



Significance of *Avicennia Marina* in the Arabian Gulf Environment: A Review

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Abstract

Mangroves are ecologically important and highly productive intertidal plants that thrive in saline to brackish environments in tropical and subtropical shallow-water habitats. *Avicennia marina* is the only mangrove species found in the Arabian Gulf (hereafter the ‘Gulf’) coastal region, marking the northernmost boundary of mangroves in the Indo-Pacific region. This species predominantly inhabits sandy substrate with low organic content and is recognized for its high tolerance to extreme temperature and salinity variations. It has also proved its resilience to the impact of the Gulf War oil spill. Despite these challenges, mangrove ecosystems in this region continue to provide critical ecosystem services, sustaining biodiversity, livelihood support, climate change mitigation, and recreational opportunities. However, in the past two decades Gulf mangroves have been facing significant threats, including extensive coastal development, shoreline modification by establishing marinas and ports, and climate change-associated impacts such as sea-level rise and altered precipitation patterns, which pose significant risks to this fragile ecosystem. These challenges endanger mangrove ecosystems’ structure and productivity and present immediate and long-term risks to associated species and ecosystem services. However, recent years have witnessed successful mangrove restoration projects, leading to expansion and notable ecological advantages, including increased biodiversity and improved shoreline protection. This review addresses the current knowledge gap by providing an overview of *Avicennia marina* distribution in the Gulf, exploring the significance of its ecosystem services, analyzing the impacts of stressors, and examining conservation and restoration efforts, with attention to nature-based and biotechnological approaches for promoting mangrove growth and conservation in the Gulf.

Keywords Mangroves · Arabian Gulf · *Avicennia marina* · Ecosystem services · Coastal development · Oil pollution · Climate change

Introduction

Mangroves are among the most productive and biologically diverse coastal ecosystems. They occur as woody plants and shrubs in the intertidal zones of tropical and subtropical coastal regions, including Africa, America, Asia, and Oceania (DeYoe et al. 2020; Adame et al. 2021). They are known for their ability to thrive in adverse environments, such as fluctuating temperature and salinity levels

and intense tidal action. Approximately 50–75 different mangrove species are in 20–26 genera and 16–20 families (Ellison 2002). The floristic diversity of mangroves is much lower than that of other tropical communities. About 25–30 species are found in India and Southeast Asia, but diversity is much more impoverished in America and Africa, with 1–5 tree species. Notably, only one species is found along the Arabian Gulf (hereafter the ‘Gulf’) coast.

Avicennia marina (Forssk.) Vierh (*A. marina*) is the only coastal vegetative salt-tolerant halophyte that thrives in environmentally challenging habitats characterized by harsh conditions such as extreme temperatures, aridity, and high salinity levels, which are widely acknowledged as constraints on mangrove growth (Ball 1988; Sheppard et al. 1992). The Gulf spans over 900 km from 24–30° N and 48–56° E (Al Muzaini and Jacob 1996), and it is bordered by Iran, Iraq,

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Kuwait, Saudi Arabia, Oman, the United Arab Emirates and Qatar (Fig. 1). The Gulf is connected to the western Sea of Oman and the Arabian Sea via the Strait of Hormuz. The region experiences high evaporation rates, from 1.4 to 2.1 m/y, coupled with limited precipitation between 0.07 and 0.1 m/y (Barth and Khan 2008). Air temperatures in the Gulf can vary greatly, with summers exceeding 40 °C and winters dropping below 10 °C (Zahed et al. 2010). These conditions and restricted access to open seas lead to hypersaline and dense waters. Salinity levels in the Gulf typically range from 38.5 to 42 (Al-Ansari et al. 2022), with localized shallow lagoons experiencing levels as high as 100 (Al Muzaini and Jacob 1996). The rivers that flow into the Gulf originate in Iran and Iraq- the Tigris and Euphrates Rivers pass through Mesopotamia in southeastern Iraq and converge to form the Shatt Al-Arab River, and the Karoun River, originating from the Zagros Mountains of Iran, joins Shatt Al-Arab downstream and ultimately merges into the northwestern Gulf.

Despite the harsh climatic conditions in the Gulf, *A. marina* is highly resilient and provides several ecosystem services. Mangrove ecosystems in the Gulf are vital hubs for fisheries, biodiversity conservation, and carbon sequestration and contribute to the ecological and socioeconomic stability of the region. However, these mangroves are presently surviving on the edge of their tolerance thresholds, and their continued existence is a matter of concern. The harsh environmental conditions make them highly vulnerable to stressors, including human-induced activities and

the repercussions of climate change. For instance, the Gulf coast of Saudi Arabia has undergone substantial urban and industrial developments, particularly around Ras Tanura/Safwa and Abu Ali Island, since 1950 (Saderne et al. 2020), and total mangrove coverage in Saudi Arabia has reduced by 55% (Amin et al. 2018; Sohaib et al. 2023). The environmental hazards linked to climate change, including elevated sea levels, more frequent storms, changes in ocean currents, and shifts in precipitation patterns, also represent considerable risks to mangroves (Gilman et al. 2007; Mahapatra et al. 2015). It may be noted that the Gulf is nearly free from any storm. The Gulf is a crucial water passage that has undergone extensive development for crude oil production and transportation, which has led to significant contamination by petroleum and its by-products. Oil spills are frequent given its significant contribution to worldwide oil sources with two-thirds of the world's proven oil reserves (Hassanshahian et al. 2020). The semi-enclosed nature of the Gulf results in a residence time of 3–5 years; hence, pollutants entering the Gulf tend to persist for a longer duration as far the basin is concerned (Sheppard 1993). However, the residence times in the coastal regions are much shorter, of the order of 10–30 days (Lecart et al. 2024).

The literature on marine plants of the Gulf (Al Muzaini and Jacob 1996), ecophysiology (Yasseen and Al-Thani 2013), and the effects of the marine environment on mangroves (Khan et al. 2002; Sheppard et al. 2010; Burt 2014; Naser 2014) has only made a brief mention of *A. marina*

Fig. 1 Map of the Arabian Gulf



mangroves, often without a detailed analysis. A comprehensive understanding of the ecosystem services provided by *A. marina* in the Gulf and the efforts towards conservation and restoration remains poorly described. Thus, there is a need for a comprehensive review that covers all essential information on the *A. marina*, especially, the significance of ecosystems services provided by the mangroves in the Gulf, the impacts of coastal developments, oil pollution and climate-change associated effects on the mangrove ecosystem and the current status of conservation and restoration efforts in this region. Accordingly, the present review is framed to cover the following objectives: (i) providing an overview of regional mangrove distribution, (ii) exploring the significance of ecosystem services, focusing on provisioning, supporting, regulating services and cultural services, (iii) analyzing the impacts of coastal developments, oil pollution, and climate change-associated effects on the mangrove ecosystem in the Gulf, and (iv) examining conservation and restoration efforts in the region, including nature-based and biotechnological approaches for enhancing mangrove growth.

Data Used

For the review, a comprehensive search was conducted across academic databases, including Scopus, complemented by additional resources such as ResearchGate, Google Scholar, and ScienceDirect, covering the timeframe from 1990 to 2024. A variety of search terms were used, incorporating combinations of “*Avicennia marina*” with “Arabian Gulf” and “Persian Gulf,” as well as keywords

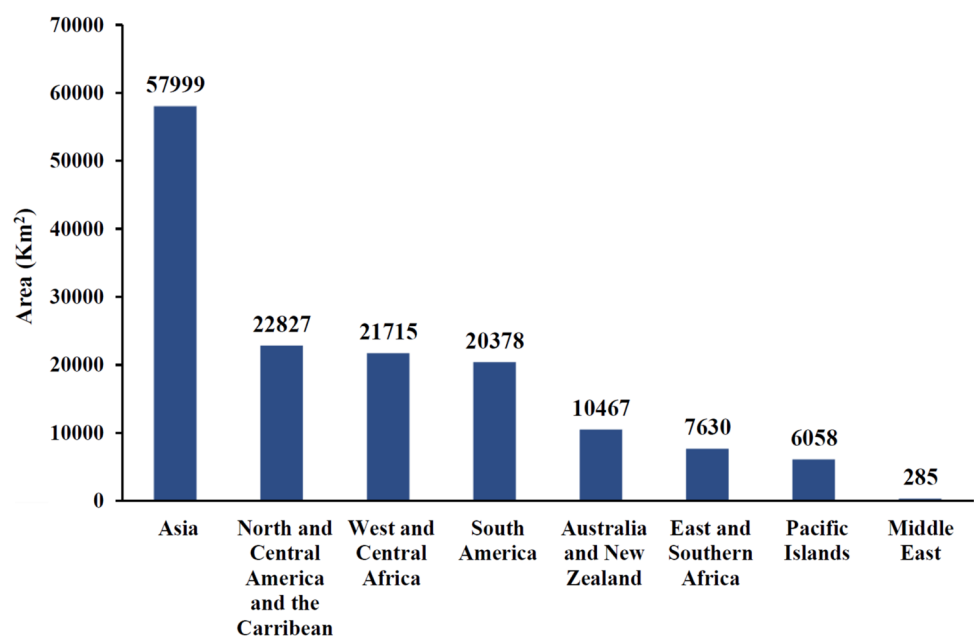
about ecosystem services, macrofauna diversity, coastal development, oil pollution, climate change, and restoration. Articles were screened based on their relevance to the specified topics, focusing on studies related to mangrove distribution, ecosystem services, impacts (including oil pollution, coastal development, and climate change), and macrofauna diversity of *A. marina* in the Gulf. In total, 72 articles specifically addressing *A. marina* in the Gulf were included in this review.

An Overview of *A. Marina* Distribution in the Arabian Gulf

Globally, mangroves are found in regions between 30° north and south of the equator, with some extending into subtropical and warm-temperate zones (Gao 1999), and cover an area 147,359 km² (Bunting et al. 2022) (Fig. 2). Mangroves occupy in 118 countries and territories, with the most extensive distribution in Asia (39.36%), followed by Africa (19.92), North and Central America (15.49%), South America (13.83%), Australia and New Zealand (7.1%), Pacific Islands (4.11%) and Middle East (0.19%).

