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Possible Future Risks of Pollution Consequent to the Expansion of Oil and Gas Operations in Qatar

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Abstract

The air, water, and lands of the Arabian Gulf countries are exposed to contamination involving organic and inorganic components resulting from industrial energy sector activities. In Qatar, marine life and air are the primary elements of the ecosystem that pollution has negatively affected since the discovery and exportation of oil and gas. For example, the mean concentration of PM2.5 reached 105 μg/m^3 in 2016. This poor air quality has been attributed to several factors: dust storms, vehicle emissions, and industrial emissions. Marine life around the peninsula of Qatar has been threatened by many factors, including discharge of desalinated seawater, oil and gas activities, and the impact of climate change. Studies conducted after multiple major events showed that levels of various types of pollutants were at acceptable levels. Some areas in the Arabian Gulf, such as the coasts of Saudi Arabia and Bahrain, are still considered chronically polluted and need continual monitoring in the long term. This review discusses the pollution status on the Qatari coastlines and the reasons behind the persistence of current levels of pollution in Arabian Gulf water. The role of microorganisms (bacteria, algae, and fungi) in a biological approach for environmental manipulation of pollution problems is discussed. The agricultural lands in Qatar are possible sites of pollution due to the potential expansion of the energy, industry, and construction sectors in the future. Currently, industrial wastewater is pumped deep into the ground, and seawater is intruding into the main-land, which is causing significant contamination of soils used for the cultivation of various crops. Possible measures are reported, and practical solutions to future pollution risks are discussed.

Keywords: air pollution, bioremediation, industrial emissions, land pollution, water pollution

1. Introduction

The quality of the ecosystem is closely related to the value of life, sustainable prosperity, and wellbeing. Thus, it is beneficial for human development and life if the environment is clean and free of various types of pollution. Increasing pollution problems in soil, water, and air resulting from energy, industry, and anthropogenic activities can cause significant threats to many aspects of the economy, agriculture, health, and wildlife (Yasseen, 2014). Industrial activities associated with oil and gas produce significant amounts of environmental pollution through all processes involved, including detection, extraction, and transportation, as well as during the processes of refining the products to obtain high-purity compounds for use in various ways.

Countries bordering the Arabian Gulf, including Iran, are suffering from the consequences of all these industrial activities related to oil and gas, including the accumulation of petroleum hydrocarbons and heavy metals in the ecosystem. Human activities involved the development of other industries might be another source of concern in the accumulation of pollutants (Abulfatih et al., 2002; Hosseini et al., 2021). Notably, Qatar and its neighboring countries have occasionally suffered from oil spills in the Gulf since the 1980s, which have resulted from catastrophic events during three major wars in the region (from 1980 to 1988, 1990 to 1991, and 2003). These events included hydrocarbon compound spills and burning oil wells and tankers, during which large quantities of oil dissipated in international seawater and settled on the shores, greatly damaging wildlife and public health (Abulfatih, Abdel-Bari, Alsubaey, & Ibrahim, 2001; Al-Thani and Yasseen, 2021a). Early reports offer examples of such damage. A report from the Food and Agriculture Organization (FAO) of the United Nations (FAO, 1979) and other studies (Al-Ansi, 1995) have shown a substantial reduction in the number of living marine organisms such as shrimp in Qatari seawater during the period between 1968 and 1995.

During the last 20 years, a great revolution in the energy sector in Qatar has thrust the country to the forefront of gas-producing countries, which was concurrent with the rapid expansion of industrialization and the urban sectors. All these activities have yielded many positive effects on the prosperity of the people and social life in this country, but negative side effects of these activities were not only expected but also inevitable. Qatar is due to host major events and tournaments, such as sports, political, and social events, which will all reflect the quality of the ecosystem. The decision-makers in Qatar always remind people to be aware of the future risk of the developments in the energy sector. Radical solutions are necessary to mitigate the possible risks and negative impact of expansion in industrial activities.

A negative impact on air quality has been seen to result from burning natural gas from industrial gas and oil sites, which releases a considerable amount of smoke and fumes that contain toxic gases. Significant damage has occurred to the quality of air in Qatar, particularly Doha, as a result of the expansion of the urban sector, including the construction of new towers and houses, as well as a substantial increase in the number of vehicles (Wiedmann, Salama, & Thierstein, 2012; Planning & Statistics Authority, Doha, Qatar [PSA, Qatar], 2013; Ministry of Development Planning and Statistics, Doha, Qatar [MDPS, Qatar], 2019; Qarjouli, 2022). Thus, the main part of the Qatar National Vision 2030 involves protecting the ecosystem from various risks of pollution due to the expansion of energy industrialization. Environmental development is the fourth pillar of the Qatar National Vision 2030 (General Secretariate for Development Planning, Doha, Qatar, [GSDP, Qatar], 2008). Notably, Qatar and its neighboring countries constitute an ecological system that is affected by the industrial activities, so they must establish sustainable environmental development. Therefore, the objectives to improve the quality of the environment in Qatar in any future project should include: (1) recognize the primary sites of pollution, (2) describe the pollution status at the main locations of ecosystem, (3) monitor all sites in Qatar including seawater, seashores, land, and air, (4) setup roadmap and suggestions for the scientists and decision makers to improve the quality of ecosystem, (5) reveal the possible steps and practical methods including biological approaches to reduce the pollution in the Gulf waters, lands, and air around Qatar.

2. Pollution Sources

Natural pollution has been recognized for many years in the Arabian Gulf region and comes from two main sources: salinity and dust. As a sign of pollution, in most Qatari lands, such as Sabkhas, salty patches, and coastal areas, problems of salinity have been created naturally or has developed from the intrusion of saline water containing significant amounts of contaminants moving from the Arabian Gulf (Abulfatih et al., 2001). Variations in salinity levels have been recognized as a common feature in these areas, even within the same confined area, which could arise from evaporation, climatic aridity, and rain scarcity as the main reasons (Yasseen and Al-Thani, 2007). This area is also exposed to annual episodes of dust storms that disrupt the atmosphere and create respiratory problems, such as shortness of breath and asthma. Human activities have been considered the primary source of pollution worldwide, and the origin of such pollution in Qatar could be mainly a consequence of the production of industrial wastewater during the extraction, production, transportation, and exportation of oil and gas.

Other sources of pollution include activities such as the creation of wastewater containing a mixture of consumed water and contaminant loads, such as effluents from domestic houses and other establishments, institutions, hospitals, factories, and others (Alsheyab and Kusch-Brandt, 2018). Many other factors affect the quantity and quality of wastewater, including human behavior, lifestyle, standards of living, the juridical framework, and the design of sewer systems (Tomar, 1999). Recent studies have suggested that wastewater of various types (such as anthropogenic and industrial) could be an alternative source of water for various purposes (Al-Thani and Yasseen, 2021a). A new concept of wastewater refinery has recently emerged as a practical method to recycle such wastewater in places that might need to conserve the water produced during various activities (Alsheyab and Kusch-Brandt, 2018). The organic components of industrial wastewater produced annually in Qatar are estimated to be about 77,000 tons per year. This amount could increase significantly in the near future given the high demands for gas, which necessitate a substantial expansion in the gas and oil sectors. However, various valuable organic and inorganic components can be extracted from industrial wastewater. For example, 27 million m^3 per year of methane could be extracted through anaerobic digestion, and fertilizers could be obtained, including about 6,166 metric tons of nitrogen and 881 metric tons of phosphorus. The development of cheap and modern techniques could increase these amounts significantly. Other materials that could be extracted include oil and grease (32,595 tons per year), alkaline substances (41,229 tons per year), chloride (81,000 tons per year), and sulfide (2,819 tons per year). Nevertheless, all of these components are considered sources of pollution and constitute threats to public health and social life unless a solution is found to counteract their outstanding negative impacts.

Changes in biological soil crusts (BSCs) due to industrial and anthropogenic activities represent another source of pollution and could release cyanotoxins into the air, causing acute and chronic human and animal health problems. Other fluctuations in the soil characteristics in response to changes in BSC might be observed in water conditions and nutrient levels, which both affect plant growth and development (Richer et al., 2012). Notably, BSC plays significant ecological roles, such as carbon fixation, nitrogen fixation, and soil stabilization. Anthropogenic activities could cause a great deal of contamination on the coasts. For example, desalination of seawater could be a source of pollution in the soil and water (Hosseini et al., 2021). The construction of desalination plants, the uptake of seawater, and the discharge of untreated brine back into the sea adversely affect the biodiversity of marine ecosystems.

3. Focus of Pollution Action

Pollution is defined as the introduction of any substance (solid, liquid, or gas) or energy (radioactivity, heat, sound, or light) that causes adverse changes in the natural environment. These types of pollution can originate from natural events or anthropogenic activities. Contaminants enter the ecosystem in two main ways: direct leaks and accidents during disposal from storage sites or industrial facilities. Three primary sites of pollution have been recognized worldwide: air, water, and land.

3.1 Air Pollution

Air pollution in the Arab world comes from many sources. A 2006 report submitted to the Economic and Social Commission of Western Asia (ESCWA) and the League of Arab States (LAS) discusses air quality and atmospheric pollution in the Arab world (El-Raey, 2006). The report provides fundamental details about these sources and the possible solution to air pollution in this part of the world. Vehicular emissions, dust, sand storms, greenhouse gas emissions, and various gases from human and industrial activities constitute the primary sources of air pollution. These gases include carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and possibly others (Bener, Dogan, Ehlayel, Shanks, & Sabbah, 2009). Burjaq, Omar, Hammoudeh, & Janahi (2020) concluded that poor air quality in Qatar is the most common reason for some diseases, such as asthma, and Qatar has the second highest prevalence of childhood asthma in the Gulf region (19.8%). Many reasons have been reported as causing such a high level of this disease, including natural sources, microbial communities, phytoplankton blooms, anthropogenic sources, vehicular emissions, industrial emissions, and construction activity. Alzoubi, Al-Bzoor, Aljalahma, & Ali (2021) recently confirmed these results and considered environmental conditions such as air pollution, temperature, and humidity as the main reasons for triggering an asthma attack.

Other sources that can also significantly contribute to air-quality deterioration include outdated power-generation stations, refineries, outdated smelters, fertilizer plants, cement manufacturing, and water desalination plants. A significant number of deaths worldwide can be attributed to air pollution, and the World Health Organization (WHO) attributes 1 in 8 to 10 deaths to indoor air pollution. Some reports estimate that deaths around the globe due to air pollution account for about 12% of total deaths worldwide (Hussain, 2020). However, this report presented conflicting outcomes about the impact of air pollution on the health of residents in the Middle East. On the other hand, some alarming reports indicate that annually, 1 in 10 deaths in the region could be attributed to air pollution (Chandrappa and Chandra Kulshrestha, 2016; Khanjani, Farahmandfard, & Eslahi, 2022). Notably, such pollution might be contributing to many diseases, including heart diseases, respiratory problems, and cancer (World Health Organization [WHO], 2014). Recent reports have provided more details, indicating that air pollution is increasing at high rates (even higher than the limit reported by the WHO), and about half a million people in the Eastern Mediterranean region die annually because of air pollution. A major part of air pollution stems from natural contaminants, such as sand, dust, and sea salt, while other sources of air pollution originate from industrial activities and vehicle emissions (Chandrappa and Chandra Kulshrestha, 2016). The State of Qatar is considered to be among the countries with the most air pollution, but reports present some controversial and troubling data (Hussain, 2020). For example, the data on air pollution in Qatar in 2005 indicated that the mean concentration of PM2.5 was 91 $\mu g/m^3$ (WHO, 2005a), which further increased to 105 $\mu g/m^3$ in 2016 (Scott, 2016). The air pollution in Qatar is considered to contain the second-highest level of PM2.5 in the region behind Saudi Arabia (PM2.5 particles were 127 $\mu g/m^3$), while the average in the United Arab Emirates (UAE) was around 64 $\mu g/m^3$. According to Hussain (2020), the air in Qatar contains 76 $\mu g/m^3$ PM, and the ozone level is over 67 ppb, while the international limit set by the WHO is 50 ppb. The general conclusion about air pollution in Qatar is that Doha has consistently high levels of air pollution attributed to dust storms, vehicle emissions, and industrial emissions. The major contributor to such emissions is greenhouse gas (GHG) emissions, followed by the industrial sector and domestic waste (Lanouar, Al-Malk, & Al Karbi, 2016).

3.1.1 Dust Storms

Dust storms have several negative impacts on various aspects of life, including soil properties and fertility (Prakash, Stenchikov, Kalenderski, Osipov, & Bangalath, 2015). Millions of tons of dust are lifted into the atmosphere and can cause severe air pollution, reduce visibility, disrupt air and land transport, and cause many accidents (UNEP, WMO, UNCCD [UWU], 2016). North Africa is the origin of dust storm events that affect the Arabian Peninsula, which have a great impact on the marine ecosystem of the Arabian Gulf and Sea, in addition to the Red Sea, although they might also provide nutrients to the water flats and sea beds (Talbot et al., 1986; Swap, Ulanski, Cobbett, & Garstang, 1996; Zhu, Prospero, & Millero, 1997). Some reports indicate that a combination of strong winds and loose dry soil surfaces in many parts of the world might cause large sand and dust storms (UWU, 2016). Many detrimental effects on various life sectors are reported, including human health, agricultural lands, infrastructure, and transport.

The estimated millions of tons of dust emitted into the air include chemical components and natural parts of anthropogenic and industrial activities that might have a negative impact on many aspects of life. Air pollution due to dust storms in most countries in the Middle East could lead to particulate matter (PM) figures of more than 60 times the permissible levels. For example, in recent months (May 2022 and earlier), a high number of sandstorms has engulfed parts of countries in the Middle East, such as Iraq, Iran, Syria, Kuwait, and Saudi Arabia. Such storms have sent thousands to hospitals with breathing problems and caused the closure of airports, schools, and government offices. Experts are blaming the mismanagement of agricultural areas, an ongoing drought, and climate change (Agency France Press [AFP], (2022, May 24). Such situations reduce visibility, increase traffic accidents, and increase respiratory diseases, coughs, rhinitis, pulmonary wheezing, acute asthmatic attacks, eye irritation, headaches, body aches, and sleep and psychological disturbances. Moreover, carcinogenic elements such as Cd, Ni. Pb, and radioactive elements have been reported in PM (Amoatey, Omidvarborna, Baawain, & Al-Mamun, 2018). Notably, Al-Thani, Koc, Rima, & Isaifan, (2018*)* found multiple inorganic elements in the dust fallout in Doha, Qatar, and provided more details about the sources and characterization. The sources of PM were mainly of natural origin (60%) and related to soil/crustal matter, marine salt, and desert dust. The remaining balance of the dust fallout was attributed to anthropogenic sources, including transport and construction. All these sources have demonstrated substantial increases accompanying with rapid growth in the economy and development of Qatar. The size of the PM was about 7.38µm, and the order of the inorganic content from greatest to smallest was Ca > Si > Fe > Mg > Al > Ti > K > Na > S > Cl (Al-Thani et al., 2018).

