International Journal of Environmental Science and Technology
https://doi.org/10.1007/s13762-024-05788-1

REVIEW

Mangroves in Egypt and the Middle East: current status, threats, and opportunities

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Received: 3 August 2023 / Revised: 19 May 2024 / Accepted: 28 May 2024

Abstract
Mangrove forests are among the Nature Based Solutions (NBS) that help in mitigating climate change effects as they sequester carbon dioxide gas four times greater than normal forests. They stabilize coastlines, reduce coastal flooding, and provide nurseries to wildlife. Only two mangrove species exist in the Middle East: *Avicennia marina* and *Rhizophora mucronata*, due to their high tolerance to the region's harsh and dry environmental conditions. This paper presents a comprehensive review on the current mangrove status in these countries, threats facing them, and rehabilitation initiatives taken to increase mangrove plantations in the Middle East. The review showed that Middle Eastern mangroves are dwarves, grow in dispatched form, have limited access to freshwater inflow, and are dominated by *Avicennia marina* specie. The largest and smallest mangrove cover were 20,400 ha and 80 ha found in Saudi Arabia and Bahrain respectively. Uncontrolled camel grazing, oil spills, habitat destruction, irresponsible tourism, and solid waste accumulation are from the major threats facing mangrove ecosystems. Climate change impacts through increased seawater salinity and temperature, microplastics, and heavy metals introduction to seawater threaten mangroves health. Various mangrove rehabilitation initiatives have taken place in Oman, Bahrain, UAE, Saudi Arabia, and Egypt as they have planted 1.5 million, 140 thousand, 1 million, 4.3 million, and 0.3 million mangrove trees respectively. This research presents some regulatory framework and policies needed for mangrove plantations rehabilitation for the mitigation of Green House Gases (GHG) and improve the livelihood of the indigenous people living along the coastal areas of the world.

Keywords Mangrove · *Avicennia marina* · *Rhizophora mucronata* · Carbon sequestration · GHG emissions

Introduction

Background

Sustainability is a frequently used term that everyone is trying to develop and adopt using innovative environmentally friendly practices, however, the long-term goal of sustainability cannot be achieved unless bigger policy decisions are made to implement correct policy and technologically sustainable solutions so that the term of sustainability is well understood by all sections of the society. It is misunderstood that climate change and sustainability are both zero carbon emissions terms while seeking a balance between providing sufficient resources for enhancing livelihoods of future generations and by not compromising the irresponsible use of Earth's resources (Heinberg 2010). World sustainability is at risk due to climate change as it is threatening the basic existence of various ecosystems.

This puts the urge to develop new systems to mitigate its impacts of climate change and have thriving ecosystems sustaining environmental and human health conditions on this planet. Since most human systems in today's world rely on fossil fuels that is suffocating the planet with greenhouse gas emissions, the sustainable and alternate solutions will depend on how we develop future systems that are less

Editorial responsibility: M.Shabani.

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dependent of fossil fuels and can sequestrate carbon and at the same time minimize greenhouse gas (GHG) emissions. However, the question is why global society, especially the developed and industrialized world, is dedicating and directing the majority of its efforts towards developing new systems while mother nature has gifted us with many and easy to use natural systems that can do a much better job for humanity in mitigating climate change? We have deforested majority of Europe and Northern America either for agriculture or to develop industrialized economies. Even large-scale deforestation has already taken place in Asia as well as in South America and deforestation is going on in Africa as well. Forests have provided food, water, fuel, fiber and shelter to humanity for thousands of years and have kept this planet ecologically healthy. Trees in thriving forestlands of the world have been sequestrating atmospheric carbon for their annual growth and storing it in their biomass tissues. Forests are also natural factories of producing limitless oxygen in the planet. Therefore, replanting part of the deforested areas on annual basis in the world is one of the best nature-based solution (NBS) available to us. Replanting trees will not only mitigate climate but will enhance recharge of groundwater systems and help make dry rivers start flowing helping us solve the problem of growing water scarcity in the world.

Forested areas with naturally grown trees, such as mangroves, tend to produce more biomass to sequester four times more carbon than if trees are grown open fields (Pregitzer et al. 2022). Mangroves trees are a nature's gift to humanity which are capable of growing in salty and brackish water in coastal areas as well as in freshwater wetlands, but natural potential for growing mangroves is in salty and brackish areas due to less competition with other plants that only are adapted to freshwater systems. Despite the many benefits that are provided by the ecosystems in mangrove forests, mangroves are being destroyed at an alarming rate. In the past century, 67% of global mangroves have been lost (IUCN, 2017). Study after study have shown that, we as humans, have destroyed more than 80% mangrove forests creating beaches and expensive beach properties for tourism. This greed of humanity has resulted not only in more GHG emissions but also destroyed a natural technology to mitigate climate change and preserve ecologically healthy coastlines in the world. Mangroves, although occupying only about 1% of the forested lands worldwide, act as a natural carbon capture agent as they can store three to four times more carbon compared to land-based forests (Nyanga 2020). During their growth, mangroves can store and accumulate from 50 to 220 metric tons of carbon from the atmosphere per acre which results in more than 24 million metric tons of annual carbon storage for the entire planet (Bartoli et al. 2020). Restoring and conserving mangrove ecosystems is vital to sustaining both coastal communities and biodiversity. Therefore, investing in the restoration of mangroves forests will bring wide-ranging benefits and their protection is a key pathway to meeting the ambitious goals laid out in the UN Sustainable Development Goals and the UNFCCC Paris Agreement for climate mitigation.

Brief introduction of mangroves plants (seed, germination of seeds and the rooting system)

Mangrove term, Rhizophoraceae, is referred to plant species that have high tolerance for salty waters and grow in tropical and subtropical coastlines (Bartoli et al. 2020). These trees are capable of growing in salty, brackish coastline wetlands (Vannucci 2000). Filtering about 90% of the seawater salt is the coping mechanism that mangroves plants use for adaptation to extreme salt environment besides using their snorkeling roots for breathing and hoarding water in their succulent leaves (Nyanga 2020). The rooting system of mangroves is highly distinctive having arch shaped roots above the water surface and these aerial roots broaden the base of the tree and stabilize the shallow root system in the soft, loose soil (Purnobasuki 2011). Moreover, the roots play a crucial role in providing oxygen for respiration in addition to providing structural support (Lovelock et al. 2006) but mainly the lenticels are how oxygen enters a mangrove and they close during high tide to prevent the trees from drowning (Purnobasuki 2011). Sahoo (2018) illustrated that the roots are peg like with a pencil size, called pneumatophores, that usually diverge from the branches and stems, and then find their way at a distance from the main tree through soil penetration. As far as the mangrove seeds are concerned, their germination starts on the tree which equips them to take root once they drop and the sprout can quickly establish itself in the soft soil of tidal mudflats before the next tide arrives if it falls at low tide (Moore 2009). In case of high tides, the seed will float and take root as soon as it finds the firm ground.

Mangrove habitats

Mangroves can conquer waterlogged soil on different substrata: sands, clayey and silty muds, and calcareous muds, hollows and cracks on rocks, coral reefs, and wadi deltas enriched with sediments deposited from tidal currents of rainwater runoff. Coastal soils are usually marginally acidic due to abundance of CO_2 that arises from aerobic respiration and organic matter decay. Some gases are emitted from the soil due to anaerobic conditions giving it anoxic soft conditions and pungent odor: nitrate is converted to nitrogen, carbon dioxide is reduced to methane, and hydrogen sulphide production occurs from sulphate reducing bacteria. Mangrove tree bark contains tiny pores or apertures called lenticels which facilitate gas exchange between the tree's interior tissues and the surrounding environment. Mangrove areas are regularly flooded by tidal waters, in a process called tidal inundation, which provides the essential salts and nutrients for mangrove survival and growth (Kumbier et al. 2021). Soils are characterized by high salinity, lower oxygen concentration, water logging, and greyish-black color due to insoluble ferric compounds reduction into soluble ferrous sulphides leading to phosphates and iron release (Afefe et al. 2019; Hinokidani and Nakanishi 2019). Mangroves are usually accompanied by wildlife depending on their geographical distribution including reptiles, migratory birds, mammals, sea life, and amphibians. Their roots provide shelters for shellfish and algae from predators while the fallen or eaten leaves are either eaten by crabs and amphipods or degraded by microorganisms into a healthy food for marine life (Paleologos et al. 2019).

Factors affecting mangroves growth

Mangroves are located in Asia, Australia, Africa, and the Americas, and they can grow in low-oxygen waterlogged mud and adapt to harsh coastal conditions (Spalding et al. 2014). There are several factors that affects the distribution, abundance, and growth rate of mangroves like: soil and water salinity, temperature, tidal currents, groundwater, land barriers, sediment supply, coastal typology, wave action, sediment yield, freshwater discharge from river catchments, water characteristics, geomorphological forms, dissolved oxygen (DO) and tidal range (Ellison 2021). Mangrove trees need freshwater sources to function where they receive a boost from wadi flash floods to overcome effects of excessive saltwater and high saline soils build up. Their ability to grow in low-oxygen soil is supported by fine sediments accumulation due to slow water movement. Moreover, the dense tangles roots of the mangroves provide the trees with stability in shallow environments against tides thus enhancing their survival and growth. Generally, mangroves prefer growing in temperatures above 19 °C and not below10 °C as they cannot resist freezing; this is one of the main factors that affects their distribution worldwide (South Florida Aquatic Environments 2023). Nutrient availability is another factor that affects mangrove's structure, growth, and productivity (Reef et al. 2010). They obtain their nutrients, specifically nitrogen, from air while phosphorous and potassium are obtained from the sea water, sediments, or animal feces. Areas with loamy sand substrate characterized with average hydraulic conductivity positively impacts mangroves growth (Abd-El Monsef et al. 2017). Mangroves thrive in environments with freshwater influx to overcome the saltwater effect and hypersaline soils build up, constant temperatures above 20 °C, and sheltered locations from high tides and storms. Their growth is enhanced at river deltas as due to controlled tide amplitude and frequency, nutrients inflow and removal of organic waste, carbon dioxide, and sulfur enhances growth environment (Paleologos et al. 2019).

Adaptation of mangrove species in the region

Globally, mangroves survive at temperatures exceeding 19 °C but not below freezing temperatures, however they do not tolerate temperature fluctuations that exceed 10 °C. As facultative halophytes, they are capable of surviving in both saltwater and freshwater habitats, however saltwater is not essential for their survival (South Florida Aquatic Environments 2023). The availability of nutrients in the mangrove's environment is controlled by various biotic and abiotic factors. Sometimes mangrove soils are nutrient deficient which lead to adopting some nutrient-conservation methods by the trees like, immobilizing the nutrients available in leaf litter through decomposition phase, using the old root channels, re-absorbing the nutrients available in leaves before they fall, having high root to shoot ration, and ever greenness; Phosphorous and nitrogen are the main nutrients impacting mangroves growth specifically ammonium uptake (Reef et al. 2010). Mangroves are observed in hyper-saline environments because the region receives freshwater seepage from groundwater and the presence of mud depositions allow mangroves to expand on them (Abdel-Razik 1991). They also thrive the best in zones abundant with brackish water where sea water mixes with groundwater (Rasul and Stewart 2015).

The reason behind the existence of only 2 mangrove species in the Middle East and Egypt goes back to their ability to adapt to the extreme and harsh environmental conditions of the region contrary to the other abundant species. The region is mostly hot, arid, its seas are extremely saline, and receive very little rainfall as well as little freshwater seepage. This also led to variance in species distribution among the region countries as *A. marina* clearly dominates in all countries in the Middle East while R. marina's existence is limited to specific areas in only few countries due to the properties of *A. marina* and its survival characteristics and adaptation methods, *however Rhizophora mucronata* grows at freshwater streams ends which is not dominant in the Middle East. The health of mangroves can be measured using many indicators as flowering status, number of propagules and seedlings, and canopy cover (Abd-El Monsef et al. 2017). Usually *Avicenna marina* gets flooded by tide water on a daily basis which can lead to waterlogging to the young seedlings, however due to its viviparous Propagules buoyancy, it can adapt to this condition (Robert et al. 2015). Although this species proved to be sensitive to high salinities based on previous studies, it has salt secretion glands that balances the concentration of salts within the leaves to moderate levels (Abdel-Razik 1991).

In their published report in 2003, the FAO discussed the capability of mangrove forests to adapt to different environmental conditions through various adaptation mechanisms as given below:

- ***Adaptation to High Temperature:*** To reduce the gained heat by the mangrove leaves due to sun exposure, mangrove trees position their leaves at an angle, usually less than 180, to the horizontal to protect it from rapid water loss rates. This specific leaf arrangement maximizes the whole canopy's photosynthesis activity and minimizes self-shading (Naskar and Palit 2015).
- ***Adaptation to Elevated Salt Content:*** plants within same species in the region use different mechanisms to adopt to various environmental circumstances in order to cope with high salt, specifically three mechanisms are adopted: tissue tolerance to high salt concentration known as accumulation, excess salt secretion, or salt exclusion by roots. For the exclusion mechanism, 90% of the excluded salt end up at the root surface which leads to its accumulation near the roots and hinder the seeds development (Ocean 2023). Generally, elevated salt amounts are deposited on the roots, stems' barks, and some is directed towards the senescent leaves which shed afterwards. Excess salts are excreted to the surface as a response to high saline environment through salt glands available on the leaf surface. *R. mucronata* copes with high salt through tolerance and exclusion mechanisms while *A. marina* uses secretion, exclusion, and tolerance (NOAA 2019).
- ***Adaptation to Successful Reproduction and Offspring Survival:*** Adult mangroves trees adopt methods to ensure successful reproduction with high production rate of propagule as a compensation for losses due to seeds dispersal in unfavorable areas, mortality, or damage caused by marine animals or insects. A lot of species do not produce fruits or seeds, but rather seedlings that grow on the parent tree after pollination and stays there for time up to a month in a phenomenon called "vivipary"; this is a reproduction adaptation with the aim of protecting the seedlings from early exposure to high levels of salt and allow them to gain support and strength before being exposed to high tides and get washed away (Vannucci 2001).
- ***Adaptation to Anoxic Soil and Waterlogging:*** *Avicennia marina* has horizontal and shallow roots that diverge outside accompanied with a number of vertical respiratory roots, known as pneumatophores; They grow above soil surface for exchanging oxygen in the anoxic sediments (NOAA 2019). On average, one tree with an average height of 2.5 m can have up to 10,000 pneumatophores (Cabahug et al. 2006). The respiratory roots have lenticels on their surface which facilitates gas exchange with the tissues present underground; These roots stay close to the surface to reach anoxic depths. *R. mucronata* aerial roots branch away from the main tree trunk up to 2 m above the soil and grow with a rate of 1 cm/day and half of the root volume is represented by air gaps. Interestingly, almost 1 quarter of a mangrove tree biomass is in its aerial roots which support the main trunk. The silt roots provide extra support for the tree against severe strain by wind and tides (Sulochanan 2013).

The tolerance of both *Avicennia marina* and *Rhizophora mucronata* to harsh environmental conditions can be measured through different indicators: production of new leaves, trunk circumference, plant height, number main and lateral branches, and size index (K. A. Abdel-Hamid et al. 2007) as well as root system growth (Naskar & Palit 2015), chlorophyll, mangrove area change, and canopy density (Hai et al. 2022). However, their tolerance to the Middle East extreme harsh conditions is best explained through the trees' height as it was observed that mangroves in the region are characterized as dwarves due to having small stature compared to mangroves found in other regions. Factors like limited nutrient and freshwater availability, high sedimentation rates in the coastal regions, arid conditions, and high salinity all contribute to the dwarf-look of mangroves in the Middle East.

Benefits of mangrove forests

Mangrove forests are naturally grown trees, primarily found in intertidal coastal zones and have numerous benefits to their surrounding environments (A. Abdel-Hamid et al. 2018). Being the most valuable coastal ecosystems in the world, Pant and Singh (2021) highlighted their survival abilities in oxygen deficit, saline, waterlogged sediments, and nutrient deficient environmental conditions.

