LITERATURE ANALYSIS AND SYNTHESIS OF THE RED SEA MANGROVE ECOSYSTEM: DECADES OF HUMAN IMPACTS AND KNOWLEDGE GAPS

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Abstract. The Red Sea mangrove ecosystem (RSME) has faced conservation issues and in anticipation of future developments in the Anthropocene. The objective of this study was to comprehensively analyze and discussed the pollution in RSME by examining the literature spanning about four decades (1977-2023). The primary emphasis focused on human-induced pollution in previous research. This article assesses the state of sustainability in the RSME to guide recommendations for its conservation and management. This will help identify knowledge gaps in the RSME's response to various factors, including temperature increases between 2000–2011 and 2012–2023, as observed in Hurghada and Jeddah. The proposed measures include (a) enhanced monitoring, (b) public awareness and education efforts, (c) allocating funding based on economic trends, and (d) adoption of Environmental, Social, and Governance (ESG) practices. Efficient management of ESG factors is strongly recommended to ensure the sustainability of the RSME's services and functions. Collecting monitoring data on pollution can provide a fundamental reference point for examining future human impacts. Therefore, restoration and conservation of the RSME should be prioritized. The synthesis of the water-energy-food Nexus should integrate the critical social, economic, and environmental dimensions including ESG implementation. This paper presents a framework for identifying knowledge gaps in the sustainable management of the RSME, particularly regarding mangrove fauna, which merits future study.

Keywords: *historical pollution, mangrove environment, environmental management, anthropogenic, conservation*

Introduction

Overall background of the Red Sea mangrove ecosystem

Studies on the Red Sea mangrove ecosystem (RSME) from various scientific viewpoints have been published since the 1980s (Mohamed, 1984; Dicks, 1984, 1986; Al-Shwafi, 2011; Hussain and Khoja, 1993; Mohamed and Al-Shehri, 2015; Balk et al., 2015; Sohaib et al., 2023; Mohammad, 2023; Rashedy et al., 2023; Blanco-Sacristán et al., 2022). The RSME has been extensively studied, particularly regarding pollution (Al-Hasawi, 2022; Elnaggar et al., 2022; Aljahdali and Alhassan, 2022, 2023; Alhudhodi et al., 2022). The Red Sea littoral had a few isolated mangrove stands in Djibouti, Egypt, Yemen, Sudan, Eritrea, and Saudi Arabia (Almahasheer et al., 2016a). Egypt has the largest population in 2021, followed by Sudan, Saudi Arabia, Yemen, Eritrea, and Djibouti (*Fig. A1*). Saudi Arabia has the largest gross domestic product (GDP) in 2019, followed by Egypt, Sudan, Yemen, and Djibouti (*Fig. A2*). Saudi Arabia produced the most oil production in 2022, followed by Egypt, Yemen, Sudan, Djibouti, and Eritrea (*Fig. A3*). Saudi Arabia emitted the most CO_2 in 2021, followed by Egypt, Sudan, Yemen, Eritrea, and Djibouti (*Fig. A4*).

With no riverine nutrient inputs, high salinities, high temperatures, and little precipitation, the Red Sea features stunted mangroves (Almahasheer et al., 2016b; Eid

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and Shaltout, 2016). The Red Sea coast has two mangrove tree species: *Avicennia marina* (Khraiwesh et al., 2013; Alharbi et al., 2019; Abroguena et al., 2022; Alhassan and Aljahdali, 2021b, c; Aljahdali et al., 2020, 2021a) and *Rhizophora mucronata* (Al-Mutairi et al., 2012). On Farasan Island, Al-Mutairi et al. (2012) observed *A. marina* and *R. mucronata* coexisting. Both species cohabit in the same mangrove habitat. Both species develop at different speeds depending on the environment. Mangrove diversity and expansion were minimal, and flora and animals exhibited severe environmental degradation, including low nutrition levels (Saifullah, 1996). The RSME is important biogeographically and ecologically as the Indo-Pacific mangrove dispersion limit (Mohamed, 1940; Khalil, 2015).

Interestingly, the *A. marina* is extensively dispersed in the northern Red Sea (Mandura et al., 1987). The majority of mangrove stands in the region are *A. marina* along the seashore, nearshore and offshore islands, or tidal creeks and channels. Narrow woodlands are characteristic of *A. marina*. These woods, however modest, can span tens of meters to several kilometers along the beach. According to various studies (El Daba et al., 2018; Alzahrani et al., 2018), the *A. marina* mangrove forest, which covers about 135 km^2 in the Red Sea, is one of the most significant plant groups in this normally dry and oligotrophic environment (Schneider et al., 2017). The relationship between *A. marina*'s carbon stores was found to be related to the total biomass (Shaltout et al., 2021). The RSME may be a hybrid ecosystem with hard and soft substrates and species from each. A new method that delivers nitrogen, phosphate, and iron has grown over 700,000 mangroves, predominantly *A. marina,* on Eritrea's treeless mud flats (Sato et al., 2005). Egypt's whole Red Sea coast is A. marina. Since Red Sea mangroves are nutrient-limited, they can grow bushy, are limited to a few coastal places, and are often found in scattered groups (Madkour et al., 2020).

Potential threats to the Red Sea mangrove ecosystem

Environmental risks may affect RSME. Global concerns concerning mangrove ecosystem contamination have been raised, notably in the Red Sea (Saifullah et al., 1989; Sabeel and Vanreusel, 2015; Nagi and Abubakr, 2013; Aljahdali and Alhassan, 2020, 2023). Human activities endanger various tropical marine ecosystems in the Red Sea due to the growing population of the six nations along the coast (*Fig. A1*). Since the turn of the century, inorganic and organic pollution has been found in the Red Sea, which was once considered clean (El Nemr and El-Said, 2014). Walker and Ormond (1982) claimed that phosphate dust from ship loading and urban sewage discharge caused localized coral reef contamination in Aqaba (Red Sea) (Cai et al., 2022). The Red Sea Gulf of Aqaba has seen significant strategic and economic growth (Al-Rousan et al., 2016). Human activity has also damaged Yemen's Red Sea shoreline (Omar et al., 2014; Saleh, 2021).

Over 30 years, industry and human activity in Saudi Arabia's coastal region have developed rapidly, introducing pollutants such as heavy metals (Bayoumi and El-Nagar, 2009; Badr et al., 2009). Managing acute and long-term oil spills requires cutting-edge technology because of the sensitivity of mangroves near communities (Bayoumi and El-Nagar, 2009). Oil output in Red Sea nations may be increasing (*Fig. A3*). Various human and natural sources contribute metals to the Red Sea (Al-Mur, 2021). Camels overgrazing in Sudan, Djibouti, and Yemen degrades habitat and threatens the RSME. Developing coastal highways, hotels, harbors, and airports, especially in Saudi Arabia, raised concerns. Poor nutrition, high salinity, UV light, and temperature are mangrove stressors that are being researched (Alhassan and Aljahdali, 2021a). Climate change causes rising sea levels, more frequent storms, higher temperatures, shifting precipitation patterns, and increasing danger. Since mangroves are vulnerable to flood length and frequency, increased flooding may reduce mangrove cover (Aljahdali et al., 2021b; Cai et al., 2022). Mangroves spontaneously minimize and adapt to climate change (Awad et al., 2023). However, polycyclic aromatic hydrocarbons (PAHs) may harm mangroves (El-Amin et al., 2017). The Red Sea coast nations' rising CO_2 emissions from 1980 to 2021 (*Fig. A4*) corroborate this.

Due to their role as coastal barriers, mangrove habitats, *A. marina* (Forssk.) Vierh., are useful for studying the biochemistry of potentially harmful metals (Mosa et al., 2022). Sustainable management of coastal mangrove lagoons requires investigating toxic metal pollution and phytoremediation (Al-Solaimani et al., 2022; Sefrji et al., 2022). The *A. marina* forests are an environmental, ecological, economic, and social challenge (Alamri et al., 2021). Human activity in cities is increasing harmful metal levels. However, how mangrove plants respond to human-caused heavy metal stress affects metal bioavailability and ecotoxicity (Alhassan and Aljahdali, 2021b; Shatla et al., 2021). Camels, road building, and silt deteriorated the lagoon in the 1990s. Mangrove communities have demonstrated some regrowth due to corrective interventions (Saleh, 2007a; Monsef et al., 2013; El-Menhawey et al., 2020; Anton et al., 2020; Shaban and Abdel-Gaid, 2020), and a restoration of mangrove vegetation at RSME has begun (Chithambaran, 2019). For instance, a generation mangrove nursery has been initiated at Umluj, Saudi Arabia (*Fig. 1*).

Figure 1. *A generation mangrove nursery at Umluj, Saudi Arabia (Photos taken by Khalid Awadh Al-Mutairi in 2022)*

The *A. marina*'s mangrove forest in the RSME is one of the most significant plant groupings in this arid, oligotrophic environment (Elsebaie et al., 2013; Kumar et at., 2010a, b, 2011; Price et al., 1987; Almahasheer et al., 2017). The disappearance of mangrove ecosystems is causing widespread concern. Only some academics have focused on Graeco-Roman mangroves despite ecological and biological issues in the news (Schneider, 2017). Mangrove ecosystems, vital to health (Sea et al., 2018; Abdel-Hamid et al., 2018), are under increasing pressure from human activity and environmental change (Ullah et al., 2017). Extreme drought and tropical/subtropical climates stimulate mangrove growth (Abroguena et al., 2022), and RSME is among the most endangered ecosystems yet economically vital (Marasco et al., 2023). For instance, regional nutrient dynamics and physico-chemical characteristics vary greatly in the Rabigh Lagoon (Aljahdali et al., 2021a) and Egypt's mangrove ecosystem (Afefe et al., 2021). Moreover, Abu Minqar, in the Red Sea near the Gulf of Suez, is endangered by pollution from coastal operations, increasing tourism boom, and hotel building at Al Ghardaqa Beach (Saleh, 2007b). Afefe (2021) concluded that the efficiency of restoration operations in various situations since environmental conditions and management regimes might affect restoration results in Egypt's RSME.

Therefore, the primary goal of the current study is to focus on the domain of human pollution research, taking into account the aforementioned literature. To this goal, the issue of RSME pollution, by reviewing the published literature based on the Scopus database from 1977 to 2024, has been delicately examined and discussed from the environment, social and governance (ESG) point of view in the present review study.

Methodology

A more thorough systematic literature review (SLR) is more suited. The SLR method from Moher et al. (2009)'s Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) was utilized in the current review study to add to the body of currently available information on "Mangrove" and "Red Sea." PRISMA is a potent evidence-based reporting standard for critical evaluation. *Figure 2* depicts the phases of the systematic method modified for this review research. Since Elsevier's Scopus is the world's largest abstract and citation database of peer-reviewed scientific literature journals, books and conference proceedings, which covers research topics across all scientific, technical and medical disciplines (Guz and Rushchitsky, 2009; Schotten et al., 2017; Atlantis Press, 2023), it was chosen for the literature analysis in the present study.