On the Arabian Peninsula, dust storms such as those in the Empty Quarter Desert cause many disturbances in countries bordering the Arabian Gulf, especially during the summer season (Francis et al., 2021). Moreover, the immense amount of dust created by cement factories has a negative impact on people and wildlife (Abulfatih et al., 2001). International events in Qatar are leading to the construction of large structures, such as airports, stadiums, hotels, transport facilities, hospitals, and any infrastructure necessary to receive many visitors to these events (Supplementary Figure. 1). These projects and events require the use of huge quantities of building materials that generate a significant amount of dust within small areas, such as the city of Doha and its suburbs. Much work is necessary for these events to be clean and free from environmental pollutants resulting from the construction of this infrastructure system (Lanouar et al., 2016).

3.1.2 Vehicle Emissions

Carbonization from vehicles using liquid fuels has caused substantial air pollution, especially in congested cities. Notably, Doha has the highest population in Qatar and the most industrial activities and governmental offices. Other towns in Qatar, such as Dukhan, Ras Laffan, and Umm Said, are smaller in size, population, and life activities, but they have great impacts on levels of air pollution as major activities of oil and gas industries are conducted there. Recent studies have concluded that road traffic in Doha is one of the main sources of PM in the atmosphere, which causes much air pollution in this city. The pollution on the main roads using non-passenger diesel vehicles is much higher than in locations with no traffic (Al-Thani, Koc, Fountoukis, & Isaifan, 2020). Most dust is generated from tire wear (33%), followed by road dust resuspension (31%), brake wear (19%), and exhaust emissions (17%). A low contribution of exhaust PM10 emissions occurs because most modern vehicles are equipped with efficient systems to reduce it in the exhaust. Therefore, the State of Qatar has pledged to achieve a promising objective of using 10% electric vehicles by 2030 (Al-Buenain et al., 2021) as a practical measure to reduce air pollution. These studies have placed much pressure on decision-makers to establish more encouraging, promising, and incentivizing measures to achieve the objective of increasing the number of electric vehicles as replacement for conventional gasoline vehicles. Electric vehicles were found to have a much less negative impact on emission of GHGs compared to internal combustion engine vehicles (Al-Buenain et al., 2021; Ministry of Municipality and Environment: The State of Qatar [MME, Qatar], 2021). As the primary transport in Doha is mainly private automobiles, all PM from vehicles (exhaust and non-exhaust emissions) contributes to air pollution. Such pollution negatively affects many life sectors, including agricultural lands and human health, but this pollution can be reduced via the adoption of several measures. For example, public transportation such as the Doha Metro Project (Supplementary Figure 1) is aimed at reducing the use of private automobiles on the roads of Doha (Al-Thawadi and Al-Ghamdi, 2019). Emissions from private and public vehicles can pollute the environment, including agricultural land and the atmosphere (Al-Thani et al., 2020), causing health issues and disruptions in many aspects of life.

3.1.3 Industrial Emissions

The energy sector is the main origin of industrial and GHG emissions into the atmosphere, followed by other industrial activities and domestic waste. Therefore, during oil and gas processing, significant amounts of emissions, including toxic gases, are produced in the environment and cause substantial contamination of the atmosphere. These emissions include GHGs such as water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). The increase in production of these gases has led to an increase in absorption of heat from the sun, which keeps the atmosphere warm (Lanouar et al., 2016).

In the Arab world, oil refineries are very common in many industrial sites. El-Raey (2006) describes the chemical components of these emissions, which include various organic compounds, volatile and non-volatile compounds, sulfur compounds, hydrocarbons, and nitrogen oxides. These pollutants not only can increase the concentration of PM2.5, but also greatly contaminate the land and seawater (Prakash et al., 2015). This has a negative impact on human health, agricultural crops, wildlife, and others (WHO, 2005b). When these compounds accumulate in the atmosphere, they absorb heat, which creates global warming and causes climate change. The sources of organic contaminants associated with fine (PM2.5) and coarse (PM2.5–10) atmospheric PM in Doha were recently measured using modern techniques to quantify the contribution of major sources, such as biogenic aerosols, fugitive dust emissions, gasoline engine emissions, diesel engine emissions, and heavy oil combustion (Javed et al., 2019). The researchers concluded that vehicular-related emissions (including gasoline and diesel engine exhaust and fugitive dust) and, to some extent, petroleum and biogenic sources were the major sources of organic pollutants. Moreover, both regional and local sources contribute to these pollutants depending on the speed and direction of the wind.

3.2 Water Pollution

Water sources in Qatar and most Arabian Gulf countries are limited as this region lacks freshwater sources such as rivers, lakes, and springs and has little rainfall (152 mm per year) (Yasseen and Al-Thani, 2013). Moreover, the resources in Qatar are supplied by scarce episodes of rainfalls and from sub-surface (well) water, such as fossil water, which forms a freshwater lens floating above a predominantly saline aquifer (Petersen, 2018). Notably, Economic and Social Commission for Western Asia, The United Nations [ESCWA] (1996) confirmed that groundwater is the main source of water in these countries, but alternative resources have been developed through the construction of non-conventional plants, such as desalinized seawater and treated wastewater from industrial and anthropogenic activities (Abulfatih et al., 2002). Recent reports have suggested additional and alternative sources of water for various domestic and agricultural purposes to meet people’s needs (Al-Thani and Yasseen, 2021a). Industrial and anthropogenic wastewater could be a future solution for water scarcity in addition to sustaining the prosperity of this region. Industrial wastewater from oil and gas activities spills into seawater during prospecting, extraction, and transportation. A significant volume of crude oil has also been spilled in the Arabian Gulf during wars and military training and continues to spill, greatly polluting seawater with millions of barrels of oil and gas components. These contaminants negatively affect marine life (Yasseen and Al-Thani, 2013; Yasseen, 2014; Hosseini et al., 2021). Other pollution drivers, including climate change and coastal anthropogenic disturbances, could also have effects on the marine environment of the Arabian Gulf.

The intrusion of oil components and highly saline water into the mainland of the Qatari peninsula could also have a negative impact on the groundwater and soil (Yasseen and Al-Thani, 2013). Recent works revealed that industrial wastewater from oil and gas activities has been pumped deep into the ground, which could cause great damage to the groundwater (Al-Thani and Yasseen, 2021a). Such a huge volume of water can be stored in artificial ponds and treated by various methods using bioremediation, phytoremediation, and phyco-remediation. Microorganisms, algae, and native plants could also be used to remove all pollutants consisting of heavy metals and degrading organic components. In the end, such water might be useful for various purposes, including agriculture and even domestic uses (Al-Thani and Yasseen, 2021a; b).

After the three major wars and the events that accompanied or followed them, it has been necessary to assess the pollution situation in the water of the Gulf in general and particularly around the Qatari peninsula. Many studies have been conducted to look at the level of organic and inorganic pollutants in the Gulf waters close to the Gulf Cooperation Council (GCC) countries. For example, Kureishy (1993) investigated the impact of the 1991 Gulf war on the marine life around the peninsula of Qatar, and it was found that Cd, Co, Cu, Hg, Ni, and Pb levels were in the normal ranges in the muscle tissues of various benthic and semi-pelagic species. Close to Qatar, Bahrain marine life was also investigated. Heavy metals (including Cd, Cu, Fe, Mn, Ni, Pb, and Zn) were found in pearl oyster (*Pincatada radiata*) in two locations during the period of March 1991 to March 1992. The levels of these heavy metals were within the limits of the WHO guidelines except for Cd and Pb (Al-Sayed, Mahasneh, & Al-Saad, 1994).

3.2.1 Case Studies after the Three Major Wars

Aboul Dahab (1994) did a case study on oil pollution in the Arabian Gulf around Qatar. The Arabian Gulf is shallow with an average depth of 35 m and is rarely deeper than 100 m (Al-Saad and Salman, 2012). At the moment oil is spilt into the sea, it begins to disperse, and the rate of dispersion depends on various environmental factors, such as the wind speed, wave size, temperature, salinity, water-column depth, specific gravity, degree of refinement, and the quantity involved (Chandrasekar, Sorial, & Weaver, 2005). The rate of spreading is affected by the viscosity, density, chemical composition, wind speed, and currents, and the emulsification of oil reduces its oil (Abdulredha, Hussain, & Abdullah, 2020; Keramea, Spanoudaki, Zodiatis, Gikas, & Sylaios, 2021). The polar components begin to dissolve and leach out of the oil slick, and the volatile components evaporate. All of these processes are termed weathering (Aboul Dahab, 1994; Interstate Technology & Regulatory Council [ITRC], 2018). Notably, oil droplets in sea water are more susceptible to weathering, adsorption and the suspension of organic and inorganic matter, consumption by zooplanktons with incorporation of oil into fecal pellets, and hydraulic transport (Lee, 2002; Awaka-ama, 2011). By adhering to suspended sediments of greater density, oil droplets dispersed in water may also sink to bottom waters and sediments, which happens naturally as the Gulf is shallow (The National Academy of Science [NAS], 2003). Since the start of the Iraq-Iran war in 1980 and the following conflicts in the region, a substantial volume of crude oils and industrial wastewater has been spilt into the Arabian Gulf, causing much disruption to marine life (de Mora et al., 2010; Freije, 2015; Hassanshahian, Amirinejad, & Askarinejad Behzadi, 2020).

The state of oil pollution after the war in 1991: Aboul Dahab (1994) studied most coastlines around the Qatari peninsula during the period of February 1991 to August 1993. Notably, two main sources of pollution on the coastline were recognized: industrial wastewater or anthropogenic pollution and natural pollution. The main objectives of that study were to describe the state of pollution on many Qatari beaches and compare it with others in the Arabian Gulf region after the war in 1991. The study covered three main oil forms in the Qatari coastal sediments and territorial waters: tarry deposits, dissolved and dispersed petroleum hydrocarbons, and total petroleum hydrocarbons (TPH). These oil forms have been considered as ubiquitous in Qatari coastal waters and sediments. This investigation was considered as the first serious study to include many parameters as previous studies were limited to the determination of dissolved and dispersed petroleum hydrocarbons in seawater after the Iraq-Iran war (1980-1988) (Hassan and El-Samra, 1988).

After several visits and samplings during the investigation, the main oil forms were determined quantitively using the methods described in the Manual of Oceanographic Observations and Pollutant Analysis Methods (Regional Organization for the Protection of the Marine Environment [ROPME], 1989). The investigation examined 10 beaches and 18 stations. Table 1 shows the average quantities of tar on Qatari beaches in comparison to those in the Arabian Gulf region known as ROPME, which includes the Kingdom of Bahrain, Iran, Iraq, Kuwait, Oman, Qatar, Kingdom of Saudi Arabia, and the United Arab Emirates.

Table 1. Average quantities of tar on beaches in the ROPME Sea area

Location	Concentration range (g m^{-1} of shoreline)
Bahrain	14-858
KSA	0-28750
Kuwait	5-2325
Oman	1-906
Qatar	58-5000
UAE	4-233

Aboul Dahab (1994).

The study concluded that tar was covering the northern and northwestern beaches of the Qatari coastlines (ROPME, 1989). However, the state of the tar pollution along the Qatari coastline is characterized by significant variations and levels. This varies from heavily polluted northern and northwestern shores to virtually pollution-free shores in the southeast. The variations were attributed to the location of Qatar Peninsula and the meteorological and hydrological conditions of the region. Dissolved and dispersed petroleum hydrocarbons were extracted immediately after collection by a solvent mixture of fluorescence-free hexane and dichloromethane (7/3 V/V). Samples were taken 1-m depth at the chosen stations along the Qatari coast during two sessions (May 1991 and December 1991). Three samples of 3 liters each were taken from each station. The fluorescence of sample extracts in hexane and blanks was measured according to the established methods (ROPME, 1989). The data were expressed as chrysene and Kuwaiti crude oil equivalents, and the detection limit of this procedure was 0.5µg (Kuwaiti crude oil per liter is equivalent to 0.042µg of chrysene per liter). Table 2 shows the results from the stations from southeast to northeast and north of the peninsula of Qatar (Figure 1).

Table 2. Dissolved and dispersed petroleum hydrocarbons in samples taken at 1-m depth from each station along the Qatari coast during two sessions

Station	Petroleum hydrocarbons concentrations (µgl^{-1})			
	May 1991		December 1991	
	Chrysene	Kuwaiti	Chrysene	Kuwaiti
Umm Said	0.42	5.1	0.55	6.5
Doha	0.40	4.8	0.37	4.4
Fuwairet	0.22	2.6	0.24	2.8
Ruwais	0.36	4.3	0.38	4.5
Al-Zubara	0.31	3.6	0.37	4.4
Dukhan	0.17	2.0	0.19	2.2

Aboul Dahab (1994).

The data show no consistent trend in the dissolved and dispersed petroleum hydrocarbons in the studied stations. This may suggest that the possible main sources of these components are harbors and coastal activities (such as those at Umm Said, Doha, and Ruwais), followed by leaching of dissolved oil from the deposited tarry materials (such as Al-Zubara). Notably, these results confirmed previous studies (Hassan and El-Samra, 1988) during and after the Iraq-Iran war (1980-1988).

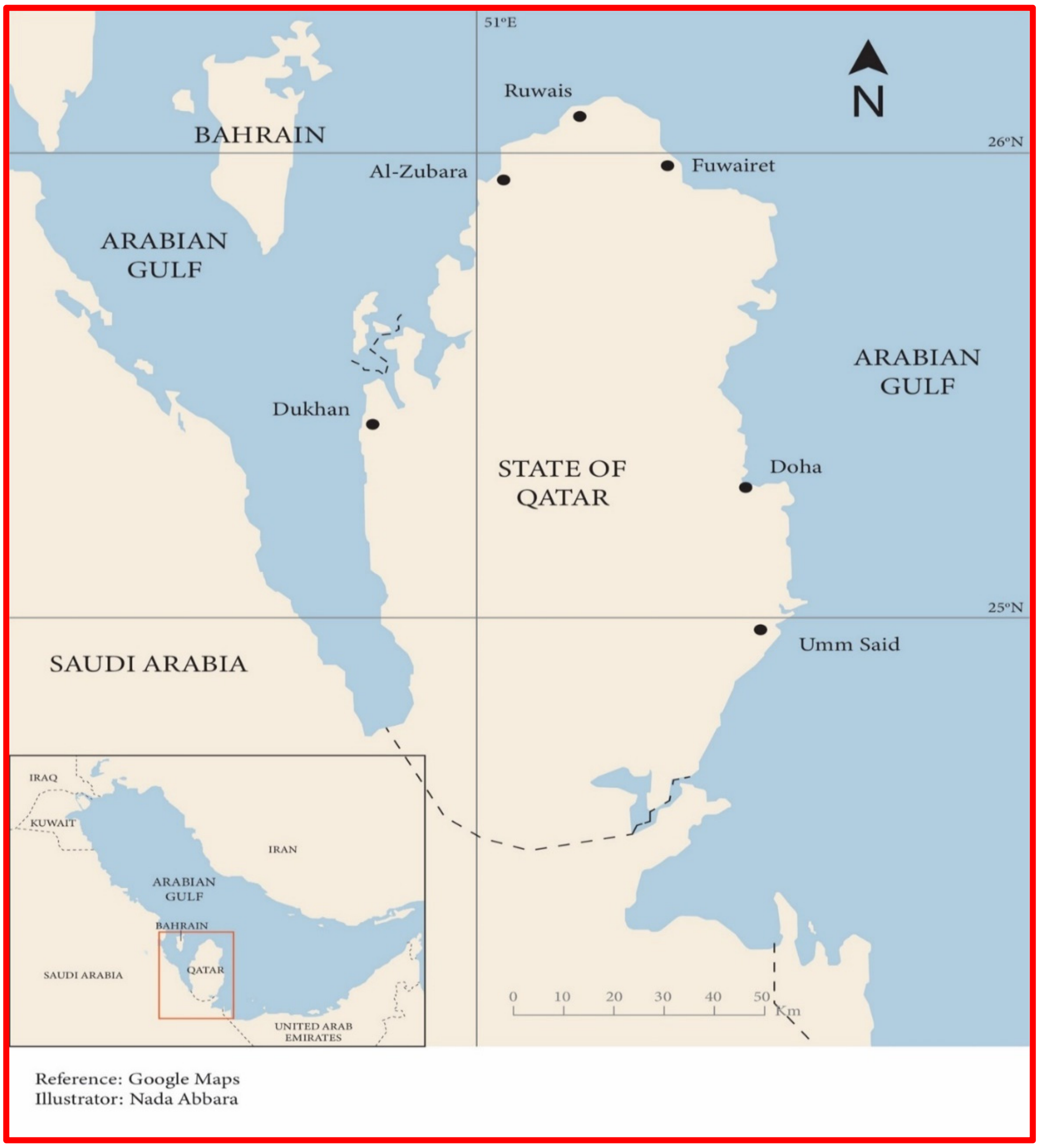

Figure 1. Map of the State of Qatar showing six stations (Umm Said, Doha, Fuwairet, Ruwais, Al Zubara, and Dukhan)

