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Perspectives of future water sources in Qatar by phytoremediation: biodiversity at ponds and modern approach

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ABSTRACT
Anthropogenic and industrial wastewater (IWW) could be an additional future source of water to support the needs of the people of the State of Qatar. New lagoons have been built using modern technologies to optimize water use and waste recycling, as well as increasing the green spaces around the country. To achieve successful development of these new lagoons, lessons should be learned from the old ponds by examining their biodiversity, ecology, and the roles played by aquatic plants and algae to remediate wastewaters at these ponds. The perspectives of using IWW (from oil and gas activities), that is currently pumped deep into the ground are presented. Instead of causing great damage to groundwater, IWW can be stored in artificial ponds prepared for ridding it of all impurities and pollutants of various types, organic and inorganic, thereby making it serviceable for various human uses. Phycoremediation, bioremediation, and phytoremediation methods adopted by algae, bacteria and aquatic native plants are discussed, and special attention should be paid to those that proved successful in removing heavy metals and degrading organic compounds. At least three native plants namely: *Amaranthus viridis*, *Phragmites australis*, and *Typha domingensis* should be paid special attention, since these plants are efficient in remediation of arsenic and mercury; elements found abundantly in wastewater of gas activities. Some promising modern and innovative experiences and biotechnologies to develop efficient transgenic plants and microorganisms in removing and degrading pollutants are discussed, as an important strategy to keep the ecosystem clean and safe.

Novelty statement
Industrial wastewater (IWW) could be an alternative source of water at the Arabian Gulf region. Currently, IWW is pumped deep into the ground causing a great damage to groundwater; little information about this issue has been reported. Such IWW can be stored in artificial ponds designed for ridding them of all impurities of various types; various remediation methods can be used. Modern biotechnology to develop transgenic plants and microorganisms to enhance these remediation methods can be adopted.

KEYWORDS
Bioremediation; fauna; flora; microorganisms; modern biotechnologies; native plants; phycoremediation; phytoremediation

Introduction

It has long been recognized that water sources at the Arabian Gulf region are limited, and the early reports show that the main sources of water are from groundwater followed by desalinization of seawater (ESCWA 1996). Recent works, however, show that wastewater of domestic and industrial activities (oil and gas) could be an additional future source of water to support the people's need, and might be alternative and further sources of water for various purposes; after removing and degrading contaminants of various kinds (Al-Thani and Yasseen 2020). The Arabian Gulf region holds about a third of the world oil supply, and the State of Qatar became one of the major gas producers around the globe which amounted to about 178 billion cubic meters in 2019. Bioremediation and phytoremediation have been adopted worldwide as cost-effective cleanup and environmentally friendly methods to achieve complete or partial degradation of organic contaminants and removing heavy metals and excessive nutrients from waters and soils (Frick *et al.* 1999; Pivetz 2001; Van Epps 2006; Campos *et al.* 2008; Ndimele 2010; Nie *et al.* 2011; Tandon *et al.* 2014; Yasseen 2014). Two major ponds were established in 1982 very close to Doha city, not more than 12 km southwest (Figure 1): Abu-Hamour that receives untreated wastewater (Figure 2) and Abu-Nakhla that receives treated wastewater (Figure 3) (Al-Thani and Yasseen 2020), and a large percentage of the treated wastewater had been used in creating green areas around Doha city, especially at agricultural sectors; alfalfa fields as an example, and also gardening practices.

The problem of contamination around Doha city increased substantially, especially in residential areas close to

