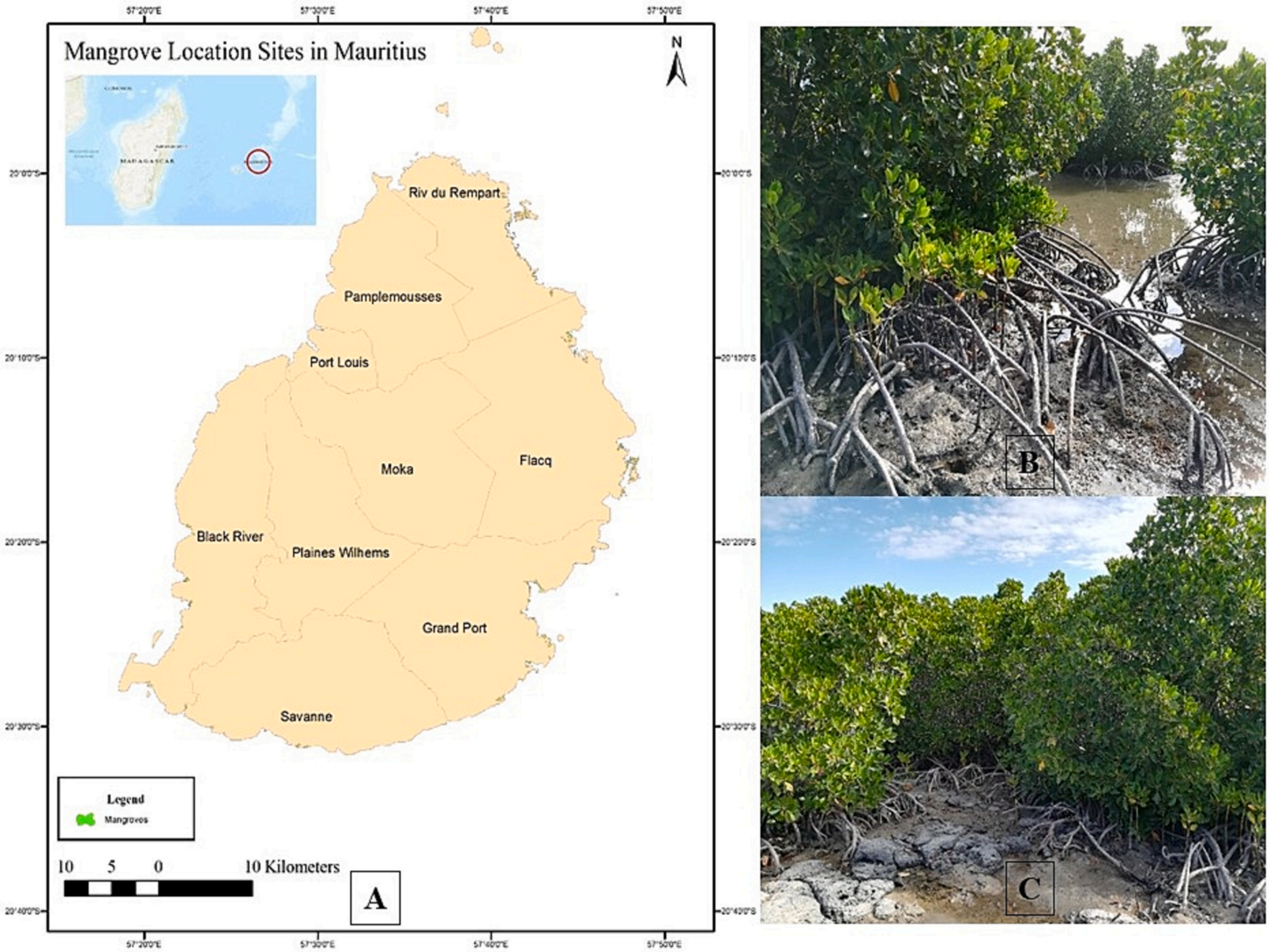

Fig. 1. Mangroves of Mauritius (A) Mangrove location sites in Mauritius (B) Exposed pneumatophores of Rhizophora forest at Pointe d'Esny, Mauritius (C) Rhizophora stand at low tide at Pointe D'Esny, Mauritius.

cover loss in Mauritius as Baird and associates (2003) report at Bras d'eau where erosion of the central beach led to a decrease in mangrove cover. To be sure, climate change is affecting mangroves worldwide (de Lacerda et al., 2022; Van der Stocken et al., 2022; Cinco-Castro and Herrera-Silveira, 2020), but to date, no such study has been undertaken on the mangroves of Mauritius. (See Figs. 2–5.)

2.3. Resource retrieval

To identify the benefits of mangroves as ecosystem-based solution to reduce disaster risk and adapt to climate change, the recent PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines were used (Page et al., 2021). We used Google Scholar,[1] Web of Science[2] and ScienceDirect[3] as portals for the research. The benefits of Google Scholar for research include its free nature, ease of accessibility and its capacity to index large volumes of data (Jeyapragash et al., 2016). Clarivate's Analytics' Web of Science is the world's leading citation search platform according to Li et al. (2018) supporting diverse tasks across multiple knowledge domains and datasets for large scale studies. ScienceDirect uses natural language in a single search portal that immediately retrieves electronic materials across numerous journals and books (Harnegie, 2013). The search was conducted for the period 2022–2002 to grab the most recent publications on the benefits of mangroves as ecosystem based solutions with English selected as language. Specific keywords were inserted into the search bar of the above-mentioned portals including ‘mangroves’ AND ‘adaptation to climate change’ AND ‘ecosystem-based solution’ AND ‘reduce disaster risk’ OR ‘mangroves’ AND ‘advantages’ OR ‘benefits’ AND ‘Mauritius’ OR ‘soft engineering’ AND ‘mangroves’ and sorted by relevance. The grey literature was also reviewed to access international and national reports on mangroves as ecosystem-based approach to reduce disaster risk and adapt to climate change. Google Search Engine was used for the same above mentioned period and the same keywords were entered into the search bar. Holleman (2017) contends that page one of Google usually captures 71% of clicks as it generally provides the most relevant data but the search here was extended till page ten to ensure a proper analysis of the topic.

2.3.1. Eligibility criteria

A list of strict inclusion and exclusion criteria were selected for the review process as shown in Table 1.