These forests serve as a transition between marine and terrestrial environments and offer various benefits to mankind, biodiversity, biotechnology, controlling land degradation, and industry. Here are some examples of their various uses:

Mankind

- *Timber and fuelwood*: specific mangrove species provide valuable timber that can be used as fuelwood for heating and cooking, lighting, animal feed, construction as mangrove timber is water-resistant and durable, furniture, and production of forest products like wood for smoking and packing boxes (Forest Resources Development Branch 1994).

- *Aquaculture and fisheries*: these forests help local fisheries and aquaculture sectors by serving as essential habitats and nurseries for a variety of fish, crabs, and mollusks thus contributing to local seafood abundance (Luom et al. 2021).
- *Traditional medicine*: different parts of mangrove trees are used to treat conditions like respiratory conditions, skin infections, and digestive disorders. Some species have compounds with antimicrobial properties that can be used in new antimicrobial agents and antibiotics development. They are also used in pharmaceuticals and as genetic resources (Abdel-Aziz et al. 2016).
- *Active ingredients and essential oils*: can be produced from mangroves and used in perfumes, skincare products, and aromatherapy.
- *Ecotourism*: these forests attract tourists who are curious to explore the distinctive mangroves ecosystems thus bringing sustainable job opportunities (A. Afefe 2021).
- *Education and scientific research*: mangroves act as living classrooms that allow students, through field trips, to study the distinct features of its ecosystem and learn about biodiversity and coastal ecosystems. They also offer a rich subject for coastal and marine, restoration and conservation, climate change research as well as ecological and biodiversity studies (Kumar et al. 2014).

Biodiversity

- *Nursery grounds*: mangrove ecosystems are rich in biodiversity serving as habitats for diverse species of birds, plants, reptiles, mammals, marine life, and amphibians which contributes to the productivity and health of coastal ecosystems (Rasul and Stewart 2015).
- *Supporting migratory birds*: they offer nesting sites for the migratory species which increases survival and conservation (Buelow and Sheaves 2015).
- *Livestock production*: for camels and goats (Syntiche et al. 2021).

Biotechnology

- *Bioactive compounds*: a wide range of bioactive compounds are produced from these trees with potential use in cosmetics, pharmaceutical, and other sectors (Cadamuro et al. 2021).
- *Phytoremediation*: certain mangrove species can clean up contaminated locations due to their ability to absorb and detoxify toxins in water and soil (Verâne et al. 2020).
- *Bioprospecting*: they offer opportunities for discovering unique genetic resources, microorganisms, and enzymes that can be used in the advancement of biotechnology.

Wildlife management

- *Biodiversity conservation*: the conservation of many wildlife species can be encouraged by preserving the habitats and food sources that mangrove ecosystems provide.
- *Habitat restoration:* for endangered species like sea turtles, crocodiles, and some bird species, mangroves are essential for maintaining and rebuilding their ecosystems.

Controlling land degradation

- *Soil improvement and erosion control*: mangroves trap sediments using their dense root system and add organic matter to the soil thus enhancing its fertility and stabilizing shorelines from erosion caused by tides and wave currents. Moreover, they protect water quality by removing pollutants and nutrients from runoff of storm water before reaching coral reefs and habitats of seagrass areas (Florida Department of Environmental Protection 2016).
- *Coastal protection*: they act as a natural barrier against cyclones and storms by reducing incoming wave heights and coastal flooding by absorbing water through their peats during storms and heavy rains (Silva and Amarasinghe 2023).

Industrial applications

- *Apiculture and honey production*: mangrove flowers are used for honey production in coastal areas as they are a nectar source for bees (Kathiresan 2021).
- *Manufacturing of multiple household items*: glue, match sticks, and hairdressing oil as well as paper products (Mitra and Biswas 2021).
- *Fragrance and flavor industry*: aromatic chemicals are produced by several mangrove species and are used as scents and flavorings in the food and beverage industry (Abraham and Chatterjee 2020).
- *Others uses*: biofuel production, bioremediation, and wastewater treatment.

Mangrove forests are also an incredible source of carbon sequestration and storage serving an important role in climate mitigation. They sequestrate massive amounts of carbon dioxide from the atmosphere and store them underwater in coastal ecosystems like salt marshes, seagrass beds, and mangrove forests for millennia in their carbon-rich flooded soils known as blue carbon (George 2019). Mangroves have carbon sequestration ability up to 4 times more than any other normal trees (Leal and Spalding 2022). Carbon sequestration is defined as the ecosystem's ability to sequester atmospheric carbon dioxide to protect mangrove environments which eventually reduces greenhouse gas emissions and mitigate climate change. However, these ecosystems are subjected to deterioration in most of the developing countries which reduces their sequestration abilities and therefore the stored carbon will be affected by this deterioration and get turned into carbon dioxide then get released back to the atmosphere (Aljenaid et al. 2022).

Coastal areas with thriving mangrove forests provide best ecosystems that are essential to the sustainability of fisheries, improving water quality, and conserving biodiversity and unique cultural identity in coastal areas of the world. A TNC-led study estimated that the protection of 200 hectares of mangroves in Belize's Turneffe region would generate approximately 106,000 tons of carbon offsets over 20 years, along with \$1.3 million yearly of avoided storm damages. TNC is working with local landowners to develop sustainable tourism plans that will protect these vital systems and the communities that depend on them (IUCN, 2017). This coastal resilience project will generate revenue from the sale of credits to support ongoing conservation and management of this habitat. Mangroves and other coastal ecosystems, plentiful in Belize, have up to five times as much capacity as inland forests to store carbon dioxide, referred to as "blue carbon" (Polidoro et al. 2010).

Environmental and food security benefits of mangroves

Mangroves are one of the most important coastal ecosystem food web parts as its debris are considered the base of the food web and it enhances the health and status of mangrove habitat. Although only covering 0.1 percent of Earth's surface, mangroves transport more than 10% of the dissolved organic carbon that is derived from terrestrial sources to the ocean. Young organisms can find a home in the one-of-a-kind ecosystem created by the intricate web of mangrove roots as they host some organisms when they are submerged: bryozoans, barnacles, sponges, algae, and oysters because the organisms need a hard surface to anchor on while feeding. Muddy bottoms are home to mud lobsters and shrimp while mangrove leaves are mulched by crabs thus enriching the soil with nutrients for other bottom feeders (Sulochanan 2013).

Fish production: Mangroves support marine life as they create ideal conditions for their spawning and algae growth: slow water flow, shallow waters, and warm seawater temperature due to decaying activities which set the mangroves as the ground for nursery, breeding, and feeding of aquatic organisms. Two facilities for fish are provided by mangroves: aerial roots create a protected ecosystem for early juveniles and larvae while litter fall from the tree establish detrital food web that many fish depend on (Sulochanan 2013). Mangrove fisheries are the most profitable part of its ecosystem as when it is carried out according to proper sustainable harvesting techniques, it can benefit numerous human populations; The locals dive for different fish species, shellfish, shrimps, and crustaceans where they keep part for themselves and sell the other to local restaurants, shops, and markets (Wolf 2012).

Carbon sequestration: Chow (2018) described mangroves as high carbon-rich forests that fix the excess atmospheric carbon for respiration with an estimate of 1.8 tC/ha-yr combining wood production, leaf litter, and root with 10–55% of sequestrated carbon stored in the belowground biomass. Due to deforestation of 50,000 km^2 of mangroves during the last century, $3.8*10^8$ tC were released from the above ground biomass while not accounting for detrital or underground biomass. Mangroves carbon density varies with location, and with the greatest carbon density present below ground, above-ground carbon density dramatically decreases by minimum 50% with land conversion to agriculture or logging activities. Mangrove plantations can sequestrate 6 tC/ha-yr while naturally existing mangroves carbon sequestration ranges from 0.15 to 2.24 tC/ha-yr. Blue carbon (BC) is the organic carbon captured and stored by carbon-absorbing plants, oceans, and vegetated coastal ecosystems: mangrove forests, tidal marshes, and seagrass meadows (Macreadie et al. 2019). BC has climate change mitigation potential; it was found that 10–20% of global mangroves are qualified for blue carbon financing that can be sustainable for 30 years and can meet national climate goals (Zeng et al. 2021).

Geographical distribution of mangroves worldwide

Mangrove forests occupied 18.1 million hectares in 1980 but this has number currently has fallen to 15.2 million (Kathiresan and Qasim 2005). Mangroves can be found in 118 countries according to (Giri et al. 2011) at 30 degrees north and 38 degrees south of the equator (Aslan and Aljahdali 2022) and have a land cover of 7.5 million hectares in South and Southeast Asia which is equivalent to 41.5% of the global mangrove forest area (Spalding et al. 1997). Mangroves are abundant in protected areas with a plenty of rainfall specifically in saline or brackish water upper intertidal zones and coastal regions of Asia, Africa, South America, Caribbean Sea, Western Atlantic Ocean, and Mexico. On the country level, four countries (Brazil, Indonesia, Australia, and Nigeria) have 41% of the world's mangroves because of warmer tropical and subtropical climates (Ricklefs and Latham 1993). Mangroves have restricted growth in the Atlantic-East Pacific with only 12 species because of colder climates whereas the Indo-West Pacific has 58 species (Bartoli et al. 2020).

Current status of mangroves in the Middle East and Egypt

The Middle East is mostly characterized by an arid and semi-arid environment with dry and hot climate during summers but have mild and wet winters except for Iraq and Iran's mountainous areas which experience extreme winter conditions, and the annual precipitation varies from 350 to 750 mm (Climate Center 2021a). However, Friis and Burt (2020) mentioned that most of the region experiences an annual average rainfall of less than 100 mm and might reach 250 mm as a maximum. The Arab Gulf is considered a landlocked sea of shallow depth (35 m) which is surrounded by the Middle East countries.

This region is characterized by high water loss as the evaporation rate is ten times greater than the input water from rainfall and rivers thus have high water salinity level (Saenger et al. 2004). In the Egyptian Red Sea, the average surface seawater temperature ranges from 20 ºC in the winter to 27.49 ºC in the summer. The Surface salinities in the Red Sea range from 39.79 to 41.52 ppt (Maiyza et al. 2022) while ranges from 39 to 41 ppt in the Arabian Gulf, also known as the Persian Gulf (Kämpf and Sadrinasab 2006). The average salinity in Gulf of Oman is 36.8 ptt and can reach a maximum between 39.5 and 40.5 ppt (Wang et al. 2013) while the Gulf of Eden's salinity is between 35.4 ppt and 36.5 ppt (Morcos and AbdAllah 2012).

Mangroves are abundant in the Middle East in various countries as shown in Fig. 1 (Oman, Bahrain, Saudi Arabia, United Arabs of Emirates (UAE), Qatar, Iran, Egypt, Sudan, and Yemen) (Almahasheer 2018). Mangrove cover in Kuwait was found to be very small (only 0.58 km^2 in 2018 and was reduced to 0.1 km^2 in 2022), (Almahasheer 2018; UNESCO 2022) that shifted our study focus to the other countries in the Middle East. The rest of the unmentioned Middle Eastern countries either have borders with the Mediterranean Sea or are placed inland and therefore mangroves do not grow there due to:

- Low tides in the Mediterranean Sea while mangroves growth is related to tidal cycles and favored in intertidal areas
- The high latitude of Libyan and Egyptian coastlines with the Mediterranean Sea, above 25N, which is higher than the common zone where mangroves have spread worldwide.

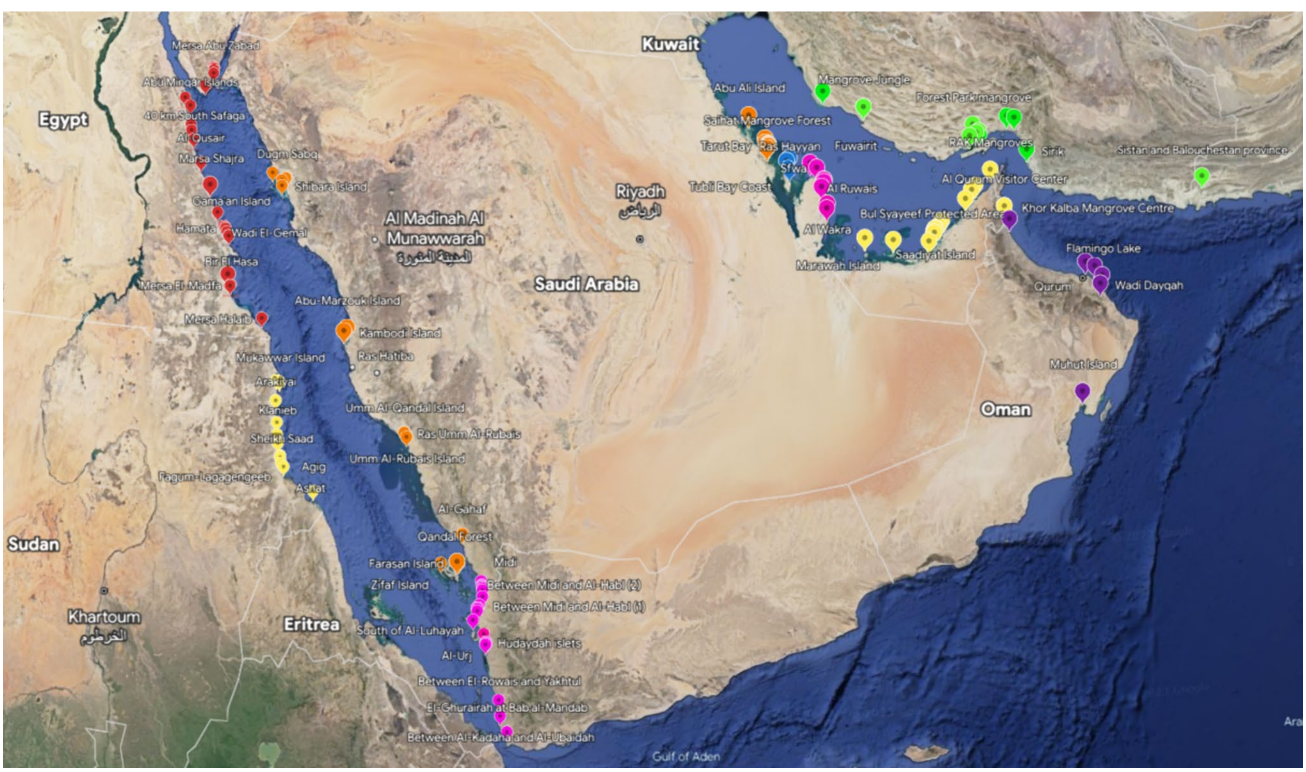

Fig. 1 Mangroves distribution in the Middle East and Egypt

Due to mangrove losses worldwide during the past 50 years (Alongi 2002) and with only limited number of studies giving the current status of mangrove in the Middle East, this study aimed at comprehensively assessing mangrove situation in the Middle East and Egypt in terms of available mangrove species and their distribution, mangrove habitats, level of degradation in the region, threats, mangrove rehabilitation strategies, and policies to promote mangroves restoration. The study's conclusion aims at improving the management and conservation of Arabian mangrove ecosystems.

Mangrove habitats in the Middle East

Mangroves in the Middle East are found in several countries that share similarities in their climatic conditions such as extreme harsh and dry environments that lack freshwater input to mangrove plantations (Climate Center 2021a). In a study by Almahasheer (2018) it was mentioned that there are only two abundant species of mangroves in the Middle East, the gray mangrove (*Avicennia marina*) and the red mangrove (*Rhizophora mucronata*), opposing to about 84 species globally because of the region's extremely harsh environmental conditions. This resulted in a low classical diversity of native mangrove species in the region due to low species variety and their composition is highly affected by geographical locations, tidal regimes, and environmental conditions of the Middle East. The conducted study showed that *Avicennia marina* is the dominant specie in the region while the co-existing of these 2 species together is observed in very limited locations. However, their existence is crucial for the stability and resilience of mangrove ecosystem as they have different ecological roles and adaptations as well as enhancing the ecological functions of existing mangrove forests through providing various services like carbon sequestration, nutrient cycling, and habitat provision. Scientifically, *A. marina* belongs to the Acanthaceae family (Asaf et al. 2021) while *R. mucronata* belongs to the Rhizophoraceae family (Su et al. 2021).