The initial documentation of mangroves in the Gulf is traced back to the fourth century BC, recorded by Aristotle and Admiral Nearchus (Saenger 2013). Few researchers have conducted spatial assessments of mangrove coverage in the Gulf, primarily focusing on national estimates. For example, for Bahrain (Abido et al. 2011), the UAE (Habshi et al. 2007, 2014; Moore et al. 2014; Leandro et al. 2022), Iran (Zahed et al. 2010; Safiari 2018; Ghayoumi et al. 2022), and Qatar (Al Khayat and Balakrishnan 2014). The overall spatial

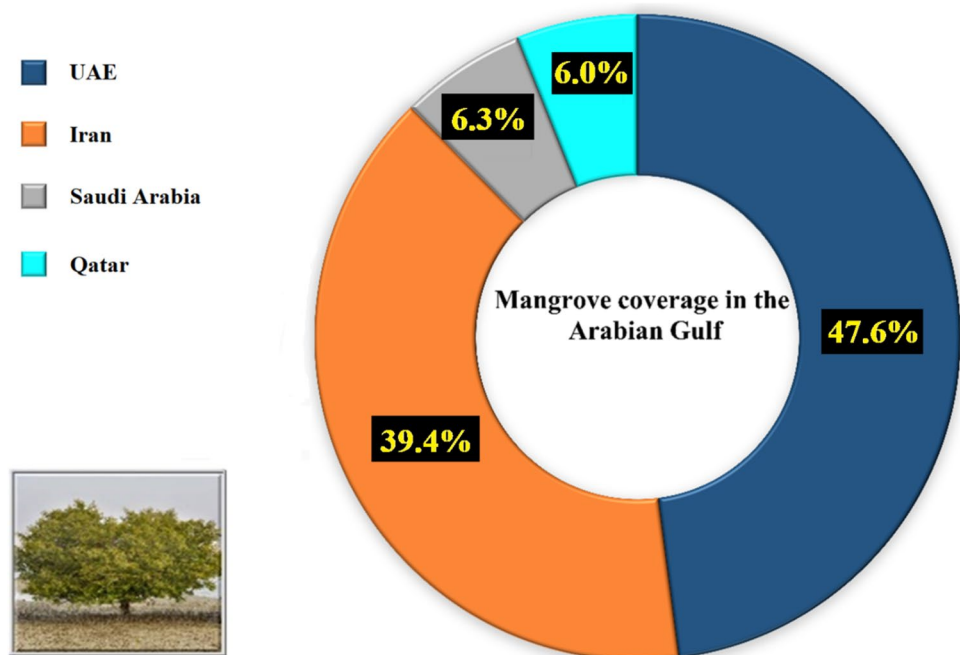
Fig. 2 The bar graph of global mangrove extent in 2020 (Bunting et al. 2022)



distribution of mangrove communities in the Gulf is estimated to be 165 km² (Al Mahasheer 2018). The author estimated the total mangrove coverage in UAE, Iran, Saudi Arabia, Qatar, Bahrain, and Kuwait to be 78.76, 65.24, 10.36, 9.97, 0.58, and 0.56 km², respectively, accounting for 47.6%, 39.4%, 6.3%, 6%, 0.4%, and 0.3% of their total coverage (Fig. 3). *Avicennia marina* is sporadically distributed at low densities all along the Gulf coast of the UAE. The highest abundance is observed in Abu Dhabi, Umm Al Quwain, and Ras Al Khaimah (Leandro et al. 2022). Mangroves in Abu Dhabi cover 10,384 ha along 547 km of coastline, constituting approximately 80% of the total mangrove forest area in UAE (Yousif and Sen 2020). The Khor al Beida mangrove forest in Umm Al Quwain is also among the largest and most genetically diverse ecosystems of the UAE, with an area of 1877 ha (Habshi et al. 2007). The existing mangrove population in Dubai are only the planted mangroves situated in Ras Al Khor. The reintroduction of the red mangrove, *Rhizophora mucronata* (*Rh. mucronata*), has resulted in a long-term survival rate of 81% in Abu Al Abyad, UAE after 11 years of plantation (Yousif and Sen 2020). The mangrove forests in Iran are ranked 43 globally and 10 in Asia (FAO 2003) with *A. marina* accounting for more than 97% of the total mangrove cover of the region (Zahed et al. 2010). In Iran, the *Rh. mucronata* is found only in Sea of Oman along southern Iranian coast. The Hara Biosphere Reserve, situated on the northern coast of Qeshm Island and the Khamir Port of Iran, has the largest mangrove ecosystem. Covering 40 km², the Khuran mangrove forest in the Hara Biosphere Reserve accounts for 45% of the total mangrove coverage of Iran (Hemmati et al. 2021).

The total area covered by mangroves in Qatar is approximately 981 ha (Al Khayat and Balakrishnan 2014), ranging from small scattered shrubs in Dawhat Zekreet on the western coast to dense swamps in the northeast Al Dhakhira and Al Khor. Natural mangroves are found in four regions of Qatar: Al-Khor, Al-Dhakhira, Erida, and Umm Sa' (Al Khayat et al. 2021). *A. marina* has been introduced to additional locations such as Al-Arish, Al-Mafjar, Al-Wakrah, Fuwairit, Simaismah, and Zekreet, particularly in areas with inlets or creek formations. Nevertheless, developmental activities such as the construction of harbors, marketplaces, and beach promenades have led to the removal of afforested mangroves in Umm Al-Hul and Al-Wakrah (Al Khayat and Balakrishnan 2014). Mangroves in Saudi Arabia covering Gulf and Red Sea coasts represent 0.14% of the global mangrove coverage (FAO 2005a). However, in the Gulf coast of Saudi Arabia, the mangroves are seen only at North Jazeerat Qurma and Tarut Bay (Sohaib et al. 2023; Elhag et al. 2015). Mangroves at Ras Sanad (Tubli Bay) in Bahrain are one of the protected areas along with Hawar Islands and Al-Areen Wildlife Park. The existing natural mangrove forests are in Tubli Bay, with the largest is in the Ras Sand area (Milani 2018; Naser 2023). The coasts of Kuwait and Iraq lack naturally occurring mangroves due to extreme temperature variations observed in the region. The 0.58 km² of vegetation estimated in Kuwait may not necessarily correspond to mangroves (Almahasheer 2018). The mangrove reintroduction in Kuwait during 1960s and 1970s were unsuccessful due to non-survival of the plants (Kogo and Tsuruda 1996; Firmin 1968). The *A. marina* was further reintroduced in Sulabikhat Bay, Kuwait, in 1991,

Fig. 3 *A. marina* distribution percentage in the Gulf coasts. (Modified from Almahasheer 2018). The mangrove coverage estimates of Bahrain and Kuwait accounts less than 1% in total, hence not included in the graph.



out of which the trees planted below 3.0 m tide line found successful (above 85%) with a growth of up to 2.5 m after 7 years (Abo El-Nil, 2001). Subsequently, mangrove plantations were established in Kuwait Bay and Subbiya channel in the proximity of Boubyan Island with a reasonable success rate (Bhat et al. 2004). In 2006, mangrove plants were reintroduced on the artificial islands of Sabah Al-Ahmad Sea City in southern Kuwait, which resulted in successful germination and establishment of plantations encompassing a total area of 0.009 km² (Loughland et al. 2020).

The mangrove coverages described above are estimated in different timeframes using different methods. Over the years, significant changes have happened in the Gulf mangroves that are not well attributed in such scattered and diversified estimates. A unified estimate of mangrove coverage is necessary to investigate the changes of mangrove trees over different periods, to relate it with the ecological transformation, to estimate carbon stocks, and to inform the conservation and restoration efforts. Recently, Rondon et al. (2023) made an attempt to estimate the extent of mangrove distribution and cover in the Gulf Cooperation Council (GCC) countries by using the forest/tree attributes obtained from the remote sensing data. Mohan et al. (2024) also utilised remote sensing techniques to derive mangrove forest regeneration age maps for the GCC, which helped to delineate the drivers of the restoration success in the region. On the other hand, the ground-level field data is important to validate the

remote sensing results. Hence, a comprehensive analysis of the mangrove coverage incorporating both remote sensing techniques and field observations is important to accurately represent the mangrove coverage of the Gulf. The timely field observations can be achieved through regional-level collaborations, which can be further integrated into the remote sensing tools.

Ecosystem Services of *A. Marina* in the Arabian Gulf

To emphasize the intrinsic link between human societies and ecosystems, the Millennium Ecosystem Assessment (MA 2005) introduced the concept of categorization of ecosystem services into four main types: provisioning (fodder, fuel, fiber and medicinal resources), supporting (nutrient cycling, primary production and habitat provision - feeding and nursery grounds), regulating (climate change mitigation, carbon sequestration, erosion prevention and flood control) and cultural services (recreation, tourism, education and cultural heritage) (Schwenke and Helfer 2021). Despite extensive research on mangrove ecosystem services worldwide, there is a scarcity of studies emphasizing the benefits of mangroves and their ecosystem services in the Gulf region. Mangrove in the Gulf provide a wide range of essential ecosystem services (Fig. 4), including maintaining biodiversity,

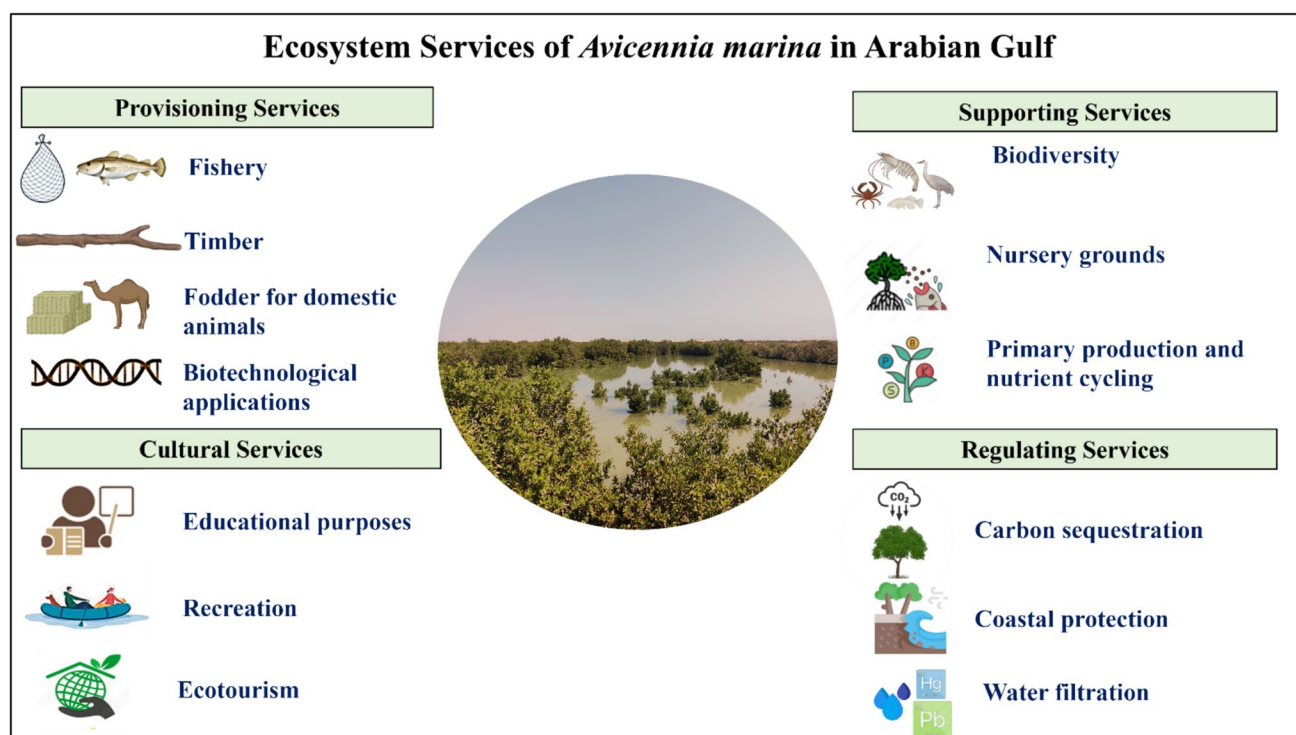


Fig. 4 Ecosystem services of *A. marina* in the Gulf

supporting livelihoods, mitigating climate change, and providing recreational opportunities (Donato et al. 2011; Moore et al. 2014). Additionally, the conservation and sustainable management of these critical coastal habitats are vital for the well-being of local community, biodiversity and preservation of their natural heritage.

Provisioning Services

Mangrove ecosystems have been utilized for various purposes over time, including as sources of food, timber, fuel, and medicine. Historically, they were used as fodder crops for domesticated animals. Prior to the discovery of oil, Gulf region relied heavily on this material for construction (Beech and Hogarth 2002).

A. marina in Iran is mainly categorized as a non-industrial and conserved tree community, providing limited exploitation for provisioning services, including the sustainable harvesting of branches, beekeeping, aquaculture, and medicinal use (Ghayoumi et al. 2022). The Hara Biosphere Reserve in Iran supports the sustainability of many rural communities along the coast. Furthermore, the mangrove functions as a crucial fishing hub, providing a livelihood for numerous fishing families, especially those involved in small-scale fisheries (Pour et al. 2017).