Table 3 shows the concentrations of petroleum hydrocarbons in the Qatari coastal sediments and the total organic compounds (TOC), which indicate that all sites along the Qatari coastline are contaminated to some extent with petroleum hydrocarbons. These components were markedly higher along the western side of the peninsula of Qatar (Dukhan and Al-Zubara) than the eastern side (Umm Said and Doha). The highest levels were found at Al-Zubara on the north-western side of Qatar. These spatial variations can be explained by the location of the Qatari peninsula and the prevailing meteorological and hydrological conditions of the region. The main wind pattern in the whole area is north-westerly, and the predominant water current is counter-clockwise, so it is expected that the consequences of these conditions would appear in the northern parts of the peninsula (Linden et al., 1990).

Table 3. Petroleum hydrocarbon concentrations (μgg^{-1} dry weight in Chrysene and Kuwaiti -crude-oil equivalents) in Qatari coastal sediments (May 1991)

Station	Water depth (m)	Sediment type	TOC %	Concentration	
				Chrysene equivalents	Kuwaiti oil equivalents
Umm Said	10	Fine sand	0.8	7.4	88.5
Doha	8	Mud and sand	0.9	4.6	54.1
Fuwairet	7	Sand and mud	0.9	6.8	81.3
Ruwais	7	Sand	1.0	9.0	107.5
Al-Zubara	8	Sand	1.3	18.1	215.3
Dukhan	7	Sand	0.6	12.0	143.2

Aboul Dahab (1994), TOC: total organic carbon.

Considering the frequent accidental and chronic oil spillage in the sea to the northwest of Qatar, heavy oil pollution in the northwestern area is expected. The northeastern and eastern coasts are not protected by coral reefs like those on the western side. Total PAH concentrations are higher in the coral reefs and their skeletal core, which are bioaccumulating these components (Sabourin, Silliman, & Strychar, 2013). The eastern side is more exposed to the influence of waves, which may accelerate the oil degradation process. Microbiological investigations are needed to determine the role of microorganisms on both the western and eastern coasts of the peninsula of Qatar. Vanwonterghem and Webster (2020) concluded that the coral reefs can be considered as microbially driven ecosystems that rely on the efficient capture, retention, and recycling of nutrients in order to thrive in oligotrophic waters. In coral reefs, microorganisms play vital roles in maintaining holobiont health and the ecosystem's resilience under environmental stress. They are also key players in positive feedback loops that intensify coral reef decline, with cascading effects on biogeochemical cycles and marine food webs. Thus, the higher levels of oil pollution detected on the western side of the peninsula can be attributed to the presence of coral reefs, while the pollution on the eastern side could be attributed to local sources of pollution such as wastes from the industrial zone and heavy traffic arriving at and leaving Umm Said Port (Aboul Dahab, 1994). Al-Thani and Yasseen (2021b) recently suggested a follow-up investigation to look at the microbiology of the sediments in the marine habitats surrounding the Qatari peninsula to assess the role of microorganisms in the coral reefs of the northwestern and western parts of the State of Qatar (Vanwonterghem and Webster, 2020). Table 4 shows the concentrations of petroleum hydrocarbons in sediments from ROPME sea areas, which were determined by applying fluorescence techniques and using Kuwaiti crude oil as a standard. The highest levels of oil in any sediment from the area investigated were found in the sandy northwest area. This suggests that accidental oil spills and chronic discharges from tankers bound for oil terminals in the northern part of the Arabian Gulf provide Qatari coasts with considerable amounts of oil wastes. The investigation concluded that spatial distribution of dissolved and dispersed petroleum hydrocarbons in Qatari waters suggests that harbors and coastal activities are the main sources of oil pollution in waters of the coastal belt, followed by leaching of dissolved oil from tarry deposits.

Table 4. Concentrations of petroleum hydrocarbons in sediments from ROPME sea area

Location	Concentration range (μgg^{-1}dw) *
Bahrain	0.5-8.5
Iraq	0.4-44.0
Kuwait	13.7-375.0
Oman	0.1-119.0
Qatar	48.0-248.0
UAE	0.1-14.7

Aboul Dahab (1994).

* The concentrations of petroleum hydrocarbons determined by applying fluorescence technique and using Kuwaiti crude oil as a standard

3.2.2 Follow-up Investigations and Assessments

Multiple studies and reports have been published since the war in 2003 as more activities and oil spills in the Arabian Gulf continued to occur (Mahboob et al., 2022). The political crises that intensified around the world and the region have been accompanied by more oil spills and exportation through the Strait of Hormuz. Almost all of these studies agree that both organic and inorganic oil-pollution components resulting from intentional or unintended spills in the Gulf region dissipate soon and might reach normal levels (Fowler, 1993; de Mora, Fowler, Wyse, & Azemard, 2004; Al-Saad and Salman, 2012). The studies conducted before and after the war in 2003 reached important conclusions that the levels of pollution of the Gulf water were high from hydrocarbon compounds and heavy metals during the conflicts. But after some time, these levels decreased to their natural levels, slightly higher, or even lower than the normal levels (de Mora et al., 2010). Notably, some areas in the Arabian Gulf are considered chronically polluted, such as the Bahrain Petroleum Company (BAPCO) industrial complex (Bahrain) and Mina Al-Fahal (Oman) (Freije, 2015).

Although the positive outcomes are an incentive for optimism and reassurance, the Gulf region needs follow-up and monitoring of the changes in pollution levels. This will be especially important if conflicts are escalated in the region and great pressure arises to increase oil and gas exports due to the great demands of energy components needed by the countries of the world. In this regard, it is necessary to discuss the content of these reports and studies that were published after the last war in the region in 2003. It is also useful to present ideas and strategies through which the impact of different pollutants can be reduced (Hassanshahian et al., 2020).

The International Union for Conservation of Nature (IUCN) and collaborators investigated the pollution status in the Arabian Gulf region during the period 1991 to 1993 (Price et al., 1994). The data from sediments and biota revealed that the highest levels of contamination were along the heavily impacted coast of Saudi Arabia between Ras al Khafji and Ras al Ghar (Figure 2). In this area, the concentration of total petroleum hydrocarbons (expressed as Kuwait crude oil equivalents) ranged from 62-1400 $\mu g\ g^{-1}$ dry wt in surface sediments, while among marine animals, clams showed 570-2600 $\mu g\ g^{-1}$ dry wt, and fish muscle showed 9.6-31 $\mu g\ g^{-1}$ dry wt.

Although the oil spills associated with the 1991 Gulf war are considered as the largest oil spills in history, investigations conducted after that war focused on the fate of the spills during those conflicts. These studies provided evidence that the effect of oil spills was restricted to approximately 400 km from the source of spillage point in Kuwait to the Saudi Arabian coastline (Ras al Ghar) and that pollutants were rapidly degraded (de Mora et al., 2010).

Figure 2. The western coast of the Arabian Gulf showing the locations of pollution from Kuwait City to Ras al Ghar (KSA)

Much of the degradation of petroleum hydrocarbons was completed within a few months of the spill, and most contaminants disappeared from the sea water, sediments, and bivalves outside the immediate area of impact or were lower than levels in samples collected from the same sites before the war (Fowler, Readman, Oregioni, Villeneuve, & McKay, 1993). Such assessments of the extent distance of oil dissipation were reported in almost the same range for other coastlines in the United States and Europe (Price et al., 1994). Therefore, the following is a brief discussion of the remediation techniques for managing the oil spills. Notably, these techniques can be summarized as environmental manipulation by mechanical recovery and chemical treatment and biological or natural biodegradation. Issa and Vempatti (2018) discuss the details of these techniques.

Remediation techniques using conventional mechanical and chemical methods are uneconomical and generate large volumes of chemical waste. This waste requires much labor, financial support, and logistic cooperation between the countries bordering the Arabian Gulf (Ayangbenro and Babalola, 2017). Moreover, such methods may take a longer time than if the oil components are left to degrade naturally by microorganisms or are removed only partially (Watt, Woodhouse, & Jones, 1993; Al-Saad and Salman, 2012). However, biological approaches have emerged as a new strategy to remediate soil and water from various types of contaminants (Al-Thani and Yasseen, 2021a). This approach has received considerable and growing interest over the last decade. The use of microbial biosorbents is ecofriendly, cost effective, and efficient for the remediation of environments contaminated with heavy metals. Biosorption techniques are used specifically to remove nonbiodegradable such as metals and dyes, and the microorganisms that can be used include bacteria, algae, and fungi.

Bioremediation of oil and industrial wastewater in the Arabian Gulf: Dell' Anno et al. (2021) showed that taxa of bacteria, fungi, and algae in many parts of the world are able to degrade petroleum hydrocarbons and to stabilize heavy metals, and thus potentially useful for the remediation of contaminated marine sediments. A huge number of studies and reports have been published regarding the fate of oil spills in the Arabian Gulf, but the outcomes of these studies are not consistent. Al-Imarah, Hantoosh, & Nasir (2007) did a survey report during the period of 1980-2005 to evaluate the pollution of petroleum hydrocarbons in water, sediments, and living organisms in the fresh water of Shatt Al-Arab (south of Iraq) and the northwestern part of the Arabian Gulf. They came to a controversial and unexpected conclusion that the level of pollution by oil components increased during times of peace and decreased during times of military conflicts in the region. The report blamed the illegal transportation of crude oil and its derivatives, as well as the discharging of oily ballast water from small vessels and effluent from petroleum refineries located on the banks of waterways (Abadan, west of Iran, on the Shatt Al-Arab River, and Al-Shuaiba on the Shatt Al-Basra, south of Iraq). Notably, this might not be the case in the southern parts of the Arabian Gulf.

This review article looks at the natural action of microorganisms to reduce the levels of pollution in the Arabian Gulf, as mechanical and chemical methods might not be feasible or practical (Watt et al., 1993; Ayangbenro and Babalola, 2017). The Arabian Gulf environmental pollution status has been assessed based on multiple studies covering a period of time that begins during the eight-year Iraq-Iran war, passes through the war in 1991, and ends after the war in 2003 in 2011. The outcomes of these studies revealed that the concentration of pollutants ranged from low to moderate and chronic contamination in areas due to organic components (petroleum hydrocarbons) and inorganic components (heavy metals) (Freije, 2015). Freije (2015) suggested effective sustainable management measures as a first step in the evaluation of the pollution status of the environment in the Arabian Gulf region.

Recent reports provide list of heavy metals that are normally found in industrial wastewater, crude oil, and gas activities around the Arabian Peninsula in general and in Qatar in particular. These metals include a large number of heavy metals, such as Ag, Al, As, Ba, B, Cd, Co, Cr, Cs, Cu, Fe, Hg, Mn, Ni, Mo, Pb, Sb, Se, U, V, Zn, and possibly others that are present at low concentrations (Osuji and Onojake, 2004; Yasseen, 2014; Yasseen and Al-Thani, 2022). These elements are classified into three main groups: essential elements (Fe, Cu, Mn, Mo, Ni, and Zn); possibly essential elements (Co, B, Se, and V); and non-essential and toxic elements (Ag, Al, As, Ba, Cd, Cr, Cs, Hg, Pb, Sb, and U) (Al-Thani and Yasseen, 2020; 2021a). Essential elements can be consumed by autotrophs for their nutrition and metabolism, but toxic elements might find their ways into the sea environment through many paths and methods. Basically, these metals are not biodegradable, they are persistent, and they can accumulate in the environment and marine animals in large amounts. Heavy metal pollution poses a major threat to all lifeforms. This is especially true when these toxic metals enter the food web causing much disruption in the sea ecosystem, leading to health concerns when marine animals are consumed by humans (Mustafa et al., 2015, Ayangbenro and Babalola, 2017; Nawrot et al., 2021).

After years of additional activities in the Arabian Gulf, seawater in the territorial water of the Kingdom of Bahrain was analyzed in 2007 for 10 metals (As, Cd, Cu, Fe, Hg, Mn, Ni, Pb, V, and Zn). At most sites of investigated, the concentration range of these elements was still within the international standards except for Cu and Hg (Juma and Al-Madany, 2008). The results suggest that the marine water of Bahrain is of good quality as the concentrations of the metals reported in the studied areas were far below the water quality standards of the United Kingdom. Al-Naimi, Al-Ghouti, Al-Shaikh, Al-Yafe, & Al-Meer (2015) found that up to 2015, the concentration of all these metals, which are normally found in industrial wastewater from various anthropogenic and industrial oil and gas activities, were within the international standards and were almost comparable to those of previous studies conducted around the peninsula of Qatar. Ivshina et al. (2015) discuss the details of how pollutants enter the food chains of humans and living organisms, including plants and marine living organisms, such as fish, shellfish, and others, as well as the consumption of groundwater. However, international records show that the contribution of oil spills during major accidents was only a small fraction of the total oil entering the environment. This report warns that that the future is not safe for oil and gas-producing countries in terms of protecting the ecosystem from pollution. Such investigations should be supported by other studies on the land and air as well. Notably, Freije (2015) reviewed these investigations in all of these countries and came to the general conclusion that the levels of pollutants of different types were within acceptable levels. The concentration of heavy metals in various sea media of the Gulf, including sediments, fish, and other marine organisms, were within the acceptable international levels, although some heavy metals were on the high sides of the normal ranges. That review and others (Al-Sayed et al., 1994; Akhter and Al-Jowder, 1997; de Mora et al., 2004; Juma and Al-Madany, 2008) reported that some selected heavy metals are found in the seawater, sediments, and some marine animals around the Kingdom of Bahrain and other countries in the Arabian Gulf. For example, Cu and Hg showed high ranges of concentrations, while the sediments had high levels of Hg and Pb with little shift above the normal range. Notably, various studies show conflicting results and conclusions about the fate of heavy metals after spills at sea. Heavy metals can accumulate in different organisms or the bottom of sea or can even remain floating at sea.