Both *Avicennia marina* and *Rhizophora mucronata*, through their unique characteristics and ecological functions, help in mitigating global climate changes through:

1. Sediment trapping and coastal protection: the unique dense rooting system of both species trap and stabilize sediments, including organic matter like carbon, which helps in raising soil levels and reducing coastal erosion over time. Additionally, the dense above-ground vegetation of mangrove habitats and complex roots function as a natural barrier during storms thus absorbing wave energy and impact. These mangrove species aid in shielding coastal communities, infrastructure, and ecosystems from the effects of climate change and minimizing habitat loss due to sea level rise (Asari et al. 2021).
2. Carbon sequestration and blue carbon storage: both species are blue-carbon ecosystems as they are very effective in absorbing and storing atmospheric carbon dioxide (CO_2) with the aid of their sophisticated root systems in their biomass and soil therefore lowering the amount of greenhouse gas CO2 in the atmosphere and contributing to climate change mitigation (Moritsch et al. 2021). The carbon sequestration potential of pure *Rhizophora mucronata* and pure *Avicennia marina* are 2.2 and 0.8 Mg C $ha^{-1}year^{-1}$ respectively (el Hussieny et al. 2021).
3. Biodiversity support: they provide nesting habitats for various animal and plant species. The resilience and general health of the ecosystem depend on the maintenance of biodiversity inside mangroves, which in turn supports the efforts for reducing climate change (Rahman et al. 2021).

This study presents an in-depth review on the status of mangroves in the Middle East. Table 1 highlights the observed locations in this study, available species in each country, and total mangrove land cover. Figure 1 shows the available mangrove sites in the Middle East. Detailed discussion for each country on the status of Mangroves is given below.

Mangroves in Oman

The Middle East is mostly characterized by an arid and semi-arid environment where the climate is dry and hot speciallyOman, known as Sultanate of Oman, has dry and subtropical climate and is characterized by dusty, hot winds and summer monsoons. Generally, it has an average annual temperature that varies from 10 to 12 °C and 16°C to 18 °C in the north and south respectively while the average annual rainfall ranges from 150 to 300 mm north and 50 to 150 mm south (World Bank Group 2021a). Its coastal line is 3,165 km long and only one species of mangroves, *Avicennia marina* (*A. marina*), can be found along it (Al-Nadabi and Sulaiman 2018). The mangroves can be found in Oman in Qurm, Muhut Island, and Shinas (Fouda and AI-Muharrami, 1996), Bandar AL Khairan (Al Jufaili et al. 2021), Flamingo lake, and Wadi Dayqah (Beuzen-Waller et al. 2019) having a total coverage of 10.9 km2 (UNESCO [65447] 2022). Figure 2 shows the mentioned mangrove locations in Oman. The recorded mangrove area in Oman was 1000 ha from the year 1990 till 2020 (FAO 2020g), which compared to 2022, gives total increase in mangrove cover by 9%.

The climate in these areas varies as following: Qurm has a desert climate that experiences low rainfall where the average annual temperature and rainfall is 27.3 °C

Table 1 Mangroves detailed locations on map, species, and area coverage in the year 2022 in the Middle East and Egypt

Country		Mangroves location		Latitude	Longitude	Available species	Mangrove stands (No.)	Total coverage (ha)	Total coverage (km^2)
1	Oman	1	Qurm	23° 37′ 5.9982″	58° 28′ 53.6448″	*Avicennia marina*	N/A	1090	10.9
		2	Muhut Island	20° 34′ 24.711″	58° 10′ 8.9508″				
		3	Shinas Mangrove Park	24° 42′ 44.2578″	56° 28′ 43.6476″				
		4	Bandar AL Khairan	23° 30′ 25.1166″	58° 43′ 52.0314″				
		5	Flamingo lake	23° 16′ 32.61″	58° 55′ 2.3448″				
		6	Wadi Dayqah	23° 4′ 58.4616″	58° 51′ 4.0608″				
2	Bahrain	1	Tubli Bay Coast	26° 11′ 44.9376″	50° 33′ 45.738″	*Avicennia marina*	28	80	0.8
		2	Ras Sanad Mangrove Forest	26° 9′ 4.3272″	50° 35′ 34.2348″				
		3	Bahrain Mangrove Forest	26° 9′ 12.2538″	50° 35′ 30.7026″				
		4	Mangrove nursery	26° 9′ 17.1252″	50° 35′ 38.9256″				
		5	Arad Bay	26° 15′ 41.6484″	50° 37′ 51.6858″				
		6	Ras Hayyan	26° 2′ 6.3846″	50° 37′ 43.9464″				
3	Saudi Arabia	1	Tarut Bay	26° 35′ 54.8484″	50° 3′ 49.5714″	*Avicennia marina* and *Rhizophora mucronata*	316	20,400	204
		2	Farasan Isalnd	16° 42′ 9.0462″	42° 10′ 18.7422″				
		3	Mangrove forest North Sanabis	26° 35′ 12.9192″	50° 4′ 59.0988″				
		4	Mangrove forest South Sanabis	26° 34′ 11.6466″	50° 5′ 24.2514″				
		5	Mangrove Eco Park	26° 44′ 3.9078″	49° 59′ 35.5662″				
		6	Ras Hatiba	21° 58′ 41.9982″	38° 56′ 13.9986″				
		7	Saihat Mangrove Forest	26° 30′ 22.6764"	50° 2′ 34.4544"				
		8	Darin Mangrove Forest	26° 33′ 0.2592"	50° 4′ 46.4376"				
		9	Sfwa	26° 37′ 52.0788"	50° 0′ 57.8916"				
		10	Abu Ali Island	27° 17′ 19.4748"	49° 33′ 50.5584"				
		11	Abu-Marzouk Island	22° 3′ 39.7764″	39° 1′ 10.293″				
		12	Kambodi Island	22° 2′ 35.631″	38° 59′ 52.4292″				
		13	Umm Ruma Island	25° 42′ 53.9994″	36° 34′ 20.9994″				
		14	Dugm Sabq	25° 36′ 12.7542″	36° 58′ 1.8402″				
		15	Gama'an Island	25° 33′ 6.5952″	36° 50′ 39.8256″				
		16	Shibara Island	25° 25′ 5.001″	36° 52′ 45.0012″				
		17	Umm Al-Qandal Island	19° 45′ 31.9998″	40° 41′ 21.9984″				
		18	Umm Al-Rubais Island	19° 39′ 39.8406″	40° 45′ 0.432″				
		19	Ras Umm Al-Rubais	19° 45′ 31.2762″	40° 40′ 54.318″				
		20	Al-Gahaf	17° 27′ 0.9756″	42° 17′ 6.126″				
		21	Qandal Forest	16° 47′ 37.5828″	42° 5′ 53.7426″				
		22	Solain Island	16° 45′ 4.4064″	42° 12′ 56.1204″				
		23	Zifaf Island	16° 43′ 45.8004″	41° 44′ 56.8998″				

Table 1 (continued)

Country		Mangroves location		Latitude	Longitude	Available species	Mangrove stands (No.)	Total coverage (ha)	Total coverage (km^2)
4	UAE	1	Sir Bani Yas Island	24° 21′ 38.8326″	52° 35′ 40.1712″	*Avicennia marina*f	2846	6,800	68
		2	Marawah Island	24° 18′ 9.036″	53° 20′ 33.7164″				
		3	Bul Syayeef Protected Area	24° 14′ 49.974″	54° 17′ 6.9936″				
		4	Abu-Dhabi Mangroves	24° 26′ 46.0782″	54° 24′ 56.4192″				
		5	Eastern Mangrove National Park	24° 27′ 21.8334″	54° 25′ 4.083″				
		6	Eastern Mangrove National Promenade	24° 26′ 47.1804″	54° 26′ 18.4554″				
		7	Saadiyat Island	24° 32′ 25.3566″	54° 26′ 7.6848″				
		8	Jubail Mangrove Park	24° 32′ 42.6588″	54° 29′ 7.461″				
		9	Ras Ghurab–Abu Dhabi	24° 36′ 20.8908″	54° 34′ 4.8678″				
		10	Ras Ghanadah	24° 42′ 51.4434″	54° 39′ 0.4536″				
		11	Ras al Khor Wildlife Sanctuary–Dubai	25° 11′ 28.5396″	55° 19′ 21.5178″				
		12	Al Zora natural Reserve–Ajman	25° 25′ 35.9394″	55° 30′ 5.2302″				
		13	Grundfos Mangrove Plants	25° 25′ 49.1694″	55° 29′ 28.2228″				
		14	Khor Al Beidah Wetlands	25° 31′ 59.1774″	55° 36′ 8.8344″				
		15	RAK Mangroves	25° 53′ 32.262″	56° 2′ 21.8688″				
		16	Al Qurum Visitor Center	25° 0′ 47.9622″	56° 21′ 41.4864″				
		17	Khor Kalba Mangrove Center	25° 0′ 54.2586″	56° 21′ 37.7388″				
5	Qatar	1	Al Thakira mangrove forest	25° 44′ 31.3434″	51° 33′ 27.6186″	*Avicennia marina*	392	1230	12.3
		2	Al Ruwais	26° 8′ 46.9212″	51° 11′ 19.356″				
		3	Simaisma	25° 34′ 39.0864″	51° 29′ 19.7802″				
		4	Fuwairit	26° 1′ 41.5668″	51° 22′ 15.261″				
		5	Purple Island	25° 41′ 19.7514″	51° 33′ 10.5588″				
		6	All Dhakira Mangroves	25° 44′ 49.2066″	51° 33′ 6.6126″				
		7	Al Wakra	25° 10′ 47.1684"	51° 37′ 6.0888"				
		8	Umm Al Hul	26° 38′ 51.2988"	44° 26′ 51.5688"				

Table 1 (continued)

Country	Mangroves location	Latitude	Longitude	Available species	Mangrove stands (No.)	Total coverage (ha)	Total coverage (km^2)
6 Iran	1 Mangrove Jungle	27° 27′ 26.3874″	52° 39′ 39.2544″	*Avicennia marina* and *Rhizophora mucronata*	3403	19,200	192
	2 Mangrove Forest Tabl	26° 46′ 53.1768″	55° 43′ 25.3518″				
	3 Sistan and Balouchestan province	25° 29′ 5.3406″	62° 0′ 10.8534″				
	4 Hara Mangrove forest protected area	26° 49′ 5.199″	55° 47′ 20.1114″				
	5 Mangrove Forests	26° 42′ 31.572″	55° 32′ 1.86″				
	6 Assaluyeh Mangrove Forest	27° 27′ 18.075″	52° 40′ 24.5346″				
	7 Forest Park mangrove	26° 58′ 49.6014″	55° 38′ 24.399″				
	8 Mel-e-Gonzeh Protected Area	27° 50′ 48.2346″	51° 34′ 53.115″				
	9 Jalabi and Hassan-Langi	27° 9′ 15.624″	56° 37′ 24.5418″				
	10 Tiyab and Kolahi	27° 6′ 58.0062″	56° 48′ 41.958″				
	11 Sirik	26° 19′ 58.3422″	57° 5′ 7.0944″				
	12 Qeshm Island	26° 48′ 39.4776″	55° 51′ 37.5114″				

Table 1 (continued)

Country	Mangroves location		Latitude	Longitude	Available species	Mangrove stands (No.)	Total coverage (ha)	Total coverage (km^2)
7 Egypt	1	Safaga Island	26° 45′ 9.741″	33° 58′ 28.7682″	*Avicennia marina* and *Rhizophora mucronata*	20 stands + 5 off-shore islands	510	5.1
	2	Mangrove Forest in Safaga	26° 36′ 56.6382″	34° 0′ 43.4982″				
	3	40 km South Safaga	26° 23′ 57.6378″	34° 7′ 0.6996″				
	4	Hamata	24° 19′ 25.1574″	35° 20′ 30.3828″				
	5	Shore of Kite Village-Hamata	24° 18′ 13.86″	35° 22′ 12.8994″				
	6	Halayeb and Sha-lateen	23° 12′ 18.8634″	35° 35′ 13.8624″				
	7	Wadi Lehmy	23° 12′ 18.8634″	35° 24′ 53.9352″				
	8	Hamata	24° 19′ 25.1574″	35° 20′ 30.3828″				
	9	Wadi El-Gemal	24° 40′ 41.0088″	35° 5′ 9.8916″				
	10	Abu Minqar Islands	27° 12′ 49.0062″	33° 52′ 35.8458″				
	11	Al-Qusair	25° 52′ 1.236″	34° 24′ 53.5932″				
	12	2.5 km South Al-Qusair	25° 50′ 46.8204″	34° 25′ 47.37″				
	13	Gouna	27° 24′ 19.7454″	33° 40′ 49.371″				
	14	Marsa Hemara	24° 8′ 3.7824″	35° 29′ 0.4524″				
	15	Hartiway Bay	24° 7′ 52.536″	35° 29′ 18.0486″				
	16	Gebel Elba	23° 7′ 45.4836″	35° 34′ 50.0586″				
	17	Al-Qusair	25° 52′ 1.236″	34° 24′ 53.5932″				
	18	Mersa El-Madfa	22° 59′ 2.1084″	35° 44′ 47.4498″				
	19	Mersa Halaib	22° 14′ 2.4108″	36° 38′ 41.4168″				
	20	Al-Qulaan	24° 21′ 31.2264″	35° 18′ 19.548″				
	21	Bir El Hasa	22° 56′ 45.15″	35° 40′ 2.229″				
	22	Ras mohamed	27° 43′ 43.863″	34° 14′ 45.837″				
	23	Nabq	28° 2′ 32.7048″	34° 26′ 46.5144″				
	24	Marsa Shajra	25° 14′ 42.5286″	34° 47′ 38.0826″				
	25	Shura Al-Man-quata	28° 12′ 28.0398″	34° 25′ 8.9508″				
	26	Shura Al-Rowais-seya	28° 11′ 11.2734″	34° 26′ 52.7568″				
	27	Mersa Abu Zabad	28° 8′ 59.0496″	34° 26′ 53.8074″				
	28	Shura Al-Ghar-qana	28° 6′ 50.3706″	34° 26′ 30.8544″				

Table 1 (continued)

Country	Mangroves location	Latitude	Longitude	Available species	Mangrove stands (No.)	Total coverage (ha)	Total coverage (km^2)
8 Sudan	1 Mohammed Qol	20° 47′ 10.2006″	37° 10′ 32.4078″	*Avicennia marina*	14	980	9.8
	2 Arakiyai	20° 19′ 14.43″	37° 12′ 24.012″				
	3 Halut	19° 47′ 32.7156″	37° 16′ 3.6336″				
	4 Klanieb	19° 30′ 13.6152″	37° 16′ 50.1564″				
	5 Mersa Atta	19° 18′ 6.4728″	37° 19′ 13.5804″				
	6 Fagum-Lagagen-geeb	19° 0′ 48.7404″	37° 24′ 27.2484″				
	7 Haydob	18° 58′ 10.0986″	37° 24′ 7.6536″				
	8 Sheikh Saad	18° 50′ 21.4434″	37° 25′ 59.9586″				
	9 Ashat	18° 44′ 50.229″	37° 30′ 54.3636″				
	10 Mukawwar Island	20° 45′ 34.8264″	37° 15′ 44.4486″				
	11 Agig	18° 14′ 8.5086″	38° 20′ 3.8724″				
9 Yemen	1 Midi	16° 20′ 56.5404″	42° 47′ 13.8186″	*Avicennia marina* and *Rhizophora mucronata*	29	930	9.3
	2 Between Midi and Al-Habl (1)	16° 15′ 59.259″	42° 48′ 29.847″				
	3 Between Midi and Al-Habl (2)	16° 14′ 37.9824″	42° 48′ 24.699″				
	4 Between Midi and Al-Habl (3)	16° 12′ 54.9282″	42° 48′ 57.4812″				
	5 Mangrove Garden in Yemen	16° 11′ 8.4798″	42° 49′ 47.8236″				
	6 Al-Habl	16° 8′ 15.3234″	42° 49′ 24.7686″				
	7 Al-Buhays	15° 59′ 6.0138″	42° 49′ 31.8144″				
	8 Between Al-Buhays and Al-Luhayah	15° 47′ 34.335″	42° 45′ 38.3868″				
	9 Al-Luhayah	15° 42′ 8.9454″	42° 41′ 20.2986″				
	10 North Al-Luhayah	15° 43′ 24.3078″	42° 42′ 16.671″				
	11 South of Al-Luhayah	15° 41′ 33.882″	42° 42′ 43.3836″				
	12 6 km South of Al-Luhayah	15° 38′ 35.4294″	42° 42′ 23.1762″				
	13 Kamran Island	15° 25′ 1.5312″	42° 36′ 0.255″				
	14 Al-Urj	15° 6′ 4.6074″	42° 52′ 20.8992″				
	15 North of Al-Hudaydah	14° 52′ 4.4862″	42° 57′ 13.3482″				
	16 Gandal islet	14° 50′ 51.453″	42° 54′ 59.493″				
	17 Mugamalah islet	14° 52′ 25.6362″	42° 55′ 17.0106″				
	18 Hudaydah islets	14° 54′ 49.1148″	42° 55′ 55.491″				
	19 Between El-Rowais and Yakhtul	13° 30′ 58.7478″	43° 15′ 43.2072″				
	20 Between Al-Kadaha and Al-Ubaidah	13° 7′ 56.2908″	43° 18′ 7.1784″				
	21 El-Ghurairah at Bab al-Mandab	12° 44′ 47.313″	43° 28′ 13.1838″				