On 14 December 2023, using the keywords 'Mangrove' and 'Red Sea', 111 papers arrived (*Fig. 2*). From the 111 papers, 5 papers (1 of corrigendum, 3 not related to Red Sea, and 1 of the duplicated title) were excluded. In addition, papers with the keywords 'Red Sea' and 'Floristic', 2 papers were found, while with the keywords 'Red Sea' and 'Economy', 8 papers were found, with two irrelevant papers being discarded. With the keywords 'Red Sea' and 'Pollution', 66 papers were found, with 8 irrelevant papers discarded. In addition, 14 relevant papers from non-Scopus were also included in this literature review study. Therefore, there is a total of 186 papers for the qualitative synthesis in this review paper for the topical discussion used in the present study (*Fig. 2*).

The daily data ranging from 1 January 2000 until 31 December 2023 for temperature, relative humidity and precipitation at Hurghada (Egypt) and Jeddah (Saudi Arabia) are obtained from CustomWeather.com Inc. Hurghada is located with coordinates 27.15 and 33.7167, while Jeddah with 21.7 and 39.1833. All graphs were made using

KaleidaGraph by 1986-2022 by Synergy Software (Version 5.0 for Windows. Synergy Software, Reading, PA, USA. www.synergy.com).

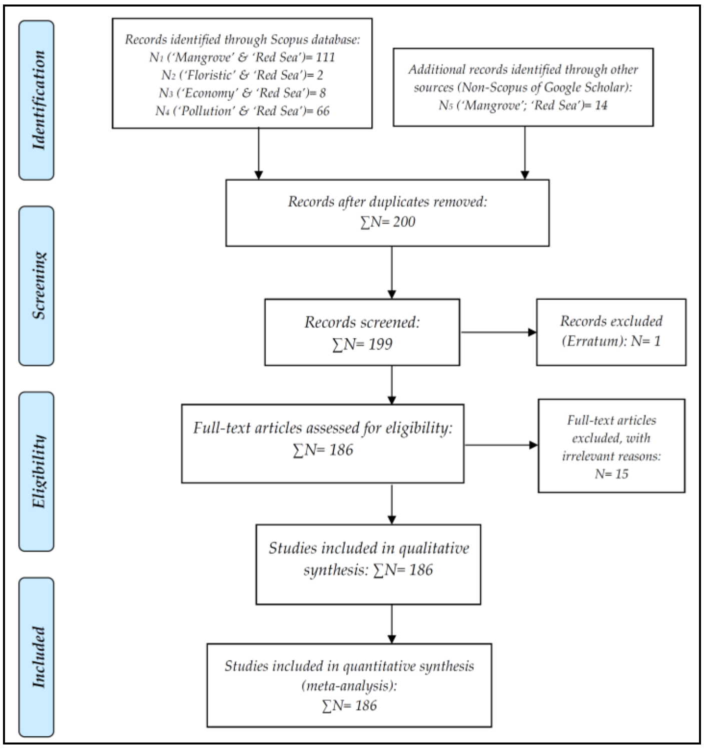


Figure 2. *Flowchart of Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) used in the present study, which was adapted from Moher et al. (2009)*

Results

From all the papers reviewed, there are papers on rare earth elements and PAHs or hydrocarbons (such as Shimy, 1997; Moursy et al., 1987; Jamoussi et al., 2022) and heavy metal (such as Idris, 2008; Masoud et al., 2019; Usman et al., 2013; El-Said et al., 2013; Ismael et al., 2022; Salah-Tantawy et al., 2022) pollution in the RSME. In addition, studies on the use of bioindicators or biomonitors of pollution in the RSME have also been reported (such as Youssef et al., 2017; Ibrahim et al., 2011; Afifi et al., 2016; Bresler et al., 1999; El-Wahab and El-Sorogy, 2003; El-Sorogy et al., 2013; Al-Hasawi, 2019; Hassanine et al., 2019; Mohammad et al., 2020; Nour and Nouh, 2020a; Al-Najjar et al., 2021; El-Kahawy et al., 2021, 2023). Most papers were reported from Saudi Arabia, Egypt, and the Gulf of Aqaba, and more studies from Yemen and Sudan are needed. Recently, papers concerning building the smart city have also been reported (Al-Sayed et al., 2022; Paszkowska-Kaczmarek, 2021). However, no studies on the Djibouti, Northern Somalia and Eritrea coasts on the RSME were reported on any pollution studies.

Discussion

The following discussion will focus on the following major aspects based on all the reviewed information. The following discussion is based on *Figure 3,* in which the following methods are proposed to understand the knowledge gaps in the RSME. This includes a) more future monitoring, b) enhancing public awareness and education, c) investment of funding is needed in line with the economic boom, and d) implementation of ESG.

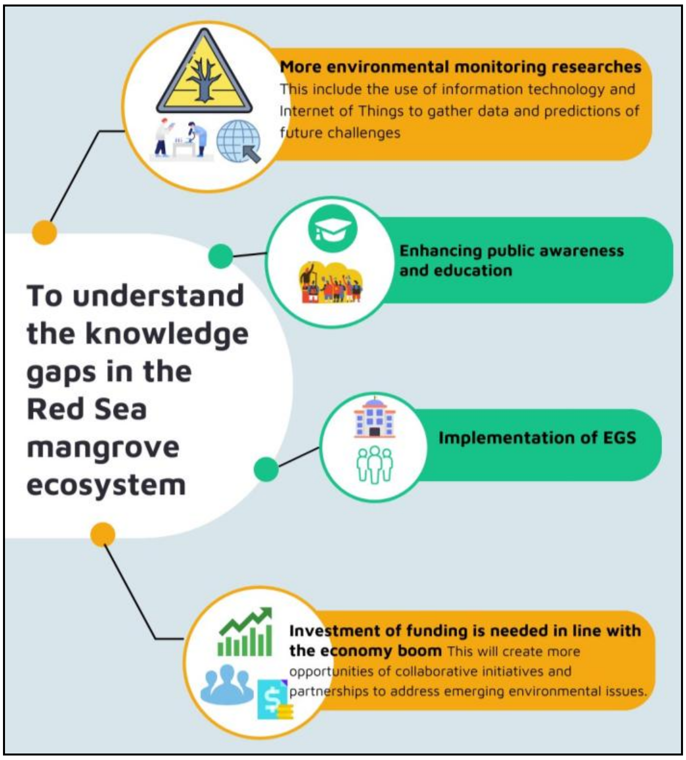


Figure 3. *Proposed methods to understand the knowledge gaps in the Red Sea mangrove ecosystem*

More future monitoring of the environment-socio-economy aspect in the water-food-energy nexus is much-needed

Based on all the literature reviewed, it can be concluded that there is always a need for conservation efforts in the water-food-energy Nexus of the RSME. Many studies reported pollution in the RSME previously (Fishelson, 1973; Idris et al., 2007; Mandura, 1997; Abelson et al., 1999; Nour and Nouh, 2020b), and this included light pollution (Ayalon et al., 2019; Tamir et al., 2020). Therefore, these monitoring studies are deemed necessary due to an unlimited provision of mangrove ecosystem services (Hanna and Muir, 1990; Abu-Hilal and Badran, 1990; Hanna, 1983), and increasing environmental stresses due to human activities causing environmental pressures on RSME (Abu-Hilal and Al-Najjar, 2004; Diamant et al., 1999; Georges et al., 2021; Teem, 2022; Ghandourah et al., 2023; Farhat et al., 2022). In addition, the many beneficial microorganisms (Khallil et al., 1991; Abdel-Wahab et al., 2001, 2022; Sefrji et al., 2021a, b; Abdel-Wahab, 2005; Ameen et al., 2015, 2016; Simoes et al., 2015; Fuad et al., 2015; Alzubaidy et al., 2016; Fahmy, 2020; Wahab et al., 2019; Abdel-Wahab et al., 2019; Bakhit and Abdel-Wahab, 2022; Fahmy, 2022), such as the decomposer Thraustochytrids (Abdel-Wahab et al., 2021), extremophilic black yeast *Hortaea werneckii* (Hodhod et al., 2020), halophilic *Aspergillus terreus* (Farag et al., 2021), and *Streptomyces mutabilis* (Hamed et al., 2021) have been recorded at the

RSME. Other species included seaweed communities (Talaat et al., 2022), podocopid ostracods (Helal and El-Wahab, 2012), macrofauna (Sabeel et al., 2015, 2025), benthic organisms (Abroguena et al., 2021; Al-Sofyani and El-Sherbiny, 2018), and the birds (Babbington et al., 2019). All of the above species have been a valuable natural resource that needs to be preserved and sustained.

The need for the monitoring study has been intensified by the ecological risk assessment and nutrient studies in the sediments of the RSME, as indicated by many reported studies. These monitoring included geochemistries of the sediments (Madkour et al., 2008, 2014; Okbah et al., 2005; Afefe et al., 2019), and ecological risk assessment of heavy metals in the sediments (El Zokm et al., 2022; Nour et al., 2018, 2019). In addition, monitoring of pollution in the sediments (Attia et al., 2013; Abdallah et al., 2015, 2016), trace metals (Badawy et al., 2021), and uranium in the sediments (Abu-Hilal, 1994), and water (Loya, 1975; El-Sorogy and Youssef, 2021) have also been reported.

In today's rapidly changing world, the significance of accurate pollution monitoring in the RSME cannot be overstated. Continuous monitoring of pollutants is crucial for understanding the state of pollution in the RSME. This information is important for the conservation and protection of RSME and the health and safety of the local communities that rely on these resources. Additionally, monitoring pollution in the RSME is essential for regulatory purposes and developing effective pollution control and mitigation strategies. Furthermore, with the Suez Harbor being a primary gateway to the Red Sea, monitoring pollution in this area is particularly important (El Nemr and El-Said, 2014). It is necessary to detect and address the main sources of oil pollution, to prevent further degradation of the marine environment and promote sustainable development in the RSME. This proposal is based on the many reported studies of oil pollution in the Red Sea (Bayoumi et al., 2009; Huynh et al., 2021).

Generally, the literature reviewed indicated that fundamental pollution monitoring studies have been focused on integrating the environment-socio-economy (ESE). The ESE aspect in the water-food-energy (WEF) Nexus is a concept that stresses the importance of the interactions between the ESE Nexus and WEF Nexus, in which the integration of both Nexuses are almost a perfect match in the RSME. Therefore, the RSME management under conservation efforts should be strategized under the monitoring of the three crucial pillars of sustainability, namely society, economy and environment of the RSME, in the three important components of WEF Nexus (*Fig. 4*).

Urbanization and increased human pressures have reduced Red Sea biodiversity Al-Mutairi et al. (2012), which is expected to increase in the future (*Figs. 5a–8a*) (Ritchie et al., 2023, 2020, 2022; Roser et al., 2023). Al-Mutairi et al. (2012) studied the floristic composition, diversity, and environmental factors of Farasan's coral islands in the Red Sea, Saudi Arabia. He proposed a phytogeographical link between studying the archipelago's flora and African and Saharan ecosystem functions. Human activities and the foreign invasive tree *Prosopis juliflora* threaten species variation. Therefore, conservation and management efforts must lead future efforts. Later, Tomas et al. (2010) examined the Farasan Archipelago's angiosperm flora floristic linkages. The archipelago's delicate flora is undervalued nationally and internationally as a conservation problem. Human activities threatening the RSME suggest that mangrove ecology must be monitored, especially in coastal regions where heavy metal pollution occurs.