The role of bacteria in bio-stabilization has been a very interesting issue in regard to the fate of heavy metals at sea. Three major groups of microorganisms have been shown to play roles in bioremediation: bacteria, algae, and fungi. Yasseen (2014) discusses the roles of these microorganisms in remediation of soil polluted with petroleum hydrocarbons. These microorganisms can achieve partial or complete degradation of organic contaminants with limited damage to the environments, and such microbial activities have proven successful, even with intervention by living plants (Frick, Farrell, & Germida, 1999).

Al-Thani and Yasseen (2020) discussed the green liver model to degrade organic compounds and phyto-mining model to accumulate heavy metals using native plants. Moreover, a model of degradation of polychlorinated biphenyls (PCBs) under natural conditions has been reported recently (Al-Thani and Yasseen, 2021a). These compounds are organic in origin or man-made and consist of C-H-Cl atoms. Microorganisms such as bacteria can degrade these compounds partially or completely or mineralize them to release mineral nutrients and some toxic components. Autotrophs can utilize the mineral nutrients while toxic compounds are sequestered in the vacuoles of living organisms in aquatic habitats such as algae.

Figure 3 summarizes the fate of oil spills and their components in seawaters such as the Arabian Gulf. Organic components are biodegraded by marine bacteria, which produce other organic compounds or metabolites. These are utilized by marine autotrophs such as seaweeds and algae. Some organic compounds (which might be toxic) are sequestered in the vacuoles (Al-Thani and Yasseen, 2021a) or contribute to metabolic pathways (Al-Thani and Yasseen, 2020).

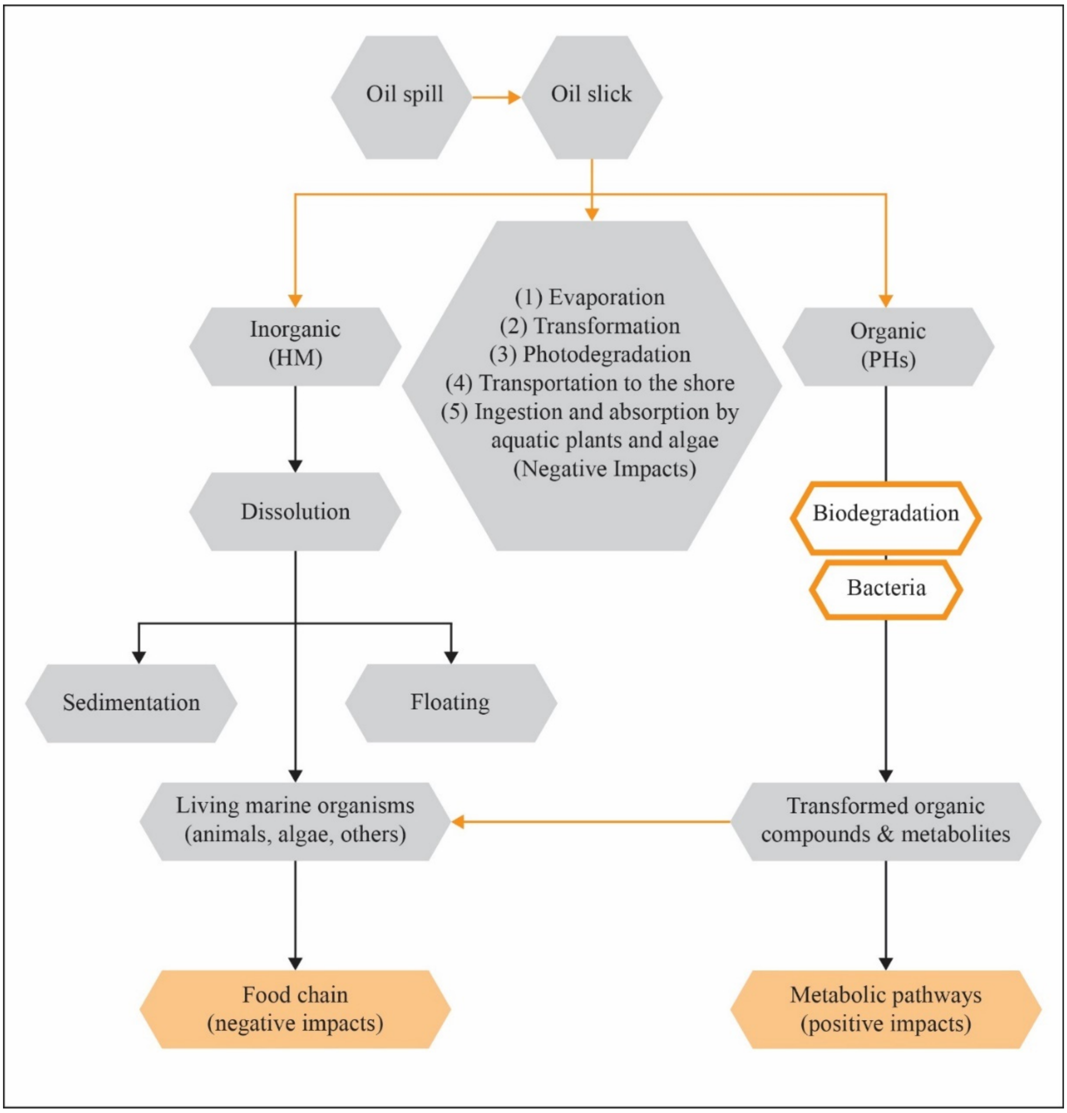

Figure 3. Diagram of the possible fate of oil spills at sea (Arabian Gulf)

The role of microorganisms in protecting the Arabian Gulf ecosystem from the consequences of dissolution of heavy metals in seawater needs to be analyzed in terms of possible mechanisms that might be adopted by microbes to stabilize heavy metals in sediments at the bottom of the Gulf and in seawater. Some recent reports have discussed these mechanisms elsewhere around the world. Igiri et al. (2018) reviewed the detoxification mechanisms that counter toxic effects heavy metals. These mechanisms include biosorption capacity as microorganisms accumulate these elements by various metabolic or physico-chemical pathways of uptake. Microorganisms such as bacteria and fungi can form biofilms that are able to remove heavy metals, while algae are able to accumulate these extra metals from sea water. Mechanisms were reported as ways to possibly reduce the toxic effect of heavy metals. One example is biosorption mechanisms, which can be classified into metabolism-independent biosorption and other methods, and the bioaccumulation depends on a variety of chemical, physical, and biological mechanisms. Other mechanisms are intracellular sequestration, extracellular sequestration, adsorption of metal ions by ionizable groups of bacteria cell walls, microbial methylation, and reduction reactions of heavy metals, through which microbial cells can convert metal ions from one oxidation state to another.

Modern biotechnology techniques are another approach to alleviate and immobilize toxic elements. A similar system might be operated at sea to remediate petroleum hydrocarbons as a huge number of microbial species are found active in bioremediation processes. Fotedar (2013) used modern techniques to identify microorganisms and recognized many bacteria species around the Qatari peninsula that proved efficient in remediation of crude oil, industrial wastewater, and their components. Table 5 shows the most common bacteria species in seawater in the

Arabian Gulf with their functions, roles, and some observations (Al-Thani and Yasseen, 2021b).

Table 5. Possible bioremediation activity of seawater polluted with petroleum hydrocarbons and trace metals by bacterial species in Arabian Gulf water around Qatar

Bacteria groups and species	Functions and roles	Observations	References
		Proteobacteria	
Cobetia marina	Bioremediation technology, Biotechnology of biofilms & enzyme function	Production of biosurfactants, degrades sulfur-containing heterocyclic aromatic hydrocarbon dibenzothiophene	Ibacache-Quiroga et al., 2013; Abouelkheir, Abdelghany, Sabry, & Ghozlan, 2021
Halobacillus profundi	Isolated from deep-sea carbonate rock at a methane cold seep	Biotechnologies, and metabolic capabilities	Hua, Kanekiyo, Fujikura, Yasuda, & Naganuma, 2007; Varrella, Tangherlini, & Corinaldesi, 2020
Pseudoalteromonas spp.[a]	Degradation of PH compounds into harmless components, or metabolites, biotechnological potential: production of antimicrobials and enzymes of industrial interest, Antimicrobial properties	Crude oil degradation	Borchert et al., 2017; Richards et al., 2017; Eras-Muñoz, Farré, Sánchez, Font, & Gea, 2022; Ganesan et al., 2022
Ruegeria mobilis	Bioremediation of phosphate triesters	_	Yamaguchi et al., 2016
Shewanella loihica	Degradation of the pollutant RDX[b]	Oxidize organic matter, reduce chlorinated pollutants, and metal ions including Fe and uranium; Biological wastewater treatment, Fe balance in the sea bed	Zhao, Deng, Manno, & Hawari , 2010; Benaiges-Fernandez, Palau, Offeddu, & Dold, 2019; Zhang, Hsu, Wheeler, Tang, & Jiang, 2020
Virgibacillus dokdonensis	Possible bio-remediator,	Biotechnology to remove Ca^{+2} from hypersaline wastewater, Possible desalination technology,	Sánchez-Porro, de la Haba, & Ventosa, 2014; Zeaiter et al., 2019; Yan, Wei, Han, & Zhao, 2022
Vibrio spp.[c]	Remediate diesel-polluted seawater	Possible iron remediation,	Titah, Pratikno, & Moesriati, 2019; Zhou et al., 2021
		CFB group [d]	
Tenacibaculum mesophilum	Possible bioremediation of polluted seawater.	Strong malachite green (MG) degradation activity, corrosion inhibitory bacteria	Qu, Hong, & Zhao, 2018; Li et al., 2021
		Low GC group (Firmicutes) [e]	
Bacillus boroniphilus	Possible remediation of boron in polluted seawater	Highly boron tolerant	Ahmed, Yokota, & Fujiwara, 2007; Al-Thani and Yasseen, 2021b

Al-Thani and Yasseen (2021b).

The classification of these microorganisms based on modern approach of Fotedar (2013).

[a]*Pseudoalteromonas* spp.: many species such as: *Pseudoalteromonas agarivorans; Pseudoalteromonas piscicida*, *Pseudoalteromonas rubra*, *Pseudoalteromonas prydzensis*.

[b]RDX: Hexahydro-1,3,5-trinitro-1,3,5-triazine.

[c] *Vibrio* spp.: many species such as: *Vibrio harveyi*, *Vibrio nereis*, *Vibrio nigripulchritudo*, *Vibrio parahaemolyticus*.

[d] Phyla of CFB group: Cytophaga, Fusobacterium, and Bacteroides.

[e] Bacteria group with genome that has 25 to 75% guanine and cytosine.

- No observations reported

Hassanshahian et al. (2020) have listed a significant number of more genera and species of bacteria that bioremediate crude oil components among other activities on the Kuwaiti and Iranian coasts, islands, and seawater of the Arabian Gulf (Table 6). These included: diesel-degrading bacteria, alkaliphilic and halophilic oil-utilizing bacteria that can grow on crude oil and utilize it as a carbon and sulfur source, other microbes that confer benefits to the marine ecosystem, such as photosynthesis, nitrogen fixation, etc., and bacteria that can grow on pure n-alkanes and aromatic compounds. These bacteria proved active in the bioremediation of sediments in seawater rich in petroleum hydrocarbons and heavy metals, and autochthonous oil and produce surface-active compounds. The list of functions and roles of these bacteria covers many aspects of remediation activities: biotechnological potentials: production of biofilms, biosurfactants, etc.; promotion of enzyme functions for industrial interest and antimicrobial properties; degradation of petroleum hydrocarbons, sulfur-containing heterocyclic aromatic hydrocarbon dibenzothiophene, and RDX (hexahydro-1,3,5-trinitro-1,3,5-triazine); bioremediation of phosphate tri-esters and diesel-polluted seawater; remediation of trace elements of B, Fe, and U; oxidation of organic matter; reduction of chlorinated pollutants; degradation of malachite green (MG); and inhibition of corrosion.

Phyco-remediation: Recent work suggests using phyco-remediation method (bioremediation of polluted water using algae) as a successful approach to degrade, destroy, and remove organic and inorganic components produced during various industrial and anthropogenic activities (Al-Thani and Yasseen, 2021a). Early reports based on polluted ponds show that ponds show peculiarities regarding the presence of cyanobacteria and algae (Abulfatih, 2002). For example, treated ponds and untreated ponds receiving anthropogenic wastewater were compared. The most dominant genera in the untreated ponds were *Chlorella* (Chlorophyta), *Oscillatoria,* and *Spirulina* (cyanobacteria), while the treated pond was dominated by *Chlorella*, *Spirogyra* (Chlorophyta), and *Anacystis* (cyanobacteria).

Table 6. Bacteria species found in Arabian Gulf that have bioremediation activity for crude oil from Kuwait and come from Iranian coasts and sea water

Bacteria groups and species	Functions and roles	Observations	References
	Phylum: Pseudomonadota		
Alcanivorax sp. e.g. *A. borkumensis* *	Biodegradation of crude oil, contribute to hydrocarbon bioremediation in the Arabian Gulf	Other microbes confer benefits: photosynthesis, nitrogen fixation, etc.	Al-Awadhi, Dashti, Kansour, Sorkhoh, & Radwan, 2012a; Santisi et al., 2015; Hassanshahian et al., 2020
Achromobacter sp.	Crude oil degrading bacteria	_	Hassanshahian, 2014; Hassanshahian et al., 2020
Halomonas spp. e.g., *H. aquamorina*, *H. elongata*	Crude oil degrading bacteria	Halotolerant/halophilic, capable of growth on crude oil, Utilize crude oil as the carbon and sulfur sources	Hassanshahian, 2014; Al-Mailem, Eliyas, Khanafer, & Radwan, 2014; Al-Mailem, Al-Deieg, Eliyas, & Radwan, 2017; Ardakani and Papizadeh, 2018
Marinobacter sp.	Alkaliphilic & halophilic oil-utilizing bacteria	Grow on pure n-alkanes and aromatic compounds, produce surface-active compounds	Al-Awadhi, Sulaiman, Mahmoud, & Radwan, 2007; Al-Awadhi, Al-Mailem, Dashti, Khanafer, & Radwan, 2012b; Raddadi, Giacomucci, Totaro, & Fava, 2017
Sphingomonas spp.	Crude oil degrading bacteria	_	Hassanshahian, 2014; Hassanshahian et al., 2020