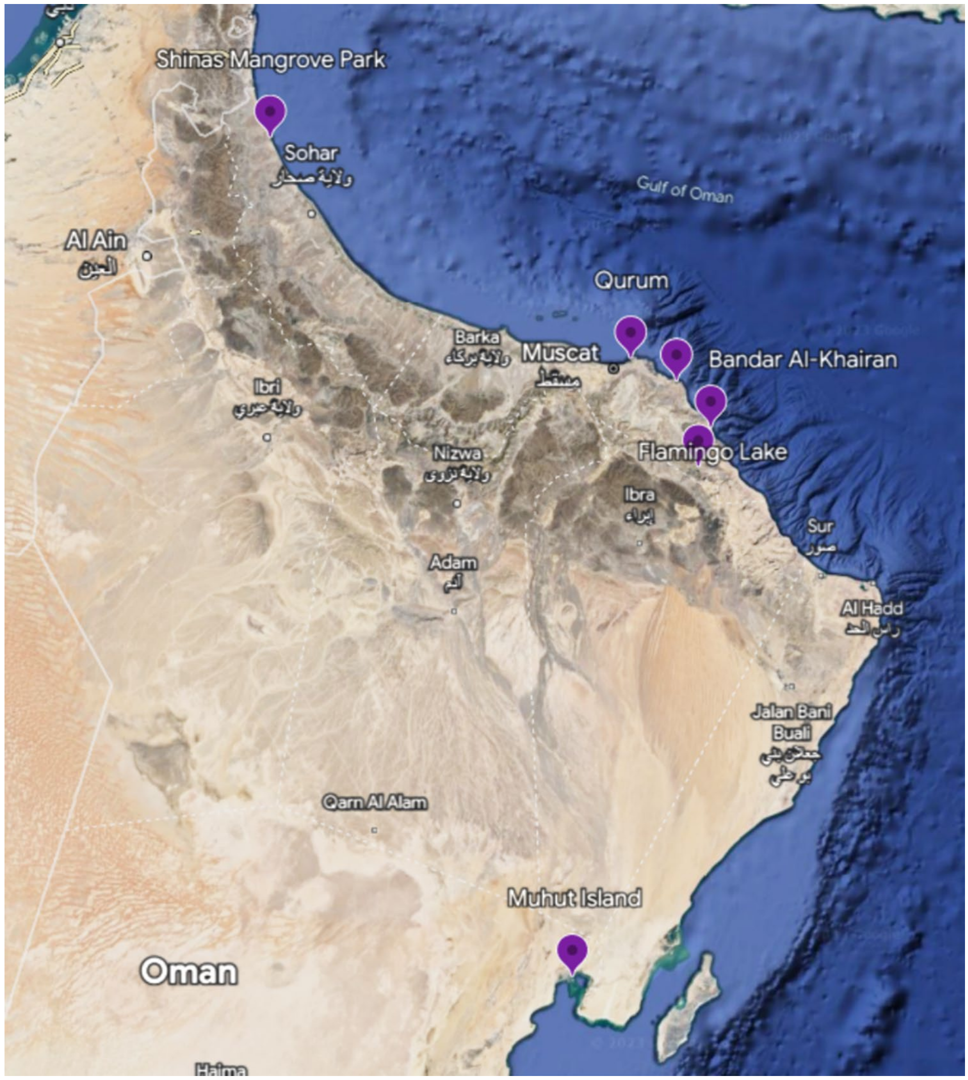

Fig. 2 Mangrove locations in Oman on map

and 100 mm respectively (Qurm Climate, n.d.), Shinas summers are arid, long, oppressive, and partly cloudy where the temperature ranges from to 16 to 37.8 °C and rainfall from 12.7 to 17.8 mm. Bandar AL Khairan has a subtropical desert climate with yearly temperature of 28.2–35.16 °C and 10.24mm rainfall while Wadi Dayqah's is 148 mm annually (Hieatt et al. 2010). Oman's mangroves grow in groups of trees separated by halophytic species or bare soil and their height varies from 3.9 to 4.5 m (Cookson and Lepiece 1997); however, Gab-Alla et al. (2010) mentioned that *Avicennia marina* is present there on the northeast coast with fair density and 5.2 m mean height.

From the factors supporting mangroves growth in Oman, besides the *A. marina*'s ability to successfully grow in harsh, arid, and high salinity environment, is having intertidal areas with gentle slow slope and that the trees are directly facing the sea. Moreover, the marine habitat around mangroves in Oman is not limited to but includes: turtles, crustaceans, shrimps, crabs, echinoderms, fish, sponges, oysters, and mollusks and the following animals exist: mammals, sand fox, Arabian red fox, birds, camels, green turtles, and the gerbil (Fouda and AI-Muharrami 1996). A detailed checklist for the present aquatic animals in Oman's mangroves ecosystem was presented by (Hassan Hashemi and Salarpouri 2013) in their study.

Mangroves in Bahrain

Bahrain, known as Kingdom of Bahrain, has a desert climate that is extremely hot during summer but mild during winter with a pleasant weather where the annual temperature ranges from 10 to 20 °C during winter while 36 °C during summer and can go up to 38–40 °C; The average annual rainfall is 80 mm (Directorate of Environmental Assessment and Planning, 2009). The only mangrove specie that can be found in Bahrain is *Avicennia marina* and can be located in: Tubli Bay Coast (Naser 2016), Ras Sanad Mangrove Forest also

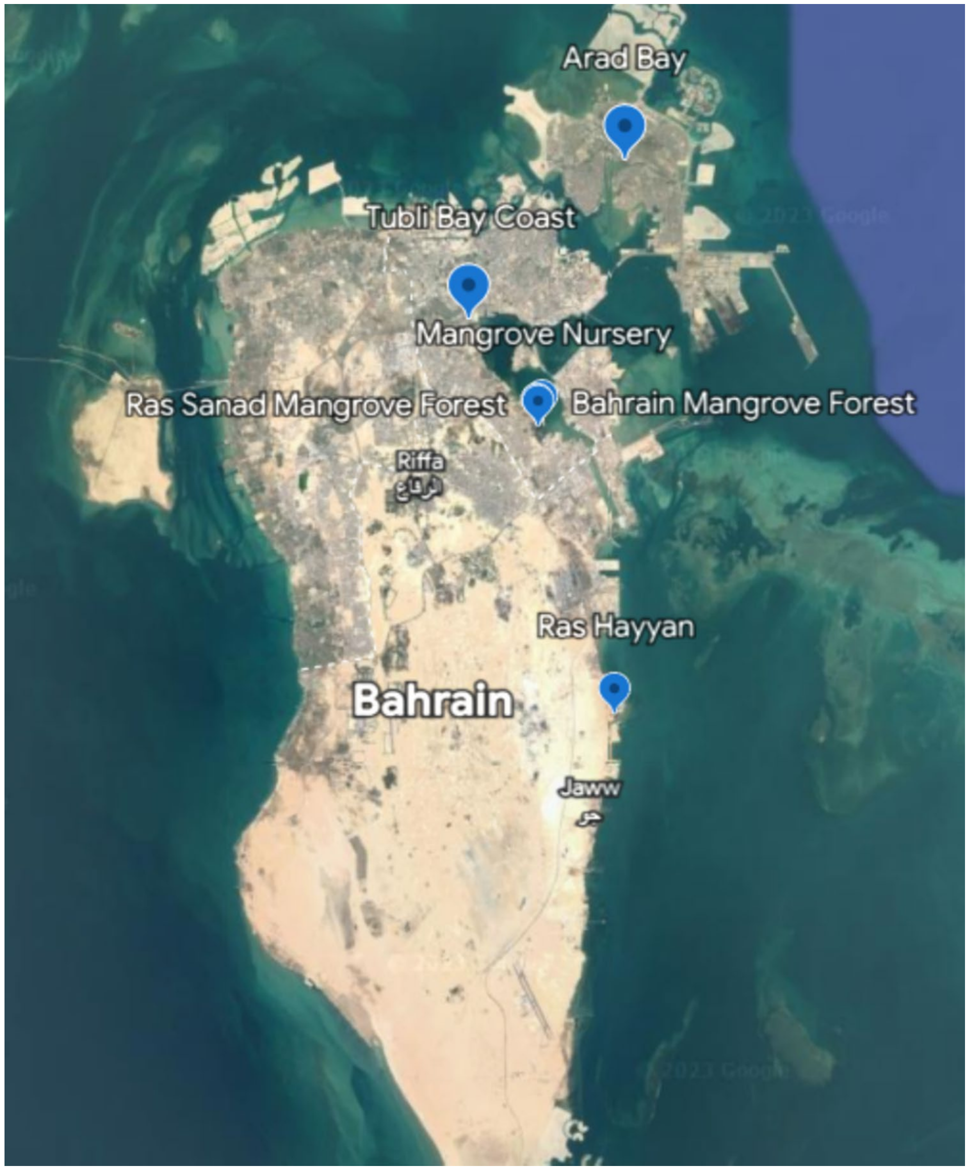

Fig. 3 Mangrove locations in Bahrain on map

known as Bahrain Mangrove Forest (Milani 2018), Arad Bay and Ras Hayan (Directorate of Environmental Assessment and Planning 2009), and the Mangrove nursery near Ras Sanad having a total coverage of 0.8 km2 (UNESCO [65479], 2022b) as shown in Fig. 3. The recorded mangrove area in Bahrain was 90 ha from the year 1990 till 2020 (FAO 2020a), which compared to 2022, gives total shrinkage in mangrove cover by 11.1%.

The climate in these areas varies as Ras Sanad has annual temperature 26.9–29.7 °C and average rainfall of 5.62 mm while Tubli's climate is very humid and hot during summer and mild and arid during winter where the average annual rainfall and temperature is 80 mm and 26.8 °C respectively. The height of the trees varies from 1 to 5.5 m with 2.7 m as an average and their locations in Bahrain have access to low salinity water that is discharged from underground springs and close farms which affects the trees growth rate as well as minimal motion of sea water (Abou Seedo et al. 2017).

In his study, (Naser 2016) showed that there are sixteen types of marine habitat in Bahrain: seagrass, rock, algae, mud, sabkha, mixed habitats, algae-rock-sand, mangrove, coral, sand, mud and sand, algae-rock-sand, deep-water mixed habitats, rock and sand, salt marsh, deep water mud, and coral-rock-sand, however the area witness animals like migratory birds, terns, herons, flamingoes, gulls, and egrets (Gillespie and Ann 2019). According to the number of available habitats and richness of species were not high due to high salinity of sediments and aridity (Abou Seedo et al. 2017).

Mangroves in Saudi Arabia

Saudi Arabia, or Kingdom of Saudi Arabia, has a desert climate where the central region experiences extremely dry and scorching summers with temperatures ranging from 27 to 43 °C in the inland regions and 27–38 °C along the coast, however, the southwestern part of the country has a semi-arid climate. In the interior parts, winter temperatures range from 8 to 20 °C, while the Red Sea's coastal areas have experienced temperatures as high as 19–29 °C (World Bank Group 2021b). The majority of the country receives less than 150 mm of precipitation annually, − 93 mm according to (Almazroui 2020), however the southwestern region receives between 400 and 600 mm. Saudi Arabia has only two species of mangroves: *Avicennia marina*, the most dominant species on mainland, and *Rhizophora mucronata* which is only found along Farasan Archipelago (S. M. Saifullah 1997). They can be found in the following locations: Tarut Bay (Abdalla 2022), Farasan Isalnd (Elbanna & Ali 2021), Mangrove forest North Sanabis, Mangrove forest South Sanabis, Abu-Marzouk Island, Kambodi Island, Mangrove Eco Park in Ras Tanura (Saudi Gazette 2012), Ras Hatiba (Mandura et al. 1988), Saihat Mangrove Forest, Darin Mangrove Forest, and Sfwa (Almahasheer et al. 2013), Abu Ali Island (Maneja et al. 2020), and Umm Ruma Island, Dugm Sabq, Gama'an Island, Shibara Island, Umm Al-Qandal Island, Umm Al-Rubais Island, Ras Umm Al-Rubais, Al-Gahaf, Qandal Forest, Solain Island, and Zifaf Island (PERSGA/GEF 2004) thus they are non-continuously occurring along the Saudi Arabian Red Sea coast line (S. M. Saifullah 1997) and having a 204 km^2 total area (UNESCO [65479], 2022a). Figure 4 highlights the mentioned mangrove locations. The recorded mangrove area in Saudi Arabia was 158,000 ha between the years 1990 and 2020 (FAO 2020c), which compared to 2022, shows degradation in mangrove cover by 87%.