Double screening was used to assess if the databases, reports and

[1] Google Scholar., 2022. [online] Available at https://scholar.google.com/ [Accessed 04 September 2022]

[2] Clarivate., 2022. [online] Available at https://mjl.clarivate.com/search-results [Accessed 04 September 2022]

[3] ScienceDirect., 2022. [online] Available at https://www.sciencedirect.com/ [Accessed 04 September 2022]

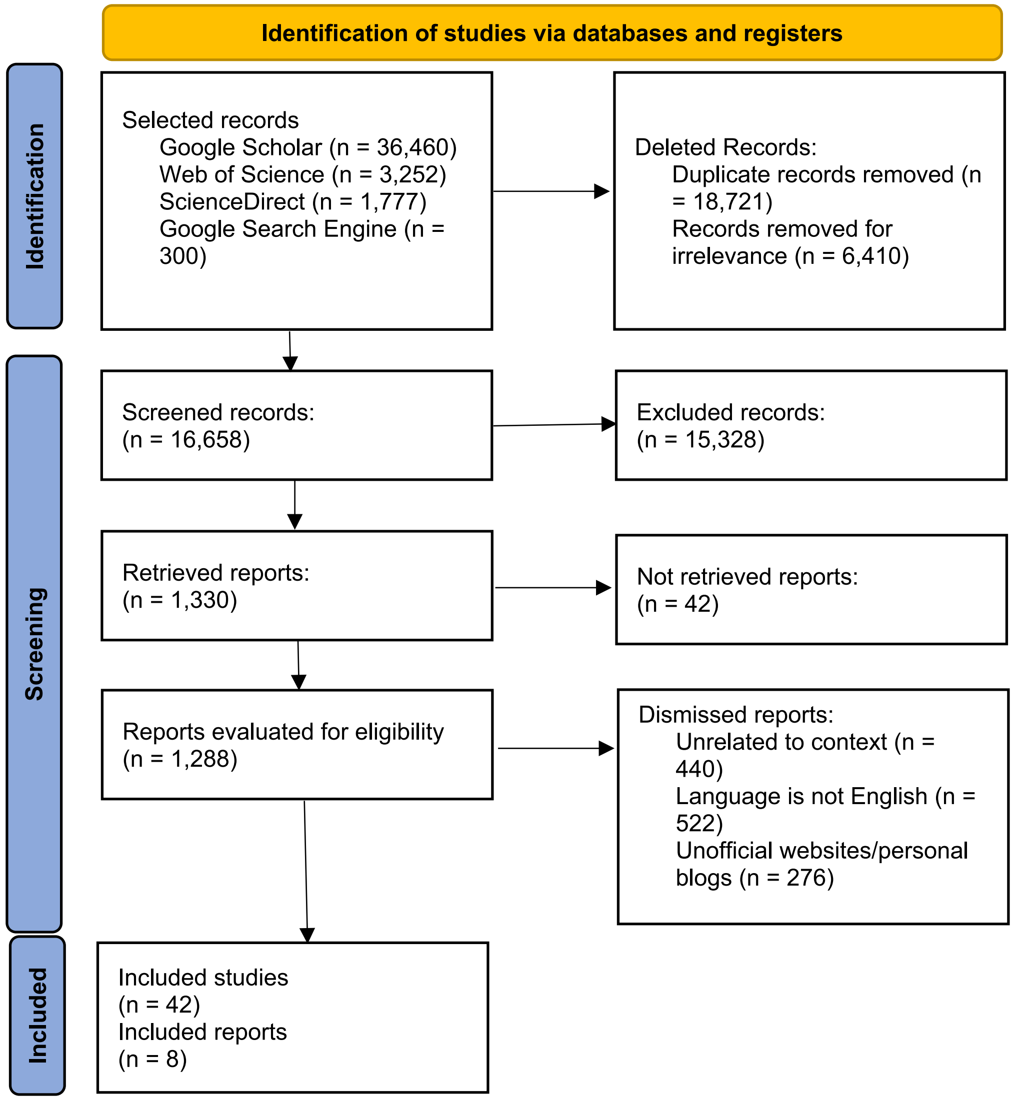

Fig. 2. PRISMA flowchart depicting the number of records screened for the current case study.

websites used for the searches and studies met the inclusion criteria of the review. The main author carried out the initial search based on the above-mentioned criteria list and one independent reviewer checked a sample of the included records and a sample of excluded records (n = 30) to ensure consistency across the results.

3. Results

3.1. Records identified

Using the PRISMA guidelines and inclusion and exclusion criteria a total of 41,789 records were identified with 36,460 records from Google Scholar, 3252 records from Web of Science, 1777 records from ScienceDirect and 300 records from Google Search Engine. 25,131 records were excluded before the screening process as they were duplicates (n = 18,721) and irrelevant (n = 6410). During the screening process, out of 16,658 records, 15,328 records were excluded as they contained only one of the keywords and were irrelevant in context. 1330 reports were thus sought for retrieval but 42 reports could not be retrieved due to broken links and unavailability of links. This resulted in 1288 reports for assessment based on the above-mentioned eligibility criteria. 440 reports were excluded as they were unrelated to the context under review, 522 reports were discarded as the publication language was not English and a further 276 reports were disregarded as they were unofficial websites and personal blogs. Finally, 42 studies and 8 reports were deemed relevant to the present study.

3.2. Top 10 papers

The top 10 papers deemed relevant to the present study are listed in Table 2 starting with the most recent.

3.3. Results relevance to research questions

The literature shows the role of healthy mangrove ecosystems as solution to reduce the effects of coastal dangers be it geological or climate induced and to further prepare for upcoming changes in the planet's climate regime. Top ten authors listed in Table 1 discuss mangroves' role in ecosystem to reduce the risk of disasters and adapt to climate change. Amongst them, Jones et al. (2020) examined how the global coastal areas were susceptible to climate change induced sea level rise and tropical storms in terms of how they are exposed, sensitive and their capacity to adapt to changes. They conclude that mangrove forests are indeed cost effective solutions to protect communities from the dangers associated with climate change. Likewise, Takagi (2019) proposes using a novel way to grow mangroves along the urban coasts