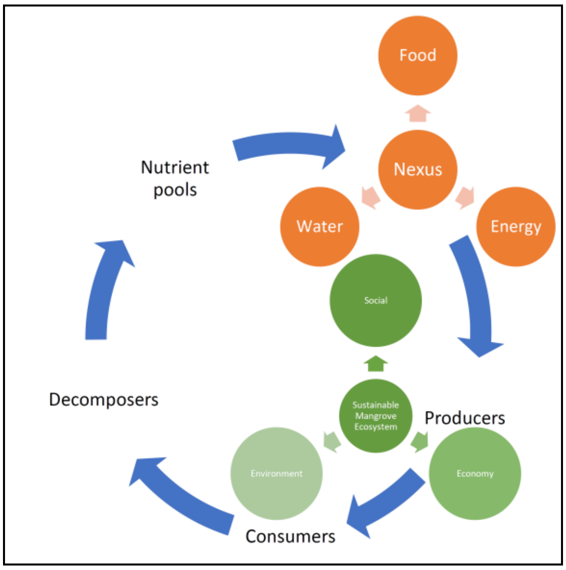
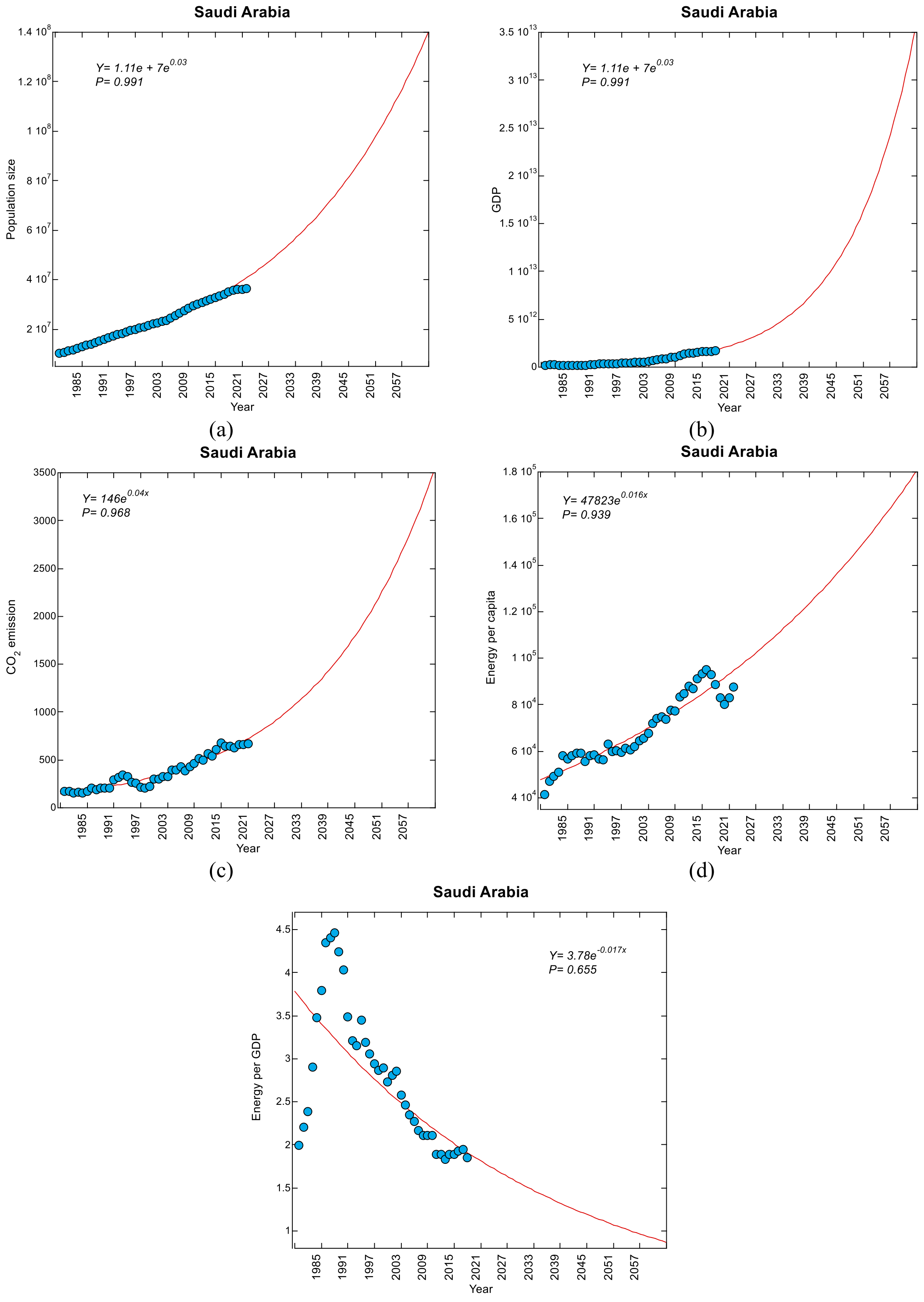


Figure 4. *Integrating aspects of society, economy and environment in completing the water-energy-food nexus in sustaining the Red Sea mangrove ecosystem under the pollution stress*

The disappearance of mangrove ecosystems is causing widespread concern. Only some academics have focused on Graeco-Roman mangroves despite ecological and biological issues in the news (Schneider, 2017). Mangrove ecosystems, vital to health, are threatened by human and environmental activities (Ullah et al., 2017). People worldwide worry about climate change. CO_2 emissions mainly cause climate change. Tropical and subtropical mangrove forests store carbon and provide many ecological services. Mangroves are among the strongest carbon stores but may also affect greenhouse gas emissions like CO_2 and CH_4 (Sea et al., 2018). This has been the reason why many studies examined the carbon stocks at RSME to understand the impact of climate change due to the possible decrement of the carbon sequestration capacity (Shaltout et al., 2020; Sea et al., 2018; Almahasheer et al., 2017; Eid et al., 2016; Saderne et al., 2019), with the carbon sequestration can mitigate the climate change variation (Awad et al., 2023).

CO_2 emissions in Djibouti, Saudi Arabia, Egypt, and Yemen have increased from 1980 to 2021 (Ritchie et al., 2020) and are anticipated to continue. Controlling the expected exponential increase in CO2 emissions in 2060 if legislation is ignored is crucial (*Figs. 5c-8c*) (Ritchie et al., 2020). Saudi Arabia (*Fig. 5d*) and Egypt (*Fig. 6d*) have rising energy per capita values from 1980 to 2021 (Ritchie et al., 2020) and are predicted to continue. From 1980 to 2021, energy per capita values decreased (Ritchie et al., 2022) and are predicted to drop in Djibouti (*Fig. 7d*) and Yemen (*Fig. 8d*). The energy per GDP values of Djibouti, Saudi Arabia, Egypt, and Yemen have decreased from 1980 to 2021 (Ritchie et al., 2022) and are anticipated to continue to fall (*Figs. 5e-8e*) (Ritchie et al., 2022).

Even though coastal plant communities are global carbon sinks, Central Red Sea seagrasses and mangroves contain minimal organic carbon (Garcias-Bonet et al., 2019). Due to their productivity and climatic tolerance, mangroves are important maritime ecosystems (Basheer et al., 2019; Baakdah, 2018). Mangroves accumulate metal in tropical and subtropical maritime environments (Alzahrani et al., 2018). Land use and land cover changes have harmed mangrove vegetation, especially in Saudi Arabia's hyper-arid, hyper-saline Red Sea coastal waters (Arshad et al., 2020).



(a)

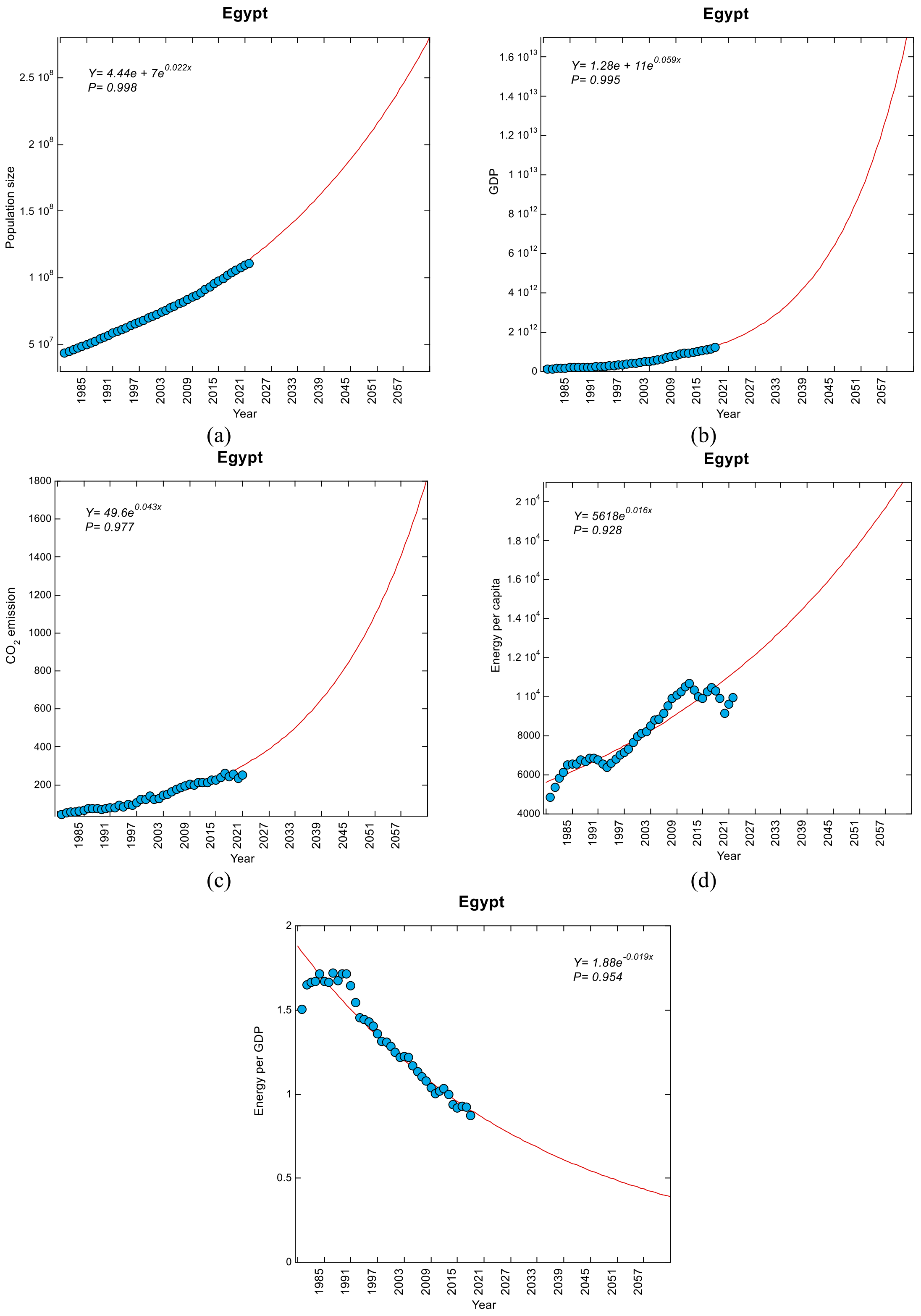
(b)