These areas have climate that slightly varies: in Tarut Bay the annual average temperature is 26.6–28 °C with 35.6 °C and 20.1 °C as the highest and lowest recorded values (Abdalla 2022) while it sometimes experiences no rainfall but can go up to 0.5 mm. In Farasan Islands, the annual average temperature is 30 °C and in the summer can go up to 40–44 °C during daytime and 2–3 °C during night (Khedher et al. 2022) while the annual rainfall is usually heavy, dense, and ranges from 100 to 450 mm (Elbanna and Ali 2021). The rest of mangrove locations resemble similar climatic

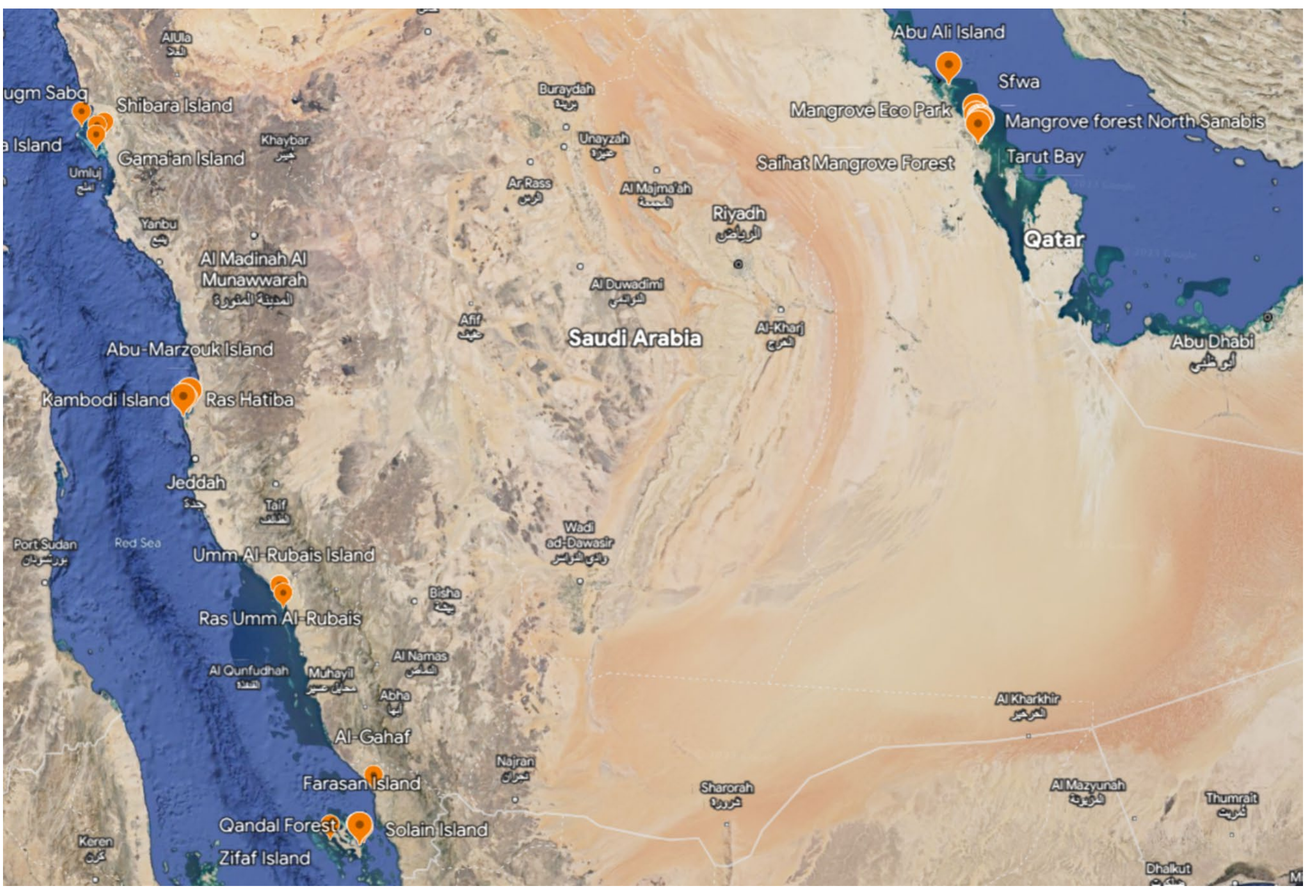

Fig. 4 Mangrove locations in Saudi Arabia on map

conditions to Tarut Bay due to geography. Mangroves grow in their communities in the form of single plant rows that ranges the sandy shores where the tall trees can be found close to the sea edge with an average height of 2.46 m that can go up to 4 m while the dwarf 1-m high trees can be observed towards the land and their average height is 0.63 m (Mandura et al. 1988).

The following characteristic factors to Mangrove locations in Saudi Arabia support their growth: presence of high nutrients in water due to intrusion of low salinity water into the Red Sea from the Gulf of Aden, small tidal amplitude (50 cm), presence of Lagoons that provide soft bottom rich in nutrients due to decomposition of organic matter, transport of algae to mangrove sites during winter which contribute to organic biomass & energy budget of mangroves ecosystem, and fixation of elemental nitrogen by Cyanobacteria thus contributing to overall nitrogen input of the ecosystem (Saifullah 1997). Moreover, S. M. Saifullah (1997) also highlighted some conditions which favored mangroves growth in the southern area of Saudi Arabia to its northern part like: having better temperature due to its location within the tropical belt and better rainfall as well as runoff due to large number of surrounding wadis, availability of microscopic organisms which increase the photosynthetic area, and the existent dead coral reef rocks are superimposed with a thick layer of soft mud which does not negatively impact mangroves growth. Mandura et al. (1988) recorded 40 species of algae there including red algae, blue-green algae, green algae, brown algae, cyanobacteria in the sabakhas, seagrass, halophytes, and animals from the following classes: coelenterata, arthropoda, Mollusca, aves. Arabian Gazelle, sea birds, shorebirds, mudskipper, fish, prawn, and migratory birds like Black headed Gulls, Egrets, Boobies, Terns, Pelicans, and sooty Gulls were also observed (Presidency of Meteorology and Environment (PME), 2005).

Mangroves in United Arab Emirates

The United Arab Emirates, known as UAE, has an arid desert climate and the average annual temperature during summer and winter ranges from 32 to 37.2 °C and 16.4 to 24 °C respectively and can reach 50 °C during summer days while the average annual rainfall ranges between 140 and 200 mm up to 350 mm in some mountainous areas (World Bank Group 2021c). Only one species of mangroves is available in UAE, *Avicennia marina*, however *Rhizophora mucronata* species was available in the historical times but disappeared (Saenger et al. 2004). Mangroves can be found across UAE in: Khor Al Beidah Wetlands in Umm Al Quwain, Al Zorah Natural Reserve in Ajman, Grundfos Mangrove Plants, (Mangrove and Al Hafiya Protected Area in Khor Kalba and Sir Bu Nair) in Sharjah, (Saadiyat Island, Jubail mangrove park, Marawah Island, Bul Syayeef Protected Area, Ras Ghurab, Eastern Mangrove National Park, Ras Ghanada, Abu Dhabi Mangroves, and Sir Bani Yas Island) in Abu Dhabi, Ras Al Khor Wildlife Sanctuary in Dubai, Al-Qurum visitor center, RAK Mangroves, and Eastern Mangroves promenade where the mangroves cover a total area of 68 km^2 (UNESCO [65478] 2022) as can be

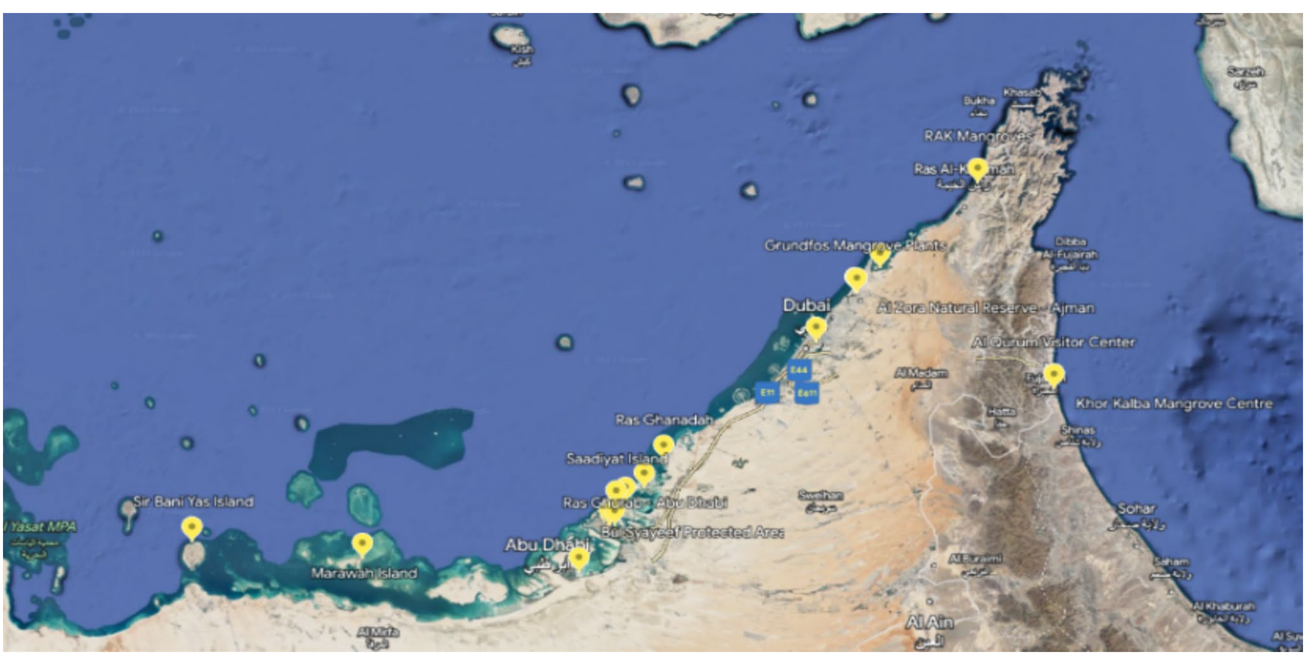

Fig. 5 Mangrove locations in United Arab Emirates on map

seen in Fig. 5. The recorded mangrove area in United Arab Emirates was 3800 ha and 4300 ha in the years 1990 and 2022 respectively (FAO 2020d), which compared to 2022, shows a 58.1% increase in total mangrove cover.

A study by Saenger et al. (2004) highlighted some of the climate variations in these areas where in Ras Alkhaima the average annual temperature in winter and summer ranges from 12.8 to 24.4 °C and 30 to 42.2 °C respectively while average rainfall is 124.4 mm annually. Dubai has long, arid, oppressive summers that are partly cloudy while its winters are dry and clear; the temperature ranges annually from 30 to 41.1 °C during summer and 14.4 to 23.9 °C during winter while the mean annual rainfall is 81 mm. As for Sir Bani Yas Island, the average temperature ranges from 19 to 37 annually and average rainfall is 9.9 mm/year. Abu Dhabi's annual mean rainfall is 65.5 mm. UAE mangroves have a patchy distribution where their density increases in the east and gradually decreases to the west (Moore et al. 2013) and the young trees are averaged with a 3-m height while the mature ones are usually 5–6 m high and can reach 10 m (Saenger et al. 2004). UAE's natural mangroves are rich in marine habitat as they include sea snakes, shrimps, crabs, sea breams, turtles, Hooded Oyster, and snapper. UAE mangroves distribution increases at areas with higher rainfalls and temperatures and decreases with aridity and location topography (Al Habshi et al. 2007). Moreover, the following animals can be observed: Western Reef Heron, Mottled Crab, Greater Flamingo, Kalba Collared Kingfisher, White Spotted Grouper, Greater Spotted Eagle, bream and wild foxes, eagles, sooty falcons, and green turtles (Emirates Nature 2023).

Mangroves in Qatar

Qatar peninsula has dry, extremely hot summers with high humidity and Shamal winds where the average temperature is 42 °C and can go up to 50 °C contrary to winters which are comfortable and the average annual temperature ranges from 22 °C to 32 °C but can drop below 15 during night; average rainfall is 75.2 mm annually (Ajjur and Al-Ghamdi 2022). *Avicennia marina* is the mangrove specie that can be found in Qatar (Abdel-Razik 1991) in the following locations: Al Thakira mangrove forest, Al Ruwais, Simaisma, Fuwairit, Purple Island, and Al Dhakira Mangroves with a total area coverage of 12.3 km^2 (UNESCO [65483], 2022). Mangrove sites in Qatar are shown in Fig. 6. The recorded mangrove area in Qatar was 500 ha from the year 1990 till 2005 (FAO 2020b), which compared to 2022, shows an increase in mangrove cover by 23%.

Al Ruwais summer mean temperature is from 20–35 °C and can reach 40 °C while winter's is from 22 to 29 °C and the average annual rainfall is 62 mm while Simaisma's annual temperature ranges between 25.2 and 43.3 with an average of 34 and 93 mm is the annual rainfall (Supplementary Materials: Year of Plantation, Hydrological Parameters, Slope, and Elevation Profiles of Mangrove Sites in Qatar, n.d.). The average annual temperature in Fuwairit is in the range of 31.1–38.9 °C during summer and 15–21.1 °C during winter and the rainfall is 12.7 mm mostly during March. Planted mangroves height vary from 1 to 3 m while the natural stands range from 1 up to 6 m (Al-Khayat and Balakrishnan 2014).

From the factors enhancing mangroves growth in the Qatar is that mangrove locations receive fine sediments with high organic matter content through long narrow runnels from the hinterland, there is mud deposition accumulating in the area behind the tidal delta in the basin, and there is freshwater seepage from underground water (Abdel-Razik 1991). Fishes, gastropods, mudskippers, crabs, and shrimps are among the marine habitat that can be found around Qatar's mangroves while these animals can be observed: Western Reef Heron, Mottled Crab, Greater Flamingo, White Spotted Grouper, Greater Spotted Eagle, bream and wild foxes, Green Turtles, and eagles and sooty falcons but they are rarely spotted.

Mangroves in Iran

Qatar peninsula has dry, extremely hot summers with high humidity and Shamal winds where the average temperature isIran, known as the Islamic Republic of Iran, has annual temperature averages during summers and winters between 25 and 35 °C and 15 and 25 °C respectively but might exceed 40 °C in south and east areas in summer or drop to 10 °C in winter at night while the average annual precipitation is 250 mm (Climate Center 2021b). Only 2 mangrove species can be found in Iran: *Avicennia marina* is the dominant while *Rhizophora mucronata* can only be found in the Sirik region (Zahed et al. 2010). Iranian mangroves can be found in Bushehr province (Mangrove Jungle and Assaluyeh Mangrove Forest), Sistan and Balouchestan province, and Hormuzgan Province (Mangrove Forest Tabl, Hara Mangrove forest protected area, Mangrove Forests, Forest Park mangrove) (Zahed et al. 2010), Gwatre Bay, Qeshm Island, and Khuran Strait (Milani et al. 2013), and in Mel-e-Gonzeh Protected Area, Jalabi and Hassan-Langi, Tiyab and Kolahi, and Sirik as well (Farshid PerciaVista et al. 2022) with a 192 km^2 total area coverage (UNESCO [65507], 2022b) as shown in Fig. 7. The recorded mangrove area in Iran was 25,760 ha and 19,230 ha in the years 1990 and 2020 respectively (FAO 2020f), which compared to 2022, gives a slight shrinkage in mangrove cover by 0.2%. Sistan and Balouchestan has a desert climate with extremely hot summers and frosted winters with a 13.76 mm annual average rainfall and 19.76–32.1 °C temperature range while annual average temperature and rainfall in Hormuzgan are

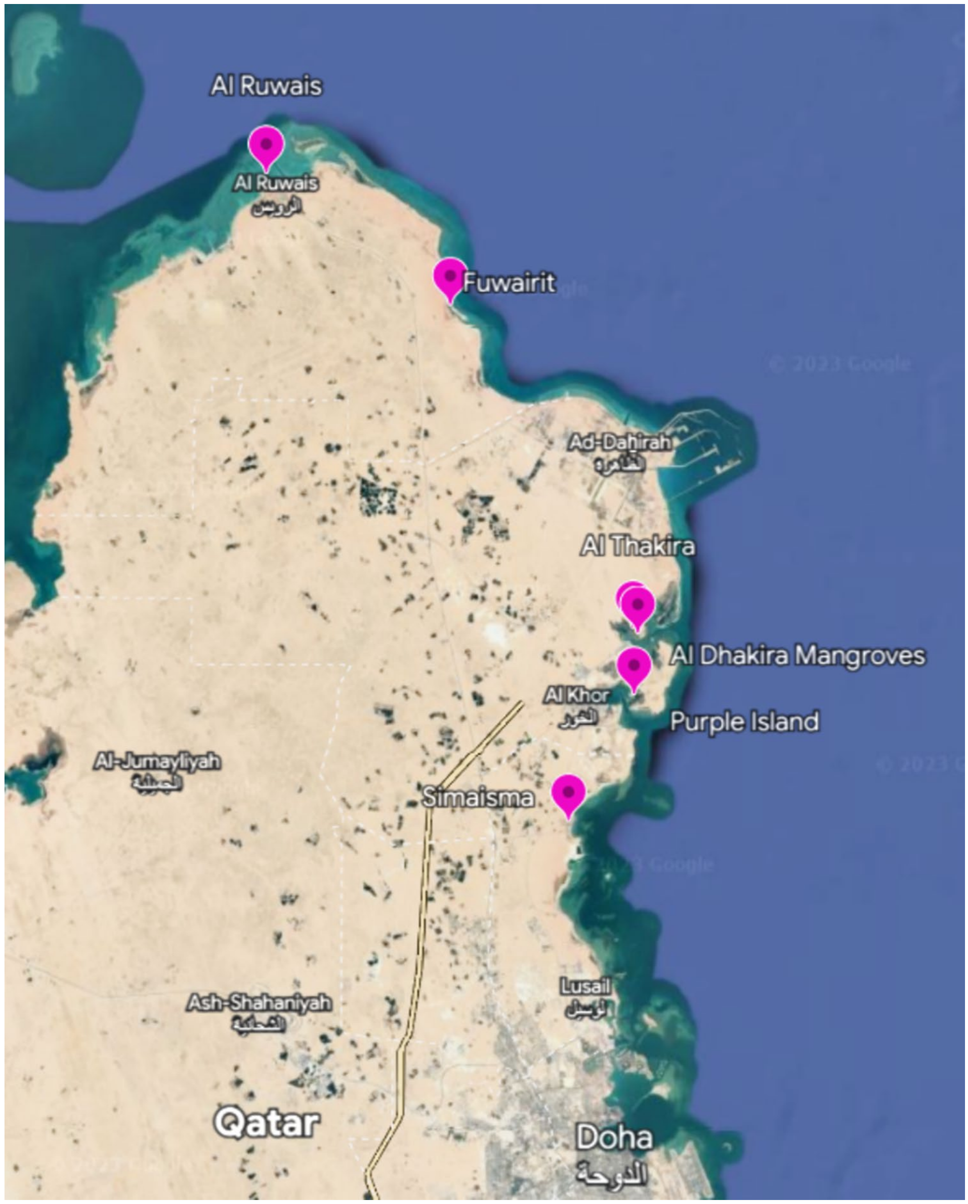

Fig. 6 Mangrove locations in Qatar on map

26.09–31.4 and 16.41 mm respectively. The yearly average temperatures in Bushehr range from 30 °C to 37.2 °C and 12.2 °C to 18.3 °C during summers and winters respectively while the rainfall ranges from 12.7 to 45.7 mm. Iranian mangrove trees have an average height of 3.54 m and various marine habitat and animals were observed there: Sea fishes, prawn and crabs, sea snake, sea turtle, and marine mammal, over 100 species sea and shoreline birds, 37 zooplankton groups, and 51 genera of phytoplankton (Zahed et al. 2010).