Few researchers have focused on the distinctive characteristics of mangroves in the Gulf, particularly their potential for biotechnological and pharmaceutical advancements. Mangroves and their microbial communities possess antibiotic resistance and relevance for advancements in biotechnological applications. A recent study of propolis from *A. marina* in the Gulf coast of Saudi Arabia revealed promising antibacterial activities against pathogenic bacteria, with four identified compounds: alginic acid, carrageenan, fucoxanthin, and cycloeudesmol (Alshiekheid 2023). Honeybee propolis, derived from mangroves, is a natural resin known for its medicinal properties and is a potential source of antibiotics. In another study, green synthesis of cobalt nanoparticles (CoNPs) using a fungal extract from *Periconia prolifica* (*P. prolifica*) derived from mangrove trees on Tarut Island in Saudi Arabia showed enhanced antibacterial properties against Methicillin-resistant *Staphylococcus aureus* (MRSA) and *Escherichia coli* (Hodhod et al. 2023). *P. prolifica* exhibited an increased tolerance for metal bioaccumulation, which is crucial for nanoparticle synthesis. Nanotechnology allows the modification of metal characteristics by controlling their size, chemical composition, and dimensions, thereby providing numerous ways to combat drug-resistant microorganisms and address environmental concerns associated with traditional approaches (Soufi et al. 2021). Developing eco-friendly synthesis of nanoparticles with antimicrobial properties indicates promising outcomes with implications for advancing nanobiological

applications in the pharmaceutical industry. The significance of the fungal group *thraustochytrids* isolated from *A. marina* and their potential role in producing polyunsaturated fatty acids (PUFAs) have been emphasized by Abdel-Wahab et al. (2021). The study revealed that several strains have exhibited promising characteristics for PUFA production, and phylogenetic analyses have revealed their close relationship with *Aurantiochytrium* species along the Saudi Arabian coast. Prior research in other mangrove species in Biscayne Bay, Florida, USA has demonstrated that *Aurantiochytrium* species can produce valuable products and generate a high biomass containing up to 70% lipids (Ganuza et al. 2019). *Thraustochytrids* can produce palmitic acid with a high-octane number, low iodine content, and high oxidation ability, making them suitable for producing high-quality biodiesel (Ramos et al. 2009). Mangrove seed, fruit, leaf, and stem extracts contain bioactive compounds with antioxidant, anti-inflammatory, and antimicrobial properties, having pharmaceutical importance (Ibrahim et al. 2022).

Supporting Services

Mangroves promote the coexistence of different species by reducing their ecological niche overlap, providing refuge for smaller creatures, and reducing the increased risk of predation. Several studies have documented macrofaunal diversity in mangrove forests of the Gulf (Ghasemi et al. 2011; Al-Khayat and Giraldez 2020; Delfan et al. 2020, 2021; Giraldez et al. 2020; Hajializadeh et al. 2020; Loughland et al. 2020; Al-Khayat et al. 2021; Vahidi et al. 2021; Nozarpour et al. 2023). Seasonal fluctuations in temperatures have a substantial impact on species biogeography in the Gulf. Although the Gulf mangrove macrofaunal communities exhibit low diversity and functional redundancy, they play crucial roles in detritus formation and nutrient restoration (Delfan et al. 2021). The dominant fauna inhabiting mangrove forests in the Gulf include brachyurans, grapsoids, and octoploid crabs. Crab species from *Camptandriidae*, *Dotillidae*, *Ocypodidae*, *Macrophthalmidae*, and *Sesarmidae* are the most frequently found in the mangrove forests in Iran (Sharifian et al. 2023). Along the UAE coast, species of the families *Ocypodidae*, *Grapsidae*, *Portunidae*, *Majidae*, *Xanthidae*, and *Leucosiidae* are predominant (Al-Ghais and Cooper 1996; Apel and Turkay 1999; Cooper 1997). The dominant macrofauna found in the mangroves of Qatar consists primarily of brachyuran crabs, including species such as *Scopimera carbricauda*, *Nasima dotilliformis*, *Mannin-gis arabicum*, and *Macrophthalmus depressus* (Al-Khayat et al. 2019). Macrofauna, most notably gastropods, are also highly efficient in nutrient cycling, as they consume fallen leaves and algae, promoting primary production within the mangroves. Among these, most of the species were identified as bioengineer crabs with high bioturbation potential

and evolutionarily adapted to temperature fluctuations of the region. Limited species diversity is observed along the southwestern Gulf coast with *Nasima dotilliformis* and *Macrophthalmus (Mareotis) depressus* as the sole bioengineer crabs specifically adapted to the region (Al-Khayat and Jones 1999; Al Khayat and Girades 2020). The development and resilience of the hyper-arid mangrove habitat in this area may highly depend on these bioengineer crabs with vital processes including substrate oxygenation and nutrient cycling. Furthermore, gastropods maintain mangrove productivity by cleaning the root systems of the encrusting organisms (Hajializadeh et al. 2020). Polychaetes is another macrofaunal group that exhibits significant abundance and diversity within the mangrove ecosystem and contributes to ecological processes (Wouters et al. 2018). *Nereididae*, *Capitellidae*, and *Paraonidae* species have been documented in mangrove habitats in Iran (Hajializadeh et al. 2020; Delfan et al. 2021; Miri et al. 2023), whereas *Perinereis sp*, *Nereis sp*, *Nephtys sp*, *Ophelina sp*, *Ceratonereis sp*, *Armandia sp*, *Eunice sp* have been reported in natural and afforested mangroves in Qatar (Al-Khayat et al. 2019).

An earlier study by Al Khayat and Jones (1999) along the coast of Qatar revealed notable differences in macrofaunal diversity between natural and planted mangrove ecosystems. Natural mangroves supported 14–15 crustacean species, 9–11 mollusk species, and 6 polychaete species, whereas planted mangroves supported 14–16 crustaceans, 8–9 mollusks, and 4–6 polychaetes. The diversity of crab species was higher in natural mangroves, with 8–11 species, compared to 3–8 species in planted areas. Additionally, certain crab species, such as *Nasima dotilliformis* and *Scopimera crabricauda*, were found exclusively in natural habitats. In a recent study, two new sponge species *Chalinula qatari sp* and *Suberitus luna sp* were identified on pneumatophores in both natural and planted mangroves along the coast of Qatar (Giraldes et al. 2020). Among these two species, *Suberitus luna sp* exhibited antibacterial properties against resistant gram negative pathogens, with potential for new antibacterial drug development. The planted *A. marina* in Sabah Al-Ahmed Sea City, Kuwait showed significant ecological improvement with species diversity increased from 20 ± 2.02 in 2010 ($1488 \pm 512 \text{ m}^{-2}$) (Jones et al. 2012) to 38 ± 3.51 in 2014 ($4821 \pm 1534.4 \text{ m}^{-2}$) (Loughland et al. 2020). Notable crab species recorded include *Macrophthalmus depressus*, *Macrophthalmus laevis*, *Illyoplax sp.*, and *Nasima dotilliformis*.

The marine ecosystem of the Gulf is distinguished by its ecological uniqueness, largely attributed to the severe climatic conditions of the region. Within this environment, the Gulf fish population occupies a central ecological niche, supporting the marine food web, serving as a significant component of commercial fisheries, providing sustenance for human consumption, and holding cultural

significance. Several fish and shellfish species utilize intertidal and subtidal habitats as feeding and nursery grounds (Al-Maslamani et al. 2012). Mangrove habitats offer diverse structural complexities, including pneumatophores and submerged vegetation, which provide essential nursery areas, refuge from predators, and foraging grounds for various fish species. In general, seasonal variations in temperature, precipitation, and salinity, along with other environmental parameters such as turbidity, tidal flow, and sedimentation, may highly influence the abundance, biomass, and habitat suitability of different fish species. Seasonal variation in the fish communities of Qeshm Island in Iran was observed with higher abundance during winter compared to summer due to lower temperatures and higher abundance of zooplanktons (Shahraki and Fry 2016). Food availability is another critical factor, and mangroves, being primary producers, sustain a diverse coastal food web that includes detritus, algae, benthic invertebrates, and planktonic communities. Moreover, the intricate network of roots and substrates creates diverse microhabitats that can support several fish assemblages, enhancing overall fish diversity and abundance. Research conducted along the Qatar coast using stomach content and stable isotope analysis showed that mangrove leaves constituted a significant part of the diet of the native shrimp species (*Palaemon khori*) throughout its post-settlement life cycle (Al-Maslamani et al. 2012). *Palaemon khori* was described as a new palaemonid shrimp species identified in mangroves of Al Khor, Qatar (De Grave and Al-Maslamani, 2006). In addition, the fish community in mangroves significantly contributes to the chemical connectivity between mangroves and adjacent habitats such as coral reefs and seagrasses. Biodiversity studies of fish species in the mangroves are very scarce in the Gulf, and most of the studies were carried out in the mangroves along the Iranian coast (Kamrani et al. 2016; Shahraki et al. 2016; Shahraki and Fry 2016; Eagderi et al. 2019; Zahedi et al. 2019; Raeisbahrani et al. 2023). Eagderi et al. (2019) documented 743 fish species along the Iranian coast and Al-Khayat and Jones (1999) documented 30 fish species in mangroves of Qatar. Al Ghais (1993) identified the Arabian tooth carp (*Aphanius dispar*) and common silver-biddy (*Gerres oyena*) in mangroves across Abu Dhabi, Umm Al Quwain, and Ras Al Khaimah. He also documented substantial presence of juvenile fish, including several species of high commercial value such as *Lutjanus fulviflamma*, *Liza macrolepis*, *Sparus sabra*, *Pseudohombus javanicus*, and *Cynoglossus sp*. Al-Khayat and Jones (1999) assessed the significance of natural and planted mangrove ecosystems in relation to fish diversity and abundance, and found that the fish diversity in natural mangroves was relatively higher (26–30 species) compared to that in the planted mangroves (13–22 species). The study emphasizes the importance of restoring mangrove ecosystems, particularly in areas with favorable physical conditions

characterized by gradual substrate deposition and organic enrichment, which may considerably enhance the diversity and population size of juvenile fish species.

Mangroves in the Gulf are also home to several avian species. For instance, the planted mangroves in Arad Bay in Bahrain supports wader populations (Naser 2023), while the natural mangroves in Khor al Beida, UAE are vital for Socotra Cormorants (Muzaffar et al. 2017). In Iran, mangroves serve as essential nesting grounds for the Western Reef Heron (Etezadifar and Barati 2013). A study conducted on planted mangroves in Fuwairit, Qatar, identified 23 bird species, including notable sightings of species such as the Lesser Crested Tern (*Thalasseus bengalensis*), Common Myna (*Acridotheres tristis*), Rock Dove (*Columba livia*), and various warblers and shrikes (Zogaris and Kallimanis 2016). This species richness is consistent with the results of other prolonged mangrove bird studies such as those in Iran, which documented 56 waterbird species in a broader mangrove ecosystem (Ghasemi et al. 2012). This indicates that mangroves are essential habitats for migrant birds despite their restricted distribution along the coast of Qatar.