(c)

(d)

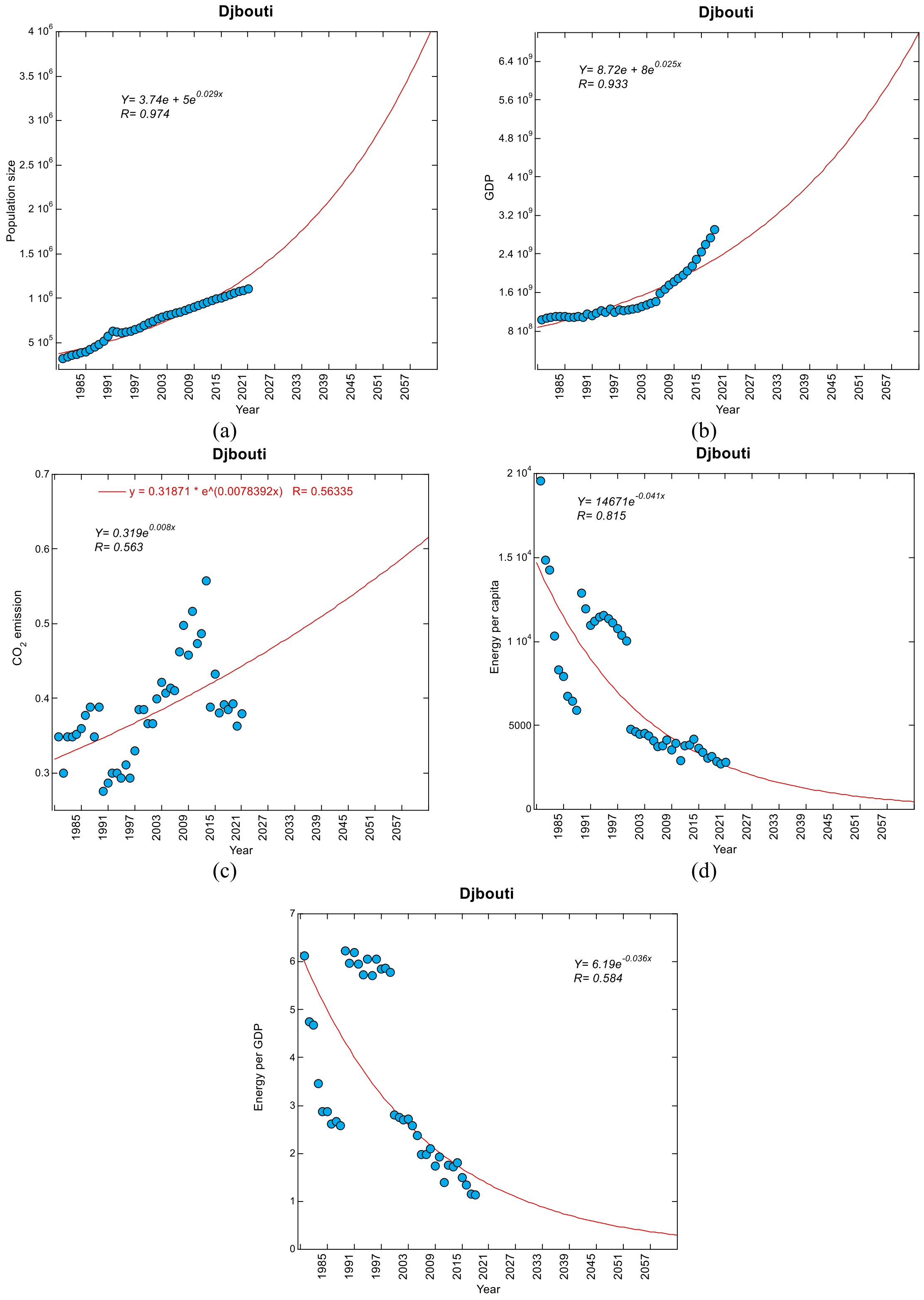
(e)

Figure 5. *Saudi Arabia. (a) Population size (Ritchie et al., 2023); (b) gross domestic product (GDP) (Roser et al., 2023), (c) carbon dioxide emission (CO_2) (Ritchie et al., 2020); (d) energy per capita (Ritchie et al., 2022); and (e) energy per GDP (Ritchie et al., 2022), based on Our World of Data. The extrapolations of the values are based on an exponential equation. Source: https://ourworldindata.org*



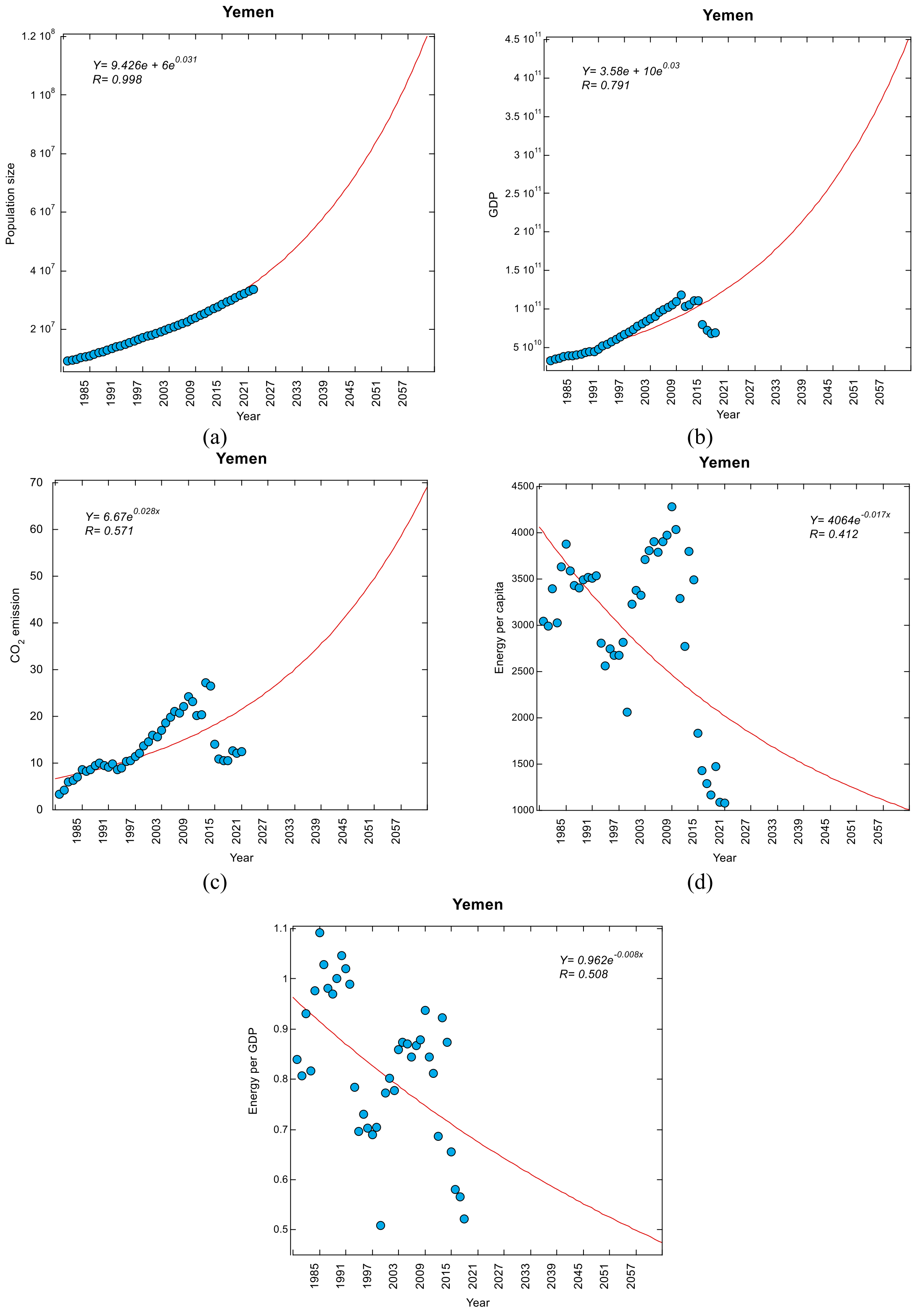
(a) (b) (c) (d) (e)

***Figure 6.** Egypt. (a) Population size (Ritchie et al., 2023); (b) gross domestic product (GDP) (Roser et al., 2023), (c) carbon dioxide emission (CO_2) (Ritchie et al., 2020); (d) energy per capita (Ritchie et al., 2022); and (e) energy per GDP (Ritchie et al., 2022), based on Our World of Data. The extrapolations of the values are based on exponential equation. Source: https://ourworldindata.org*



(a) (b) (c) (d) (e)

Figure 7. *Djibouti. (a) Population size (Ritchie et al., 2023); (b) gross domestic product (GDP) (Roser et al., 2023), (c) carbon dioxide emission (CO_2) (Ritchie et al., 2020); (d) energy per capita (Ritchie et al., 2022); and (e) energy per GDP (Ritchie et al., 2022), based on Our World of Data. The extrapolations of the values are based on an exponential equation. Source: https://ourworldindata.org*



(a) (b) (c) (d) (e)

Figure 8. *Yemen. (a) Population size (Ritchie et al., 2023); (b) gross domestic product (GDP) (Roser et al., 2023), (c) carbon dioxide emission (CO2) (Ritchie et al., 2020); (d) energy per capita (Ritchie et al., 2022); and (e) energy per GDP (Ritchie et al., 2022), based on Our World of Data. The extrapolations of the values are based on an exponential equation. Source: https://ourworldindata.org*

Mangrove environments are plentiful and ecologically important. However, their little plants show that RSME is nutrient-limited. Low carbon-to-nutrient stoichiometric ratios in Red Sea mangrove leaves imply nutrient depletion, but experimental confirmation shows that iron nutritional constraint is worse. Given the low nitrogen inputs from the land, mangrove sediments may fix atmospheric nitrogen (N_2) (Qashqari et al., 2020). Due to the RSME's hot, salty waters, climatic change is attracting attention (Eid et al., 2019; Afefe et al., 2020). Climate change mitigation efforts use mangroves to store carbon (Afefe et al., 2020). Due to its high salinity and warmth, the Red Sea may be a calcifying environment resistant to ocean acidification. Due to their role as ecosystem carbon sinks and land conversion, coastal ecosystems, particularly mangroves' "blue carbon" (Eid et al., 2019), are attracting increased attention. Industrial pollutants, dredging and erosion silt, pesticide runoff, untreated sewage, and agricultural waste are removed by mangroves from coastal seas. Logging for fuel wood affects sediment characteristics and threatens biodiversity (Almahasheer et al., 2016a).