Pseudomonas spp.	Crude oil degrading bacteria, autochthonous oil bioremediation	Isolated from a crude oil-contaminated sediment at sea	Radwan and Al-Hasan, 2000; Pasumarthi, Chandrasekaran, & Mutnuri, 2013; Perdigão et al., 2021
Psychrobacter sp.	Crude oil degrading bacteria	Oil-degrading organotrophs, clean soil from crude oil and other industrial discharges	Radwan and Al-Hasan, 2000; Aboud, Abd Burghal, & Laftah, 2021
Stappia sp.	Halophilic oil-utilizing bacteria	Grow on pure n-alkanes and aromatic compounds	Al-Awadhi et al., 2007; Al-Awadhi et al., 2012b; Liu and Liu, 2013
Vibrio spp.	Crude oil degrading bacteria	Most of these bacteria are infectious	Radwan and Al-Hasan, 2000, Al-Awadhi et al., 2012a; Fotedar, 2013; Al-Thani and Yasseen, 2021b
Zavarzinia sp.	Crude oil degrading bacteria	Possible biological agent to remediate crude oil	Al-Mailem et al., 2014; 2017; Hassanshahian et al., 2020
Phylum: Actinomycetota			
Actinobacterium spp.	Crude oil degrading bacteria	Showing hydrocarbon bioremediation potential	Radwan and Al-Hasan, 2000; Perdigão et al., 2021
Cellulomonas sp. **	Halophilic oil-utilizing bacteria	Grow on pure n-alkanes and aromatic compounds	Al-Awadhi et al., 2007; Al-Awadhi et al., 2012b
Citricoccus sp.	Alkaliphilic oil-utilizing bacteria	Grow on pure n-alkanes and aromatic compounds	Al-Awadhi et al., 2007; Al-Awadhi et al., 2012b
Continued: Phylum: Actinomycetota			
Dietzia spp. e.g., *Dietzia maris*	Alkaliphilic oil-utilizing bacteria	Grow on pure n-alkanes and aromatic compounds	Al-Awadhi et al., 2007; Al-Awadhi et al., 2012b; Al-Mailem et al., 2014; 2017
Georgenia sp.	Halophilic oil-utilizing bacteria	Grow on pure n-alkanes and aromatic compounds	Al-Awadhi et al., 2007; Al-Awadhi et al., 2012b
Gordonia spp. e.g., *G. bronchialis*,	Crude oil degrading bacteria	Bioremediation of sediments polluted with petroleum hydrocarbons and heavy metals	Al-Mailem et al., 2014; 2017; Kim, Dong, Kim, & Lee, 2019
Isoptericola sp. **	Halophilic oil-utilizing bacteria	Grow on pure n-alkanes and aromatic compounds	Al-Awadhi et al., 2007; Al-Awadhi et al., 2012b
Microbacterium sp.	Halophilic oil-utilizing bacteria	Grow on pure n-alkanes and aromatic compounds	Al-Awadhi et al., 2007; Al-Awadhi et al., 2012b
Phylum: Actinomycetota			
Nocardia sp.	Crude oil degrading bacteria	_	Hassanshahian, 2014; Hassanshahian, et al., 2020
Tistrella spp.	Crude oil degrading bacteria	_	Al-Mailem et al., 2014; 2017; Hassanshahian, et al., 2020

Micrococcus sp.	Alkaliphilic oil-utilizing bacteria	Grow on pure n-alkanes and aromatic compounds	Al-Awadhi et al., 2007; Al-Awadhi et al., 2012b
Phylum: Bacillota			
Bacillus spp. **	Alkaliphilic & halophilic oil-utilizing bacteria	Grow on pure n-alkanes and aromatic compounds	Al-Awadhi et al., 2007; Al-Awadhi et al., 2012b
Oceanobacillus sp.	Alkaliphilic oil-utilizing bacteria	Grow on pure n-alkanes and aromatic compounds	Al-Awadhi et al., 2007; Al-Awadhi et al., 2012b
Planococcus sp.	Crude oil degrading bacteria	Produce biosurfactant with petroleum as sole source of carbon	Radwan and Al-Hasan, 2000, Guo et al., 2022
Phylum: Bacteroidota			
Flavobacterium spp.	Crude oil degrading bacteria	Diesel-degrading bacteria	Al-Mailem et al., 2014; 2017; Chaudhary, Kim, Kim, & Kim, 2019; Hassanshahian, et al., 2020
Gaetbulibacter spp.	Crude oil degrading bacteria	_	Al-Mailem et al., 2014; 2017; Hassanshahian, et al., 2020
Owenweeksia spp.	Crude oil degrading bacteria	_	Al-Mailem et al., 2014; 2017; Hassanshahian, et al., 2020

*Identification of these bacteria was based on modern techniques: 16S rRNA gene sequences.

**Oily alkaline Kuwaiti coasts have a self-cleaning potential.

- No observations reported.

Notably, some peculiarities were noticed regarding the presence of some genera in either of the two ponds: *Chlorogonium* (Chlorophyta), *Lyngbya*, and *Spirulina* (cyanobacteria) were found in only the untreated pond, while *Anabaena* (cyanobacteria) and *Oedogonium* (Chlorophyta) were found in only the treated pond. Thus, aquatic habitats should be monitored regularly since some genera of algae and cyanobacteria might be considered as a sign of pollution, while the presence of others are signs of good-quality water (Yasseen, Abulfatih, Nasher, Abid, & Al-Mofti, 2001; Al-Thani and Yasseen, 2021a). The presence of some species of algae and cyanobacteria in aquatic environments has been used to evaluate the status of water pollution (Sen, Alp, Sonmez, Kocer, & Canpolat, 2013; Al-Thani and Yasseen, 2021a).

Thus, algae can be used as phytoremediators to clean waters contaminated with various types of heavy metals and petroleum hydrocarbons in various parts of the world, including oceans and lakes (Paleologos, Al Nahyan, & Farouk, 2018; Khazali and Taghavi, 2021; Rushdi et al., 2021). Algae have been recognized as important living groups to control metal concentrations in lakes, ponds, rivers, oceans, and wetland habitats. For example, *Chlorella* is a good example of an alga capable of accumulating heavy metals (Alharbi, Alfaifi, & El-Sorogy, 2017). Chandler (2019) investigated the ability of algae to remediate the elements As and B in some springs from the Sang-E-Noghreh area, Iran. Al-Thani and Yasseen (2021a) showed that members of four major divisions of algae and cyanobacteria in these ponds are considered as good candidates for phyco-remediation: Chlorophyta, Cyanophyta (cyanobacteria), Euglenophyta, and Ochrophyta (diatoms) (Yasseen, 2014).

It is believed that algae species from various groups can absorb and accumulate these elements from their environment into their bodies. Lessons from these investigations can be utilized to evaluate and monitor the Arabian Gulf water regarding the pollution caused by crude oil spills. Notably, a huge number of taxa of algae have been recognized in the Arabian Gulf from multiple studies. For example, the list of marine algae reported by Basson (1992) included 207 taxa, including 91 taxa from Rhodophyta, 50 taxa from Phaeophyta, 42 taxa from Chlorophyta, 22 taxa from Cyanophyta, and one taxon each from Xanthophyta and Haptophyta. Sohrabipour and Rabii (1999) reported another list that included 153 taxa of marine algae from the Arabian Gulf and Oman Sea. The list included 87 species that were in new recorded taxa: 48 Rhodophyta, 18 Chlorophyta, 16 Phaeophyta, 3

Xanthophyta, and 2 Cyanophyta. This study corrected some scientific names reported previously.

Thus, much work needs to be done to evaluate the ability of various taxa of marine algae to remediate crude oil and industrial wastewater in the Arabian Gulf. Some examples are given regarding recent findings about the potential of some macroalgae to bioremediate polluted seawater in this region. For example, Al-Homaidan (2007) and Al-Homaidan et al. (2021) have investigated the potential of brown algae (Phaeophyta) to bioremediate seawater polluted with crude oil and considered some of these algae species as bioindicators for heavy metals or petroleum hydrocarbons. Many brown algae species have been chosen for such investigations, but the highest heavy metal accumulation has been observed in *Padina boryana*. There is early evidence that *Padina gymnospora* can be used as a monitoring species for heavy metals, including Cd, Cu, Fe, and Pb. Ameen et al. (2022) recently concluded that *Ulva* spp. (green algae) and *Padina* spp. (brown algae) are efficient as biomonitoring agents for heavy metal pollution on the Arabian Peninsula's eastern and southern coasts. The species used should be chosen locally and sampled carefully at the in same depth at low tide in spring or early summer. They concluded that some brown algae species can be used for biomonitoring heavy metal pollution on the western coast of the Arabian Gulf. However, further investigations are needed to identify some other brown algae that have the ability to bioremediate polluted seawater.

Bibak, Sattari, Tahmasebi, Agharokh, & Namin, (2020) investigated the ability of some macroalgae species from The Arabian Gulf, which included *Cladophoropsis membranacea* (green algae), *Hypnea hamulosa* (red algae), and *P. gymnospora* (brown algae). The outcomes of this study clearly showed that the brown algae can be used to determine amounts of some metals, such as Al, Cd, Co, Fe, Mn, Ni, and Pb; red algae can be used to determine other kinds of metals (As, Cr, Cu, Mg, S, and Zn); while green algae showed the least absorption of all these elements. These algae are plentiful in the north of the Arabian Gulf, so they can be used as bio-indicators for marine pollution studies. Such data could also be useful for comparison with future information of marine pollution in the Arabian Gulf.

Fungi and other marine living organisms: Besides bacteria and algae, fungi of various taxa, including some yeast genera, have been proven efficient in remediating polluted soil (Al-Thani and Yasseen, 2020). Many fungi species have the ability to produce particular enzymes such as catalases, peroxidases, and laccases, which are able to degrade organic contaminants or immobilize heavy metals. Many fungi genera have been reported for bioremediation of aromatic hydrocarbons, such as *Aspergillus*, *Curvularia*, *Drechslera*, *Fusarium*, *Lasiodeplodia*, *Mucor*, *Penicillium*, *Rhizopus*, and *Trichoderma* (Dell'Anno et al., 2021). Al-Sulaiti, Al-Shaikh, Yasseen, Ashraf, & Hassan (2013) showed that yeast species from Qatar might be useful candidates to remediate polluted soil and could be found in the Arabian Gulf. These species included *Candida* spp., *Trichosporon mucoides*, *Cryptococcus* spp., *Pichia angusta*, and *Kloeckera* spp.

A recent investigation by Fotedar et al. (2022) on yeast biodiversity from the Gulf coastal water surrounding Qatar found 842 isolates belonging to 82 species and representing two main phyla: Ascomycota (23 genera) and Basidiomycota (16 genera), which were identified by modern technology. *Candida* spp. and *Pichia* sp. are promising candidates for bioremediation of polluted seawater as these fungi species are found at sites with high amounts of total petroleum hydrocarbons (TPHs). Therefore, future research should concentrate on these species and possibly other fungi that might be found in sediments and soils of the Arabian Gulf.

Various contaminants might find their ways into the tissues of marine organisms, and their accumulation should attract attention from scientists and research centers to look at the consequences of their presence in marine animals, especially those that eaten by humans. Some of these living marine organisms are considered as biomonitoring agents, such as the pearl oyster (*Pinctada radiata*), which accumulates trace metals (Cd, Pb, V, and Zn) in their soft tissues (Karami, Bakhtiari, Kazemi, & Kheirabadi, 2014). Notably, Hassan (2017) covered the levels of organic and inorganic contaminants and the variation among seasons throughout three years in three arthropods in the marine water around the peninsula of Qatar: *Portunus pelagicus*, *Balanus Amphitrite*, and *Palaemon khori*. The heavy metals included As, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, V, and Zn, while the organic contaminants included methylmercury (CH_3Hg), organotins (OT), and polychlorinated biphenyls (PCBs). This study is considered the first baseline study concerning the seasonal variations of these contaminants in the marine organisms and coastal water around Qatar.

Although the levels of all contaminants in animal tissues, water, and sediments were in acceptable ranges according to international standards, monitoring these components is crucial for protecting the marine ecosystem from future fluctuations with the increasing production of oil and gas in not only Qatar, but in all countries bordering the Arabian Gulf. Further studies on the marine water around Qatar confirmed the conclusion that most pollutants with organic and inorganic components are at acceptable levels and that the concentrations of PAHs and heavy metals are in the low range, suggesting a low risk to marine life and the food chain (Hassan et al., 2018; Hassan, Abou-Elezz, Abuasali, & Al-Saadi, 2019). However, a recent study might sound an alarm in this region, which has been teeming with industrial activity resulting from the increasing demand for gas and oil and after the acceleration of events in various parts of the world (Abou Elezz, Castillo, Hassan, Alsaadi, & Vethamony, 2022). Notably, this study concluded that total mercury (THg) might cause major environmental pollution problems in subsequent years, which places scientists, research centers, and decision-makers in a critical position to find a solution to the increased possibility of marine pollution in the Arabian Gulf region.

Moreover, oil- and gas-related activities cause significant damage to different ecosystem components, such as coral reefs, algal mats, mangrove forests, and other habitats. Oil spills and relevant implications can also severely affect the main sources of desalinated water (Al-Azab, El-Shorbagy, & Al-Ghais, 2005). The coastline of Qatar shows substantial development from the construction of tourist resorts, including swimming pools, restaurants, various entertainment venues, hotels, and others, and these activities could have greatly negative impacts on marine life (Burt et al., 2017; Burt and Batholomew, 2019).

3.3 Land Pollution

Pollution on mainland Qatar is affected by many activities, including natural, industrial, and anthropogenic activities, which negatively affect human health not only directly, but also through other sources, such as air pollution (as discussed above), intentional and unintentional oil spills and accidents, and pumping of industrial wastewater deep into the earth, thereby contaminating the groundwater (Al-Thani and Yasseen, 2020). The intrusion of polluted seawater into the mainland of the peninsula of Qatar could be a reason for the development of land pollution in Qatar in the future (Al-Thani and Yasseen, 2020; 2021b). Thus, many concerns have been described about the accumulation of heavy metals in agricultural lands in Qatar in response to anthropogenic and industrial activities.

Usman, Al-Ghouti, & Abu-Dieyeh, (2019) found that *Tetraena qataransis* at Ras Raffan gas facilities (northeast of Qatar) accumulates Cd, Cr, Cu, and Ni. These trace elements are normally found in industrial wastewater, and this native plant has proved to be a good candidate for toxic metal phyto-stabilization. Thus, they concluded that the presence of this native plant and others in such areas reflect their tolerance of these toxic trace elements. Recently, Alsafran, Usman, Al Jabri, & Rizwan (2021) found that the levels of As, Cr, and Ni in agricultural soil samples were significantly higher than their normal acceptable levels in soil, and these metals could be hazardous to human health, such as by causing cancer. Recent work showed that halophytes can remediate saline and polluted soils with heavy metals (Yasseen and Al-Thani, 2022). Associated microorganisms also help these halophytes to improve their phytoremediation action.

3.3.1 Natural Activities

The land of Qatar is affected by multiple harsh environmental conditions, including drought, salinity, high evapotranspiration, irradiance, high temperature, and dust storms. Such factors do not allow many plants and crops to survive, grow, or produce a yield (Yasseen and Al-Thani, 2013). Notably, Norton et al. (2009) and Abdel-Bari (2012) reported about 400 species of wild plants, of which about 270 species were indigenous, while the remaining ones were either introduced, cultivated, or naturalized. The high concentration of PM2.5 in the atmosphere might contain heavy elements, such as Cd, Ni, and Pb, and possibly other radioactive elements with carcinogenic effects (Amoatey et al., 2018). These elements might accumulate in the soil and plants and cause health problems when consumed by humans and livestock (Al-Thani and Yasseen, 2020; 2021a). Yasseen and Al-Thani (2022) recently discussed the phytoremediation of saline soils, which are rich in Na^+ and Cl^-, by halophytic native plants. They listed more than 26 halophytes that proved to be efficient in removing these ions using structures such as salt glands and salt bladders and by adopting a succulent mechanism.