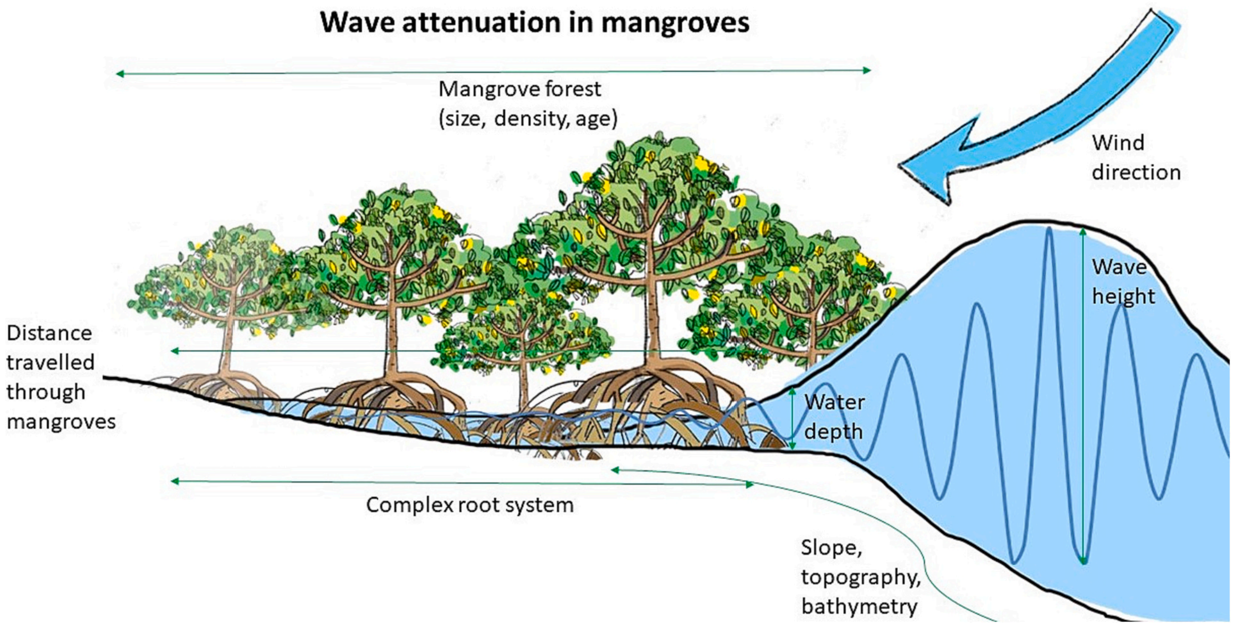

Fig. 3. Mangroves such as Rhizophora species have intricate and interconnected root systems that lower wave height under 70 cm in height and decrease wave energy as these pass through mangrove forests by up to 99% across a 500 m wide mangrove forest.

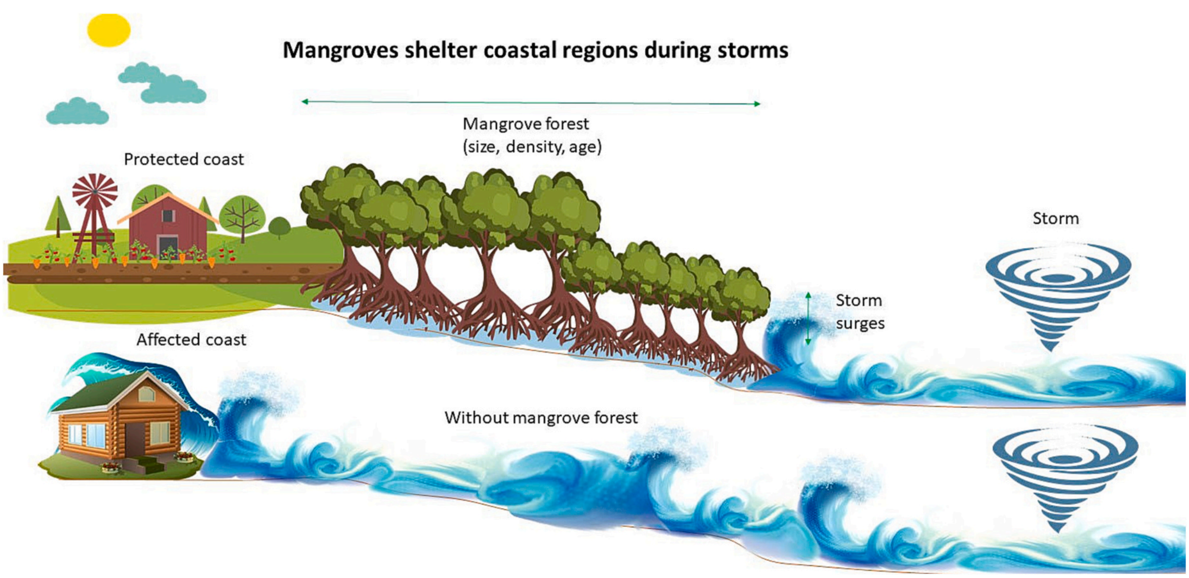

Fig. 4. Mangroves shelter coastal regions during storms as they limit the exchange of water and store water when forests are of the proper size thus decreasing the vulnerability of coastal inhabitants to storm surges further reducing economic impacts and death toll.

especially for developing countries to cope with future environmental conditions while Friess and Thompson (2016) propose solutions to implement mangrove payment for ecosystem services as a strategy to reduce disaster risks in coastal regions. Thus, the above mentioned results answer RQ1 positively that indeed mangroves are nature-based solution to reduce the risk of disasters and adapt to climate change. With Mauritius' coast-dependent-economy and social development highly at risk, it is thus imperative to gear towards solutions that are sustainable and cost effective.

Additionally, the literature also records several benefits of mangrove making them effective nature-based assets including reducing the risk of coastal floods (Menéndez et al., 2020; Gijsman et al., 2021, sheltering coastal regions during storms (Hochard et al., 2019a, 2019b; Narayan et al., 2019) and stabilizing the coastal region and preventing erosion (Uddin et al., 2019; Das, 2020). These attributes are also seen to be relevant to species of mangroves that grow in Mauritius namely, *Rhizophora* and *Brugueira* species. Thus, key attributes of mangrove forests that make them effective as nature based solution to reduce the risk of disasters and adapt to climate change for Mauritius are concluded to be in reducing coastal flood risk, sheltering coastal regions during storms and stabilizing the coast which are further discussed in the next section. Consequently, these attributes answer RQ2 of the study on the attributes of mangroves that make them effective as nature based solution to reduce the risk of disasters and adapt to climate change. Likewise, the literature (Del Valle et al., 2020; Thampanya et al., 2006; Brinkman et al., 1997) confirms the ability of the local mangrove species in Mauritius to be effective in the above mentioned functions which also positively answers RQ3.