Tropical and subtropical mangrove forests store carbon and provide many ecological services. Mangroves are commercially and ecologically valuable. They provide natural resources, coastal stability, development protection, pollution absorption, fisheries feeding and breeding grounds, and pollution absorption (Almahasheer et al., 2016a; Eid and Shaltout, 2016). Mangroves reduce coastal erosion by expanding seaward and occupying new coastal habitats (Alhassan and Aljahdali, 2021a). In addition to safeguarding coasts, mangroves offer food and refuge for many marine animals, including fish and shellfish (Abu El-Regal et al., 2014; Aljahdali and Alhassan, 2020; Al-Kahtany et al., 2023a). Upwelling nutrients and organic matter from mangrove leaf litter strengthen tropical coastal marine food webs (Almahasheer et al., 2016a; Eid and Shaltout, 2016). Despite the mangrove ecosystem's environmental and economic benefits (Alhassan and Aljahdali, 2021a; Eid and Shaltout, 2016), mangrove regions have declined. Many tropical regions destroy mangrove forests for aquaculture, land reclamation, and other purposes (Arshad et al., 2020). Coastal development severely damages mangrove substrate, hydrological regimes, and ecology (El Nemr and El-Said, 2014). According to growing evidence, mangrove forests are being lost worldwide (Khalil, 2015). Thus, scientists and conservationists must safeguard the RSME. Mangroves near the Red Sea shore are less lush than those along tropical beaches in Southeast Asia but provide important ecological roles. They protect coral reefs by absorbing sediment loads from seasonal precipitation surges and producing commercial fish (Abu El-Regal et al., 2014; Al-Kahtany et al., 2023b). Due to its hostile environment, RSME is especially susceptible to overexploitation.

According to Mohamed (1984), a short ecological evaluation of Sudanese Red Sea salt marsh mangrove vegetation was done between 1980 and 1982. Four types of locations have pure *A. marina* (Forsk) Vierh stands of various sizes. Camel grazing, salt pans, and, to a lesser extent, cutting cause degradation in accessible regions. The camel tribesmen who controlled grazing protected the severely damaged aggregations. Abohassan et al. (2012) examined two *A. marina* mangrove stands in Yanbu and Shuaiba, Saudi Arabia's Red Sea coast. Ground plots and random coring measured aerial and fine roots, whereas allometric equations calculated above-ground biomasses such as stems, branches, leaves, and total biomass. Abohassan et al. (2012) prompted more research into site productivity, health, and yearly biomass increase.

Hence, continuous research, community public monitoring, and research requirements will always be needed. The mangroves' physical habitat, floral and faunal populations, and short- and long-term consequences of natural and human-induced causes must be better understood. Basic and problem-focused research is needed to establish management standards. Ecosystem research involves both basic and issue-specific research. The basic study examines how genetic features affect animal adaptation to living and inanimate environments. Understanding community structure and functioning requires studying species' physiology, reproductive biology, and inter- or intra-specific interactions during their ontogenetic stages. Pathological and epidemiological changes must be monitored in this context. Application- and problem-oriented research investigates human-caused environmental changes and develops resource conservation and sustainable usage principles. This is only feasible if the organisms and their variety have been found via fundamental research.

Future environmental monitoring of RSME contamination is required and ongoing. This study used biology, conservation, taxonomy, ecophysiology, ecology, and pollution studies to examine RSME contamination. Basic monitoring studies could provide further information on the RSME's potential responses to increased temperature from 2000-2011 to 2012-2023 (*Fig. 9*). Previous reported studies indicated the impact of temperature increment on the species distribution in the Red Sea (Furby et al., 2014; Qashqari et al., 2020; Banc-Prandi et al., 2022).

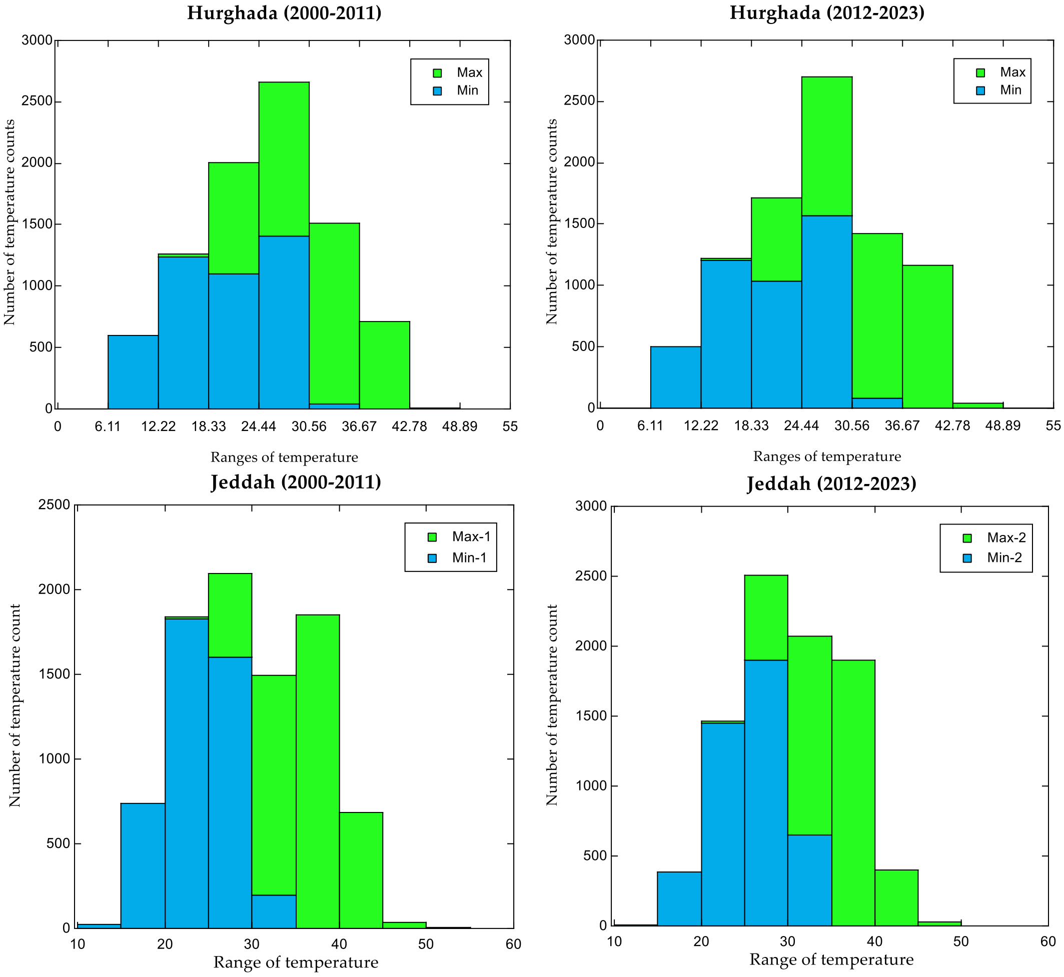
Human activities will alter RSME species composition. Effective management is suggested to decrease anthropogenic influences on RSME function. The top conservation priorities for the next decade will be expanding protected areas, including marine protected areas and nature reserves, continuing rehabilitation and reforestation programs, and raising public awareness and community participation in conservation. This matches RSME urbanization and industrialization (Hanna and Muir, 1990; Abu-Hilal and Badran, 1990; Hanna, 1983). The monitoring studied could involve and be facilitated by information technology and the Internet of Things.

Based on the extrapolation modelling in *Figure 10,* when reaching year 2068.4 (day 25000 from day 0, counting from 1 January 2000), the temperature is extrapolated to reach 28.93°C + 4.10°C = 33.03°C at Jeddah, and the temperature is extrapolated to reach 24.80°C + 5.00°C = 29.80°at Hurghada, based on the modelled linear regressed (*Fig. 10*). According to NOAA (2023), the Earth's temperature has risen by an average of 0.08°C per decade since 1880. The rate of warming since 1981 is more than twice as fast: 0.18°C per decade.

Enhancing public awareness and education

The conservation of the RSME and its ecosystems is of utmost importance in ensuring this unique marine environment's long-term sustainability and preservation. Public awareness and education play a crucial role in this endeavor, as they contribute to a collective understanding of the value and fragility of the RSME and the need for its protection. By increasing public awareness, individuals can make informed choices and take actions that positively impact the RSME's conservation efforts (Al-Sayed et al., 2022; Paszkowska-Kaczmarek, 2021).

Public awareness and education help foster stewardship and responsibility towards the RSME, encouraging individuals to participate actively in conservation initiatives. With a greater understanding of the importance and biodiversity of the RSME, people are more likely to support sustainable practices and advocate for effective conservation policies. Furthermore, public awareness and education also contribute to the economic benefits of the RSME. By promoting the RSME as a valuable tourist destination and highlighting its vibrant coral reefs and diverse marine species, public awareness campaigns can attract visitors willing to engage in responsible and sustainable tourism practices. By educating the public about the negative impacts of activities such as overfishing, pollution, and habitat destruction, awareness campaigns can help reduce these threats to the RSME. Public awareness and education are crucial in mobilizing a collective effort towards RSME conservation.



Hurghada (2000-2011)

Hurghada (2012-2023)

Jeddah (2000-2011)

Jeddah (2012-2023)

Figure 9. Comparison of temperature (maximum and minimum) in Hurghada (Egypt; graphs on the top) and Jeddah (Saudi Arabia; graphs on the bottom), between two periods of study, namely 2000-2011 (1 January 2000 to 31 December 2011; N = 4383) and 2012-2023 (1 January 2012 to 31 December 2023; N = 4383). Note: Hurghada is located with coordinates 27.15 and 33.7167, while Jeddah with coordinates 21.7 and 39.1833. The data are provided by CustomWeather.com Inc

Public awareness and education are vital in conserving the Red Sea and its ecosystems. They help to promote a deeper understanding of the Red Sea's value and vulnerability, encourage responsible behavior, and garner support for conservation efforts. Public awareness and education are essential for the success of RSME conservation efforts. They play a critical role in raising awareness about the importance of the RSME's biodiversity and ecosystems and the threats they face.