3.3.2 Industrial Activities according to the Guidelines Set up by Chapman and Pratt (1961)

The levels of heavy metals and essential elements in native soils and wild plants on the peninsula of Qatar reveal that their concentrations are in a normal acceptable range (Abdel-Bari, Yasseen, & Al-Thani, 2007; Al-Thani and Yasseen, 2020). Al-Sulaiti et al. (2013) revealed that industrial wastewater causes a great reduction in the germination percentage and seedling growth of plants and crops, and subsequent growth has shown signs of toxicity as substantial burning spreads out on all leaves. Supplementary Figure 2 clearly shows that industrial wastewater has a moderate salinity level (EC of about 4 to 5 dSm^{-1}) and leads to a reduction in seed germination of local crops such as fenugreek (*Trigonella foenum-graecum*) and forage plants such as alfalfa (*Medicago sativa*). In the stages of seedling and vegetative growth, such water causes great signs of toxicity. The first sign of toxicity starts at the tips of leaves, as found in barley (*Hordeum vulgare*) seedlings (Supplementary Figure 3). In the end, the whole plant is burned by the toxic substances from this industrial wastewater. Furthermore, if soil containing many plants is irrigated with industrial wastewater in the vegetative growth stage, the whole plant will be burned rapidly, as is found in Rhodes grass (*Chloris gayana*), as shown in Figure 4. It seems that fresh industrial wastewater is very toxic to plants before microorganisms start to degrade the organic components, at which point the toxicity is partially or completely abolished. Notably, plants differ in their response to industrial wastewater. For example, common reed plants (*Phragmites australis*) appear to be very resistant to such industrial wastewater and even thrive in soil irrigated with it before transferring their rhizomes to such soil (Supplementary Figure 4). Other plants, such as *Sporobolus ioclados* and *Medicago sativa*, show some forms of resistance to polluted soil, and while some of them die, others thrive, as shown in Supplementary Figures 5 and 6.

The electrical conductivity of industrial wastewater was described as having a moderate salinity level (4–5 dSm^{-1}), but after irrigation, the soil salinity levels dropped even lower (about 3 dSm^{-1}; data not published). Therefore, the negative impact of industrial wastewater on germination and the subsequent seedling stage and vegetative growth cannot be explained only by the osmotic effect (Yasseen, Al-Thani, Alhadi, & Abbas, 2018). The toxic effects of the organic and inorganic components of such water could be the main reason for signs of toxicity. Interestingly, toxicity signs of industrial wastewater were acute and rapid when such water was used in direct contact with seeds during the germination and seedling stages. The same results were obtained with the sand culture technique (Al-Sulaiti et al, 2013). However, the use of soil culture showed different results as plants differed in their responses: some plants died or were partially affected, while other plants thrived in soil irrigated with industrial wastewater.

(A) (B)

Figure 4. *Chloris gayana* (Rhodes) plants were grown in soil irrigated with tap water (A). Upon vegetative growth, these plants were then irrigated with industrial wastewater (B). Signs of toxicity prevailed in the whole plant

Haider et al. (2021) recently reviewed the response of plants to petroleum hydrocarbons. They discussed the negative impact on various parameters of plant growth, physiology, and biochemistry. These effects included reduction of seed germination and nutrient translocation, induction of oxidative stress, disturbance of metabolic activity, and reduction of plant productivity. These studies and experiments indicated that most types of life, especially plants, experience toxic effects from TPH compounds, polycyclic aromatic hydrocarbons (PAHs), and added dehydrating agents such as mono-, di-, and tri-ethylene glycol (MEG, DEG, and TEG, respectively) and kinetic hydrate inhibitors (KHIs), which are in industrial wastewater produced during the production of gas and oil (Teamkao and Thiravetyan, 2012; Al-Sulaiti et al., 2013). MEG, DEG, TEG, and KHIs are added to prevent gas hydrate formation in pipelines in most locations of gas production around the world, such as the North Sea, the Gulf of Mexico, South America, and the Middle East, including the Arabian Gulf region. Using industrial wastewater for the irrigation of plants might lead to desiccation, as shown in Figure 4 and Supplementary Figure

3.

However, the presence of these compounds in soil that is in contact with microorganisms might expose them to complete or partial degradation (Teamkao and Thiravetyan, 2012), thereby causing a reduction in their toxic effects. Industrial wastewater degradation might lead to intermediate metabolites that can be used in many metabolic pathways (Al-Thani and Yasseen, 2020; 2021a). Thus, one possible measure to find a solution to water scarcity in the Arabian Gulf region in the future is to treat the industrial waste water with native microbial flora to degrade the organic components and reduce the negative impact of heavy metals. This could be used instead of the continually pumping of industrial wastewater deep into the earth, thus reducing the exposure of groundwater to pollution (Al-Thani and Yasseen, 2021a; 2021b).

The implementation of modern biotechnologies using the gene bank of native plants and microorganisms of Qatari soils is a promising approach for cleaning industrial wastewater and preventing accumulation of toxic contaminants. This could help to protect the ecosystem and avoid future risks of pollution. Notably, the last two decades have witnessed a significant number of studies on the use of aquatic and terrestrial plants to phytoremediate polluted ponds and agricultural lands worldwide. These plants include *Ceratophyllum demersum*, *Festuca arundinacea*, *Gossypium* spp., *Hydrocharis morsus-ranae*, *Lolium* spp., *Medicago sativa*, *Mirabilis jalapa*, *Nuphar lutea*, *Phragmites communis*, *Salvinia natans*, and *Typha latifolia* (Peng, Zhou, Cai, & Zhang, 2009; Babovic, Drazic, Djordjevic, & Mihailovic, 2010; Tang et al., 2010). Other native plants from the flora of Qatar were reported as being efficient candidates for removing heavy metals and metabolizing organic components of petroleum hydrocarbons in Qatari lands (Al-Thani and Yasseen, 2020). Some native plants, such as *Cyperus* spp., *Juncus rigidus*, *Polypogon monspeliensis*, and *Salicornia europaea*, can phytoremediate polluted soil containing As and Hg, which are metals found in industrial wastewater from gas extraction.

Microorganisms show effective activity in decomposing organic compounds and stabilizing heavy metals in the rhizosphere. Many bacterial and yeast species have been reported as being possible bioremediation candidates for Qatari lands. These species include some bacteria, such as *Staphylococcus* spp., *Lactococcus lactis*, *Micrococcus luteus*, *Kocuria kristinae*, *Bacillus megaterium*, *Pseudomonas* spp., *Stenotrophomonas maltophilia*, *Sphingomonas paucimobilis*, *Burkholderia* spp., and *Enterobacter cloacae*. Yeast species found in these soils include *Candida* spp., *Trichosporon mucoides*, *Cryptococcus* spp., *Pichia angusta*, and *Kloeckera* spp. (Al-Thani and Yasseen, 2021a; 2022). Interesting results were obtained with some native plants, such as *Phragmites australis* and *Sporobolus ioclados,* as these plants thrive in soil irrigated with industrial wastewater and seem to be resistant to petroleum hydrocarbons (Supplementary Figures 4 and 5).

4. Solutions to Outstanding Problems

Successful ecological restoration and maintenance of a healthy environment are based on several principles: information, problems, plans, solutions, and monitoring (Yasseen and Al-Thani, 2013). Regarding the pollution in Qatar and the Arabian Gulf region in general, information is still needed from investigations using advanced and modern techniques to determine the pollution problems facing people in various life sectors. The governments of this region are enthusiastic and keen to setting up plans and finding solutions to the problems of pollution for various aspects of life. Monitoring achievements is a crucial step toward saving the area from deterioration due to expansion in the energy sector and the consequences of luxury lifestyles.

At the national and local levels, each country has its own peculiarities regarding control of polluting emissions into the environment from different sources. Notably, Doha represents the State of Qatar, along with many small towns, some of which are industrial centers for gas and oil facilities. It is a busy city with severe vehicle traffic and towers that are very close to each other. Such a situation requires serious action to limit the effects of air pollution on people. Therefore, to improve air quality, the government can enact a significant number of measures: *(a) Encouraging urban expansion horizontally*. This means halting any new construction inside Doha and encouraging such actions away from the center of the capital, *(b) Controlling the sources of emissions of dust and PM, whether their origin is from the local fine sand and soil or from episodes of dusty storms.* This control comes from various measures and methods and from the enactment of draft laws and legislations. Examples include reducing the usage of PM-forming appliances, prohibiting smoking indoors and in malls, regularly maintaining vehicles, and walking to one's destination instead of traveling via vehicle, *(c) Using modern and contemporary technology to analyze and simulate the data of dust cyclone waves.* Some works were conducted to study the impact of severe dust storms on the optical properties and surface radiation (Prakash et al., 2015) by adopting a technique to simulate the storm that occurred in March 2012 in the Arabian Peninsula. This was done by using a regional weather research forecast model that was fully coupled with a chemistry/aerosol module (WRF–Chem). The outcome of this study was comparable to the available information from ground-based and satellite observations. In recent work by Fountoukis, Harshvardhan, Gladich, Ackermann, & Ayoub (2020), an integrated analysis was conducted on the most severe dust storms in the Middle East, including Qatar, over the last 20 years using the same simulation technique along with satellite data, PM surface measurements, and Aerosol Robotic Network (AERONT) observations. The model's performance has proven to be encouraging for further use in operational forecasting of dust storms in the region*, (d) Adopting the correct foundations in city planning and building towers and blinding systems that support a clean environment and have basic advantages in reducing energy consumption*. Encouraging the use of solar energy is also recommended (International Trade Administration [ITA], 2020), *(e) Transporting and moving people within residential complexes at a minimum level so that the population is not affected by daily pollution resulting from the movement of vehicles, wind, and dust, (f) Adopting a new policy of eliminating leaded gasoline, encouraging the use of electric cars, and replacing aging vehicles and industrial production facilities, (g) Using clean energy fuels, including natural gas stations.* Such an option places a significant amount of pressure on the Qatari government to increase the production of gas given that international demands for natural gas are increasing tremendously as political crises intensify, and *(h) Intensifying green areas and forestation around Qatar to mitigate the impact of heavy winds and dust storms, even though this option requires water resources.* Thus, industrial wastewater might be an alternative resource for water in the future.

Figure 5 shows measures that the government of Qatar could adopt to reduce air and land pollution. Regarding water and land pollution, multiple actions are required, such as gathering information, permanent monitoring, and identifying problems facing the environment, agriculture, economy, and people's health. At present, the amount of data available concerning the accumulation of pollutants (organic and inorganic) is within acceptable ranges (Abdel-Bari et al., 2007; Al-Naimi et al., 2015). Increasing green areas and improving soil conditions and air quality are required (Al-Thani and Yasseen, 2021a). Furthermore, continuous monitoring of the accumulation of pollutants in Qatari waters and lands should be maintained as recent works have sounded an alarm that continued expansion of the energy sector might pollute agricultural land (Usman et al., 2019; Alsafran et al., 2021; Abou Elezz et al., 2022).

Figure 6 summarizes the sources of pollution in the Arabian Gulf area. Three main sources have been recognized. The first, is spills of petroleum hydrocarbons and other oil residues that are deposited in the intertidal zone as a result of wars, military exercises, and transport (Fowler, 1993; Al-Saad and Salman, 2012; Rajendran et al., 2021). The second, is anthropogenic and industrial activities near the shores (Rushdi et al., 2017; Khazali and Taghavi, 2021; Rushdi et al., 2021). The last one is discharge of brine after desalination of seawater (Paleologos et al., 2018; Hosseini et al., 2021). Recent reports discuss the main pollution drivers that are affecting marine environments in the Arabian Gulf region, including climate change, oil and gas activities, coastal anthropogenic disturbances, and desalination activities (Alharbi et al., 2017; Paleologos et al., 2018; Hosseini et al., 2021).

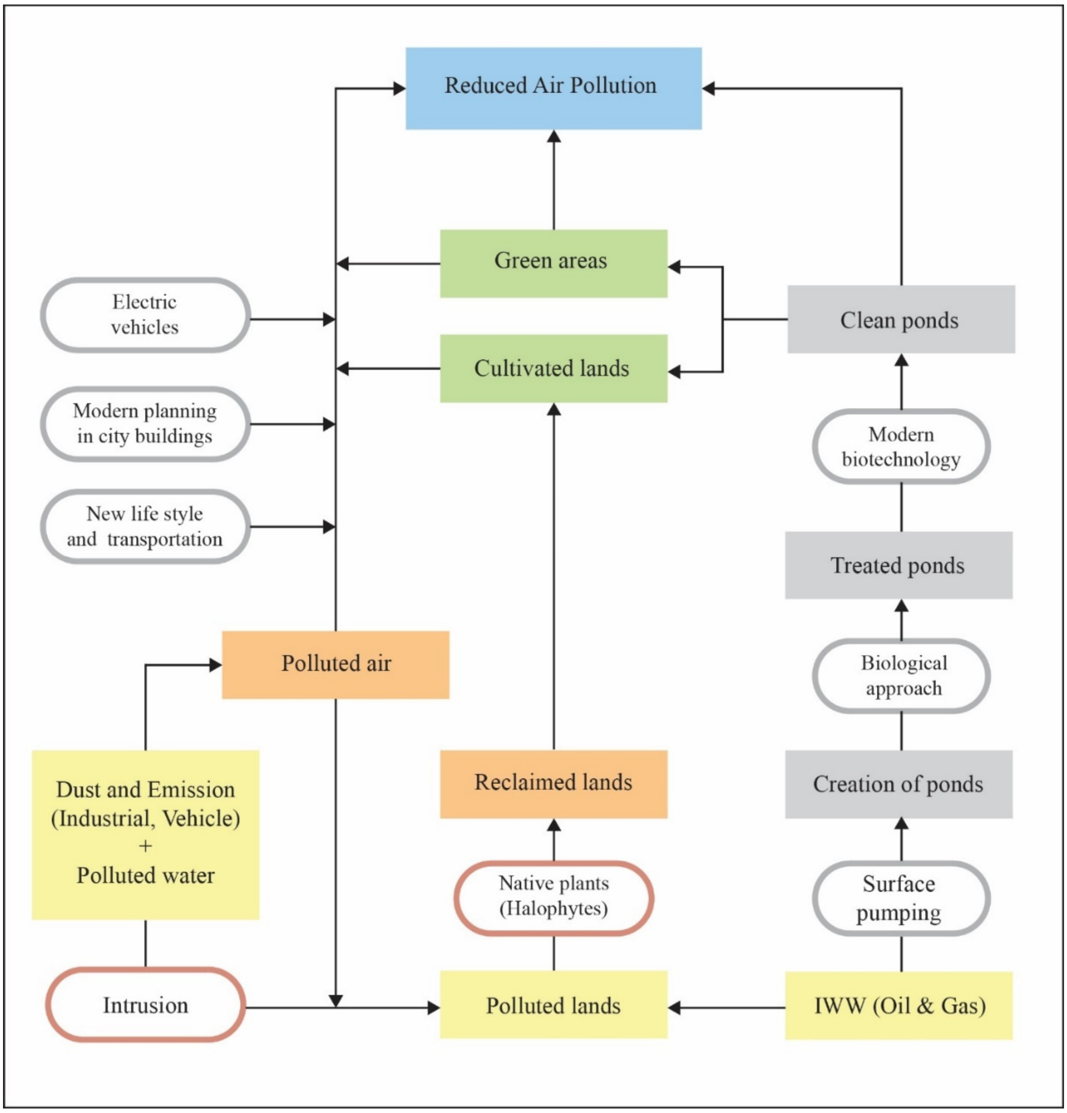

Figure 5. Possible measures that the Qatari government could take to reduce land air pollution

Currently, brine produced after desalination processes is discharged back to the sea, which causes much pollution and creates significant damage to the ecosystem and marine life. At present, more than 100 billion liters (27 billion gallons) are discharged per day of water from desalination plants around the globe (Chandler, 2019). An important method to keep the seawater of the Arabian Gulf safe from further deterioration is to treat such brine by various modern biotechnologies and industrial methods and to reduce their toxicity. Therefore, it is necessary to limit the discharge of untreated brine from desalination plants into the Gulf water. Instead, such water can be pumped into artificial ponds, and the brine water can be remediated by adopting modern and advanced biotechnologies to remove toxic metals and metabolize organic compounds using efficient native plants (Al-Thani and Yasseen, 2021a). These reports indicate a new trend in treating highly concentrated brine and converting it into useful chemicals, such as sodium hydroxide and hydrochloric acid, various metals, and possible other products. Thus, such desalination processes could become more useful and have meaningful objectives in the future (Abu Sharkh et al., 2022). However, further investigation is needed to assess the values of such studies, affordability, and the economic advantages of such trends (Shahmansouri, Min, Jin, & Bellona, 2015). Moreover, brine may contain organic compounds, especially those from seawater contaminated with oil spills, and follow-up studies are needed to look at the possibility of extracting such compounds and using them in industry and recycling programs.