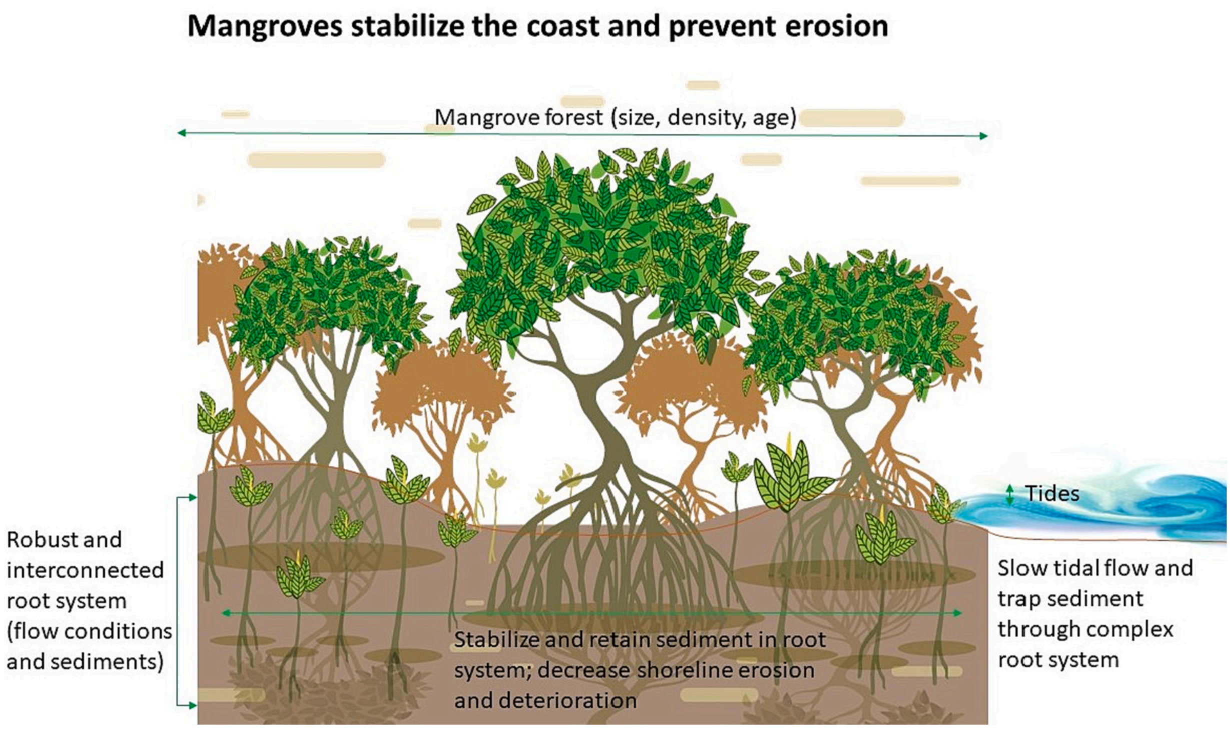

Fig. 5. Mangroves stabilize the coast and prevent erosion through their robust root system as incoming silt loads are trapped within the mangrove systems across stems, twigs and fallen leaves and the pneumatophores that spread laterally, eventually rising in height and hastening the sedimentation process and helping in stabilizing the coast.

Table 1
Selected list of criteria for review process with inclusion and exclusion reasons.

Criteria	Inclusion	Exclusion
Context	Records containing selected keywords only were retained	Records containing only one keyword or unrelated to search were discarded
Time scale	Records published during the period 2002–2022 inclusive were considered	Records published before 2002 were excluded
Language	Records published in English only were considered	Records published in other languages were excluded
Nature of provider	Peer reviewed journals, educational organizations, commercial organizations, national reports, individual official reports were considered	Personal blogs and websites with no official ownerships were discarded
Search facility	Records with mangroves to reduce disaster risk and adapt to climate change were selected	Publications on mangroves in other contexts were eliminated
Access	Records with specific direct link for access were considered	Records with broken and no direct link were excluded

4. Discussion

4.1. The need for green solutions in Mauritius

As an island nation, Mauritius depends heavily on its coastal zone where a number of commercial and recreational activities take place including agriculture, tourism and fishing. Small scale fisheries especially are a prized activity for coastal communities both for cultural reasons and as a source of livelihood. Mauritius is also globally recognized as a 'Top Island Destination' for its sun, sea and sand holidays typically founded on the exquisite coastal environment and related activities (UNDP, 2014). The ICZM (Integrated Coastal Zone Management) Framework (2010) as quoted by the Government of Mauritius (2019) estimates the value of the coastal regions of Mauritius to be beyond one trillion rupees. The Economic Development Board of Mauritius reports that the Ocean Economy represents more than 10.5% of the GDP of Mauritius employing over 20,000 people excluding coastal tourism with seaport related activities, coastal tourism and seafood related activities make up 90% of this GDP contribution. In addition to this, the coastal strip of Mauritius has invaluable ecological importance both in terms of the biodiversity that reside in the estuaries, mangroves, beaches and tidal flats and ecological services that these ecosystems provide such as protecting coastal areas and stabilizing the land.

As global warming induced climate change has been taking its toll on nations around the world, Mauritius has not been untouched. According to the Third National Communication Report of Mauritius on climate change (Republic of Mauritius, 2021), recently, there has been a rise in temperature of 1.39 °C between 1951 and 2020 in comparison to the 1961 to 1990 average, a considerable drop in rainfall by 104 cm during the period 1951 to 2020, in comparison to the 1961 to 1990 period, a peak in sea level by 8 mm in the last decade (2011−2020) in comparison to the rise of 4.7 mm/yr for the period 1987–2020 together with an increased frequency of extreme weather events like flash floods. The GFDRR (2016) list tropical cyclones as the number one risk to the island through the generation of wind, flood and storm surge hazards. Fortunately, Mauritius is located at the end of the cyclonic belt in the Indian Ocean and so there has limited exposure to cyclone; nonetheless, every year, remnants of cyclones eventually hit the island resulting in recurrent flooding that damage crops, livestock and even buildings (CaDRi, 2020). Sea level rise as a consequence of melting of glaciers because of increasing global temperature is also damaging the coastal zone of Mauritius with certain beaches, victims to erosion, losing up to 20 m in width. Many areas are experiencing more profound effects of flooding because of sea level rise such as at Riviere des Galets, Quatre Soeurs and Deux Freres where seawater has been creeping inland into the yards of inhabitants while storm surges have been worsening and destroying belongings and amenities (Government of Mauritius, 2011).