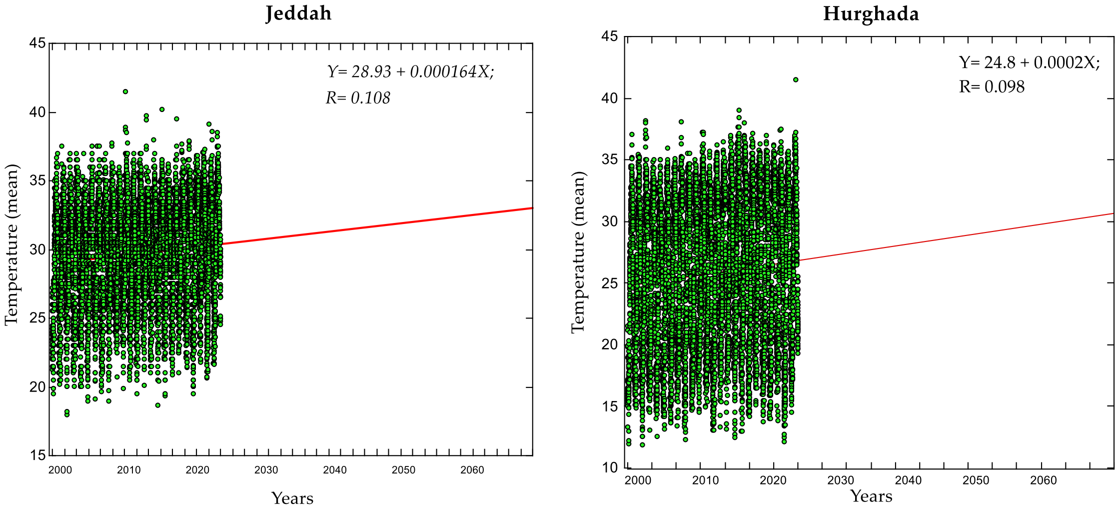


Figure 10. *Average daily temperature from 2000 until 2023 and extrapolation until 2068. The data of temperature from 2000 to 2023 was provided by CustomWeather.com Inc. (with permission)*

This societal aspect is crucial to reducing the human impacts threatening the RSME. The population of Djibouti, Saudi Arabia, Egypt, and Yemen has grown from 1980 to 2021 (Ritchie et al., 2023) and is predicted to continue (*Figs. 5a-8a*). Due to the significant economic motivation, RSME conservation efforts must incorporate the human behavioral (societal) aspect. The Greeks and Romans first encountered mangroves in the Indian Ocean, which may have started Red Sea society (Schneider, 2017). Schneider (2017) cited Theophrastus' and explorers' Red Sea and Gulf of Aden findings as examples of scientific accuracy. Finally, the importance of Graeco-Roman mangrove characteristics and their links to Red Sea indigenous inhabitants is growing. The Red Sea coast's urbanization is another major driver of mangrove ecosystem deterioration (Sohaib et al., 2023; Rashedy et al., 2023). Socially, RSME should foster fundamental mangrove and community research to understand species reproduction, growth, nutritional biology, adaptive physiology, biochemistry, and genetic characteristics.

Sato et al. (2005) developed a fertilization system that eliminates runoff. Seeds are sown where needed and protected from wrasse and waves using innovative technologies. Adding a sheep stress meal to mangrove material containing fat-soluble vitamins and minerals can provide enough nutrition. There is evidence of varied mangrove deterioration nearby. Without restoration and conservation, the coastline, fisheries, coral reefs, and seagrass meadows may perish. Conservation efforts in the region are hindered by a lack of institutional and human resources, legislative safeguards and enforcement, ignorance, data gaps, and fast coastal development (Khalil, 2015).

Nagi and Abubakr (2012) reported that Yemen's Red Sea coast has lush mangroves. Still, due to environmental exposure, the Gulf of Aden and Arabian Sea beaches need to be completed, save for a few locations. They reported that Yemen's mangroves are threatened by urbanization, aquaculture, tourism, logging, oil pollution, solid waste dumping, animal grazing, fishing, landfilling, and household sewage. Oil pollution, fishing boat debris, and a proposed aquaculture farm threaten the northernmost part of

Al-Luhayyah's beach. Fishing boats moored or sailing from town cross these woodlands' waterways. It faces several anthropogenic issues due to the adjacent municipality. Woodcutting and camel grazing impacted Al-Khawbah (Nagi et al., 2012).

Using local geology, Monsef et al. (2013) found the best mangrove plant places in the southern Saudi Arabian RSME. Site needs were met by considering drainage, soil type, and geomorphology. The southern half of the research zone may have more mangrove stands than the northern half (Monsef et al., 2013). At Wadi-Dara on the Red Sea, 100 acres may be planted, allowing for about one million people. They guided the environmental impact assessment, which revealed a minimal risk due to predicted net zero emissions, a 75% green city, and excellent waste recycling. However, they ignored how anthropogenic activities, notably Wadi-Dara heavy metal pollution, influenced Red Sea biodiversity. According to Arshad et al. (2020), shrimp farm effluents affected a nearby mangrove woodland during and after its closure. The shrimp farm boosted the mangrove forest, but once it closed, it steadily degraded, according to Arshad et al. (2020). Spectral vegetation study of Sentinel-2A satellite photos showed a negative association between seaport development dredging and the nearby vulnerable mangrove forest in 2016 and 2017. Their findings showed that spectral vegetation indicators might track and study human influences on coastal vegetation. They recommended strict activity tracking, analysis, and regulation to fight RSME sustainability issues.

Increased anthropogenic nutrient inputs will promote mangrove expansion and nutrient status in the Central Red Sea, affecting the ecosystem. A nutrient deficit may prevent mangroves from synthesizing proteins and other molecules needed to adapt to RSME, including high temperatures and lack of fresh water. Thus, plants lacking nitrogen may be more susceptible to Central Red Sea environmental challenges. Future studies should examine these reactions and how food restriction affects stress resistance (Eid and Shaltout, 2016). Research may be coordinated to solve WEF Nexus complex processes and produce robust and sustainable WEF systems. This would educate the public about the protection and conservation of RSME (Hanna and Muir, 1990; Abu-Hilal and Badran, 1990; Hanna, 1983).

In sum, public awareness and education also empower individuals to make sustainable choices in their daily lives, such as reducing the use of single-use plastics, practicing responsible fishing methods, and supporting conservation organizations. By increasing public awareness and education, individuals can learn about the unique RSME and the actions needed to protect them. This knowledge and awareness can lead to a ripple effect, as individuals share their understanding with others and inspire a collective effort towards conservation. Public awareness and education are key to fostering a sense of stewardship and responsibility towards the RSME. By increasing public awareness and education about the importance of the RSME and the threats they face, individuals can become advocates for conservation and take proactive steps to protect and preserve the RSME. Public awareness and education are vital tools that can mobilize a collective effort towards conserving the RSME.

Investment of funding is needed in line with economic boom

The REME conservation plan aims to protect and conserve the unique mangrove ecosystems found in the Red Sea region. Investing funds into this conservation plan will contribute to the preservation of these vital habitats and safeguard the rich biodiversity and ecological balance of the RSME. Furthermore, by protecting mangrove forests in the Red

Sea, we also ensure essential ecosystem services such as carbon sequestration, coastal erosion prevention, and the support of coastal fisheries (Hanna and Muir, 1990; Abu-Hilal and Badran, 1990; Hanna, 1983). These efforts will benefit the local communities that rely on these ecosystems for their livelihoods and contribute to global climate change mitigation and the overall health and resilience of the RSME. By investing funds into the protection and conservation of RSME, we can ensure the long-term sustainability and resilience of coastal communities and preserve the invaluable services these ecosystems provide for local and global communities. Investing funds in the conservation of RSME is crucial for maintaining the resilience and sustainability of coastal communities. It is important to note that while the completion provides a comprehensive description of the benefits and importance of investing funds in the conservation of RSME, it needs to mention the sources provided specifically (Afefe et al., 2020, 2021).

From 1980 to 2021, Djibouti, Saudi Arabia, Egypt, and Yemen's GDP values increased (Roser et al., 2023) and are predicted to rise (*Figs. 5b-8b*). Historically, hydrocarbon discoveries and large commercial harbors have driven human economic activity (El-Kahawy et al., 2018). The Line City ending to the Tabuk RSME has recently been environmentally sensitive. Saudi Arabia's Smart City-Line links four ecologies. The unique scenery and beaches stretch southeast of Neom beyond the Red Sea islands (Al-Sayed et al., 2022). The most appealing sustainability feature is preserving 100% natural life since they utilize only natural energy and no cars (Al-Sayed et al., 2022; Paszkowska-Kaczmarek, 2021).

Dicks (1984) indicated in 1984 that the Red Sea is a substantial offshore oil producer (Cai et al., 2022). Commercial harbors were built because ships passing via the Suez Canal utilized the Red Sea. Several ships pass through the Canal daily and pump out their bilges to dispose of their trash efficiently. Even a small quantity of bilge pumping and rubbish collection by each vessel would have a tremendous impact (Moursy et al., 1987). The Red Sea-Dead Sea Water Conveyance is building a 180 km pipeline to transfer water from the Red Sea to the Dead Sea. The two oceans' hydrographic properties differ, affecting biodiversity (Georges et al., 2021). Abu AI-Regal et al. (2014) investigated if Red Sea mangrove zones are important for reef fish larvae. In 2010, beach seine nets took juvenile fish from three mangrove areas over three seasons. Three times, the net was dragged 100 yards. The 269 juvenile fish gathered represented 21 species and 19 families. The most common species accounted for 86% of the fish caught. Egypt's RSME yielded nine species. Many caught fish have high economic worth.

Kabil et al. (2022) evaluated and studied the effectiveness of Egypt's Southern Red Sea tourist destinations in enhancing coastal tourism for the blue economy. Tourism duration, size, cost, coral reef quality, hotel count, and region's capacity to welcome tourists were considered. Employee and tourist numbers were inputted. Regardless of the efficiency model, Safaga-Quseir tourism facilities were more efficient. The weakest-performing tourism industry was Ras Banas, with 29 attractions. Osypiska and Woniak (2019) examined 9498 animal bones and 8644 mollusk shells from Berenike Trogodytika to learn about the Hellenistic citadel and port on the Red Sea's climate, local food economy, and nutrition. In the first half of the third century BC, the early Berenike garrison ate cereals, fish, and mollusks, with occasional sheep and goat meat. Ramsay and Parker's (2016) Roman Aqaba Project archaeological research aims to illuminate the imperial Roman economy in the East by rebuilding the economics of the historic Red Sea port of Aila. The report included a project component with plant remnants found in soil samples from 1994–2003.

Lefebvre (1998) argued that the Eritrea-Yemen Hanish Islands war affects southern RSME security on a global, regional, national, geopolitical, and economic scale. The conflict between Yemen and Eritrea centers on maritime resources. As foreign nations and northern Red Sea states have joined the battle, geopolitics and economics have hampered de-escalation. Even though Eritrea and Yemen have moved for international arbitration, Spaargaren (1977) studied the osmoregulation of a few Gulf of Aqaba decapod crustaceans.

Therefore, an investment of funding is needed and justified in line with the economic boom in the RSME. Transboundary and international collaborative initiatives and partnerships could achieve this more easily. In sum, investing funds in the protection and conservation of RSME is essential for preserving the region's rich biodiversity and ecological balance. Furthermore, the cooperation and involvement of local communities and their leaders are crucial for the success of mangrove restoration activities

The knowledge gaps for future studies: implementation of ESG

This section will focus on the social and governance factors in the ESG. United Nations' Principles for Responsible Investment require enterprises globally to assist sustainable development (Principles for Responsible Investment, 2017). ESG knowledge is needed to retain public, stakeholder, and investor trust and save the planet. Companies must support society and the globe as sustainability becomes more important. ESG shows corporate social responsibility. UK, Japanese, and European capital market regulators demanding ESG disclosure are showing growing interest. ESG is preferred by developed nations but being considered by emerging ones (Janah and Sassi, 2021; Liu et al., 2023; Singhania and Saini, 2023; Lee et al., 2016; Waddock and Graves, 1997; Weber, 2014; Chauhan and Kumar, 2018; Kiriu and Nozaki, 2020; Baraibar-Diez and Odriozola, 2019).