Mangroves are a significant component of primary producers in coastal ecosystems since they contribute essential organic matter and nutrients to local food webs (Alfaro 2008). Primary production within mangrove ecosystems is exported to adjacent coastal habitats via ontogenetic migration and trophic relays (Kneib 1997). Studies indicate that mangroves, through their organic detritus, can directly or indirectly nourish a variety of species. Deposit feeders such as crabs and worms, which primarily consume organic matter, actively contribute to decomposition by breaking down organic material and accelerating the degradation of organic matter within the sediment (Hope et al. 2020). For instance, the burrowing behavior of brachyuran and decapod crabs (bioturbating engineer crabs) alters the biological and ecological composition of the mangrove environment by transferring carbon and energy to higher trophic levels (Al-Khayat and Giraldez 2020). Due to the limited presence of mangroves in the Gulf, intertidal microbial mats and seagrasses are other major contributors to primary production. Al-Maslamani et al. (2012) conducted a study to assess the relative contribution of several primary production sources to the nutrition of juvenile shrimp in Al-Khor Bay, located on the Qatar coast. The research revealed that mangroves were the least significant contributor among primary producers. Conversely, seagrasses not only produce substantial amounts of organic matter but also capture particulate organic material from other ecosystems, thereby playing a crucial role in supporting coastal food webs. A similar observation has been reported for mangroves in the Qeshm Island, Iran with minimal contribution to dietary components of fish. The main contributors to primary productivity in the region were identified as cyanophyta-dominated algal mats

associated with tidal flats (Shahraki et al. 2014). Contrasting primary production dynamics between the mangrove ecosystem in Iran and Sundarbans (India) with significant differences in the composition and sources of particulate organic matter have been discussed (Ray and Shahraki 2016). In the mangroves of Iran, phytoplankton dominates the particulate organic matter pool, followed by the microphytobenthos and leaves. In contrast, the Sundarbans exhibit a more balanced contribution from phytoplankton and riverine sources, with increased riverine input during winter due to higher rates of litterfall post-monsoon, enhancing mangrove-derived contributions. The environmental conditions further influence primary productivity, with the mangroves in Iran characterized by higher dissolved oxygen levels (6.60 to 9.06 mg/L) compared to the Sundarbans (6.75 to 6.82 mg/L), which favor phytoplankton bloom and primary productivity. Moreover, the significance of benthic primary producers in contributing to organic carbon and nitrogen dynamics in sediment was explained by the high nitrogen content found in the mangroves of Iran, which is associated with the predominance of nitrogen-fixing cyanobacteria within the microphytobenthos.

The limited contribution of mangroves to primary production in the Gulf can be attributed to various important factors. The monospecific stands of *A. marina* in this region are smaller and less dense compared to other regions, leading to lower productivity (Sheppard et al. 1992). In addition, the higher salinity levels in the Gulf result in increased energy consumption by the mangroves, leading to a decrease in their productivity and ability to supply organic matter to nearby habitats (Parida and Jha 2010). Seagrasses such as those found in Al-Khor Bay exhibit greater resilience to changes in salinity and are able to maintain high productivity even under such conditions (Touchette 2007). As a result, they play a more significant role in primary production in coastal ecosystems. Moreover, the lagoon-like environment within the mangrove, along with the variations in the tidal pattern, creates an environmental setting for minimal export of particulate organic matter (Kruitwagen et al. 2008). However, the intertidal mangrove creeks in Iran were inundated exclusively during spring tides, greatly altering the role of mangroves as feeding areas and thereby decreasing the opportunity for fish to exploit resources derived from mangroves (Shahraki et al. 2014).

Regulating Services

Mangroves help in mitigating climate change by sequestering and storing carbon. Table 1 illustrates the significant contribution of mangrove ecosystems to the global carbon dynamics.

Despite their contribution to carbon sequestration, the total carbon storage of mangrove ecosystems in the Gulf is relatively lower than the global range. Table 2 highlights the

Table 1 Global estimates of carbon dynamics in mangrove forests

Parameter	Value	Reference
Annual carbon sequestration rate	14.2 Tg C yr ⁻¹ (1.71 ± 0.17 Mg C ha ⁻¹ yr ⁻¹)	Alongi 2018
Carbon stock	5.85 Pg C, (Based on estimated global mangrove area of 83495 km ²)	Alongi 2020
Above and below ground carbon stock	• Aboveground carbon stock: 115 ± 7 Mg C ha⁻¹ • Belowground carbon stock: 741 ± 30 Mg C ha⁻¹ (Based on the total carbon stock of 856 ± 32 Mg C ha ⁻¹)	Kauffman et al. 2020
Carbon stock from tropics and sub-tropics	• Tropics: 895 ± 90 Mg C ha⁻¹ • Sub-tropics: 547 ± 66 Mg C ha⁻¹	Sanders et al. 2016
Regional carbon stock distribution	• Asia-Pacific: 1094 Mg C ha⁻¹ • Latin America: 939 Mg C ha⁻¹ • West Central Africa: 799 Mg C ha⁻¹ • Arabian/Oman Gulf: 217 Mg C ha⁻¹	Kauffman and Bhomia 2017

Table 2 Mean sediment and total carbon stocks in natural and planted mangroves in the Arabian Gulf

Natural/Planted mangroves	Study location	Sediment depth (cm)	Sediment carbon stock (Mg C/ha)	Total carbon stock (Mg C/ha)	Reference
Natural mangroves	United Arab Emirates	8–300	36.7–367.0	77.4–514.5	Schile et al. 2017
	Saudi Arabia	28–83	71–113	-	Cusack et al. 2018
	Qatar	21.67–50	6.23–33.74	45.70 ± 3.70	Chatting et al. 2020
	Iran	0–60	443.4–1045.2	443–1045.2	Mahmoudi et al. 2022
	Bahrain	10–70	24.52–31.97	-	Naser 2023
Planted mangroves	United Arab Emirates	12–100	50.9–175.8	51.3–182.3	Schile et al. 2017
	Saudi Arabia	102–103	51–63	-	Cusack et al. 2018
	Bahrain	10–70	14.23–19.07	-	Naser 2023

sediment carbon stock and total carbon stock estimated in the natural and planted mangroves in the Gulf.

Cultural Services

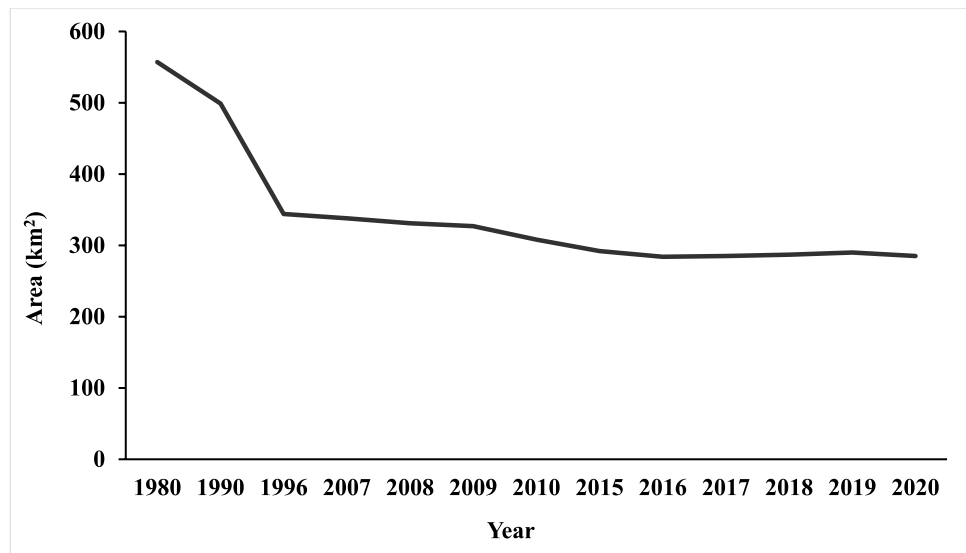
While the section on ecosystem services predominantly focuses on provisioning, supporting, and regulating services, the discussion on cultural ecosystem services in the Gulf is relatively limited because of the lack of documentation and attention in the literature. Mangrove habitats in the Gulf contribute to cultural services by providing ecotourism and recreational activities (Spalding and Parrett 2019). These ecosystems function as natural attractions, drawing visitors into bird watching, wildlife photography, nature walks, and boat tours/kayaking (Moussa et al. 2024). Kayaking tours are increasingly favored for exploring mangrove ecosystems in the Middle East, notably in the UAE and Qatar, offering experiences in Abu Dhabi's Mangrove National Park, Ras al Khaimah (Ryan et al. 2012), and Al Khor mangroves in Qatar. Additionally, Ras al Khor in Dubai stands out for its walkways, facilitating leisurely observation of flamingos in their natural habitat.

Impacts on Mangrove Ecosystems

Over the past two decades, the global extent of mangrove ecosystems has decreased by 35% (Feller et al. 2017), and the rate of decline of mangrove ecosystems across the world is estimated to be approximately 0.22% per year (Pan et al. 2021). According to Bunting et al. (2022), the global mangrove area has been decreased by 5,245 km² (3.4%) from 1996 to 2020, while the Middle East experienced a net loss of 272 km², corresponding to a percentage decrease of approximately 48.8% from 1980 to 2020 (Fig. 5).

Coastal areas have been adversely affected by human activities, and the consequences significantly impact mangrove forests due to their proximity to urban areas (Burt 2017). The deterioration of marine ecosystems in the Gulf, mainly due to urbanization, ongoing industrial operations, and recreational development, presents a severe and immediate danger to mangrove trees (Khan and Kumar 2009; Waleed et al. 2024). Pollutants that enter mangrove ecosystems via solid waste, oil, or industrial effluents have

Fig. 5 Middle east mangrove extent (1980–2020). Modified from FAO (2007) and Bunting et al. (2022)



the potential to cause root damage, which in turn can impair the respiratory and osmoregulatory functions of plants (Adame et al. 2021). In addition, species associated with mangroves also experience immediate and long-term effects from these pollutants. In addition to these effects, aquaculture-based shrimp farming is identified as a major threat to mangrove ecosystems, particularly in Saudi Arabia, primarily due to the degradation of water quality resulting from the release of wastewater (Almahasheer et al. 2013).

The following subsections briefly explain the causative forces, which degrade the mangrove ecosystems in the Gulf:

Land Reclamation and Coastal Development

Dredging, land reclamation, and landfilling have become a standard practice in the Gulf that converts shallow intertidal habitats into areas suitable for coastal development. The rapid growth of industrial and urban development in the Gulf region, including construction of artificial beaches, marinas, hotels, promenades, and artificial islands, has jeopardized the coastal ecosystems. During the early 1990s, 40% of the Gulf coast was degraded and modified through dredging, reclamation, and pollution, causing biodiversity and productivity loss (Al Ghabban and Price 2002; Khan et al. 2002). With 85% of the population living within 100 km of the coast, continued population growth exacerbates the situation, leading to massive losses of mangroves.

The Nayband National Park, located in Nayband Bay, is home to one of Iran's most significant mangrove communities. These mangrove forests span two large bays, Asalouyeh and Basatin, which have been adversely affected by the Pars Special Economic Energy Zone (PSEEZ) activities. The Nayband mangroves initially expanded between 1990

and 2002, possibly due to rising temperatures and increased precipitation. However, after 2002, a decline in mangrove health and area was observed, suggesting that industrial and urban development post-1997 intensified the natural stresses from climate change and anthropogenic pressures (Etemadi et al. 2021). Sewage discharge from gas refineries has led to the disappearance of many mangrove trees, particularly at the western end of Asalouyeh Bay, near the South Pars facility. Additionally, the construction of a road at the entrance of Basatin Bay disrupted the natural flow of water, causing mangrove trees in this area to wither and disappear. This results in sediment accumulation in the main channel. Research indicates that there has been a significant loss of 34.11 hectares of mangrove forests in Nayband Bay due to industrial activities associated with PSEEZ development (Etemadi et al. 2021). Vahidi et al. (2020) documented that the macrofaunal population in the Hara Biosphere Reserve of Iran experiences stress due to natural and anthropogenic influences.