Mangroves in Egypt

Egypt's summer average annual temperatures reach 38 °C up to 43 °C where the northern areas experience cooler temperatures with a maximum of 32 °C like the Mediterranean coast while it can go up to 49 °C in the western and southern deserts. In winters, the average yearly temperature is 14 °C and the rainfall has a yearly average of 51 mm (FAO 2016). Two mangrove species were observed in Egypt: *Avicennia marina* and *Rhizophora mucronata* (A. Abdel-Hamid et al. 2018) and they can be found in Safaga,

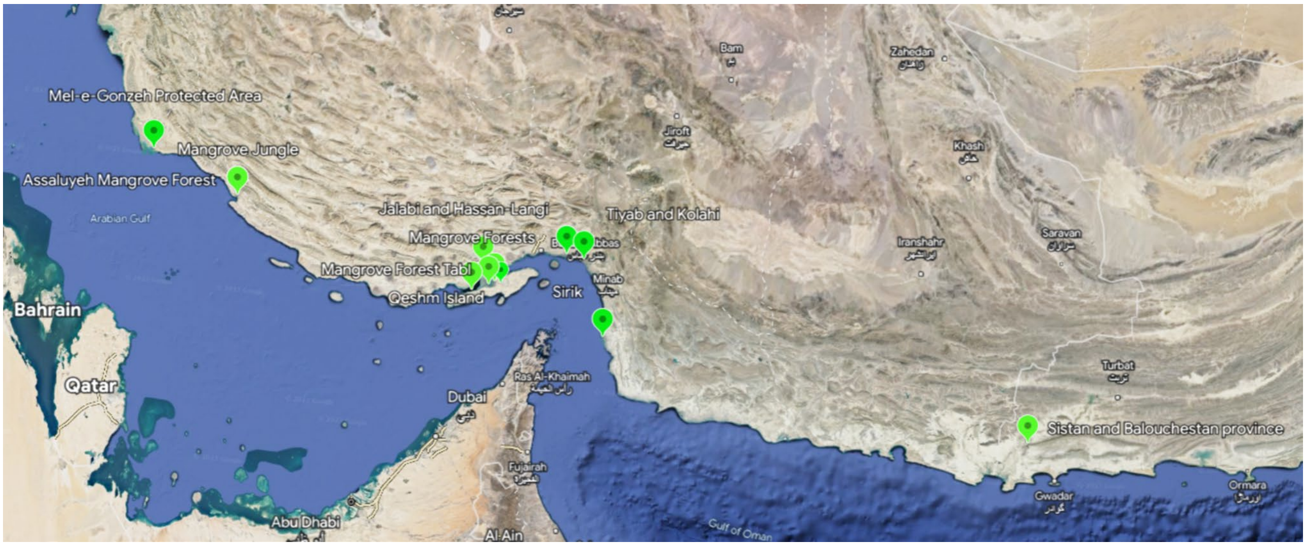

Fig. 7 Mangrove locations in Iran on map

Al-Qusair, North Islands, Marsa Alam, and Marsa Hemara, Ras Mohamed, Shalateen and Halayeb, and El-Gouna (A. Afefe 2021),Hamata (Madkour et al. 2020), Nabq protectorate (Galal 1999), Wadi Lahami (Hering et al. 2017), Wadi El Gemal (Khaleal et al. 2008), Abu Minqar Islands (Saleh 2007), Gebel Elba (Afefe et al. 2021), Hurghada 0(el Hussieny et al. 2021), Mersa El-Madfa and Mersa Halaib (Hussien Shaltout et al. 2006), Al-Qulaan and Marsa Shajra (Abd-El Monsef et al. 2017), and Shura Al-Manquata, Shura Al-Rowaisseya, Mersa Abu Zabad, and Shura Al-Gharqana (PERSGA/GEF., 2004) with a total coverage of 5.1 km^2 (UNESCO [65507], 2022a). Figure 8 shows these locations on map. The recorded mangrove area in Egypt was 390 ha and 500 ha in the years 1990 and 2020 respectively (FAO 2020e), which compared to 2022, shows an increase in the mangrove cover by 2%. *A. marina* distribrution is most abundant along the Red Sea coast line starting from Nabq (Rasul and Stewart 2015) while *R. mucronata* predominates from Mersa El-Madfa to Mersa Halaib (K. A. Abdel-Hamid et al. 2007).

The climate varies in these areas as they are distributed along the Red Sea coast. Nabq has an average rainfall less than 100 mm/year while the air temperature ranges between 14 °C and 45 °C annually (Galal 1999). Hurghada's dry desert climate results in temperature variations where daytimes are hot with up to 42 °C temperature while nights are cold with 18 °C temperature (Mahmoud et al. 2018), annual temperature of the Red Sea ranges between 21 and 28 °C with an average of 24 °C (Egyptian Government 2015), while the average rainfall is 76 mm annually (Unicef, n.d.). Wadi El-Gemal average temperatures are between 33 °C during summer and changes to 19.8 °C during winter and average rainfall is 17.4 mm on annual basis (Khaleal et al. 2008). Hamata has a similar climate to Wadi El-Gemal. The highest temperature in Quasir is 29 °C while the lowest is 17 °C where the average annual temperature and rainfall are 24.7 and 4 mm respectively (Climate Data n.d. 2023).

Egyptian mangroves exist in small patches that are few square kilometers wide (Abd-El Monsef et al. 2017) and the trees usually survive in shallow waters like lagoons or sand bars close to the shoreline (Abdel-Hamid et al. 2018) where they rarely grow in broad forests but grow in narrow clusters on the offshore and nearshore islands and fringe channels and tidal creeks (Rasul and Stewart 2015). They usually grow in one of three forms: in a sea channel, in an enclosed bay that is protected by a coralline ridge, or in a community form that grows to an extensive intertidal flat (A. Afefe 2021). Trees height ranges from 5 to 7 m which gives them small shrub-like look and their width varies from 50 to 100 m (Rasul and Stewart 2015).

There are four environmental conditions that affects mangroves growth in Egypt: water characteristics, man-made modification, climatic conditions, and geomorphological aspects of the islands, lagoons, and bays of the Red Sea (A. Afefe 2021). Egypt's annual temperature, having a minimum of 20 °C, is one of the most important factors impacting mangroves growth in Egypt as these trees prefer warmer climates. The marine habitat existing around the Egyptian mangroves include fauna like barnacles, fish, sea snakes, crustaceans, molluscs and flora like algae. Moreover, the following terrestrial biota can be observed including insects, camels, snails, spiders, crabs, and various bird species like Sooty Falcons, Sooty Gulls, and Ospreys (Sandilyan and

Fig. 8 Mangrove locations in Egypt on map

Fig. 9 Mangrove locations in Sudan on map

Kathiresan 2012; Shobrak and Aloufi 2014; Moustafa et al. 2023).

Mangroves in Sudan

Sudan has hot summers with mean annual temperature between 26 °C and 32 °C and can reach 43 °C in the northern regions while precipitation varies geographically: southern regions receive 1500 mm, central regions receive from 200 to 700 mm, while the northern regions are always dry. Currently, only *A. marina* exists, however both Bruguiera gymnorrhiza and *Rhizophora mucronata* species were reported to exist in the past and *R. mucronata* were observed near the Egyptian borders, north of Halaib (PERSGA/GEF 2004). Mangroves in Sudan can be found in Mohammed Qol, Arakiyai, Halut, Klanieb, Mersa Atta, Fagum-Lagagengeeb, Haydob, Sheikh Saad, Ashat, Mukawwar Island, and Agig (PERSGA/GEF 2004) as can be seen in Fig. 9 with a total land cover of 9.8 km^2 (UNESCO [66310] 2022a).

Mangrove habitats along the Red Sea shores of Sudan were classified according to their morphological behavior and habitat into classes: (1) small mangrove aggregations, (2) off-shore islet forests, (3) shore-line forests, and (4) relic thin populations. Mangrove stands are small and thin, accordingly their height and width ranges from 1 to 2 m and 15 to 300 m respectively. They are abundant near creeks and fringing tidal inlets, on near-shore islets, and along shorelines. Sudan's southern coast receives great amounts of freshwater influx from surface runoff which explains the bigger and denser stands, however taller *Avicennia marina* trees can be observed in some northern areas as they receive freshwater seepage from underground and have sandier, better oxygenated substrates (Mohamed 1984). Mangrove areas in Sudan include various habitats: tidal inlets, seagrass beds, bays, intertidal flats, coral Reefs, rocky shores,

Fig. 10 Mangrove locations in Yemen on map

and saltmarshes. Land animals are also dominant including: camels, insects, roosting flocks of fruit bats, and fishing and insectivorous birds (Osman and Elbashier 2019).

Mangroves in Yemen

Yemen is an arid sub-tropical country with annual mean summer and winter temperatures of 25–35 °C and 15–22.5 °C respectively and average rainfall is 39 mm annually. *Avicennia marina* is the dominant mangrove species, however *Rhizophora mucronata* coexists with it in two stands near Al-Hudaydah and Kamaran Island. Mangrove trees in Yemen in Midi, Al-Habl, Mangrove Garden in Yemen, Al-Buhays, Al-Luhayah, Kamran Island, Al-Urj, north of Al-Hudaydah, Mugamalah islet, Hudaydah islets, between El-Rowais and Yakhtul, between Al-Kadaha and Al-Ubaidah, and El-Ghurairah at Bab al-Mandab (PERSGA/GEF 2004). These locations are shown in Fig. 10 and they have a 9.3 km^2 total land cover (UNESCO [66310] 2022b). Yemen mangroves grow near channels and inlets, shorelines, and off-shore islands as thin forests and they are commonly found on the north coast rather than the south and central coasts. Mangroves distribution can be classified based on their ecological features into four areas: (1) South of Al-Hudaydah to Bab al-Mandab area: mangroves are affected by the high aridity and shoreline topography so the stands are thin and separated, (2) Al-Urj to Al-Hudaydah: stands are confined to small islets and dew tidal inlets and their size is limited, (3) Al-Khawbah to Ras Isa: mangroves density is small and interrupted by large shore areas, and (4) Midi to Al-Luhayah: highest mangrove density can be found here leading to a semi-continuous belt by the shore (PERSGA/GEF 2004).

Human impacts and local threats to mangroves in the Middle East

Despite their importance and adaptation to harsh environmental conditions, mangroves are subjected to various threats that impact their survival. They can be classified into natural and anthropogenic threats.

Natural threats

- *Sea level rise:* rising sea levels threatens mangroves health by leading to increased salinity levels and tidal inundation which inhibits photosynthesis and tree productivity thus shortening its life span (Shehadi 2015). Climate change was highlighted as the major threat to mangroves thrive in Iran (Zahed et al. 2010).
- *Storms and cyclones:* serious storms and cyclones can occur in the Middle East, especially during the monsoon season, leading to storm urges, heavy rainfall, and strong winds. These weather events can physically harm the mangrove environment by uprooting the trees and causing erosion.
- *Extreme temperatures:* high temperatures are common in the Middle East, and extreme heat events beyond mangroves tolerance ranges reduce photosynthesis and cause leaf damage thus decreasing the overall mangrove health (Adame et al. 2021).
- *Sedimentation and erosion:* mangroves are susceptible to erosion and sedimentation by natural processes and their roots may become buried by excessive sedimentation, which will restrict their access to nutrients and oxygen. Also, sediment required for mangrove development and stability may be lost due to erosion (Nardin et al. 2021).
- *Salinity fluctuations:* mangroves have evolved to withstand a certain range of salinity. However, their health may be impacted by salinity variations that occur naturally, such as tidal cycles or intense weather. While abrupt drops in salinity might restrict the availability of nutrients, abrupt rises in salinity can cause salt stress (Chen and Ye 2014).
- *Disease and pests:* a wide range of pests and diseases affects mangroves and they can be impacted in terms of growth and survival by bacterial, fungal, and insect infestations. For instance, middle eastern mangroves have been reported to be impacted by the fungus causing "mangrove dieback" (Osorio et al. 2017).

Anthropogenic threats

- *Shrimp farming:* the rapid expansion of shrimp aquaculture as an industry is a main reason for mangroves loss globally as their wet lands are cleared and converted to artificial shrimp ponds. This alters mangrove ecosystems resulting in changing the hydrology, introducing non-native diseases and species, using wild fish as feed, losing various socio-economic and ecological ecosystem functions, capturing wild shrimp, polluting the environment due to effluent disposal, and losing livelihoods (Ashton 2008).
- *Human activity:* like reclaiming land for infrastructure and urbanization, land conversion to agriculture fields, aquaculture, loading and shipping operations, waste landfilling, and sewage discharge which all threaten man-

groves health in the area (Milani 2018). This was highly observed in Tubli Bay in Bahrain.

- *Overexploitation and unsustainable fishing practices:* these practices threaten mangrove ecosystem as overexploitation of mangrove resources, like timber, as well as overharvesting of fish and crabs associated with mangroves with unsuitable fishing tools can disrupt the food chain and reduce biodiversity.
- *Invasive species:* introducing invasive animal and plant species threatens native mangrove ecosystems as they disrupt ecosystem dynamics, reduce biodiversity, and outcompete native mangrove species (Biswas et al. 2018).
- *Uncontrolled camel grazing:* highly observed in Gebel Elba and Wadi El Gemal in Egypt (Afefe 2021).
- *Irresponsible tourism:* using mangroves for tourism and recreation negatively impacts mangroves as tourists disturb mangroves wildlife specifically birds, collect souvenirs like seeds or leaves, and trample in the sensitive pneumatophores. Mangrove growth can be hindered by Littering and solid waste dumping specifically cans and plastic bags as they release pollutants that could harm the health of mangroves and smother leaves and pneumatophores (Spurgeon 2002).
- *Coastal development:* industrialization, land reclamation for urbanization, tourism infrastructure, and rapid coastal development have resulted in the degradation of mangrove habitats.