Figure 7 shows the main reasons behind the land pollution in Qatar, including seawater intrusion at the surface and subsurface (Abulfatih et al., 2001), industrial wastewater pumping deep into the earth, wastewater pumping at the surface, such as Karaana lagoon (Al-Thani and Yasseen, 2021a), and environmental factors of the Gulf, which could lead to worsening of the pollution on the land through anthropogenic activities, environmental conditions, scarcity of rain fall, and climate change (de Nicola, Aburizaiza, Siddique, Khwaja, & Carpenter, 2015). The last factors are not controllable or are imposed on the ecosystem. Therefore, finding solutions for land pollution in Qatar requires more information and the use of available phytoremediation techniques, modern biotechnology, and biological and genetic approaches (Abulfatih et al., 2001; Yasseen, 2014; Al-Thani and Yasseen, 2020; 2021a; Yasseen and Al-Thani, 2022).

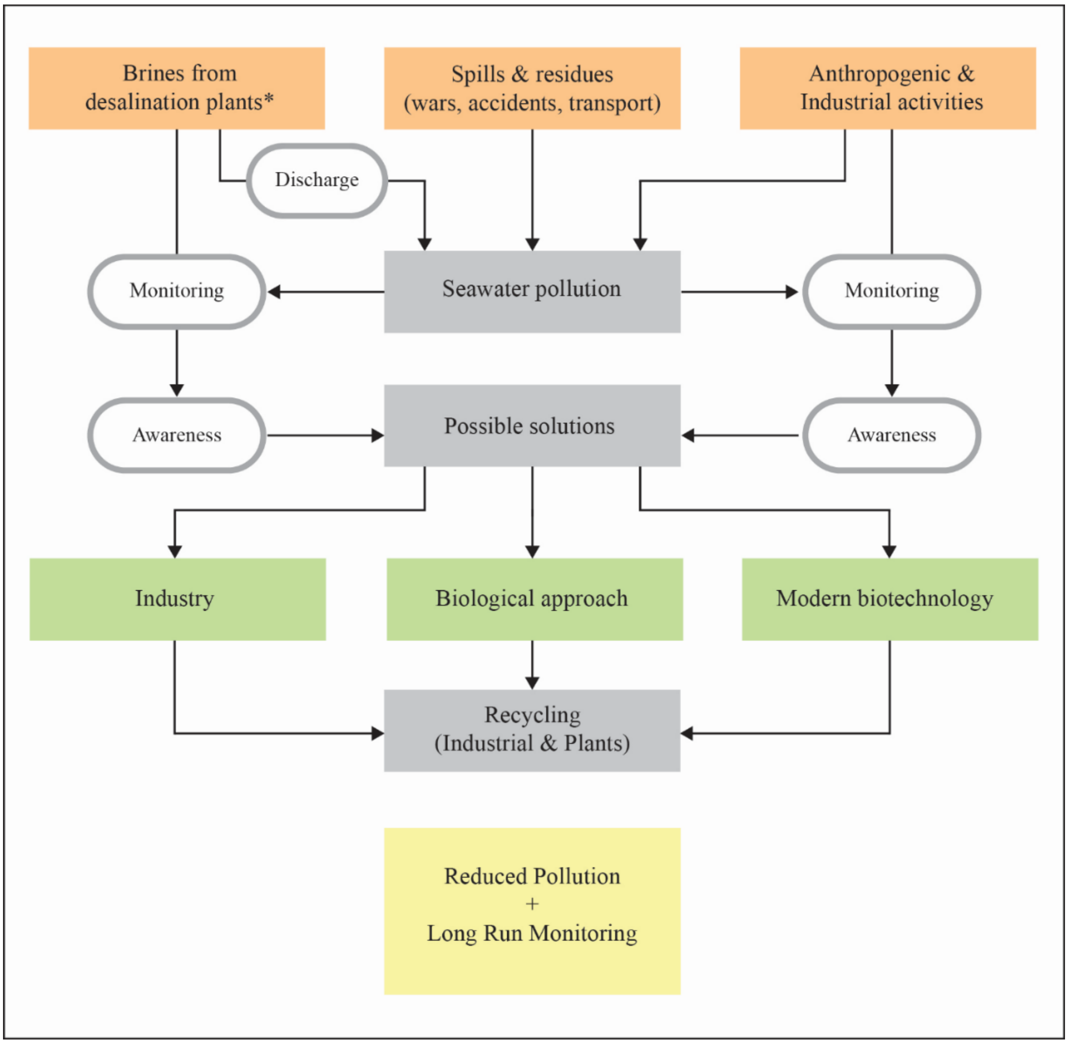

Figure 6. Possible methods that could be adopted to reduce the pollution of the Gulf waters

* Discharging brine water after desalination might be one reason for worsening pollution around the Arabian Gulf.

Therefore, instead of pumping industrial wastewater deep into the earth, it could be pumped on the surface and treated using modern technology to remove heavy metals and to let microorganisms degrade petroleum hydrocarbons (Al-Thani and Yasseen, 2020; 2021a). Industrialization and recycling programs may help to eliminate heavy metals from the soil and to keep the ecosystem safe from pollutants.

Reduced pollution in the air, water, and land (as shown in Figures 5, 6, and 7) can be achieved by multiple measures and methods. One measure is changes in lifestyle, developing new plans for modern constructions, reducing toxic gas emissions from vehicles, and lower transportation activities. Another measure, is increasing green areas by encouraging more planting. Modern biotechnology and biological approaches could also be adopted, such as bioremediation, phytoremediation, and phyco-remediation. Aquatic and halophytic plants among the flora of Qatar have proven efficient in remediating water and lands. Lastly, toxic ions and heavy metals could be removed using native plants and adopting modern industry and active recycling programs to avoid the risk of possible pollution to the ecosystem and food web.

The air, water, and land in the Arabian Gulf region are vulnerable to pollution naturally, but it mostly results from anthropogenic and industrial actions. Sources of pollution include dust storms, vehicle emissions, and industrial emissions, which affect underground water, seawater, seashores, ponds, agricultural lands, Sabkhas, and Rawdahs (fertile depressions that are usually rich in vegetation). Solutions to these problems require serious concerted efforts among various parties, including governmental and scientific agencies, academic institutions, and research centers to work together and establish the necessary steps and legislation to implement plans and activate monitoring systems. Increasing awareness among the people in the Gulf region is also a prerequisite for any success in terms of practical measures for implementing plans to reduce pollution in various locations.

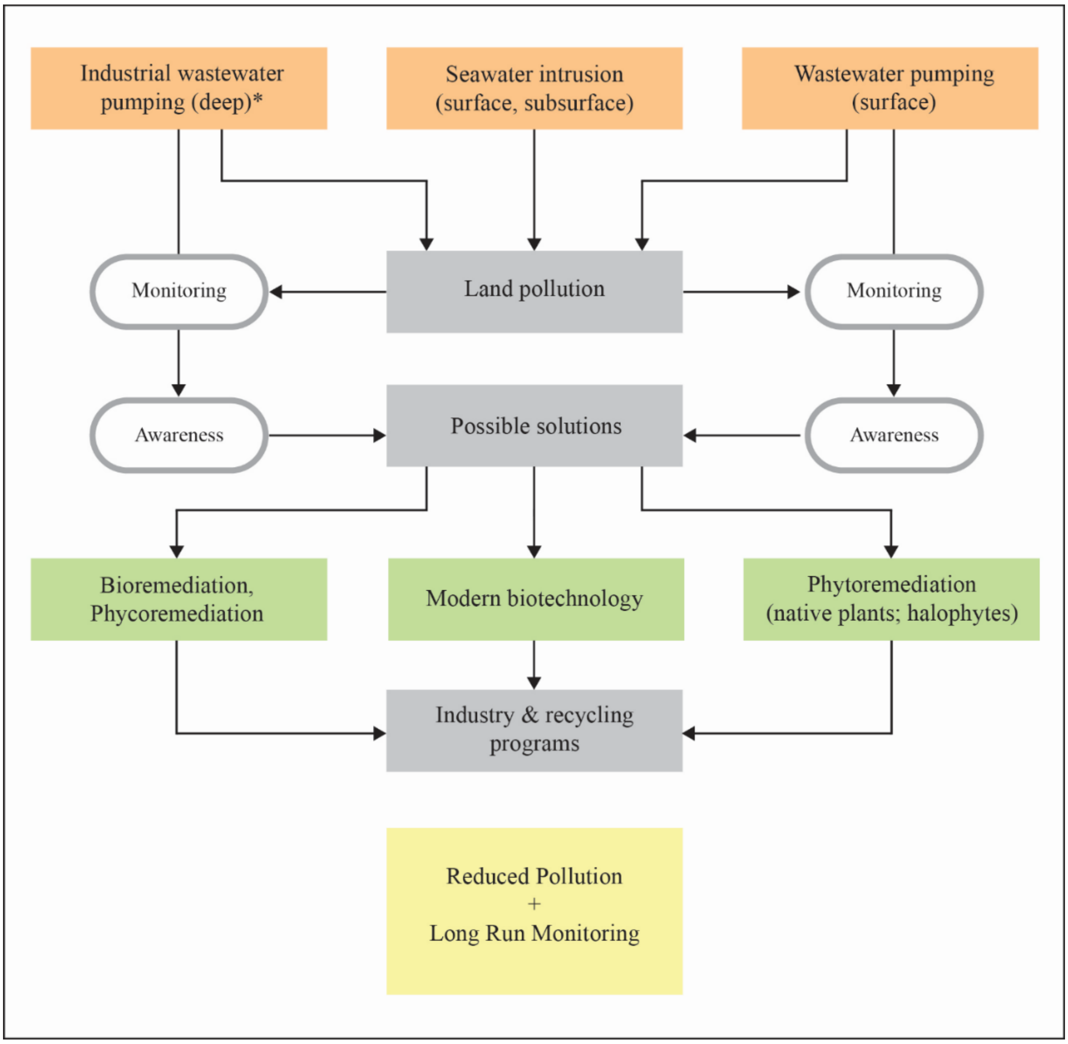

Figure 7. Possible methods that could be adopted to reduce the pollution of Qatari land

* Currently, industrial wastewater is pumped deep into the ground, causing pollution to the ground water.

5. Concluding Remarks

Although Qatar is a wealthy country with natural oil and gas resources and all requirements of modern life available, such a situation does not mean that people live without problems related to the environment and health. Air pollution in Qatar is a reality requiring immediate solutions and sustainable long-term monitoring. The levels of pollution in land and water are currently within the internationally acceptable rates, but the future might entail serious pollution risks if industrial wastewater continues to spill or is pumped deep into the ground or to the surfaces of the land and sea. In the future, the risks of pollution resulting from accumulation of heavy metals (such as arsenic, lead, and mercury) will become a natural outcome of activities associated with the energy sector. Therefore, halting of industrial wastewater pumping into the ground, treating such water to be used for various purposes, and keeping trace elements away from reaching the food chain are important. The discharge of brines after desalination of seawater back into the Gulf instead of treating it for various uses should be stopped. Natural flora and microorganisms in the soil and seawater might have a great impact on the degradation of petroleum hydrocarbon compounds.