Analysis of satellite images of 39 years from 1972 to 2011 indicated a substantial decrease ($\approx 55.93\%$) in mangrove coverage in Tarut Bay in Saudi Arabia due to urbanization, consequences of the Gulf War, oil pollution, and insufficient rehabilitation measures (Al Mahasheer et al. 2013; Youssef et al. 2015). According to Sohaib et al. (2023), coastal recreational activities such as road construction, building development, residential complexes, landfilling, and sewage discharge pose a significant threat to mangroves in Saudi Arabia, potentially resulting in their complete eradication. Activities such as dredging and landfilling can disrupt water and sediment flow, and block or eradicate water channels that supply oxygen to mangrove roots. This can lead to extended periods of submergence and oxygen deprivation, resulting in conditions such as hypoxia.

Additionally, sediment removal or addition can bury or damage mangrove roots, destabilize soil, and increase erosion or habitat collapse. The death of pneumatophores decreases adequate aeration within the root zone. This reduction further limits oxygen availability to the root system, affecting the respiration rate, nutrient uptake, and metabolism. Disturbed sediments during dredging may also contain pollutants that can accumulate in mangrove sediments and tissues, thereby affecting ecosystem health. Likewise, Tubli Bay in Bahrain significantly declined mangrove spatial extent from 328 hectares in 1967 to 48 hectares in 2020, reflecting a 95% loss (Aljenaid et al. 2022). The regional Red List assessment of particular species in Bahrain classifies mangroves as ‘Critically Endangered’ (Abdulla and Naser 2021). The mangrove area in Tubli Bay is surrounded by a tidal channel that receives partially treated sewage and agricultural run-off from various farms (Al-Sayed et al. 2005).

The coastline of Dubai has been extended from 50 km to over 250 km through the construction of man-made islands for real estate, ports, and oil infrastructure. This expansion has resulted in considerable deterioration and loss of mangroves. Research indicates that there was a decrease in mangrove vegetation at certain locations by as much as 20% from 1972 to 2000 as a result of land reclamation for infrastructure development (Khan and Kumar 2009). Furthermore, the release of untreated wastewater, disturbance of natural sedimentation processes, interference with water circulation, and depletion of freshwater resources provide additional risks to mangroves, indicating that mangroves on the Abu Dhabi coast, including Umm AnNar, Mossafah, Ras al-Khaimah, and Khor Kalba, are threatened by construction and land infilling (Boer and Aspinall 2005). Globally, similar reports regarding the effects of coastal development on mangroves have been observed, however, the loss in terms of ha area is relatively low in the Gulf compared to some of the largest mangroves in the world, but is higher in terms of percentage loss. Nguyen et al. (2022) utilized remote sensing techniques to evaluate the deforestation and degradation of mangroves in Quang Ninh, Vietnam. Between 1987 and 2020, the study documented a significant decrease of 2,168.3 ha, primarily attributed to urbanization, uncontrolled aquaculture, and other competing land. Moshchetto et al. (2021) investigated the impact of urbanization and legislative changes on mangroves in southern Brazil, and reported a loss of approximately 10.6 km² of mangroves in Santos and São Vicente estuarine over a 20-year period due to irregular low-income urban settlements and land-use pressures from the Port of Santos, the largest port in Latin America. Although no notable alterations have been reported in the natural mangroves on the northern coast of Qatar, these mangroves are currently facing threats resulting from the disposal of dredged materials, which impede the growth of mangrove seedlings. Moreover, mangroves

planted in certain locations were removed while developing beaches or promenades (Al Khayat et al. 2021). In another study, Al-Khayat and Giraldez (2020) reported the absence of several mangrove-associated crabs from Al Khor mangroves in Qatar, which had previously been observed by Al-Khayat and Jones (1999), most likely due to increasing anthropogenic influences in the region.

Climate Change and Associated Impacts

Climate change and anthropogenic activities threaten mangrove ecosystems, collectively contributing to the alteration and degradation of mangrove habitats. Climate change, characterized by rising air temperatures and more frequent and intense storm events, shifts in rainfall patterns, increased drought occurrences, and alterations in ocean circulation, has resulted in a decline in mangrove ecosystems, with reductions in geographical area, changes in structural composition, and decreased primary productivity (Cinco-Castro and Herrera-Silveira 2020). Structural changes of mangroves in the Hara Biosphere Reserve of Iran were studied under the influence of wet and drought seasons over a 31-year period (1986–2017). Increased precipitation during the rainy season (1986–1998) resulted in an expansion of the largest patch area and a decrease in patch numbers from 1281 to 911, indicating habitat expansion. Subsequent to year 1998 under prolonged droughts, number of patches increased to 1639 with decreased patch extent indicating habitat degradation and fragmentation (Shirmohammadi et al. 2024). Coastal areas prone to cyclones, storm surges, and saltwater intrusion are at higher risk of reduced ecosystem resilience. Ghayoumi et al. (2022) investigated the present distribution of *A. marina* and assessed the variations in its forecasted potential distributions under the IPCC’s future climate scenario. This study revealed a significant decline in suitable habitats for *A. marina* in Iran between 2060 and 2080 under RCP 8.5, with the species expected to occupy only 2.1% of the study area compared to the current 12.5%, primarily affecting the eastern regions of the Gulf and the Sea of Oman. The increased severity of droughts has reduced mangrove coverage and productivity along the Gulf Coast in the past few decades, and this trend is expected to continue in the future, posing an increased threat to the resilience of the remaining mangrove ecosystems in the coming years (Mafi-Gholami et al. 2017, 2019, 2020a). Drought is likely to lead increased salinity levels, surpassing the tolerance threshold of mangrove species.

The 95th percentile global mean SLR in the year 2100 is 2.3 m (IPCC 2021). Coastal areas in the Gulf with low elevation are highly vulnerable to SLR as a result of ongoing widespread land reclamation for industrial and residential activities. The increase in sea level is expected to result in the retreat of the seaward margin of mangroves and

contribute to the continuous decrease in their areas. Moreover, these alterations might lead to the emission of substantial amounts of stored carbon, further intensifying the effects of global warming (Kristensen et al. 2008). Hence, mangroves will face intensified pressures in the coming decades with rising sea levels, particularly threatening the inundation in low-lying mangrove areas, leading to habitat loss and fragmentation and consequently diminishing mangrove carbon stocks (Davar et al. 2021).

Sea level rise is considered as the primary climate change driver responsible for the diminishing spatial extent and biomass of both tall and dwarf mangrove structures along the coast of Iran (Nerem et al. 2018; Pirasteh et al. 2021) and Tarut Bay in Saudi Arabia (Babu et al. 2012) is considered to be a major factor for the 10–20% of the total global mangrove reduction (Gilman et al. 2007; Ellison 2015;). Historically, mangroves have adapted to sea-level changes by moving towards land if space is available for expansion or upward if enough parameters are available for growth (Etemadi et al. 2018). At a SLR of 3 m, significant portion of the mangrove ecosystems in the Tarut region of Saudi Arabia could be susceptible to flooding, resulting in a gradual displacement of mangroves towards inland areas (Babu et al. 2012). Etemadi et al. (2021) observed that sea level has been increasing at a rate of 4 mm/year in the southwest region of Iran. The author emphasized the significance of tidal range as a determining factor in mangrove movement and relocation. Notably, the low tidal range recorded in the study area (1.5–2 m) makes mangroves highly susceptible to SLR.

Projections of sea level changes in the Gulf under different RCPs suggest an increase ranging from 6.1 to 9.8 mm/year by 2100 (Irani et al. 2017). Mafi-Gholami et al. (2020a) investigated the changes in spatial extent of mangroves in response to SLR due to the projected RCP 8.5 scenario in Iran along the Gulf (Khamir and Tiab coast) and Sea of Oman (Jask coast). This highlights that the above-ground biomass and below-ground biomass were anticipated to increase by 47–64% and 41–48%, respectively. The estimated mangrove area reductions for a 100 cm sea level rise, assuming no landward development, are 72% for Jask (157 ha), 49% for Khamir (3319 ha), and 49% for Tiab (500 ha) (Nerem et al. 2018). Continuous sedimentation input from rivers can maintain and expand mangrove ecosystems in Khamir and Tiab (Mafi-Gholami et al. 2107). In contrast, the building of the River Jagin dam in 2008 drastically lowered sedimentation rates in Jask following a rainfall event that subsequently reduced mangrove area and quality through changes in natural flow and sediment transport (Dahdouh-Guebas et al. 2005). The mangrove communities in South Florida, USA, is anticipated to experience a major destabilization due to SLR and will undergo transition to other estuarine ecosystems such as mudflats as the sedimentation rates for these ecosystems are lower than

that for mangroves (Parkinson and Wdowinski 2022). The study on the evaluation of projected SLR and the associated impacts are very limited in the Gulf. Recently, based on the CMIP6 Shared Socio-economic Pathways (SSPs), Abdulla et al. (2024) estimated a rate of increase of sea level of the order of 3.5–4.5 mm/year along the coast of Qatar, which is quite different from the historical changes. This suggests that a detailed investigation on the projected SLR and related changes in the mangroves is necessary in the Gulf considering the latest IPCC scenarios.

Oil Pollution

Oil pollution originated from both natural and anthropogenic sources has persisted in the Gulf in the past decades. Two significant conflicts in the last three decades, including the Iraq-Iran war from 1980 to 1988 and the First Gulf War in 1991, resulted in massive oil spills, with the latter causing extensive and possibly the most significant irreversible damage to the marine ecosystems of the Gulf region (Nadim et al. 2007). Mangroves are highly susceptible to the deleterious impacts of oil pollution due to immediate harm and the prolonged retention of significant amounts of non-degraded hydrocarbons in sediments over extended periods following the spills (Cappello et al. 2012). Around 5.5 million tonnes of oil have been spilled into mangrove-lined coastal areas worldwide since 1958, potentially affecting at least 126,000 ha of mangrove vegetation (Duke 2016).

The short-term response of *A. marina* pneumatophores to oil slick exposure during tidal waves has been previously investigated (Partani et al. 2015). The pneumatophores of *A. marina* showed notable absorption during high tide, with more than 70% of the oil content attached to the epidermis. This attachment is significant during night-time and winter conditions, characterized by lower temperatures and reduced radiation rates. While sunlight typically increases the evaporation rate and viscosity, reduced temperature conditions can counteract these effects by reducing the evaporation rate. This suggests that seasonal variations and diurnal changes may influence the natural physical adsorption of crude oil by mangroves.

An earlier study by Boer (1993) documented the morphological adaptive responses of mangroves in Saudi Arabia to oil contamination. It was observed that oil primarily infiltrates through lenticels, leading to accumulation within the epidermis. When it penetrates the endodermis, it causes mortality in affected sections while promoting new growth below. Upon exposure to oil, *A. marina* develops branching aerial roots from compromised pneumatophores and adventitious roots from stems up to 50 cm above the sediment to maintain oxygen supply and structural stability. Additionally, the formation of a bitumen layer on the sediment surface after oil evaporation acts as a barrier, entrapping oil beneath

and influencing root function. The author also reported that the deployment of seawater sprinklers for cleaning oiled plants and soils in 1991 significantly enhanced mangrove survival, highlighting the importance of such intervention measures.

Oil pollution detrimentally affects all stages of mangrove reproduction, resulting in reduced fruiting, propagule dispersal, and the successful establishment of new generations. Oiled trees produced nearly half the fruit weight of non-oiled trees, with only 17% of viable seedlings recruited from polluted sites compared to unpolluted sites (Youssef et al. 2000). In another study, a significant reduction in aerobic and anaerobic microbial populations and activity, with a predominant abundance of hydrocarbon-utilizing bacteria, was reported in oil-polluted sediments (total recoverable hydrocarbon concentration = 34200 mg/kg) of mangroves along the UAE coast (El-Tarabily 2002). Such suppression of the microbial population may have profound implications for nutrient cycling and the decomposition of organic matter within the mangrove ecosystems. The predominance of hydrocarbon-degrading bacteria suggests a shift in microbial community composition, which may also reduce the overall efficiency of nutrient cycling. Furthermore, such disruption in significant biochemical processes can have adverse effects on other biota, including fish and crustaceans.