Impact of excessive coastal development on mangrove losses in UAE Paleologos et al. (2019) focused on multiple factors that are threatening mangroves growth in the Abu Dhabi. First, as a result of the increased desalination activities in the region, the coastal salinity increased which created hyper-saline environment that requires high suction from the mangrove roots for freshwater extraction which stunts the trees growth. Second, seawater temperature has increased by 7–8 °C due to high energy production and desalination practices which decreased the total dissolved oxygen in the water and thus directly impacting mangroves survival. Third, cement factories are placed near mangrove areas in Abu Dhabi which emits heavy metals like Pb, Ni, Cd, Hg, Sulphur and nitrogen oxides, carbon monoxide, and particulates into the atmosphere which deposits in the water bodies eventually thus negatively interfering with mangroves ecosystem. Fourth, the rapid small islands development in UAE as well as bridges construction for their connection will stress the existing mangrove ecosystems due to microplastic and zinc introduction to the water from brake pads and rubber tires on the roads. Finally, accelerated artificial canals creation changed the shallow lagoons' water currents which increased algae development in the water due to its slow movement as well as burial of some mangrove roots as a result of dredging activities.

- *Pollution and oil spills:* mangrove ecosystems can get contaminated by pollution from a variety of sources, such as oil spills, phosphate balls, agricultural runoff, sewage runoff, and industrial waste. Excessive nutrient inputs can cause eutrophication, which can affect mangrove trees by creating algal blooms and oxygen depletion. Oil pollution is the main reason for mangrove degradation in the Persian Gulf as it affects water quality and contaminate mangrove habitats (Zahed et al. 2010). The following is a case study about the impact of oil pollution on Saudi Arabian mangroves.

Oil toxicology effect on mangroves in Saudi Arabia Farooqui et al. (2015) has reported that *A. marina* seedlings are very sensitive to oil exposure as a field study conducted with them showed 96% death rate when the seedlings were subjected to crude oil transported by weather resulting in yellow curled leaves. Oil spills could have a number of long-term effects on mangroves as under stress they may exhibit significant variations in either their reproductive timing strategy or growth rate. In order to withstand contamination's physical or chemical effects, they can develop additional morphological adaptations. The Arabian Gulf's mangrove ecosystem was primarily impacted by the significant oil spill caused by the Gulf War as besides having indirect impact on mangroves habitat, it can directly kill it. The spilled oil in 1991 during the Gulf War left the Saudi Arabian Gulf with a black layer of tar along its mangrove cover as the layer was made at a higher altitude than the normal soil temperature and the ecological impacts are still under study.

Mangrove rehabilitation strategies in the Middle East

Mangrove forests are disappearing as the global cover was estimated to be 19.8 million km2 in 1980 but has currently fallen to 15 million km^2 (Kathiresan 2008). Rehabilitation is defined the partial or full replacement of the functional or structural features of an ecosystem that have been lost or destroyed or replacing these features with alternative ones that have better ecological, social, or economic value; Restoration, which is a unique case of rehabilitation, is the process of bringing an ecosystem back to its original state as closely as possible (Field 1999). People have gained interest in rehabilitation because of the increase in environmental awareness over the past thirty years as well as the fact that the world's mangrove resources have recently decreased due to the pressures of food production, wood chipping, industrial and urban development, and population growth. Loss of natural mangrove vegetation can happen due to wrong land use or climatic impacts (Field 1999). Not to specify, but countries like United States of America (USA) enacted multiple local ordinances and state laws for mangroves protection as a result for environmental movements and the requests of environmental activists concerned about biodiversity protection, conservation, and sustainable ecosystem use (Melana et al. 2000).

In recent years, a number of popular mangrove restoration strategies have drawn interest and demonstrated promise. Here are some examples:

- ***Community-Based Mangrove Restoration*****:** using this strategy, local communities are actively involved in the restoration of mangroves. It acknowledges the significance of local expertise, involvement, and ownership in reaching successful restoration results. Community based restoration initiatives frequently include sustainable management techniques, livelihood enhancement, and capacity building (Teutli-Hernández et al. 2021).
- ***Ecological Mangrove Restoration (EMR)*****:** the goal of EMR is to restore mangrove ecosystems' natural ecological processes and services. It involves simulating the structure of a natural forest, planting a variety of native mangrove species, and taking hydrological dynamics into account. The objectives of EMR are to increase self-sustainability, improve ecological services, and increase biodiversity (Aheto et al. 2016).
- ***Natural regeneration*****:** the main goal of natural regeneration is to allow mangroves to recolonize degraded regions naturally on their own, without any human intervention. This method is based on preserving the surviving mangrove stands, reducing disturbances, and making sure the suitable environmental conditions for natural seed germination and distribution are available (Kairo et al. 2020).
- ***Blue Carbon and Climate Change Mitigation*****:** mangroves play a significant role in reducing the effects of climate change because of their exceptional capacity to capture and store carbon. High carbon stock locations are prioritized in this strategy for conservation and restoration while taking into consideration the role of mangroves in sequestering carbon (Murray et al. 2023).

Successful ambitious global mangrove restoration goals will positively benefit biodiversity, carbon sequestration, coastal protection, and fisheries production. It is crucial to keep in mind that small-scaled mangrove restoration projects, although being better suited for community management, might not produce benefits at landscape size while on the other hand, large-scale restoration programs failed more often. The solution is adopting sustainable mangrove restoration techniques that boosts the efficacy of smaller projects and reduces the risks associated with the bigger projects. The key is to invest in capacity building of institutes and communities as well as connecting suitable investors with the restoration opportunities (Lovelock et al. 2022).

In the light of all that, it was important to display the successful mangrove rehabilitation and plantation initiatives that took place all over the Middle East.

Mangrove rehabilitation initiatives

Mangrove rehabilitation in Oman

An action plan has been launched by the Environment Authority (EA) to plant 1.5 million mangrove seeds in Khor Ghawi in Wilayat Al Jazir and Al Wusta's Wilayat Mahout Wetland Reserve in Oman in July and August 2022 as a part of the national initiative to plant 10 million trees. The authority intends to plant mangroves in the aforementioned locations to enhance marine organism biodiversity, be a natural habitat for endemic and migratory birds, reduce carbon footprint, and protect lagoons from erosion. During the see ds cultivation in July, the approved international sites will be used to determine the target sites' tidal conditions for determining the precise planting times. Half a million seeds were planted on 29th July 2022 in Khor Ghawi in Wilayat of Al-Jazer, then a million seeds were planted from 31st July to 11th August 2022 in the Wetland Reserve with a 30 cm separation distance. Eventually, the planted area will contain 13.5 hectares of mangroves with a rate of 1000 seeds per 300 m (Oman Observer 2022).

The sultanate has already been planting massive amounts of mangroves for over 17 years (UN Environment Program 2018). Oman mentioned in their master plan for management, conservation, and restoration of Mangroves that there are 13 possible locations suitable for mangroves plantation; There will be temporary nurseries established for seeds plantation with various annual capacities: 5000 pots in Mahawt Island, 5000 pots/year in Khawr Shinas, and 15,000 pots/year in Ras Al Had (Pacific Consultants International and Appropriate Agriculture International Co., 2004) In preparation for COP27, Oman Environment Authority planted 754,000 seedlings in 32 locations along the coast by the end of July 2022 for supporting the following goals: positively impacting the livelihood of communities located near the project location, protecting endangered fish species, restoring mangroves and capturing greenhouse gases, increasing fish stock, and most importantly achieving 2023 Sustainable Development agenda goals (Towards COP27 2022).

Mangrove rehabilitation in Bahrain

Back in 1988, Bahrain declared mangroves of Ras Sanad a Wildlife Reserve and plantation activities for mangroves restoration were carried on but their success was limited (Milani 2018). In 2013, Bahrain initiated the Mangrove Planting Project (MPP) which involved transplanting mangrove seedlings to different locations across the nation where two plant nurseries were established to make this easier: an inside and outside self-irrigation nursery (UN-Bahrain 2023). Following COP26, Bahrain decided to quadruple its mangrove cover to reach 3.6 million trees by 2035 in accordance with the United Nations Framework Convention on Climate Change to achieve the conference goals following a methodology that starts with surveying the country for potential suitable locations for mangroves growth, partnering and coordinating with stakeholders for establishing new nurseries, then planning to accelerate the seed collection and potting process. This will be achievable through a sequence of steps: (1) seeds collection from Tubli Bay, (2) seeds potting in the inside and outside nurseries, (3) seeds transportation previously to established nurseries, and (4) seedlings transportation to the previously selected locations (UN-Bahrain 2023). Moreover, the Kingdom has succeeded in achieving 100% of the annual afforestation goal, by planting 110,000 mangrove seedlings, and about 140,000 trees in several governorates.

Mangrove rehabilitation in Saudi Arabia

In parallel with the launch of the "International Day for Preserving the Ecosystem of Mangroves" in Jubail Industrial City, the National Center for Vegetation Coverage Development and Desertification Control announced the signing of four afforestation contracts for a period of two years each. The purpose of these contracts is to produce and plant 2,200,000 mangrove trees on the northern and southern coasts of the Red Sea and the Arabian Gulf as well as providing other services such as fencing and care for the planted trees. The center had announced the planting of about one million mangrove trees within the Heritage Village and Al-Sawarmeh projects in Jazan. Moreover, The Kingdom aims to plant more than 100 million mangrove trees in the coming years, as part of Saudi Vision 2030 and mitigate the effects of climate change. In the future, it aspires to grow 10 billion mangrove trees.

Aramco company has prepared a program to rehabilitate mangrove forests to the Kingdom's white sand beaches where the program is a living defense against desertification and the restoration will create a huge natural carbon dioxide sink. Aramco began planting its first mangrove seedlings in 1993 in Abu Ali Island, and in 2020 it planted 2 million trees as part of its projects to reduce climate change (Maneja et al. 2020). It has also planted more than 4.3 million mangrove trees in sites along the coasts of the Arabian Gulf and the Red Sea with the support of thousands of volunteers from both company and community (Pinheiro 2020). Currently, two million mangrove seedlings are being planted in the city of Yanbu. This initiative was part of a study commissioned by the Research Institute at King Fahd University of Petroleum and Minerals to re-establish mangrove forests along the shores of the Arabian Gulf. All partners questioned whether the mangroves would be a success, and now the northern shores of the Dahna desert are home to mangrove forests as a living proof for the project’s success.

Mangrove rehabilitation in United Arab Emirates

UAE has boosted its ambition to expand mangrove forests by boosting the mangrove planting target in its second National Determined Contribution (NDC) under the Paris Agreement from 30 to 100 million trees by 2030. The country is already a home to 60 million mangrove trees which form forests spanning an area of 183 $km^2$and capture 43,000 tons of carbon dioxide annually. With the additional plantation of 100 million trees, UAE mangrove forests will cover 483 $km^2$and sequester approximately 115,000 tons of carbon dioxide annually. Moreover, UAE organizes many activities that involve community participation in mangrove seedlings plantation and then taking a cruise to enjoy the beauty of the trees. Highlighting their activities and initiatives, more than 100 NYUAD community members gathered during a day in a unique ecosystem near Jebel Ali to plant 5,000 mangrove trees in less than an hour. This initiative lined with the UAE's national goal announced at COP26: planting 100 million mangroves by 2030. Their efforts did not stop here as Abu Dhabi has succeeded in planting one million mangrove seeds in various locations around the harbor in the Al Dhafra region using drones, as part of the first phase of a mangroves drone planting project in support of the Abu Dhabi Mangroves Initiative with a 48% success rate. This Initiative was announced in February 2021 during the visit of His Royal Highness Prince William, Duke of Cambridge to the UAE.

Mangrove rehabilitation in Qatar

Over the past few years, environmental officials from the environmental department in Qatar have succeeded in doubling the area of mangroves to 9 km^2 about three years ago to 14 km^2 in their cultivation areas on the country's shores along the Gulf resulting in 55 percent increased rate in its area. The Ministry of Environment and Climate Change planted mangroves in 4 areas on the northern and eastern coast after it was limited to the Al Khor and Al Thakhira areas. There are now different sites where mangroves are planted in large areas estimated at thousands of hectares, as mangroves have succeeded in each of Ruwais, Umm Al-Houl, Fuwairit and Ras Kitchen. The country aimed at planting 1 million mangrove trees by 2022 and 10 million trees by 2030. Al-Khayat and Balakrishnan (2014) documented mangrove planted locations in Qatar (Fuwairit, Simaisma, Zekreet, and Al Mafjar).

Mangrove rehabilitation in Iran

Iran is planting mangrove seedlings on 86 hectares of coastal land across the Bandar Length port city as part of its expanding agenda. Hormozgan in Iran has the most mangrove forests among the Arab Gulf countries and it supports almost 93% of Iran's mangroves reaching 10,305.2 hectares (Erfanifard et al. 2022). Moreover, Iran occupies the 43rd place in the world in terms of mangrove forests. In 1991 and 1993, some mangrove reforestation was carried out on approximately 400 ha of land in the Persian Gulf and Oman Sea coastal areas and then Khouran Straits area was protected under various reserves. The Ramsar site was established in 1975, the UNESCO (MAB) Biosphere Reserve was established in 1976, and the "Important Bird Area" was designated by BirdLife International in 1994 to protect the entire Khouran Straits region (Mangroves of Asia, 1980-2005: Country Reports, 2007). A study conducted by Milani et al. (2013) showed that the growth in Iranian mangrove landcover took place between 1973 and 2010.

Mangrove rehabilitation in Egypt

Multiple mangrove rehabilitation initiatives started in Egypt beginning 2007. The FAO started planting *R. mucronata* seedlings in 2007, and then ITTO and ASRT continued mangrove plantations in Egypt in 2010 and 2017, respectively (MALR et al. 2009; Spurgeon 2002). These plantations have become trees now and are currently at different stages of age, heights, and density and can be seen at Hamata, Egypt. The FAO focused on identifying suitable sites for mangrove plantation specifically community-based rehabilitation, and several sites were recommended on Red Sea Marine Parks (Hamata's mangrove cluster, Sharm El-Qebly, and Wadi Lahmi), Nabq Protected Area (Marsa Abo Zabad, Shora Al Marqautta, Al Garghana, and Shora Al Rowaisseya), and Elba Protectorate (El-Hamirah and Adal Deep El-Hamirah) (Spurgeon 2002). The project's specific objective was to carry out studies and establish pilot projects on the sustainable use, conservation, and rehabilitation of mangroves in order to acquire the experience needed for the creation and implementation of a national mangrove conservation and development program. The ITTO started their plantation program in June 2003 where the project lasted for 36 months and succeeded in adding a total of 125,500 square meters (31.3 acres) of cultivated area for mangrove expansion, putting 7.5 acres into operation for agricultural self-renewal in the "Ariar Valley", transplanting 30,000 *A. marina* variety of mangrove from the existing nurseries, and planting *R. mucronata* variety in Hamata and El Quseir (MALR et al. 2009).

The MERS project, developing a participatory mangrove ecosystem restoration model as a nature-based solution to climate change, is an Egypt based project handled by the Center for Applied Research on the Environment and Sustainability (CARES) at the American University in Cairo (AUC) which aims at contributing to sustainable food production, climate resilience, and reducing the barriers within the developing communities. The project duration is five years and MERS main activities include plantation, restoration, and regeneration of 10,000 new mangrove seedling each year in selected degraded mangroves sites along the Red Sea coast line.

Mangroves rehabilitation policies in the Middle East

Not only the Middle Eastern countries but the entire international community need to make joint efforts and a firm commitment to reverse the loss of critically important mangrove habitats worldwide. These efforts will require all countries in the region to work together and with some of current global leaders such as the Conservation International, the Nature Conservancy, and the World Wildlife Fund who appear to be making genuine efforts in providing skills, drive, leadership, and developing and promoting policies for climate mitigation at global level and help countries to implement practices to contain global temperature increase to 1.4°C. The Nature Conservancy (TNC) has played a key and critical role in promoting the restoration and replanting of mangroves in coastal areas. Therefore, before proposing some of the innovative policies for mangrove restorations in the Middle East, it is good to learn from other case studies in the world.