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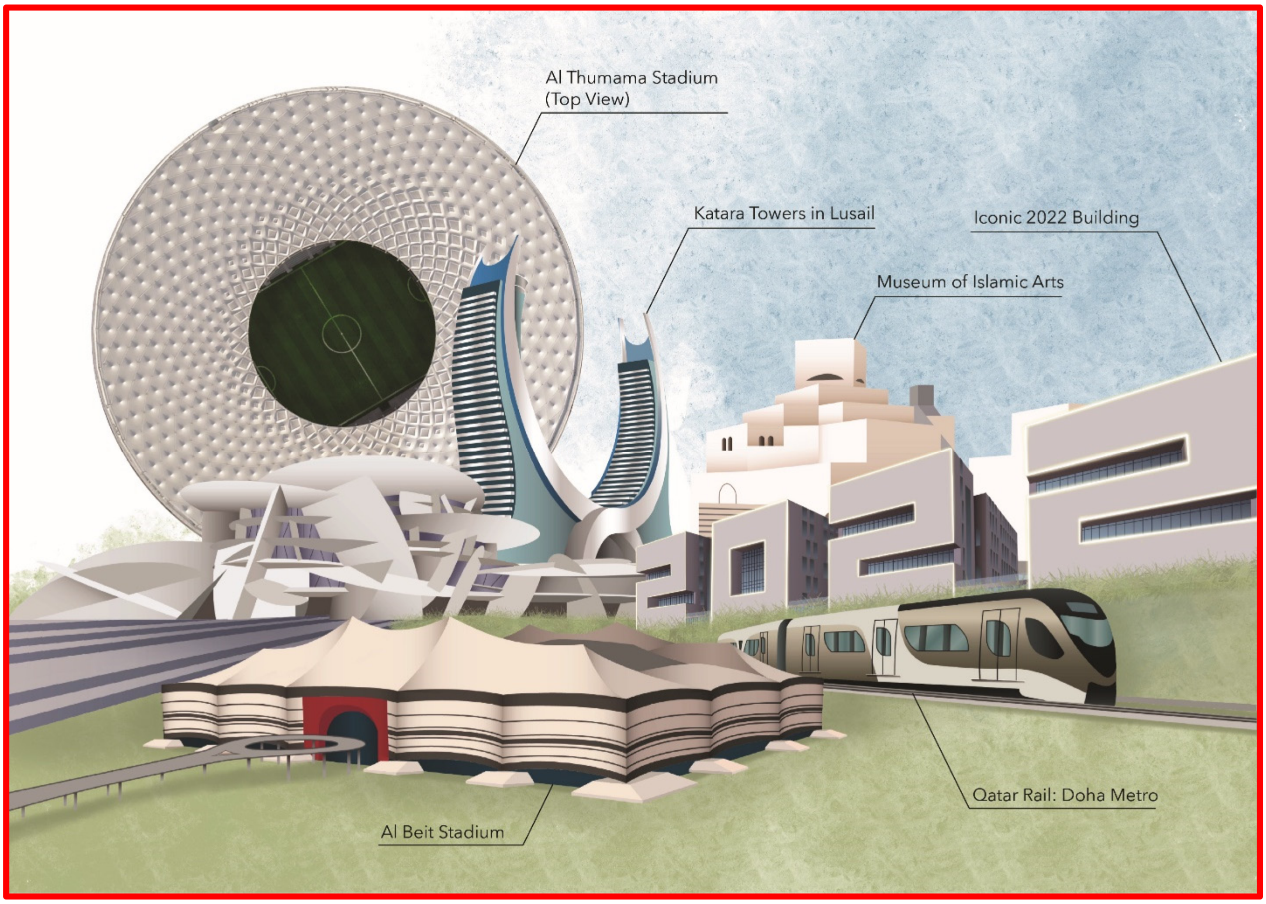
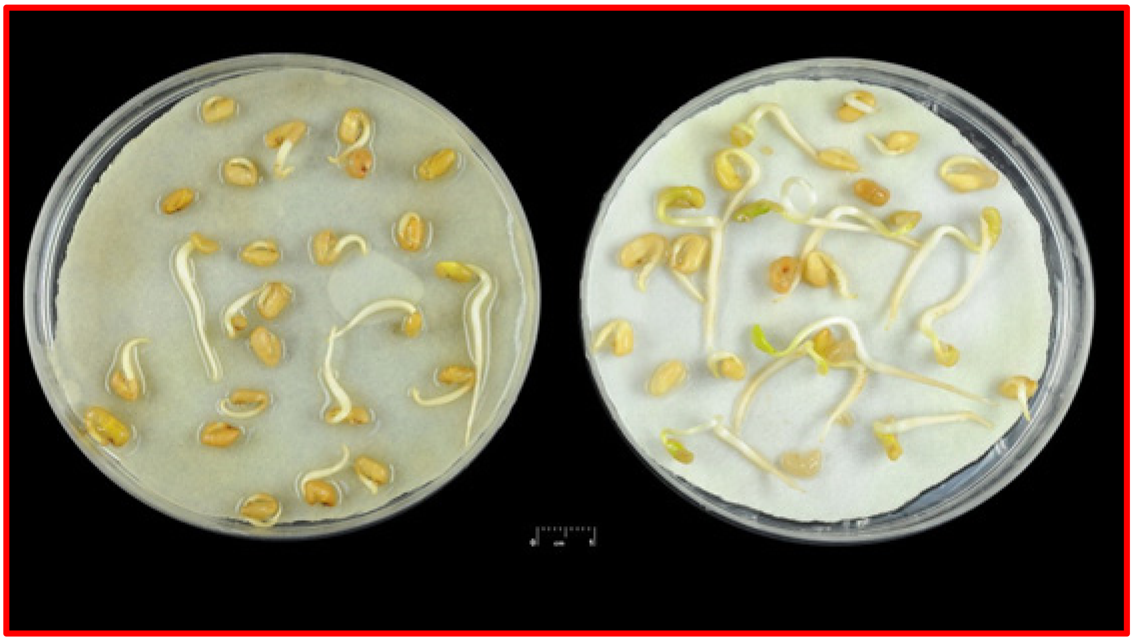


Supplementary Figure 1. New infrastructures are being constructed in Qatar, which is preparing to host major tournaments and events



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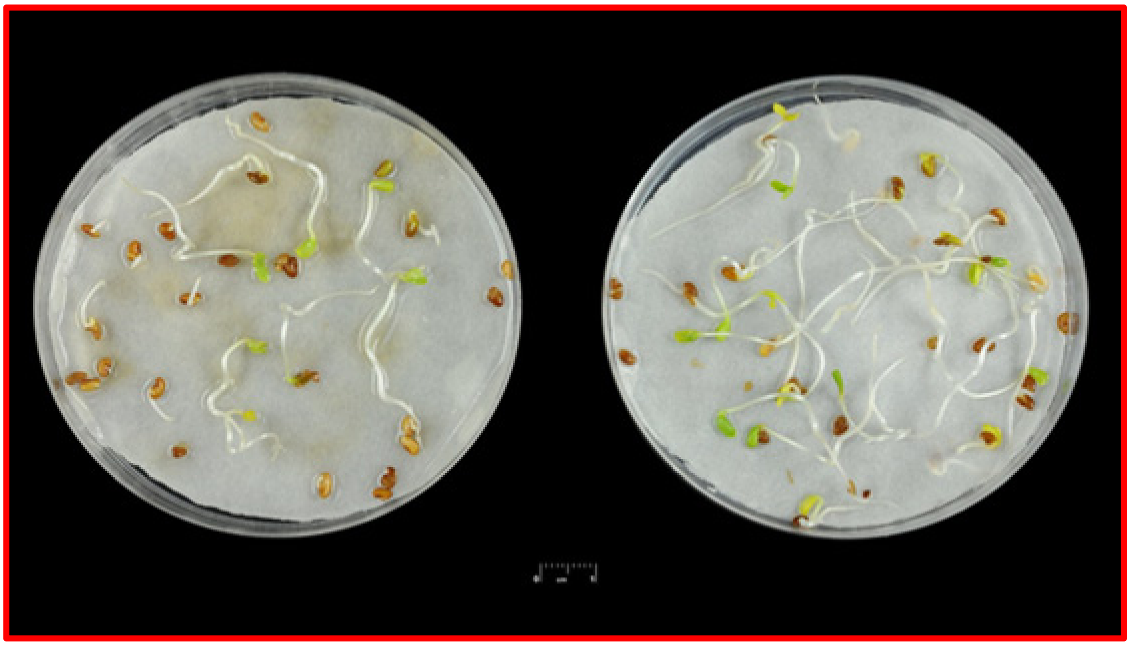


A B

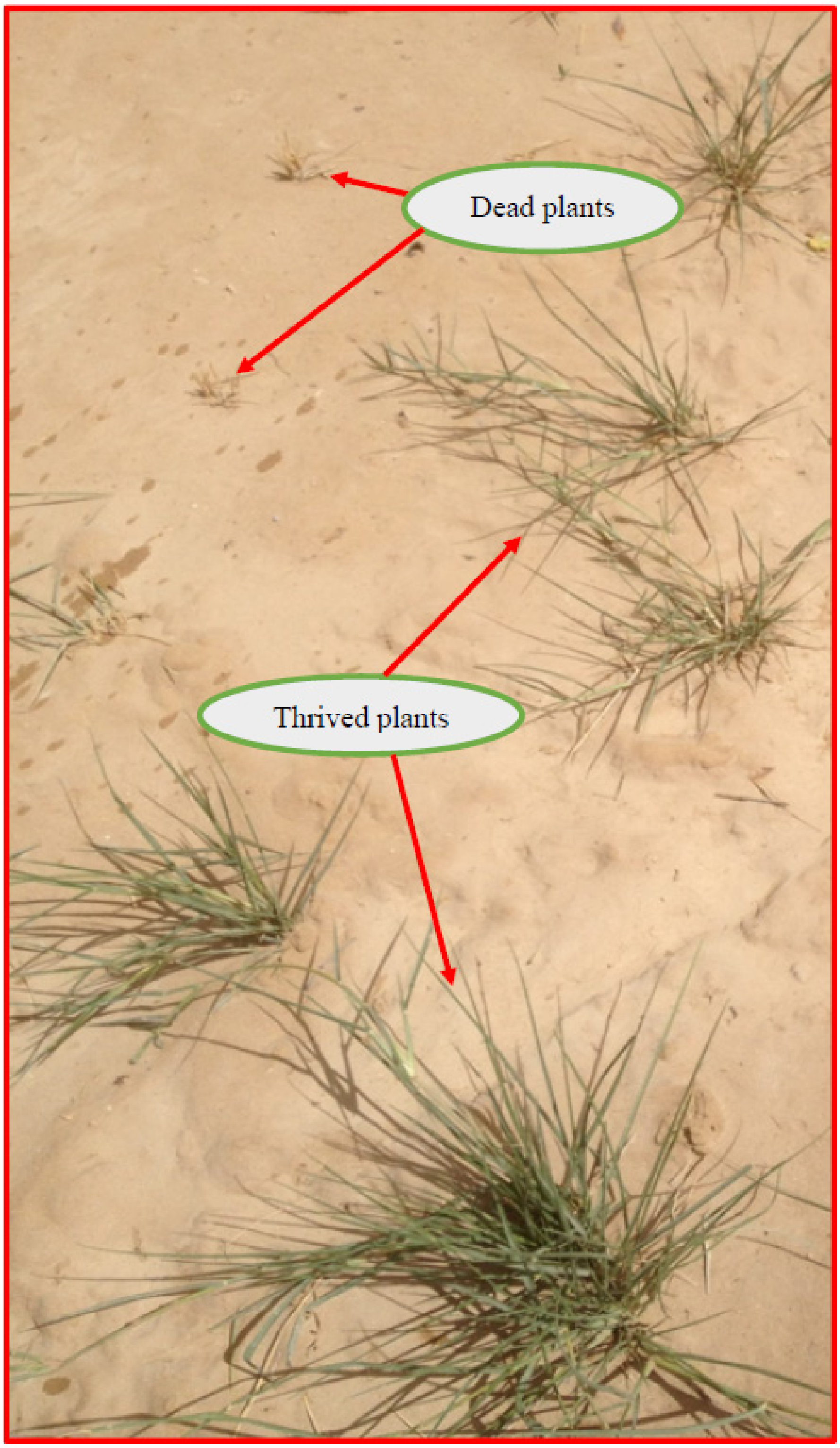
Supplementary Figure 2. Germination test of Fenugreek (*Trigonella foenum-graecum*) and Alfalfa (*Medicago sativa*) seeds at IWW(A), and distilled water (B). Note the great reduction in the germination percentage in A as compared to B. (EC of IWW ranged between 4-5 dSm^{-1})

Note: IWW was brought from Ras Laffan Gas facilities in March 2013.

Supplementary Figure 3. Sign of toxicity appears first at the tip of leaves of barley seedlings and spread down to the whole plants. Sand culture was irrigated with IWW and at the seedling stage burning and yellowing signs were obvious

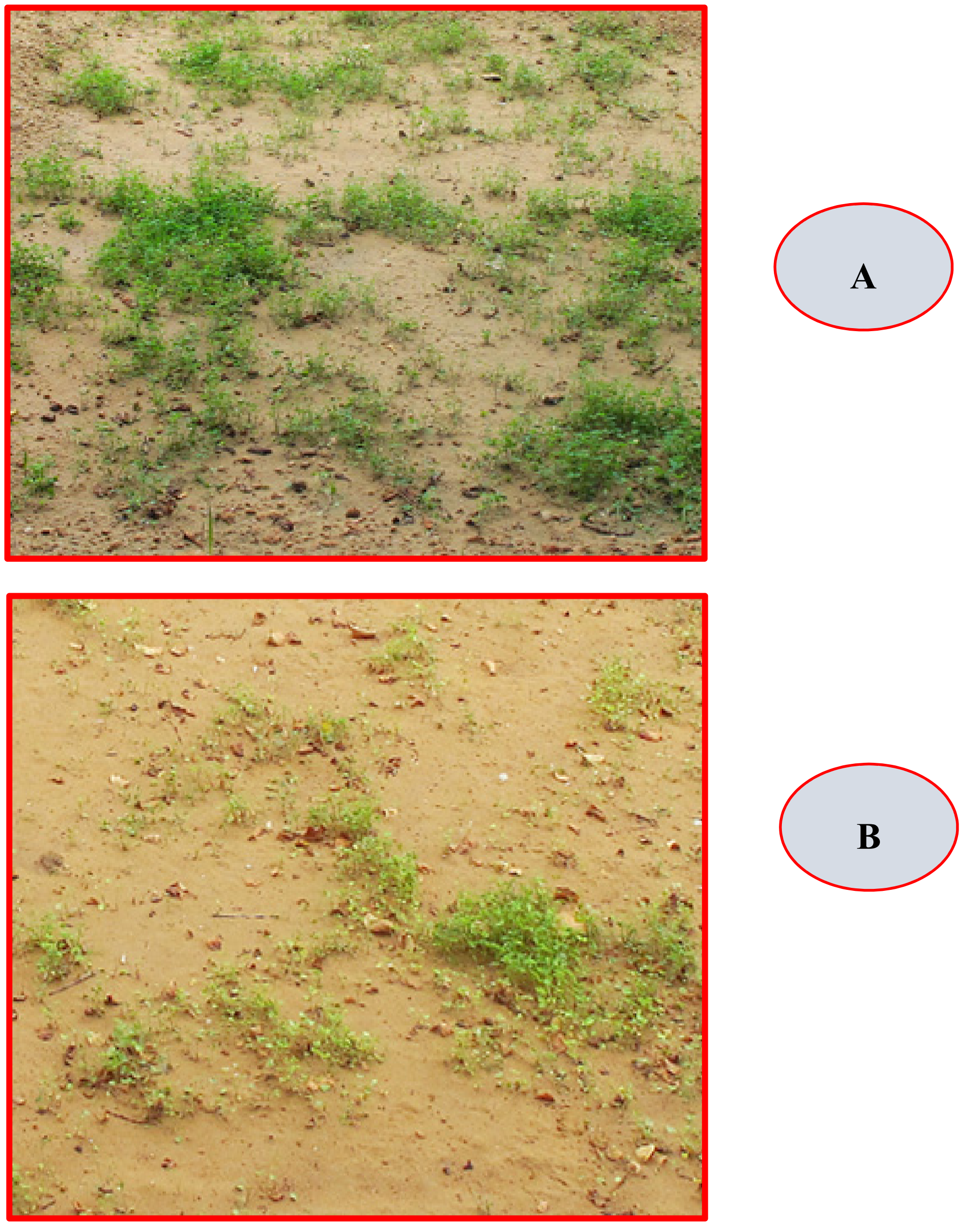
Note: IWW was brought from Ras Laffan Gas facilities in March 2013.

Supplementary Figure 4. *Phragmites australis* plants thrived after two months in soil irrigated with IWW



Supplementary Figure 5. Many *Sporobolus ioclados* plants were thrived after two months in soil irrigated with IWW, while some plants were left dead

Note: IWW was brought from Ras Laffan Gas facilities in March 2013.



Supplementary Figure 6. Alfalfa (*Medicago sativa*) plants growing in soil irrigated with tape water (A), and others irrigated with IWW (B). Notice the impact of IWW on the growth of this plant

Note: IWW was brought from Ras Laffan Gas facilities in March 2013.