Extensive defoliation and destruction of mangroves along the Saudi Arabian coast occurred due to 1991 Gulf War oil spill (Sadiq and McCain 1993). Over 20% of the mangroves on the eastern coast of Saudi Arabia have been severely damaged by oil pollution and experienced high levels of inundation by oil residues (Sheppard et al. 1992). Higher concentrations of metals such as arsenic, cadmium, cobalt, copper and barium have been reported in mangrove sediments along the Saudi Arabian coast (Sadiq and Zaidi 1994; Rabaoui et al. 2020). A recent study by Sardi et al. (2020) reported a decrease in mangrove coverage in the Gulf, which was attributed to the coating of oil on pneumatophores, resulting in the death of a few mangroves. Increased heavy metal concentrations have been reported in the Basatin and Bikhdoon mangrove areas of Iran, primarily due to the discharge of industrial effluents in Nayband Bay. Hence, significant reduction in mangrove coverage have occurred in the Basatin and Bikhdoon mangrove areas, from 130 ha in 1956 to 96 ha in 2015 and from 46 ha in 1956 to 41 ha in 2015. The major sources of pollution near these mangrove areas include expansive natural gas fields, refineries, petrochemical companies, and manufacturing facilities (Etemadi et al. 2021). In contrast, the Malgonze mangrove area, located away from oil pollution sources, has experienced a steady increase in coverage, expanding from 9.3 ha in 1956 to 11 ha in 2015. Along with the exceptionally harsh climatic conditions in Kuwait that challenge mangrove growth, the 1991 Gulf War oil spill reportedly affected 50% of the mangroves,

resulting in a 30% mortality rate (Barth 2001). Al-Khayat et al. (2021) reported that natural mangroves located along the northeast coast of Qatar, which are vital habitats for the mollusk community, are facing threats due to the impact of oil pollution originating from nearby shipping facilities and oil refineries.

Studies conducted outside the Gulf have also emphasized the detrimental effects of oil spills and associated activities on mangrove ecosystems, including the mangroves in Bangladesh (Chowdhury and Akber, 2015), Indonesia (Mardias-tuti et al. 2020), the Guyana coast in South America (Aaron et al. 2023), and Nigeria (Gundlach 2018). A total loss of about 4415 ha of mangroves occurred in the East of Bonny River, Nigeria, between 2008 and 2015, primarily attributed to oil spills, the construction of pipeline corridors, and the growth of illegal refinery sites (Gundlach 2018). The author further stated that the elevated oil levels in both surface and subsurface sediments pose a significant obstacle to natural regeneration, suggesting that without active restoration efforts, recovery may take more than 30 years or potentially never happen due to alterations in the sediment that hinder seed establishment and growth. The short- and long-term effects of oil spills on mangroves in the Gulf have not been thoroughly investigated in the literature. However, a recent study conducted in Spencer Gulf, southern Australia, evaluated the recovery of *A. marina* mangroves utilizing field data collected over two years and aerial image analysis spanning 26 years post-event, the Era tanker oil spill in September 1992 that affected approximately 100 ha (Connolly et al. 2020). The study revealed that severely impacted areas exhibited minimal recovery during the initial decade following the spill. Nevertheless, between 10 and 25 years after the incident, seedling growth resulted in a gradual increase in canopy cover, reaching 35% of pre-oiling levels, with predictive models estimating a complete canopy recovery may require up to 55 years and occur by 2047. This indicates the importance of long-term monitoring and adaptive management measures to help mangrove ecosystems recovery after oil spills.

Replantation and Restoration Efforts in the Gulf

The restoration of mangroves in the Gulf region is viewed as a natural approach to mitigate the consequences of climate change, safeguard fisheries, and preserve coastal ecosystems. Several Gulf nations have launched initiatives aimed at conserving and planting mangroves, which have led to notable ecological benefits, including enhanced biodiversity, carbon sequestration, more intricate habitats for species, shoreline protection against sea-level rise and floods, increased fisheries, and increased local mangrove growth

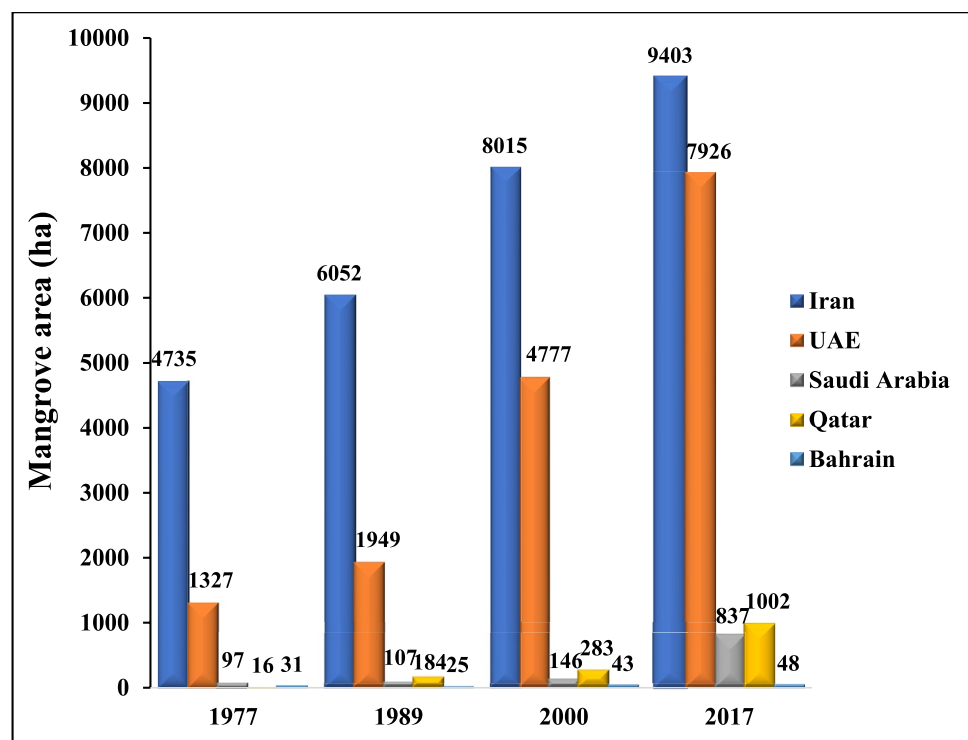
(Al Khayat et al. 2019; Elmahdy et al. 2020; Erfteimeijer et al. 2020; Friis and Burt 2020; Loughland et al. 2020; Farshid et al. 2023). Several studies have documented that transplanted mangroves significantly contribute to sediment organic carbon within the Gulf (Cusack et al. 2018; Schile et al. 2017; Naser 2023) and other regions, such as Vietnam (Pham et al. 2017); Ecuador (DelVechhia et al. 2014), Indonesia (Kusumaningtyas et al. 2022), and Myanmar (Aye et al. 2023). Milani (2018) assessed the extent of mangrove forest coverage and monitored changes between 1977 and 2017 in the Gulf and the Sea of Oman using remote sensing and satellite imagery. The mangrove forest area in Iran has been increased by 4,667 ha, the UAE by 6,599 ha, Saudi Arabia by 740 ha, in Qatar by 986 ha, and in Bahrain by 16 ha (Fig. 6). The implementation of sustainable development and management techniques within the mangrove ecosystems of the area, is largely responsible for this increase.

Various methods have been employed for mangrove restoration, afforestation and replanting, including direct planting of seeds or propagules, transplanting seedlings sourced from natural habitats, and cultivating seedlings and trees in nurseries before reintroducing them to their original habitats (Aboel-Nil 2001). Based on the physicochemical characteristics of mud from intertidal flats of islands along the Kuwait coast, several researchers have reported that these areas are suitable for mangrove growth (Clayton 1986). The planting of mangroves in the Al Khiran region of Kuwait has been ongoing since 2003, establishing the most extensive stands in the country. Over 30 species of sea birds have

been attracted to the area because of the presence of *A. marina* and salt marsh plants such as *Halocnemum strobilaceum* (Jones et al. 2012). A study conducted by Aboel-Nil (2001) demonstrated the successful cultivation and establishment of mangroves derived from stocks in Bahrain and the UAE, resulting in substantial plant growth and ecological improvements. After seven years, mangrove plants sourced from Bahrain reached an average height of 250 cm, closely resembling that of their parent trees in their natural environment. Bahrain prioritized the conservation of mangrove ecosystems and associated ecological services by designating the Ras Sand area in Tubli Bay as a national nature reserve in 1986 and recognizing it as a Ramsar Convention wetland site for birds in 1997 (Naser et al. 2016). A nationwide restoration program was launched in 2013, which introduced annual mangrove transplantations in Tubli, Arad Bay, and other coastal locations. In 2016, 1763 mangrove seedlings were planted in cooperation with the Supreme Council for the Environment, primarily to increase carbon sequestration (Abdulla and Naser 2021). Bahrain aims to achieve carbon neutrality by 2060, with an interim target of reducing CO₂ emissions by 30% by 2035. As a strategic approach, Bahrain has declared its intention to quadruple existing mangrove land by 2035 to achieve a specified reduction in CO₂ emissions (Alsabbagh and Alnaser 2022).

Since 1981, collaborative efforts involving governmental organizations, students, and scholars have been underway along the coast of Qatar to initiate mangrove plantation and restoration endeavors (Al Khayat and Jones 1999). Most

Fig. 6 Mangrove Forest area expansion (1977–2017) across Gulf nations. (Modified from Milani 2018)



planted areas are found close to coastal lagoons and inlets; the three most significant areas are Umm Al Hul, Al Mafjar, and Fuwairit. Planting trees in the early stages was difficult because strong waves would uproot the saplings or foraging camels would harm them. However, mangroves have established themselves on several east coastal sites after extensive replanting efforts. Unfortunately, most of the mangroves planted in Umm Al Hul have been cut down for infrastructure projects, such as building new ports and oil companies (Al Khayat and Balakrishnan 2014). Al Khayat et al. (2019, 2021) assessed the long-term effectiveness of compensatory planting of mangroves, particularly emphasizing their role in supporting biodiversity conservation. Over a span of three decades, no significant differences in the physical parameters of the sediment and benthic macrofauna were observed between natural and afforested mangroves. These findings contrast with those observed in a previous study conducted at exact locations a decade after afforestation, where benthic macrofauna diversity, total organic carbon and clay contents were lower at afforested sites than at natural mangrove sites (Al Khayat and Jones 1999). This further suggests that the compensatory planting of mangroves has the potential to mitigate biodiversity loss resulting from coastal development. Mangrove forests in Saudi Arabia have undergone a restoration process facilitated by both government and industrial plantation efforts via the Ministry of Agriculture. An increase in mangrove coverage in the northern Tarut Bay and Tarut Island by 0.21 km² from 2000 to 2010 and by 1.4 km² from 2010 to 2018 was documented along the Saudi coast (Li et al. 2019). The observed increase in mangrove coverage is primarily attributed to mangrove breeding and plantation efforts, despite the ongoing threats from industrial activities in the region.