In the same manner, disaster risk is exacerbated by human activities including rapid urbanization, industrialization and unsustainable

Table 2
Top 10 papers identified in the review.

S/N	Author(s)	Paper Title	Year	Source	Summary
1	UNEP	Ecosystem based adaptation	2022b	UNEP	Several case studies on ecosystem based strategies for climate change adaptation including using mangroves as natural flood defenses.
2	Charrua et al.	Assessment of the vulnerability of coastal mangrove ecosystems in Mozambique	2020	Ocean & Coastal Management	Discusses how mangrove forests in Mozambique are susceptible to the effects of climate change and their potential as nature-based solutions.
3	Ruckelshaus et al.	Harnessing new data technologies for nature-based solutions in assessing and managing risk in coastal zones	2020	International Journal of Disaster Risk Reduction	Outlines the application of technologies to assess coastal risk reduction and ecosystem benefits and reviews multiple case studies for policy and investment strategies for coastal communities.
4	Jones et al.	Global hotspots for coastal ecosystem-based adaptation	2020	PloS one	Evaluation of the vulnerability of coastal communities to specific climate change initiators and the capacity for ecosystem based adaptation using mangroves.
5	Takagi, H	Takagi, H., 2019. "Adapted mangrove on hybrid platform"–coupling of ecological and engineering principles against coastal hazards	2019	Results in Engineering	Describes an innovative approach to grow mangroves along urban areas as ecosystem-based strategy to reduce the risk of disasters for developing countries in order to withstand coastal threats.
6	McVittie et al.	Ecosystem-based solutions for disaster risk reduction: Lessons from European applications of ecosystem-based adaptation measures	2018	International journal of disaster risk reduction	Highlights lessons learnt from implementing ecosystem based strategies across different land uses including mangroves and how this is done cost effectively with other co benefits.
7	Friess, D.A. and Thompson, B.S.	Mangrove payments for ecosystem services (PES): a viable funding mechanism for disaster risk reduction?	2016	Ecosystem-Based Disaster Risk Reduction and Adaptation in Practice	Reviews problems and solutions in implementing mangrove payment for ecosystem services as strategy to decrease disaster risks in coastal regions.
8	Lo, V.	Synthesis report on experiences with ecosystem-based approaches to climate change adaptation and disaster risk reduction.	2016	Convention on Biological Diversity (CBD)	Provides extensive information on ecosystem-based techniques to reduce the risk of disasters and adapt to climate change while improving livelihoods and maintain ecosystem services.
9	Renaud et al.	The Role of Ecosystems in Disaster Risk Reduction	2013	United Nations University Press	Thoroughly describes how and why to use ecosystems to reduce disaster risk and combat climate change and how to use mangroves as coastal bio shields.
10	Temmerman et al.	Ecosystem-based coastal defense in the face of global change	2013	Nature	Highlights the necessity of ecosystem-based techniques as sustainable solutions compared to hard engineering structures.

planning of the coastal zone which has substantially affected coastal ecosystems and habitats (Ramessur, 2002). For example, sand dunes that used to cover many parts of the island playing an important role in cushioning sea waves has all but disappeared on the main island in the name of development. As more people choose to settle in hazard prone regions such as the coastal zone, exposure to coastal hazards invariably pitches, which, compounded by decreased vegetation cover like wetland filling, create new risks. It is expected that climate change will alter coastal communities' vulnerability, with future projections suggesting that the magnitude and recurrence of climate and weather associated events such as cyclones will increase together with rising sea levels. While interventions like early warning systems are crucial to save lives (Del Valle et al., 2020), coastal shielding mechanisms to safeguard assets and limit economic loss often have more harmful effects on the natural environment compared to ecosystem based methods (Schoonees et al., 2019; Temmerman et al., 2013).

4.2. *Mangroves as ecosystem-based solution to reduce the risk of disaster and adapt to climate change in the coastal area*

Using mangroves to limit the threats of coastal dangers and adjust to modifications in the coastal environment is not a present-day idea, perhaps only a new name. The capacity of mangroves to protect and stabilize the coast is widely acclaimed (Karimi et al., 2022) especially when it comes to their effectiveness compared to concrete barriers in dissipating the energy of breaking waves, trapping sediment, reducing erosion and stabilizing shorelines (Schoonees et al., 2019). Likewise, healthy and dense mangrove forests can substantially decrease the impacts of tsunamis as demonstrated by Kelty et al. (2021) forest prototype that successfully measured tsunami wave attenuation capacity in mangroves. The benefits of mangroves to reduce the risk of disasters and adjust to a changing climate identified through the review process are discussed below.

4.3. *Reducing coastal flood risk*

Mangroves contribute significantly in reducing the risk of floods in low lying regions of the coastal zone (Hochard et al., 2019a, 2019b; Menéndez et al., 2020; Gijsman et al., 2021). There is evidence that contend that mangroves have the capacity to lower wave height by 13 and 66% over a distance of 100 m of forest (McIvor et al., 2012a, 2012b). Mangroves have specific characteristics that influence how waves decrease through the forest including their dense above ground canopy and their particular robust root structure that lessen water flow and scatter wave energy (Marois and Mitsch, 2015; Gijsman et al., 2021). Most researchers and scientists in fact agree that mangroves can attenuate wind and swell waves which are under 70 cm in height (e.g. Quartel et al., 2007; Vo-Luong and Massel, 2008; Bao, 2011), by even 50–99% across a 500 m wide mangrove forest. As waves pass through mangroves, several factors affect wave height including water depth which is based on the topography and bathymetry of the location and tidal phase, wave height, mangrove tree species, age and size (McIvor et al., 2012a, 2012b). According to Bao's (2011) study on mangroves in Vietnam measured along 92 transects, mean wave height decreased by 21% over the first 40 m of the forest, 17% over the following 40 m and an overall reduction of 35% over the first 80 m forest (McIvor et al., 2012a).