Interestingly, studies have yet to be conducted on implementing ESG to manage the RSME effectively. Therefore, the connection between mangrove fauna and ESG must be better studied. This is a visible knowledge gap between RSME and pollution protection incorporating ESG. Hence, future studies should focus on ESG implementation to manage RSME effectively in connection with mangrove fauna. Hence, the knowledge gaps in the studies of RSME are identified as a need for ESG elements and connection to the mangrove fauna.

ESG reporting improved Chinese companies' financial market performance, according to Weber (2014). Results were comparable when duplicated in other developing nations. According to Chauhan and Kumar (2018), ESG disclosure helps Indian public corporations with information concerns. In impoverished countries, ESG transparency matters independent of enterprise ESG actions. The knowledge asymmetry of ESG data in underdeveloped nations may explain this. Emerging nations, like Japan Kiriu and Nozaki (2020) and Europe Baraibar-Diez and Odriozola (2019), should analyze how past-year ESG measures affect financial performance.

The RSME plays a crucial role in the region's marine biodiversity and is vital to the livelihoods of coastal communities. The RSME restoration projects can provide numerous ecosystem services, such as coastal defense, flood inundation control, carbon sequestration, and protection against extreme weather events (Hanna and Muir, 1990; Abu-Hilal and Badran, 1990; Hanna, 1983). The ESG practices in mangrove conservation efforts are essential in the Red Sea to ensure these ecosystems' long-term sustainability and resilience.

Tebet et al. (2018) found an inadequate institutional framework for sustainable management in a protected area of Brazil's Paranagua Estuarine Complex surrounded by traditional communities. Lovelock et al. (2022) covered global mangrove restoration concerns and solutions. Carbon sequestration, fisheries production, biodiversity, and coastal protection may result from ambitious mangrove restoration goals. Communities and institutions must create expertise and procedures to connect restoration possibilities with supporters and investors for sustainable mangrove restoration. Global reporting standards will help modify management and monitor mangrove restoration (Alnasser et al., 2024). Mangrove governance has had mixed outcomes using good governance and procedural justice in decision-making. Despite numerous mangrove management case studies, global mangrove governance comparisons could be sparse (Golebie et al., 2022). By incorporating ESG practices in mangrove conservation efforts in the RSME, we can safeguard the ecological integrity of these ecosystems and promote the well-being and prosperity of local communities (Lee et al., 2016; Waddock and Graves, 1997). This is been an important component in the conceptual framework for restoration and conservation at RSME (*Fig. 11*).

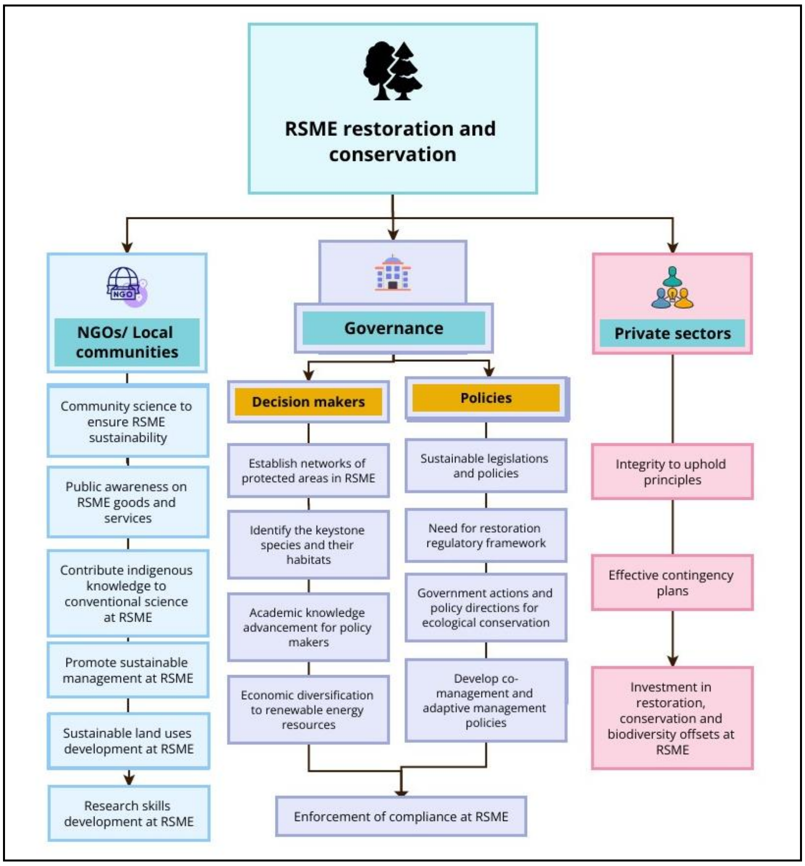


Figure 11. *A conceptual framework for restoration and conservation at Red Sea Mangrove Ecosystem (RSME) (Adapted from Sam et al., 2023)*

The conceptual framework in *Figure 11* is drawn based on the connections among the geomorphology, hydrology, and structural characteristics associated with the functions and services provided by this RSME. The methodological approach is fundamentally concerned with the particular characteristics of the arid environmental setting of the RSME and the socio-economic aspects of restoration and conservation. This approach to mangrove restoration includes stages for planning, implementing, and monitoring mangrove restoration programs in arid environments. An example of mangrove restoration is the Umluj mangrove area (*Fig. 1*).

Social: NGOs, local communities and private sectors

Socially, the non-governmental organizations (NGOs), local communities and private sectors form the very connected component of S under ESG (*Fig. 11*). Undoubtedly, engaging and involving local communities in decision-making processes and conservation efforts, as their cooperation and support**,** are crucial for the success of restoration activities. Partnering with regional NGOs, such as the Organization for the Conservation of the Environment of the Red Sea and the Gulf of Aden, to coordinate and implement regional conservation and management initiatives for RSME (Afefe et al., 2020, 2021). Increasing institutional awareness among the public is needed to control mangrove pollution and eliminate pollutants and their threats. This is important to promote sustainability by contributing indigenous knowledge to conventional science and green sustainable development at RSME with better research skills development. Hence, besides the government agencies, collaborating with NGOs and local stakeholders can mutually benefit one another to develop sustainable financing mechanisms for mangrove conservation and restoration projects in the RSME.

Governance

Conceptually, it is clear that the governance in ESG is an indispensable ingredient in the restoration and conservation at RSME (*Fig. 11*). Establishing and enforcing conservation policies and regulations to the policymakers is imperative to prevent deforestation and degradation of RSME. The governance protective measures may include establishing an institutional and legislative framework, using environmental laws and effective management to implement and enforce regulations. A strict law should be implemented to prohibit and limit mangrove degradation activities like unrestricted camel browsing and wood cutting. Making biodiversity conservation as protected areas a social-ecological concern is a solution (Tebet et al., 2018). Decades of conversion and degradation endanger mangroves (Lovelock et al., 2022). Management is complex since mangrove ecosystems are terrestrial and marine, typically straddle regional or national boundaries, and are valued differently by local, national, and international stakeholders.

Golebie et al. (2022) explored global governance linkages in mangrove social-ecological systems. Conservation success depended on legitimacy, justice, and integration in all three governance systems. These procedural fairness standards highlight stakeholder inclusion in mangrove management. They recommended clearly defined duties for all governance actors, transparent policy development communication to stakeholders, fairness in process and outcome, and sustainable conservation resource access. Supsup et al. (2023) examined biodiversity in four Palawan municipalities in the western Philippines through field surveys. According to their estimates, many Palawan indigenous species endure human pressures. They found much of the natural forest in challenging terrain and high heights. Identification of keystone species with their critical habitats contain protection gaps, and a revision to accommodate fragile and endemic species is proposed, as shown in *Figure 11*.

It is important that merging biodiversity data helps restoration, conservation and management at RSME (*Fig. 11*). Arifanti et al. (2022) investigated Indonesian mangrove management issues and strategies. They found that sustainable mangrove management and support of the national blue carbon agenda require improving mangrove forest function and value, integrating mangrove ecosystem management, strengthening political commitments and law enforcement, involving all stakeholders (especially coastal communities), and advancing research and innovations. Liu et al. (2023) studied public ESG perceptions. ESG policies in China are new and need to be completed. Policymakers and firms may use the data to determine public needs and enhance ESG communication on social media and policy. Singhania and Saini (2023) contrasted developed and emerging ESG regulations.

Mohamed et al. (2023) examined Zanzibar's laws, regulations, and sustainable mangrove management from 1890 to the present. They asserted that forest guards, chiefs, and elders ruled before Zanzibar became a British protectorate in 1890. The colonial government established land administration rules, regulations, and processes to protect mangrove forests. They wanted more diverse and inclusive rules. Government agencies should coordinate contradictory laws and obligations to protect mangroves.

In recent studies, clear knowledge gaps have yet to be reported in ESG elements (Arifanti et al., 2022; Mohamed et al., 2023; Rosenberg, 2011). Hence, by integrating ESG practices into mangrove conservation efforts in the Red Sea, we can ensure that these ecosystems continue providing valuable services and benefits to the environment and the communities that rely on them. In summary, the successful conservation of mangrove ecosystems in the Red Sea requires the implementation of practices. Finally, monitoring and modelling pollution landscape, continuously mapping coastline (Abdel-Hamid et al., 2018) and governance management (Sam et al., 2023) at the RSME are also deemed necessary for the future of RSME preservation and conservation. This is proposed for effective, sustainable economic growth in the RSME.

Conclusions

Based on the present review and synthesis, several key strategies are proposed to address knowledge gaps and enhance the protection and conservation of RSME (Restoration and Sustainable Management of Ecosystems). These include: (a) establishing more comprehensive and continuous monitoring programs, particularly involving both scientific and community-based approaches; (b) enhancing public awareness and education through community science, local engagement, and the incorporation of indigenous knowledge; (c) increased investment and funding aligned with economic growth, especially focusing on renewable energy diversification and private sector involvement; and (d) effective implementation of ESG principles, with particular attention to integrity, contingency planning, and biodiversity offsets. The current review provides a governance-driven framework that integrates NGOs, policy-makers, and private sectors to support ecosystem restoration and coastal sustainability. However, knowledge gaps persist in the understanding of keystone species, their habitats, and the translation of academic knowledge into decision-making processes for ecological conservation.

Moreover, the need for a restoration-specific regulatory framework and co-management policies remains critical, as enforcement and compliance mechanisms are still underdeveloped. Private sector roles, though promising, require further clarity and incentivization to enhance investments in restoration and biodiversity. The integration of sustainable land use models and research skill development at the local level also demands greater focus. Pollution monitoring data must be expanded to serve as a baseline for identifying future anthropogenic effects, particularly in the face of environmental degradation and climate change. Furthermore, the inclusion of ESG elements in faunal conservation and the development of adaptive management strategies represent emerging areas for future research. Addressing these gaps will be vital for ensuring long-term sustainability and resilience of RSME ecosystems.