The mangrove plantation and rehabilitation project in the UAE began in the late 1970s and has significantly expanded mangrove areas. The impact of coastal development on mangroves has been diverse, resulting in both positive effects, such as reduced salinity and increased nutrient availability in certain areas, and adverse effects, due to the conversion of mangrove habitats for development purposes in other areas. UAE implemented a temporary ban on mangrove harvesting and initiated mangrove planting programs in response to the challenges presented by development and overexploitation (Saenger et al. 2002). In the late 1980s, 17 mangrove stands were identified and mapped in the UAE. During this period, the Ras al Khor mangrove wetland in Dubai was established and planted, and it was later designated as a Ramsar Site because of its ecological importance (Embabi 1993). By 1990, mangrove coverage had expanded from 35 km² in 1980 to 38 km² (Saenger et al. 2002). In the following years, there was a consistent increase, with the area expanding to 40 km² in 2000 and to 41 km² in 2002 (Habshi et al. 2007). By 2017, mangrove coverage had significantly expanded to

79 km² (Al Mahasheer 2018). The southeast UAE coast has larger expanses of mangroves because of extensive restoration and planting efforts in recent years (Mateos-Molina et al. 2021). In a reforestation initiative on Mubarras Island, 300 *A. marina* mangroves were relocated and replanted because of construction activities. Depending on their size, the mangroves were carefully excavated using either manual or mechanical methods, and then transported with their root balls securely wrapped in burlap. Subsequently, they were replanted in a newly constructed tidal channel. Despite a high initial mortality rate, 31% of the mangroves survived after 12.5 months, demonstrating the viability of relocating more extensive mangroves to expedite ecosystem service provision (Erftemeijer et al. 2021a).

Biotechnological Approaches for Mangrove Restoration

The rich microbial communities inhabiting the mangrove sediments, water column, and plant tissues, are crucial for nutrient cycling and biogeochemical processes. In particular, microbes engage in processes that impact nutrient dynamics, such as nitrogen fixation, denitrification, ammonium oxidation, and phosphate solubilization (Reis et al. 2017). Despite significant advancements in omics approaches, research on mangrove microbial communities has predominantly focused on microbial diversity. Studies on mangrove microbial communities in the Gulf have explored spatial and temporal variations in bacterial populations influenced by environmental and anthropogenic factors (Al-Sayed et al. 2005), the isolation of crude oil-degrading strains like *Vibrio* sp. and *Halomonas* sp. with potential for bioremediation in polluted environments (Fakhrzadegan, 2024), and the role of mineral-forming bacteria with diverse metabolic pathways in carbonate formation (Farhat et al. 2023). While these studies enhance the understanding of microbial diversity, they do not adequately address the functional interplay between microbes and mangroves, which is crucial for improving mangrove-microbe interactions and mangrove resilience in extreme conditions.

Sustainable Practices for Enhancing Mangrove Growth and Resilience

The plant growth-promoting bacteria (PGPB) exert direct and indirect effects on plant growth by enhancing nutrient availability, facilitating transport, synthesizing plant growth regulators, producing metabolites that combat pathogens, and modulating stress hormones. These microbes exhibit essential traits, including nitrogen fixation and solubilization of potassium and phosphorous, that may collectively contribute to mangrove growth and resilience (Zhuang et al.

2020). In a recent review by Dey et al. (2024), the importance of root-associated PGPB in enhancing mangrove's ability to withstand extreme environmental conditions has been emphasized while highlighting the potential uses of these bacteria as an eco-friendly approach in mangrove restoration. Halotolerant, rhizosphere-competent, plant growth-promoting actinobacteria isolated from mangrove rhizosphere sediments in the UAE exhibited considerable potential for enhancing mangrove growth under harsh coastal conditions (El-Tarabily et al. 2021). In particular, a consortium of *Streptomyces coelicoflavus*, *Streptomyces polychromogenes*, *Streptomyces bacillaris*, and *Streptomyces mutabilis* UAE1 and *Streptomyces ferruginous* significantly improved shoot and root biomass compared to seawater-irrigated plants, with notable increase in photosynthetic pigments, plant growth regulators such as auxins and polyamines. The combination of phosphate-solubilizing bacteria *Oceanobacillus picturae* and rock phosphate was more effective in promoting mangrove growth in phosphorus-deficient sediments than individual treatments (El-Tarabily and Youssef 2010). This method provides a sustainable alternative to the expensive and ecologically harmful triple superphosphate commonly used for phosphate amendment.

Research has shown that PGPB isolated from *A. marina* has the potential to be used in agricultural crop production and improve plant growth. A study in the Indian Sundarbans elucidated the potential of *Halomonas* sp., isolated from the rhizosphere of *A. marina*, in enhancing rice growth under increased salt and arsenic stress conditions (Mukherjee et al. 2019). The bacterial strain produced exopolysaccharides that augmented osmotic tolerance and sequestered arsenic, thereby significantly improving plant growth under stress conditions. Bacterial endophytes were isolated from *A. marina* propagules along the Saudi Arabia's Red Sea coast to assess their possible advantages for crops like barley and rice as well as their natural host under conditions of increasing salt. *Gordonia terrae* KMP456-M40 was the most effective isolate out of the 172 that were screened and improved rice biomass by 62%, increased mangrove seedling root length by 65%, and raised barley ear weight by 65% (Soldan et al. 2019). A recent investigation conducted in the Umm Al Quwain mangroves of the UAE identified a novel bacterial *Bacillus* species, SW7, isolated from mangrove sediments. The strain exhibited significant PGPB traits, including tolerance to high salinity (11% NaCl) and elevated temperatures (50 °C), as well as the ability to solubilize phosphate and potassium, and produce the plant hormone indole acetic acid. In a greenhouse experiment, SW7 demonstrated the capacity to enhance tomato seed germination, leaf number, density, and water mass without adversely affecting essential photosynthetic pigments such as Chlorophyll a, Chlorophyll b, and carotenoids (Afridi et al. 2024). However, given the paucity of studies pertinent to the Gulf, it is

imperative to investigate the extremophilic PGPB and the potential traits they exhibit under biotic and abiotic stress. The potential of *A. marina* endophytic fungi as a sustainable solution for combating fungal diseases in tomato crops in Saudi Arabia has been studied (Al Husnain et al. 2023). The study involved isolating and characterising fungal isolates, followed by 18 S rRNA gene sequencing for phylogenetic categorization and identification of various fungal species, as well as subsequent screening assays to determine antagonistic activity. *Cladosporium sphaerospermum* exhibited the strongest inhibition, while *Trichoderma asperellum* displayed the least antagonistic activity among the studied endophytes. Fungal biocontrol agents that include beneficial endophytic fungi can form symbiotic relationship with the plants by producing antimicrobial chemical without harming plant tissues and providing disease resistance through the synthesis of bioactive metabolites (Kohl et al. 2019). The results provide an excellent case for using *A. marina* as a possible biocontrol agent, with more research needed to understand the long-term effectiveness of fungal endophytes under a variety of agricultural conditions.

Fish by-products, such as fishmeal powders and soluble fish emulsions, are often utilized by farmers as eco-friendly and sustainable alternatives to traditional chemical fertilizers. These substances can be employed independently or in conjunction with other supplements to foster crop development and enhance the biological properties of soil (Moursy et al. 2022). Applying fish emulsions, along with actinobacterial isolate *Streptomyces griseorubens* UAE1 to mangrove seedlings of *A. marina* resulted in substantial improvement in their growth (Al Anoud et al. 2024). The rich content of essential amino acids, proteins, fatty acids, and macro- and micronutrients likely contributed to the increase in dry weight, shoot and root lengths, and total leaf area. Compared to control or *Streptomyces griseorubens* UAE1 treated seedlings, those treated with fish emulsions showed higher nutrient uptake. Seaweed extract has also been used as a biostimulant to stimulate mangrove growth. A recent study investigated the combined effect of using a commercially available seaweed extract generated from kelp and introducing endophytic plant growth-promoting actinobacteria to mangrove seedlings. The results revealed that the combined treatment with *Streptomyces tubercidicus* UAE1 inoculation and seaweed extract treatment improved the dry biomass, photosynthetic pigments, and plant growth regulators, in addition to increasing the absorption of several micronutrients such as phosphorous and magnesium (Alkaabi et al. 2022). Seaweed extract is a crucial biostimulant for mangroves because of its capacity to improve soil nutrient content and stimulate soil microbiota. The addition of seaweed extract to mangrove sediments enhanced soil health, leading to superior plant responses during periods of stress. Furthermore, seaweed extracts have been reported to decrease

electrolyte leakage and lipid peroxidation, lower the Na^+/K^+ ratio, and increase Ca^{2+} content, thereby mitigating ionic disparity and increasing the biomass and total leaf area (Ali et al. 2021). The nutrient-rich liquid wet sludge from an off-shore sewage treatment facility on Mubarras Island in Abu Dhabi demonstrated significant growth and survival of mangrove seedlings (Erftemeijer et al. 2021b). The increased levels of total nitrogen (8.9 ± 0.1 mg/L) and total phosphorous (7.8 ± 0.2 mg/L) within the sludge enhanced various growth parameters, such as leaf number and leaf and root biomass. This study suggests that sludge from sewage treatment plants could effectively irrigate mangrove seedlings in nurseries and plantations, particularly in arid regions where nutrient-poor soils and limited freshwater resources pose challenges for mangrove establishment. These improvements in mangrove growth not only benefit individual plants but also contribute to global carbon sequestration and the sustainability of marine ecosystems by potentially reducing atmospheric CO_2 levels.

In another study, the lignocellulosic components of *A. marina* were characterized to highlight their significance in a bio-based economy for the production of high-value chemicals derived from cellulose and hemicellulose, such as furfural. All biomasses averaged 70% volatile solids, with stems and pneumatophores exhibiting higher sugar, arabinan, xylan, and glucan content (Almardeai et al. 2017). This research emphasized the importance of utilizing *A. marina* as a lignocellulosic material with considerable potential for the production of high-value chemicals and biofuels. Leveraging *A. marina* biomass in biorefinery processes, including bioenergy generation and chemical synthesis, can help alleviate dependence on limited freshwater resources while fostering sustainable economic growth in these areas. In general, these studies suggest that such nature-based applications hold promising potential as fertilizers/biostimulants for supporting growth and nutritional demands in mangroves, and as sustainable options for marine agriculture.

Genetic Adaptations of *A. Marina* to Salinity and Environmental Stressors

Mangroves, in general, exhibit facultative adaptation, which enables them to grow effectively in both fresh and saline waters. This remarkable adaptability highlights the significance of regulated gene expression patterns, which enable them to respond to varying salinity levels in their environment (Krauss and Ball 2013). A considerable number of microorganisms that have evolved to high salinity levels are concentrated in the rhizosphere of salt-tolerant plants, demonstrating a higher prevalence of genes that help alleviate salt stress compared to those found in bulk soil (Fan et al. 2021; Zheng et al. 2021).

Nelson et al. (2022) analyzed the transcriptomes of *A. marina* from various tissues (pneumatophores, stems, leaves, flowers, seeds) across four distinct Indo-Pacific environments (Red Sea, the Gulf, Bay of Bengal, Red River Delta) for a comprehensive understanding of tissue-specific and environment-specific gene expression patterns. The study reported several expressions of genes that are highly crucial for the adaptation of *A. marina* in intertidal habitats, with the higher expression of most genes observed along the Red Sea coast. Several genes were uniquely expressed in *A. marina* pneumatophore, elucidating their adaptive traits for survival in saline and oxygen-deficient environments including aquaporins and metallothioneins. Aquaporins facilitate water uptake essential for maintaining hydration in hypersaline conditions (Zhou and Yang, 2019), while metallothioneins provide protection to plants from toxic metal accumulation and oxidative stress, (Huang and Wang 2010). Other unique genes include *aspartate-semialdehyde dehydrogenase*, which is involved in nitrogenous amino acid synthesis and rhizosphere nutrient assimilation; *Protein-L-isoaspartate O-methyltransferase* which repairs damaged proteins under stress; *Axyloglucan endo-transglycosylase* which remodels cell wall hemicellulose for salt-resistant matrices; and *glutathione S-transferase* which detoxifies reactive oxygen species (Huang and Wang 2010). Thus, *A. marina* is an ideal subject for researchers investigating salt tolerance or stress-regulating genes.