Similarly, the root system of mangroves, be it prop roots such as those of *Rhizophora* species or knee roots as in *Bruguiera* species can significantly decrease water flow. Brinkman et al. (1997) made the observation at Cocoa Creek, Australia; less than half waves' climax energy dissipated over the initial 80 m of *Rhizophora* forest. Likewise, in species which do not possess aerial roots, wave attenuation is less through trunks and tree base and higher through foliage and branches as demonstrated by the works of Quartel et al. (2007) and Mazda et al. (2006). Typically, older mangroves can also more robustly decrease the energy of waves because of their dense foliage structure. Thus, as Menéndez et al. (2020) state, the natural flood defense mechanism that mangroves provide help reduce annual flooding by approximately $65 billion per year and provide over $250 million as assets to decrease flood risks to many 20 km coastal strips around the world, especially near coastal cities. Wave attenuation capacity in mangroves can typically be measured either in situ based on real time data or using numerical simulation models. To date, few research works have been undertaken around the world to measure the wave attenuation capacity of mangroves probably because it is quite a complex activity. At this stage, there is no published material on the effects of mangroves in reducing wave energy in Mauritius. This however provides an avenue for research as mangroves exist typically as small patches in the estuarine zones of Mauritius with the largest forest being Pointe d'Esny, a 0.22 km^2 Ramsar site, narrow belts across the east coast at Trou d'eau Douce, Poste Lafayette, patches in the south at Maconde, on the west coast at Le Morne, Case Noyale and Tamarin and on the north coast at Baie du Tombeau and Poudre d'Or. Reforestation and afforestation of mangroves frequently take place in Mauritius by various organizations hence it would be worth to investigate the rationale behind such endeavor in terms of flood risk reduction (Magnan et al., 2021).

4.4. Sheltering coastal regions during storms

The role of mangroves as natural bio-shields are especially critical in protecting coastal communities against hazardous storm events. Cyclone damage is expected to rise due to increased exposure as more people settle in coastal areas and because of recurrent severe storms induced by changes in the climate system (Mendelsohn et al., 2012). Projected sea level rise (0.26 m to 0.98 m by 2100) is also expected to exacerbate storm impacts by accelerated flooding thus threatening the existence of low-lying areas (Jones et al., 2020). Mounting evidence suggests the importance of mangroves in sheltering coastal regions and communities during storms. Severe wind, atmospheric pressure and wave conditions associated with cyclonic conditions can induce surges that can dangerously elevate local sea levels (Resio and Westerink, 2008). Storm surges propagate through mangroves because of friction losing their velocity as they do so (LeBlond, 1978; Friedrichs and Madsen, 1992; Montgomery et al., 2019). Several authors including Dasgupta et al. (2017) and Montgomery et al. (2019) refer to mangroves as buffers that provide effective coastal flood protection as they limit the exchange of water and store water when forests are of the proper size in terms of the time it takes for wave energy to dissipate.

Del Valle et al. (2020) further demonstrate how *Rhizophora* species mangrove forests reduced the impacts of hurricanes on economic activities in Central America. The study reveals where mangrove width is below 1 km, category 3 hurricanes have the ability to reduce nightlights close to 24% while areas where mangroves equal to or are wider than 1 km are relatively unaffected. Nightlights are typically used as a proxy in measuring moneymaking activities (Donaldson and Storeygard, 2016) including economic impacts (Mohan and Strobl, 2017; Hochard et al., 2019a, 2019b). In the same way, mangroves can significantly reduce death toll as Das and Vincent's (2009) analysis on the impacts of the 1999 super cyclone which affected Orissa, India, demonstrate. Because of the presence of mangroves, death rate decreased by 1.72 for each village over 10 km of the coastline. Deb and Ferreira (2017) also demonstrate how surges amplified up to 57%, velocity by 2730%, inundation distance increased by 10 km and flood areas by 18% when mangroves are absent along the Sundarbans mangroves of Bangladesh where *Heritiera* species are generally dominant but which also includes *Rhizophora* and *Bruguiera* species.

McIvor et al. (2012b) state that it is quite complex to measure changing water levels during storm surges hence resulting in limited studies in that area. As far as Mauritius is concerned, Sauer (1962) describes how tropical cyclones affected coastal flora by visually analyzing the coast a few months before and after one of the most severe cyclones that formed in the Indian Ocean, Carol, hit the island. Sauer reports that where mangroves were present, there was little disturbance of unconsolidated substrates along bays and sheltered shores with none of the older trees affected by storms save a few uprooted seedlings and remarks that storm drift was entangled in the branches of mangroves about 2 m above normal water line. While Douce (2014) uses a numerical model to demonstrate the role of coral reefs in attenuating cyclonic waves on the east coast of Mauritius at Belle Mare, no such initiative has been undertaken for mangroves so far.

4.5. Stabilizing the coastal region and preventing erosion

Because of the energetics of littoral ecosystems, changes in coastlines like accretion and erosion is a fairly common process. Woodroffe (1993) thoroughly describes the link between mangroves and the morphodynamics of shorelines. Mangroves can basically grow in several environment including sand and lava but they prefer muddy substrates (Chapman, 1976; Woodroffe, 1993). Autochthonous sediment usually forms from carbonate sediment mixed with peat from mangrove roots while allonchthonous sediment comes from river, tides and the sea (Woodroffe, 1993). Wolanski and Pickard (2018) also state that dredged substrates that have been dumped and deep sediment can also supply to allochthonous materials as they are carried by waves and ships. Thus, the accumulation rates of both types of sediment, be it organic and inorganic, are different in different areas (Woodroffe, 1993). The sedimentation process, where fine grained and particles consisting mainly of clay deposit on the forest floor is one of the main processes that build land and therefore contribute to accretion. Mangroves favor this exercise as they diminish water flow and trap sediment through their complex root systems and pneumatophores while the finer roots play a critical role as sediment binders (Woodroffe, 1993; Chaudhuri et al., 2019). Similarly, mangroves can maintain sediment through their pneumatophores thus decreasing shoreline destruction and degradation (Barbier et al., 2011).