In this section, we will share case studies from two countries, namely Belize and Bahrain. In a recent study by TNC (2021) where TNC negotiated the largest debt restructuring of Belize for marine conservation that the world has ever seen. In this effort, TNC proposed economic pathways and conservation efforts for reducing Belize's national debt by $360 million where Belize agreed to the concept of "Belize Blue Bonds," and restructured its $553 million of debt that will result in $180 million in cash flow for marine conservation over the next 20 years. In addition, Belize committed to protect 30% of its oceans by improving the management of its coastal and marine resources through a marine spatial plan and strengthening environmental protection laws for climate mitigation. As part of this agreement, Belize plans to plant 200 hectares of mangroves in the Turneffe region generating 106,000 tons of carbon offsets over 20 years by working with local landowners to develop sustainable tourism plans for the communities that depend on them. This coastal resilience project will generate revenue from the sale of carbon credits to support ongoing conservation and management of this habitat. This the best example of partnership and implementation of new policies for the reforestation of mangrove forests in Belize.

The second example is from Bahrain where the country has decided to expand green spaces and double the mangrove trees to mitigate climate change and achieve Bahrain's goal of reaching net zero by 2060. At COP 26 meeting in Egypt, Bahrain made a commitment to the goals of the United Nations Framework Convention on Climate Change where Bahrain will take several initiatives including doubling the area under mangroves to reach 3.6 million trees by 2035. This is best policy decision Bahrain has made for the expansion of mangrove cultivation to generate carbon offsets.

Limited number of studies are available where set of policies are suggested to governments for reforestation and minimizing the risk for degradation of existing mangrove forests. Osman and Elbashier (2019) proposed following policies for the rehabilitation of mangrove forests in the Middle East and to minimize their degradation:

- Declare mangrove forests as protectorate areas
- Developing plans for managing mangrove sites
- Creating regulations for ensuring the protection of mangrove trees
- Encourage governments and private sectors to plant more mangrove trees and get involved in the rehabilitation initiatives
- Establish research centers in each country to study the science of mangroves and their growth parameters
- Creating national and local committees for mangroves management
- Increase awareness in local communities using educational tools on the benefits of mangrove to the society
- Control the excessive cutting and animal grazing on mangrove trees through regulations.

Suggested innovative policies and the framework for mangrove conservation and reforestation

All countries with existing mangrove stands need to modify their current policies on ***marine planning and ocean management,*** and develop new policies that are sound, affordable, sustainable, and forward looking to the conservation and restoration of existing mangrove and promotion of reforestation of degraded mangrove sites adjacent to coastal ecosystems such as coral reefs, seagrass meadows, and seaweeds. One of most promising pathways is to implement Environmental Impact Assessment policies in consultation and engagement with stakeholders, especially coastal communities to protect mangroves and other coastal wetlands. Following are the key recommendations on policy framework:

Develop new policies using carrot and stick* approach *for mangroves conservation and Preservation: The first step before developing any new policy should be to start a dialogue with stakeholders. Policy makers need to reach out to all stakeholders and organize ***listening to sessions*** with local coastal communities to highlight the value of mangroves for the society, and its impact on environment. Educate them about blue carbon economy and increased carbon sequestration when mangroves are protected or restored. Also, discussion needs to be made on what happens if mangroves are degraded or destroyed by the local communities through animal grazing and/or wood cutting. If mangroves are destroyed permanently, these ecosystems will emit the carbon back to the atmosphere that they have stored for centuries in mangrove trees and into oceans and these degraded sites will become sources of greenhouse gases. Experts estimate that as much as 1.02 billion tons of carbon dioxide are being released annually from degraded coastal ecosystems, which is equivalent to 19% of emissions from tropical deforestation globally (Lee et al. 2019). Mangroves, tidal marshes, and seagrasses are critical in protecting coastal water quality, healthy fisheries, and coastal protection against floods and storms. For example, mangroves are estimated to be worth at least US$1.6 billion each year in ecosystem services in the world to support coastal livelihoods (Lee et al. 2019).

A good policy would be to declare all mangrove sites as nationally protected sites with significant benefits to local coastal communities responsible for maintaining, preservation and conservation of mangroves as an incentive (carrot approach). Studies have shown that the economic value of mangrove forests to the ecosystems is about US$91,000 which is more than other marine ecosystems such as coral reef, seaweeds, seagrass etc. (Kathiresan 2021). Policies can provide benefits to local communities in the form of free education to children, nutritious lunch in schools to children, incentives to start local industries with low interest rate loans like poultry, dairy, fish, and food processing enterprises which will help local livelihood. Also, part of the policy should be to put a complete ban on animal grazing and wood cutting for mangrove conservation. Heavy fines to those who will violate these policies (stick approach) and some incentives who those who become local guardians on maintaining and safeguard of mangrove forests (carrot approach).

Second, new policies should be developed for small and large business houses building resorts, hotels, shopping centers and other infrastructures like manufacturing/building material plants in coastal area. These business houses must meet the strict environmental standards for environmental degradation such as soil, water and air pollution and must pay for carbon credits generated in response to GHG emissions so that these enterprises are carbon neutral. The income from these carbon credits must be put in an escrow fund and used only for mangrove preservation, maintenance, and reforestation purposes. This will encourage local communities to start nurseries for growing mangrove seedling and brining more area under reforestation of mangroves.

Third, a good public transport system in the country could use Singapore model where there is environmental tax on buying cars to minimize GHG emissions. This environmental tax is collected as additional registration fee (ARF). Under this policy, cars with value under $20,000 are charged ARF of 100% at the time of purchase, cars that value in the range of $20,001 and $50,000 will be taxed ARF 140% of the car value, and for cars with a value above $50,000, will be taxed ARF of 180% of value. This policy discourages people to buy cars and encourages them to either use public transport system or bicycles as a means of transport. This policy in Singapore was developed to control carbon emissions from the use of automobiles. Also, under the policy where cars emit low carbon emissions of less than or equal to 160 g/km, the car owners are entitled to a rebate that ranges from $5,000 to $20,000. On the other hand, car owners will be penalized with a surcharge that ranges from $5,000 to $20,000 if their vehicle emits carbon more than or equal to 211 g/km.

Other policies could use Sweden model where there is very high parking fee if employees park their cars in parking lots near their offices unto $10 an hour. This is to discourage employees/workers to drive cars, but cities provide free parking spaces for the bicycles. Again, it is a carrot and stick system approach in policy development.

Enhance the role of collaborative research on mangrove ecosystem and biodiversity enrichment: collaborative research offers a comprehensive understanding of mangrove ecosystems, biodiversity, and the factors affecting their resilience and health. While the obtained knowledge is necessary for making educated decisions and implementing conservation measures that protects mangrove habitats, collaborative research enriches biodiversity in various ways:

- *Assessing ecological processes and interactions* scientists study the complex ecological processes in mangrove ecosystems and examine seed dispersal, pollination, nutrient cycling, and predator–prey relationships. Key ecological linkages and their significance in preserving biodiversity can be identified by understanding these processes and the interactions between species
- *Understanding species composition and distribution* research efforts facilitate the identification and documentation of wide variety of plant and animal species present in mangrove environments. Researchers can gain a better understanding of the distribution patterns, abundance, and ecological requirements of different species by conducting surveys and assessments and effective conservation and management techniques require this knowledge
- *Engaging local communities and stakeholders* engaging with stakeholders, indigenous groups, and local communities is a common aspect of collaborative research. Through the integration of traditional ecological knowledge into scientific study, this participatory approach facilitates information sharing and community involvement in conservation initiatives. Research will match the needs of people depending on mangrove ecosystems by involving the local communities which will lead to enhanced biodiversity protection
- *Restoration and conservation practices* techniques for mangrove conservation and restoration are developed and improved through collaborative research. Through examining the efficacy and success of various restoration techniques, scientists can improve strategies that support

the restoration of ecosystem functions and biodiversity. It also helps in directing adaptive management techniques and assessing the long-term results of restoration programs.

- *Investigating threats and conservation challenges* this research addresses the threats faced by mangroves like climate change impacts, human activities, pollution, and habitat degradation. Researchers can assess the effects of threats on biodiversity by studying them then develop strategies to mitigate them. The identification of priority locations for conservation and restoration initiatives is another benefit of this research.

Carry out vulnerability assessments on the existing mangroves: in order to comprehend the effects of vulnerability assessment and its application on mangroves, as well as to develop a framework for adapting to climate change, this evaluation employs a variety of measurement techniques.

The first measuring technique includes three dimensions: sensitivity, exposure, and adaptive capacity. Sensitivity indicates how much exposure has affected the mangroves, exposure refers to the external factors that stress the mangroves like decreased freshwater and higher carbon dioxide concentrations, while adaptive capacity is defined as a system's capacity to adapt to the effects of climate change and is indicated by a number of factors as information and technology (Ellison 2015).

The second measuring technique is using mangrove vulnerability index thorough framework for examining how the social and environmental context responds to change; Three variables are evaluated: hazard mangrove index (HMI), biological mangrove index (BMI), and Physical Mangrove Index (PMI) (Yunus et al. 2018). These variables combine to form the mangrove vulnerability index (MVI). Each index includes parameters that should be tested to assess the mangroves vulnerability under this certain scope. Parameters to be tested for HMI include wave and wind, sea level change (Gilman et al. 2008), precipitation (Arnous et al. 2011), and human activity (Goldberg et al. 2020) while BMI includes tidal ranges (Ellison 2015), soil and geomorphology and elevation ranking (Krauss et al 2010), distance to coastline (Mafi-Gholami et al. 2020), salinity, canopy density and normalized dense vegetation index while PMI includes mangroves height and species.

Therefore, vulnerability assessment, through the tested parameters under each index, yields outcomes that help us assess what parameters to focus on exactly hence we can shape the policies based on the modifications/parameters tested.

Finally, governments must take the responsibility to protect, sustain, conserve and augment mangrove forests through promotional as well as regulatory measures. The promotional measures should develop and regulate policies at the federal government in collaboration with local governments and local communities for 'Conservation and Management of Mangroves in coastal areas as a matter of national pride and commitment to minimize GHG emissions as a global responsibility and protect people from risks of climate change.

Summary and conclusion

Mangrove forests are one of the best NBS that sequester excess CO_2 from the atmosphere at a rate four to five times greater than normal forests. Their benefits are numerous including: coastal flood reduction, coastlines stabilization, water quality enhancement, providing nesting areas to migratory birds and nurseries to wildlife, providing abundance of local seafood, improving local economies, and helping countries meet their commitment/targets to net zero carbon emissions. This paper has shown that factors affecting mangroves growth are: temperature, coastal water salinity, sediment yield and supply, coastal typology, groundwater, wave action, tidal currents, tidal range, DO, and other water characteristics. Fish production and carbon sequestration are among the best environmental and food security benefits of Mangroves. Currently, mangroves occupy 15.2 million hectares globally contrary to occupying 18.1 million hectares in 1980. This indicates that destruction of mangrove forest has continued during the period of industrial revolution and still going on. Worldwide, mangroves can be found in Africa, South America, Asia, Western Atlantic Ocean, Caribbean Sea, and Australia. They can be found in the Middle East in: Oman, Bahrain, Saudi Arabia, UAE, Qatar, Iran, Egypt, Sudan, and Yemen. There are only two abundant species of mangroves in the region: *Avicennia marina* and *Rhizophora mucronata*, as they are the only species that can tolerate the region's extremely harsh, dry, and hot environmental conditions. Detailed locations of mangroves in each of the nine countries are mentioned.

The key findings of this review article are:

(1) Only selected species of mangroves flourish in the hot climates of the Middle East due to lack of fresh water from rains compared to more than 80 species that have been found in the tropical countries like Indonesia.
(2) Saudi Arabia has the largest mangrove cover of 20,400 ha while Bahrain has the smallest area of 80 ha. The smallest mangrove height can be found in

Bahrain (1 m long) while the tallest can be found in UAE (10 m long). The average height in the region varies from 4 to 6 m.

(3) Mangroves in the region are dwarves due to high sea surface temperatures exceeding 31 °C in summers, low precipitation, high salinities over 40 ppt, and minimal riverine nutrient inputs which results in 2–4 m average trees in height

(4) Mangroves growth in Oman and Bahrain is affected by intertidal areas with gentle slow slope and access to low salinity water that is discharged from underground springs and close farms, respectively.

(5) Mangrove trees in Saudi Arabia, Qatar, and Egypt are impacted by presence of high nutrients in water with small tidal amplitudes and lagoons presence, receiving fine sediments and high organic matter content, and geomorphological aspects of the lagoons and bays of the Red Sea, respectively.

(6) Mangroves tolerate the Middle East harsh environmental conditions through: (1) adaptation to high temperature, (2) adaptation to elevated salt content by filtering about 90% of the seawater salt, (3) successful reproduction and offspring survival, and (4) anoxic soil and waterlogging.

(7) Various factors threaten mangroves survival including: hydrology alterations, groundwater input reductions, extreme drought, high nutrient loading, and fluctuations in seawater level.

(8) Oil pollution and mangrove leave's overexploitation through camel grazing are the two main reason for mangrove degradation in the Persian Gulf.

(9) To overcome the impacts of threats facing mangroves, several rehabilitation initiatives have been taken in the Middle East: (1) Oman announced a national initiative to plant 10 million trees and has succeeded in planting 1.5 million mangrove seeds in Khor Ghawi in Wilayat Al Jazir and Al Wusta's Wilayat Mahout Wetland Reserve as a start, (2) Bahrain has decided to quadruple its mangrove cover to reach 3.6 million trees by 2035, (3) Saudi Arabia has planted 2 million trees with Aramco in 2020 then planted more than 4.3 million mangrove trees in sites along the coasts of the Arabian Gulf and the Red Sea where the kingdom's goal is to plant more than 100 million mangrove trees in the coming years as part of Saudi Vision 2030, (4) UAE aims at expanding its mangrove forests from 30 to 100 million trees by 2030 and they are achieving it through organizing many activities that involve community participation in mangrove seedlings plantation and then giving the access of a cruise to move around the mangroves for proper management of mangrove forests, (5) in addition to introducing new plantation methods using drones one million mangrove seeds were planted in the Al Dhafra region, Qatar aims at planting 1 million mangrove trees by 2022 and 10 million trees by 2030 while Iran is planting mangrove seedlings on 86 hectares of coastal land as part of its expanding agenda across the coastal city.

(10) Finally, Egypt has developed policies and goals for reforestation of mangroves in the country and started planting *R. mucronata* seedlings in coordination with the FAO in 2007. Then, the ITTO and ASRT continued mangrove plantation in 2010 and 2017 respectively. Some of the research institutions, like CARES at the American University in Cairo, have initiated research projects to promote the plantation of mangroves in partnership with local communities in Marsa Alam.

On the basis of research conducted in this paper, they key recommendations are:

- The Middle East countries' governments are advised to invest more in mangroves reforestation and relevant tourism activities. More money should be added into the science research fund to study the factors impacting the growth or degradation of mangroves in the region, support more rehabilitation actions, and take inspiration from the showcased rehabilitation initiatives.
- Countries need to develop policies and future strategies for zero carbon emissions using the carbon offset credits from mangrove plantations just like Bahrain has set a goal of zero emissions by 1960. Also, Egypt needs to expand its connectivity with global leaders of Carbon Credits as Belize has taken advantage of their initiatives on mangroves to get concessions from international banks/donor to reduce their national debt by almost $360 million.
- Investments in mangrove conservation and restoration efforts in the region will give the highest return on investment in mitigating climate change and help in thriving the economy of surrounding coastal communities. The success of NBS will not be sustainable unless the surrounding local communities are involved, and their livelihoods are positively impacted from implementing mangrove-based projects with incentive policies.

Acknowledgements The American University in Cairo's Center for Applied Research on Environment and S, School of Science and Engineering acknowledge the support received from HSBC/ Climate Solutions (CSP) Partnership for funding the project "Developing

Participatory Mangrove Ecosystem Restoration Model as a Nature-Based Solution to Climate Change (MERS)".

Author contributions All authors contributed to the study conception and design, data collection and analysis. The first manuscript draft was written by Toqa Allah Waleed and all authors reviewed and commented on previous versions of the manuscript. All authors read and approved the final manuscript. The authors have no relevant financial or non-financial interests to disclose.

Funding Open Access funding enabled and organized by Projekt DEAL. The work was funded through the project "Developing Participatory Mangrove Ecosystem Restoration Model as a Nature-Based Solution to Climate Change (MERS)".

Data availability All data generated or analyzed during this study are included in this published article.

Declarations

Conflicts of Interest The authors declare that they have no conflict of interest.

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