Studies utilizing cDNA libraries from NaCl-treated *A. marina* seedlings have identified several genes involved in salt stress responses. Major categories of which includes reactive oxygen species scavengers, transcription factors and ion homeostasis (Mehta et al. 2005). Reactive oxygen species such as catalase (*Cat1*) and ferritin (*Fer1*) exhibited short-term induction in response to salt and oxidative stress, while cytosolic Cu-Zn superoxide dismutase (*Sod1*) levels remained unaltered. The *Sod1*, *Cat1*, and *Fer1* mRNA levels were elevated in response to iron exposure, light stress, and direct H_2O_2 treatment, suggesting their involvement in oxidative stress response mechanisms (Jithesh, 2006). Similar expressions of genes were observed in *A. marina* grown under different environmental conditions of South Sinai, Egypt. The increased expression of *Fer1* indicated its critical role in preventing oxidative stress by neutralizing reactive oxygen species and sequestering iron (El-Atawy et al. 2021). They suggested that the observed differences in gene expression patterns were attributable to variations in salinity, which modulated the genetic response of the plants. However, the study did not compare the specific salinity variations among the sites. Such studies on elucidating the molecular responses can be highly important for the Gulf mangroves, which endure extreme stressors, including intense light and elevated temperatures. High amounts of 1-aminocyclopropane-1-carboxylic acid deaminase (ACCD)

were generated by a strain of *Pseudoalteromonas maricaloris* isolated from the rhizosphere of *A. marina* along the Abu Dhabi coast. When applied to *A. marina* seedlings, the strain substantially reduced 1-aminocyclopropane-1-carboxylic acid (ACC) levels and increased plant growth regulators, which improved growth compared to control seedlings (El-Tarabily and Youssef 2011). ACC serves as a crucial intermediate in the ethylene biosynthesis pathway and regulates ethylene levels in plants, which are produced under biotic and abiotic stress conditions. The enzyme ACCD catalyzes the conversion of ACC into α -ketobutyrate and ammonia, thereby decreasing ethylene production when its levels are increased and aids in the restoration of root and shoot development (Singh et al. 2015).

Research Gaps and Future Scopes

Given the distinctive climate, the limited distribution of monospecific *A. marina* in the Gulf, and the increased susceptibility of mangroves to anthropogenic and natural stressors, studies on the mangroves in the Gulf remain limited despite being widely acknowledged as an important marine ecosystem. The existing literature notably lacks a comprehensive investigation of ecosystem services provided by mangroves in the Gulf, particularly with regard to regulating and cultural services. Mangrove habitats extend beyond being mere tourist spots because they can also be considered invaluable natural education centers that could indeed provide experiences that can educate both global tourists and local residents. This can be achieved through structured tours and educational programs, including research activities in schools and universities to disseminate knowledge and cultivate environmental awareness. Such initiatives could offer students direct contact with nature and instill a sense of environmental stewardship at an early stage. The economic evaluation of ecosystem services is an additional area of research that requires further assessment. Utilizing data from more than 1,300 studies, Brander et al. (2024) estimated the economic value of mangrove ecosystem services at approximately USD 77,927/ha/year. In addition, evaluating the economic value of planted and natural mangroves encourages funding organisations and stakeholders to support mangrove restoration initiatives. For instance, Das et al. (2017) in his study reported that planted mangroves in Gujarat, India contribute significantly to the fishery sector valued at USD 0.57 billion annually. This highlights the significance of ecosystem services provided by transplanted mangroves should not be underestimated. It further emphasizes the importance of continued research and investment to enhance the ecological benefits of mangroves in the Gulf. Research in the Gulf has yet to adopt a comprehensive framework that integrates ecological, social, and economic dimensions in addition

to environmental aspects, despite the fact that studies conducted worldwide have highlighted the economic values and livelihood evaluations of mangrove ecosystems.

The microbes in the mangrove ecosystem along with the other biotic and abiotic components play crucial role in maintaining the mangrove rhizosphere. These microbes possess a wide range of biotechnological applications, including the synthesis of enzymes, pharmaceutical compounds, biofuels, antimicrobial agents, and other products. Recent studies in the Gulf region focused on enhancing mangrove resilience and development, primarily along the UAE coast. More metagenomic research is necessary to investigate the unique strains of mangroves in the Gulf that are highly adapted to severe environmental conditions, as the microbial community of mangroves in the Gulf remains largely unexplored, particularly with respect to fungi and hydrocarbon-degrading microbes. Oil-degrading microbial consortia exhibit potential for enhancing oil degradation and are viable candidates for bioremediation applications. A comprehensive analysis of biotic and abiotic factors, including temperature, salinity, and pollutant concentration, is also important for understanding the microbial composition. The widespread use of chemical fertilizers and the requirement to increase agricultural yields in parallel with growing populations have raised significant concerns regarding food safety. Impacts associated with climate change have made it increasingly challenging to achieve sustainable agriculture in semi-arid to hyper-arid regions while ensuring efficient utilization of limited freshwater resources. Mangrove bacteria possess highly valuable genes for stress tolerance, as they have evolved to develop structural and physical adaptations while enduring intense abiotic stress. The potential for isolating salt-tolerance genes from mangroves for application in improving salt-sensitive crops should be thus an important concern in mangrove microbial research in the Gulf. Addressing this research gap presents an excellent opportunity to integrate mangrove restoration with agricultural improvement by enhancing food security and ensuring the resilience of both natural and agricultural ecosystems.

Prioritizing the mapping of mangrove ecosystems and establishing Marine Protected Areas (MPAs) across the Gulf is paramount. These efforts are crucial for understanding mangrove distribution and identifying vital habitats and areas for conservation. While expanding the boundaries of MPAs as a critical step, it is equally important to protect and incorporate the value of ecosystem services into conservation guidelines to ensure effective preservation. Considering the rapid coastal development and escalating anthropogenic pressure in the Gulf, utilizing spatial data such as ecological mapping facilitated by Geographic Information Systems (GIS) can be highly beneficial for accurately delineating the distribution of mangroves and identifying areas of the highest conservation priority. Given the importance of physical

and biological interconnections, restoration efforts and practices should prioritize the connectivity between mangroves and other ecosystems, such as seagrass beds and coral reefs. Anthropogenic stressors, temperature and salinity variations, and hydrodynamic processes are other factors that must be considered while conducting site-specific research. Further research is necessary to fully elucidate the long-term effects of restoration techniques, with emphasis on how climate change is influencing the hydrological and chemical parameters of mangroves.

Assessing past changes and predicting future conditions in mangrove habitats is crucial for understanding their vulnerability to climate change and implementing effective management strategies. Few studies attempted to map the spatial coverage of mangroves in the Gulf (Almahsheer 2018) and assessed the changes in the mangrove area between different years (Rondon et al. 2023). Apart from the satellite mapping, site-specific surveys and sampling are also important to accurately assess the mangrove ecosystems in the Gulf, including physical, chemical and biological characterization. Climate change poses various stresses and disturbances to mangroves. Satellite data coupled with projects can help predict the regional or global responses of mangroves to climate change, guiding adaptive management strategies to ensure the long-term stability of mangrove ecosystems. For instance, Mafi-Gholami et al. (2020b) used various data along with satellite imagery to assess the changes in mangroves along the northern coasts of the Gulf and Sea of Oman to climate change impacts. This study projects changes in mangrove coverage by 2100 along the Gulf and Sea of Oman coasts under the RCP 8.5 climatic scenario. Rising sea levels (~9.9 mm/yr) are expected to cause a 50–60% reduction in mangrove area, with the Sea of Oman experiencing the most significant loss due to high subsidence rates. In close agreement with the statistical model's projections of 48–55% and 56%, respectively, the CA-Markov algorithm estimated mangrove area losses of 52–55% for the Gulf and 61% for the Sea of Oman by 2100. Such comparative studies that assess mangrove exposure across different coastal regions provide crucial insights into regional vulnerability. An earlier review by Ward et al. (2015) identified several critical concerns about the future of Gulf mangroves in the face of climate change. The authors emphasized the scarcity of data on sediment accumulation, surface elevation changes, and expected temperature rises and precipitation patterns, making it challenging to predict climate change impacts on mangroves in the Middle East region. Currently, there is a major lack of a nationwide plan for assessing the vulnerability of mangrove ecosystems to the impacts of sea-level rise in the Gulf.

Sustainable development and management practices incorporating Integrated Coastal Zone Management (ICZM) are crucial in the Gulf for sustaining healthy mangrove

ecosystems that can be highly productive and enhance ecosystem services. Coastal development projects that adhere to ICZM can enhance local biodiversity and abundance if they are constructed in suitable areas with minimal impacts from the environment. ICZM serves as a holistic approach to balancing development and conservation, promoting economic and environmental resilience. Balancing resource extraction, maritime activities, and environmental conservation is essential for ensuring long-term stability, ecological health and safeguarding the ecological services that mangroves provide for future generations in the Gulf region. However, the broader engagement of authorities is necessary to ensure sustained growth and protection. Gulf countries have demonstrated an increasing interest in reducing carbon emissions and combating climate change by adopting sustainable and environmentally friendly practices. This commitment is evidenced by their hosting of international events such as the Conference of the Parties (COP) to the UN Framework Convention on Climate Change (UNFCCC), which highlights their dedication to global efforts. Moreover, the establishment of ambitious targets, such as aiming for net-zero emissions by the mid-century, exhibits a proactive approach towards mitigating the impacts of climate change. Within this context, the conservation of local mangrove ecosystems has emerged as a critical component, serving as a significant carbon sink, coastal protection barrier, and biodiversity reservoir. By prioritizing the preservation of these ecosystems, Gulf countries not only safeguard invaluable natural resources, but also reinforce resilience and advance sustainable development imperatives.

Conclusions

Mangrove forests in the Gulf are known for their remarkable resilience and flourishing in one of the driest mangrove habitats globally. The current review highlighted the crucial importance of *A. marina* in the Gulf for providing ecosystem services essential to both ecological resilience and local community livelihoods. However, the Gulf mangrove research lags behind global efforts, particularly regarding ecosystem services. Mangroves function as crucial nurseries and refuge grounds for numerous species, indicating their importance in marine food chains and their role in maintaining connectivity between the ecosystems such as coral reefs and seagrass beds. Studies in the Gulf have revealed differences in carbon storage between natural and planted mangroves, emphasizing the importance of proper management and preservation of restored and transplanted mangroves to maximize their carbon sequestration potential. Given the documented mangrove loss in the region, urgent action is required to conserve and manage Gulf mangroves to mitigate the effects of climate change and anthropogenic

coastal development. The increased vulnerability and deterioration of the Gulf mangroves due to natural and anthropogenic pressures have resulted in several initiatives to manage and restore these ecosystems. However, coordinated regional efforts are necessary to integrate mangrove-related information across all aspects for a thorough comparison and critical meta-analysis. Despite obstacles posed by coastal development and industrial activities, innovative restoration approaches have shown efficiency in promoting mangrove growth and ecosystem recovery. Studies have also concluded that PGPB associated with mangroves are highly valuable for encouraging sustainable agricultural practices and enhancing resilience, with the potential to convert saline agricultural lands into highly productive and economically beneficial areas. Ongoing investment in restoration programs, along with stringent management and monitoring, is essential to ensure the long-term success of these efforts and preserve the valuable ecosystem services provided by the only mangrove species, *A. marina* in the Gulf.

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