Since erosion is ongoing, when mangroves grow with their deep anchoring roots, they retain sediment making coastal regions stable. Incoming silt loads are trapped within the mangrove systems across stems, twigs and fallen leaves and the pneumatophores that spread laterally, eventually rising in height and hastening the sedimentation process and helping in stabilizing the coast (Karimi et al., 2022; Uddin and Hossain, 2013). But to thoroughly understand how sediment is transported in mangroves, a detailed analysis of mangrove-water-sediment interactions is required. In line with this, Kazemi et al. (2021) used a plume modeling technique to demonstrate that the porosity of mangrove roots can prevent erosion. Examining the coast of southern Thailand, a region dominated by *Avicennia* and *Rhizophora* species, Thampanya et al. (2006) observe an erosion rate of 1.6 and 6.7 $m\ y^{-1}$ in the absence of mangroves while presence of mangroves showed positive accretion in the range of 1 to 8.9 $m\ y^{-1}$. Chow (2018) further contend that since mangroves can quickly grow given the right type of sediment, they can also decrease sea level rise effects. Alongi (2008) in fact states that mangroves can keep pace with sea level rise through his assessment of mangrove sedimentation relative to sea level rise. Regarding Mauritius, Sumner et al. (2021) has put together a comprehensive review of erosion studies carried out in Mauritius in the last twenty years both inland and along the coast. While some studies have been carried out on shoreline changes along beaches such as the work by Bheeroo et al. (2016) based on a GIS-DSAS model to investigate how coastlines change in northwest Mauritius and Doorga et al. (2021) at two sandy beaches in the west and south of the island, no study has been undertaken on erosion and accretion in mangroves so far.

4.6. Nature based solutions versus coastal engineering structures in Mauritius

Conventional coastal engineering techniques like embankments, dykes and sea walls are often favored to decrease the impacts of coastal hazards but are challenged due to their high maintenance costs and negative environmental effects eventually (Schoonees et al., 2019). For instance, Ragoonaden (1997) reports that in several places along the coast of Mauritius such as at Flic en Flac and Blue Bay where seawalls have been built, erosion occurred on the seaward side of the walls and how beaches close to coastal structures like solid groins and vertical sea walls were damaged following the passage of the intense tropical cyclone Hollanda in 1994. Ragoonaden also notes how several illegally and poorly constructed groins on beaches aimed at preventing flooding ended up causing permanent large scale beach erosion in many areas. At Riviere des Galets, a small coastal village in the south of Mauritius highly vulnerable to coastal hazards, the government has invested millions of MUR in sea walls and gabions to protect the community, but these have failed repeatedly over the years with rising sea levels causing waves to now overtop the seawalls. According to estimates made by the Government of Mauritius. (2010), the cost of repairing coastal infrastructure and buildings lies in the $ 0.5 billion while the cost of relocating vulnerable communities exposed to frequent flooding and storm surges is $ 312 million. In line with this, Duvat et al. (2020) mapped the nature based measures put in place in Mauritius since the 1960s and observe a significant shift from conventional man-made structures to ecosystem-based and combined strategies in more recent years mainly due to the failure of hard structures and the availability of external funds to design effective policies.

In the local context, it is critical to thoroughly assess the geomorphology of the site in question and understand the ecology of mangroves before embarking on nature based projects. This in fact pointed out by Renaud et al. (2016) who highlight the fact though ecosystems and society are linked, there is a need to analyze the complex vulnerability, risk and environmental factors in a case specific and systematic manner. The statement is also supported by the EPA Network and ENCA (2020) group discussion in mainstreaming nature-based approaches recognizing a need in developing a better evidence base (case studies reflecting effectiveness and cost and benefits analysis) and comparing man-made and natural techniques to comprehend their benefits and/or differences. Regarding this, Table 3 compares engineering solutions to mangroves as nature based solutions showcasing their sustainability and effectiveness to reduce the risk of disasters and adapt to climate change. So far, research demonstrates that both *Rhizophora* and *Bruguiera* species that are found in Mauritius have the inherent capacity to cushion waves making them effective in flood risk management in the coastal zones with mangrove forests in general protecting inland habitats and stabilizing coastal regions. Nonetheless, it is important to run pilot studies locally to investigate on their impacts such that they can be translated to larger scales. Likewise, these solutions can be coupled to engineering techniques in the form of hybrid approaches to make them more effective. For instance, Cruz et al. (2016) utilize a remarkable technique for increasing the survival of newly planted mangroves in sites which are prone to erosion and negatively affected by waves by examining the wave climate of the location and integrating suitable wave breakers to protect saplings in the short run.

Thus management strategies and further in depth studies into ecosystem based solutions for disaster risk reduction and climate adaptation is critical especially for small islands that Wilson and Forsyth (2018) emphasize have high potential for ecosystem based responses. Colls et al. (2009) state that ecosystem-based adaptation decreases communities' vulnerability to both climate and non-climate risks while providing several environmental, socio-economic and cultural benefits. Ecosystem based approaches to disaster risk reduction and climate change adaptation form an integral part of the 2015 Sendai Framework for Disaster Risk Reduction (UN, 2015a), the 2030 Agenda for Sustainable Development and the Sustainable Development Goals adopted by the United Nations General Assembly in 2015 (UN, 2015b) and the 2015

Table 3
Comparison of engineering solutions used in Mauritius versus mangroves as nature based solution.

Component	Engineering solutions	Mangroves (nature based solutions)	References
Sustainability	Seawalls, gabions failed repeatedly over the years requiring regular maintenance	Mangrove ecosystems can sustain themselves in the long run	Ragoonaden (1997); Nunn et al. (2021)
Natural habitat	Erosion noticed in several areas where seawalls, gabions have been built	Conserved and/or restored allowing other ecosystems like coral reefs and seagrass beds to flourish	Duvat (2009); Anisimov et al. (2020)
Storm surge propagation	Inland water storms enhanced	Lowered as mangroves store water	Sauer (1962); Anisimov et al. (2020)
Sediment accumulation	Disturbed and/or halted by structures	Supported	Ragoonaden (1997); Esquivel et al. (2022)
Land subsidence	Exacerbated by soil drainage and wetland reclamation	Counterbalanced	UNEP, 2020
Water quality	May degrade	Enhanced	Ragoonaden (1997); Esquivel et al. (2022)
Fisheries and aquaculture	Reduced	Improved	UNEP, 2020; Nunn et al. (2021)
Carbon sequestration	None	Crucial carbon sinks	UNEP, 2020; Nunn et al. (2021)
Cost-benefit appraisal	Moderate to high	High because of multiple advantages of ecosystems	UNEP, 2020; Nunn et al. (2021)
Creation of structure	Moderately difficult	Relative high because of natural dynamics and variability	Nunn et al. (2021)
Human recreation	Artificial landscape is negatively perceived	Natural landscape is positively perceived	Duvat et al. (2020); Magnan et al. (2021)
Existing research	Moderate with many failures	Limited	Renaud et al. (2016); Magnan et al. (2021)
Health hazards	None	May permit disease spread	Siwiendrayanti et al. (2020)
Space	Moderate	High, not applicable to coastal cities	van Wesenbeeck (2016)
Social and political acceptance	Widely accepted	Limited to certain areas	Anisimov et al. (2020)
Regulating hydro-meteorological cycle	None	Critical component of coastal and riverine hydro-meteorological cycle	UNEP, 2020
Mitigating potential heatwaves	None	Lower surface and air temperatures through shade and evapotranspiration in coastal and riverine regions	UNEP, 2020
Biodiversity	Decreased	Rich	UNEP, 2020

Paris Agreement to address climate change (UNFCCC, 2015). The 2021 Glasgow Climate Pact (UNFCCC, 2022) also notes the importance of ensuring the integrity and protection of ecosystems when taking action to address climate change while a recent publication by the UNEP (2022) emphasizes the need for ecosystem based solutions such as constructed wetlands to decrease the impacts of disasters like flood related risks which have increased by 134% since 2000 (WMO, 2021).