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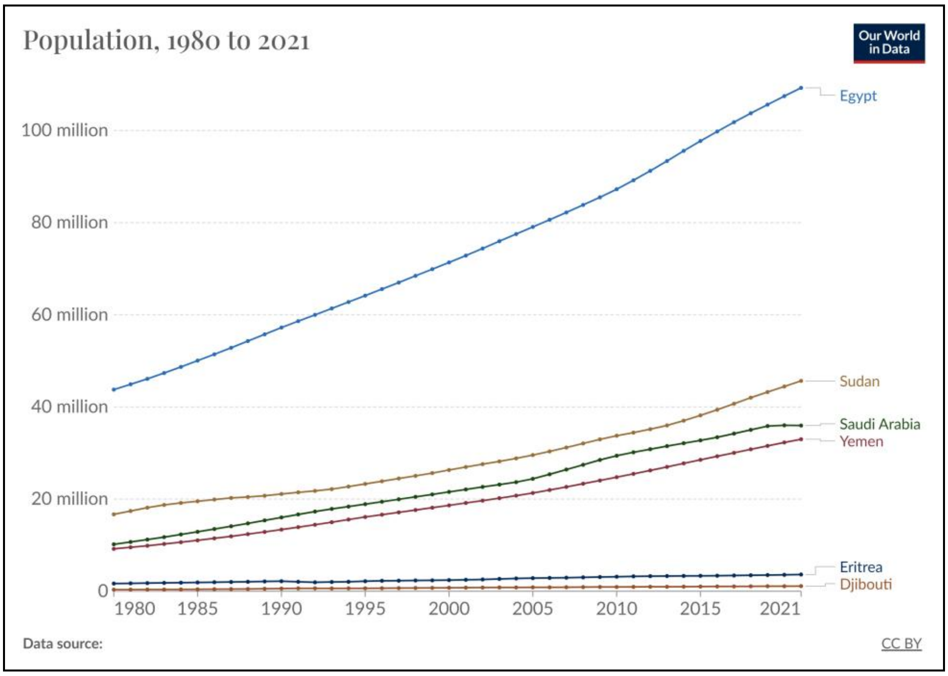
APPENDIX

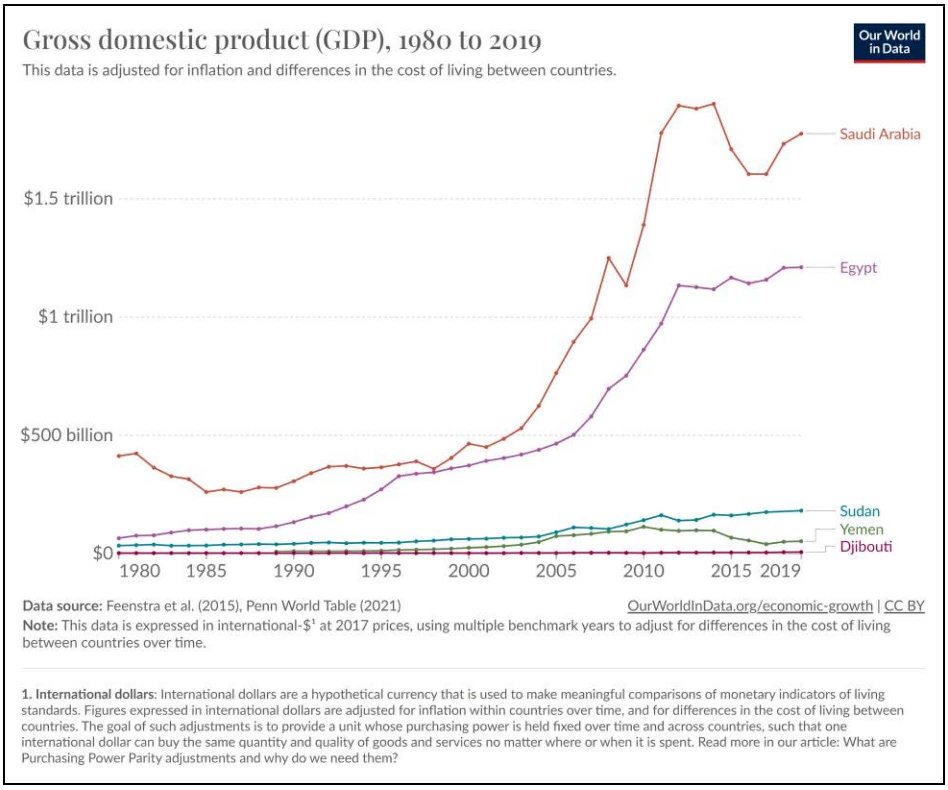


Population, 1980 to 2021

Data source:

CC BY

Figure A1. *Population sizes in the six countries surrounding the Red Sea from 1980 to 2022 (about 4 decades). Source: https://ourworldindata.org*



Gross domestic product (GDP), 1980 to 2019

This data is adjusted for inflation and differences in the cost of living between countries.

Data source: Feenstra et al. (2015), Penn World Table (2021)

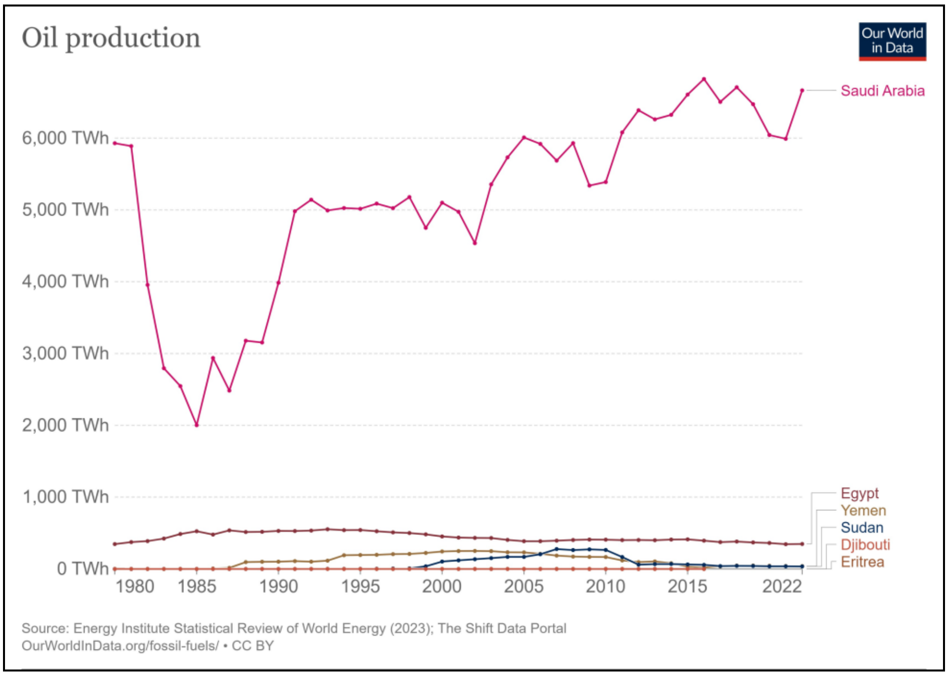
OurWorldInData.org/economic-growth | CC BY

Note: This data is expressed in international-$[1] at 2017 prices, using multiple benchmark years to adjust for differences in the cost of living between countries over time.

1. International dollars: International dollars are a hypothetical currency that is used to make meaningful comparisons of monetary indicators of living standards. Figures expressed in international dollars are adjusted for inflation within countries over time, and for differences in the cost of living between countries. The goal of such adjustments is to provide a unit whose purchasing power is held fixed over time and across countries, such that one international dollar can buy the same quantity and quality of goods and services no matter where or when it is spent. Read more in our article: What are Purchasing Power Parity adjustments and why do we need them?

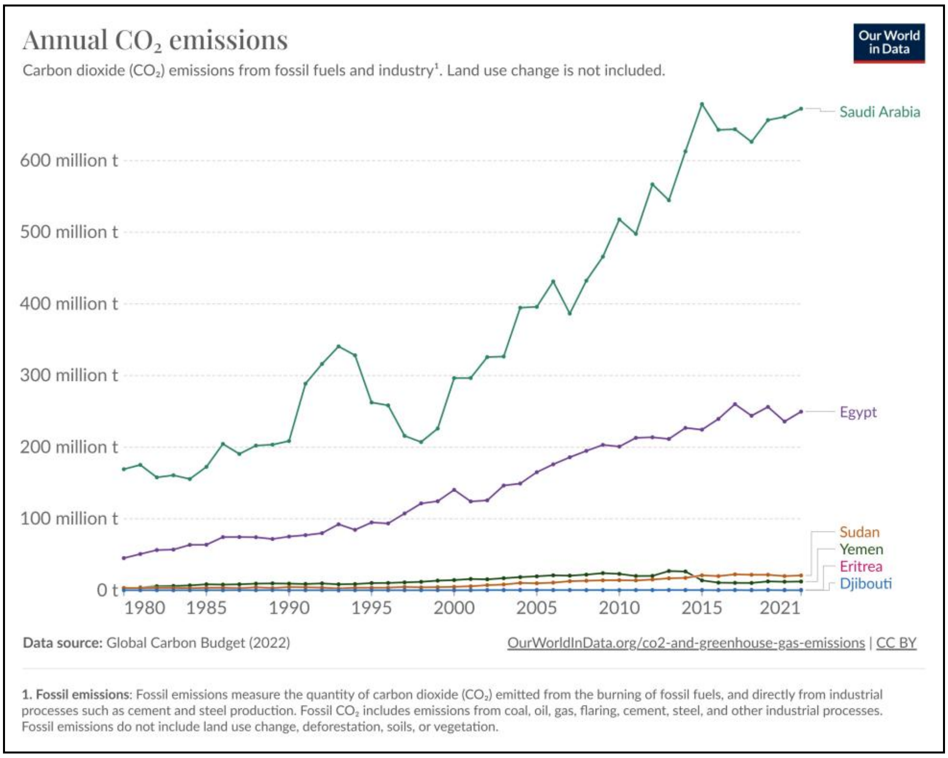
Figure A2. *Gross domestic products in the six countries surrounding the Red Sea from 1980 to 2022 (about 4 decades). Source: https://ourworldindata.org*

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/2304_70317067


Oil production

Source: Energy Institute Statistical Review of World Energy (2023); The Shift Data Portal
OurWorldInData.org/fossil-fuels/ • CC BY

Figure A3. *The oil production (This has been converted into primary energy equivalents (i.e. terawatt-hours (TWh) of energy) for comparability across our other data on energy) in the six countries surrounding the Red Sea from 1980 to 2022 (about 4 decades). Source: https://ourworldindata.org*


Annual CO_2 emissions

Carbon dioxide (CO_2) emissions from fossil fuels and industry[1]. Land use change is not included.

Data source: Global Carbon Budget (2022) OurWorldInData.org/co2-and-greenhouse-gas-emissions | CC BY

1. Fossil emissions: Fossil emissions measure the quantity of carbon dioxide (CO_2) emitted from the burning of fossil fuels, and directly from industrial processes such as cement and steel production. Fossil CO_2 includes emissions from coal, oil, gas, flaring, cement, steel, and other industrial processes. Fossil emissions do not include land use change, deforestation, soils, or vegetation.

Figure A4. *Annual carbon dioxide (CO_2) emission in the six countries surrounding the Red Sea from 1980 to 2022 (about 4 decades). Source: https://ourworldindata.org*

DOI: http://dx.doi.org/10.15666/aeer/2304_70317067