5. Limitations

Due to the limited time period, only one independent reviewer checked a sample of the resources retrieved for the analysis. Also, the present study focuses on the effectiveness of *Rhizophora* and *Bruguiera* species as ecosystem based solution in the context of Mauititus. While mangroves (in general) as ecosystem based solution have been comprehensively reviewed globally, there are few current original research works on *Rhizophora* and *Bruguiera* species specifically and their capacity and effectiveness in reducing flood risk, sheltering coastal regions during storms and stabilizing the coast. Likewise there are very few published works on mangroves as ecosystem based solution in the context of SIDS and island nations. Therefore, references had to be made to older published materials.

6. Recommendations

This study on mangroves as nature-based approach to reduce the risks of disasters and adapt to climate change with Mauritius as case study reveals several barriers to effectively put in place nature-based approaches. The following recommendations are made to bridge this gap:

1. More experimental research is needed on the physico-chemical properties of mangroves such as in wave attenuation, flow conditions etc. to understand how these systems function in face of vulnerabilities.
2. Variations caused by climate change like sea level rise, frequent storm surges, higher wave heights etc. are providing an opportunity to investigate into nature-based solutions as engineering solutions fail repeatedly.
3. When designing nature based solutions with mangroves, it is critical to ensure long term monitoring in project design and implementation to provide evidence of their benefits/dis-benefits.
4. When embarking on nature based solution with mangroves, it is also recommended to use ecosystem valuation of natural capital to fully assess the range of benefits of such an approach.
5. More case studies in the context of island states to demonstrate the potential of nature based solution for nations with limited resources are required.
6. Baseline data should be gathered before embarking on mangrove afforestation/reforestation projects for comparison purposes.
7. Although *Rhizophora* and *Bruguiera* species have been found to be effective nature-based solution, further research is needed to investigate their robustness as an instrument to reduce the risks of disasters as well as their ability in withstanding changes in climate via-a-vis phytosociology and biodiversity within the ecosystem.

7. Conclusion

Coastal hazards are imminent dangers to coastal communities and are expected to become worse due to looming changes in the world's climate system. Small islands like Mauritius are especially at risk due to their isolated geographic position, small size and limited resources. In this situation, the use of natural resources as natural defense and protection strategy is profitable both financially and for achieving sustainable development. This study assessed the relevance of mangroves as an ecosystem-based technique to reduce the risks of disasters and adapt to the changing climate system in Mauritius' context following the PRISMA flowchart model. Amongst 41,789 records obtained from Google Scholar, Web of Science, ScienceDirect and Google Search Engine, 50 studies were deemed relevant to the current research. The benefits of mangroves identified in the local context include attenuating waves by up to 99% depending on mangrove coverage, protecting inland areas from disastrous storm surges plus assets and lives and stabilizing the coastal zone and preventing erosion. Several coastal engineering structures have been used in Mauritius such as seawalls and gabions to reduce disaster risk, but these have failed over the years to give way to more robust hybrid strategies. This study thus positively answered its research questions on the use of mangroves as nature based solution to reduce the risks of disasters and adapt to a new climate in Mauritius' context, the key attributes of mangroves for this purpose and the capacity of the local mangrove species to do so.

Nonetheless, the study also reveals that for mangroves to be effective ecosystem based assets, they must meet certain criteria such as being mature and large enough. Mangroves are typically cited as effective flood barriers resulting in frequent restoration and afforestation projects to increase community resilience yet studies also state that mangroves can reduce wind and swell waves by 13 and 66% over a distance of 100 m of forest. While mangrove sites less than 100 m wide can reduce daily waves, they cannot dissipate the impacts of surges and high waves. In the case of Mauritius, this is an important point to note as mangroves typically occur as small patches less than 100 m wide. Therefore, it is wrong to assume that mangroves are safe ecosystem based solution to reduce the risk of coastal hazards if they are small in size and young. This inaccurate perception could in fact increase the vulnerability of coastal inhabitants to cyclonic surges and high waves as they become reluctant to move from vulnerable sites. Likewise, mangrove restoration is so easy, especially for *Rhizophora*, that very often this is done without proper planning and risk assessment of the selected sites. Planting the wrong species of mangroves in certain sites or even the right species in the wrong sites can have disastrous repercussions on the local ecosystem. Local community involvement is thus of paramount importance in using mangroves as ecosystem based solution together with the involvement of ecologists and scientists. But given the vulnerability of island nations to coastal hazards, hard structures like seawalls are often preferred despite their side effects when compared to the longer time scale required for mangroves to grow and become mature enough to withstand these threats. In such cases, hybrid techniques involving growing mangroves alongside hard structures could prove to be useful in both the short and long term. In this Decade on Ecosystem Restoration, the role of mangrove forests as ecosystem based solution to reduce disaster risk and adapt to climate change is critical not only for biodiversity conservation but for socio-economic well-being as well thus contributing to the United Nations Sustainable Development Goals. In line with other research works on the role of mangroves as ecosystem based solution for disaster risk reduction and climate change adaptation, this study also concludes that the resilience of coastal communities can significantly increase with healthy and dense mangrove forests. Therefore, Mauritius should research further into ecosystem based solutions as this will substantially help decision makers, researchers and the public at large to consider restoring degraded mangrove sites and promote ecosystem-based approaches to reduce disaster risk, adapt to climate change, enhance marine spatial planning and better coastal zone management.

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Declaration of Competing Interest

This manuscript has not been previously published and is not under consideration in the same or substantially similar form in any other peer-reviewed media. To the best of our knowledge, no conflict of interest or other, exists.

Data availability

Data will be made available on request.

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