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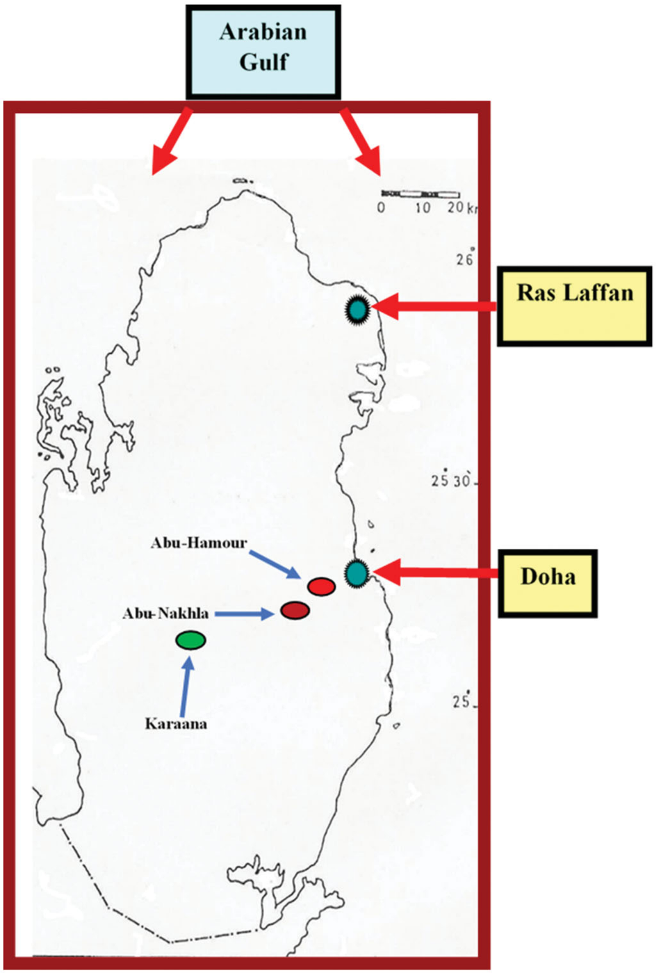

Figure 1. Map of Qatar showing the location of the two ponds on the outskirts of Doha.

those ponds. Many studies have been carried out to evaluate the environmental impacts of these ponds on agriculture, public health, economy, general lifestyle, and wildlife. Regarding the untreated ponds, these studies (Abulfatih *et al.* 2002) recommended that such ponds must have a negative impact on human health, livestock, and groundwater quality because of their contents of pathogenic microorganisms and hazardous chemicals (Al-Naimi 2002; Elhag 2002; Sweileh 2002; Al-Thani 2003). Therefore, it was recommended that the local authorities should abandon such ponds and not allow any further dumping of wastewater in them, as such ponds are very close to highly populated areas with all hazards of dissemination of germs and microbes, as well as possible contamination of the grounds water, damage to wildlife, and reduced quality of air and esthetic value. Moreover, these studies also covered the treated ponds, which come to the same conclusion that in the long run, such ponds might have had the same environmental impact on general public health and the lifestyle of people (Elobaid *et al.* 2018). With the increase of wastewater volume from industrial and domestic activities, the problem of contamination of some areas around Doha city increased considerably, especially those close to those ponds. This motivated the people to complain to the government, as these ponds badly affected the people in some parts of Doha city in terms of insects, disgusting smells, and many health issues.

On the other hand, since the discovery and export of oil (1938) and gas (1991) in Qatar, industrial wastewater (IWW) produced during the extraction and production has been pumped deep into the earth, which could pose a great threat to water quality in wells. Such IWW might be mixed up with groundwater, and if such water is used for agricultural purposes, it can cause a great threat to the plants and humans when entering the food web (Van Epps 2006).

Figure 2. Untreated wastewater pond (Abu-Hamour). Look at the *Phragmites australis* plants flourished at this pond and *Aeluropus lagopoides* can survive such habitat.

Figure 3. Treated wastewater pond (Abu-Nakhla). Good habitat for many aquatic plants, *Typha domingensis* and phytoplanktons thrived in this pond.

Therefore, two main sources of pollution impacting public life at Doha, the main city in Qatar, and perhaps be around the country: anthropogenic wastewater and IWW. In fact, local authorities have long considered stopping pumping anthropogenic wastewater into these ponds, and replacing them with new lagoons with modern and advanced methods and technologies of getting rid of pollutants of various kinds (organic and inorganic); purification of wastewater is essential to meet the international standards and to be used for irrigation of some fields and as drinking water for livestock and cattle. Moreover, scientists and decision makers are fully aware of the impact of IWW on the human life, crops and livestock. Some energy companies and research centers have already engaged in such efforts and projects (Al-Sulaiti *et al.* 2013; Yasseen 2014).

The current status

No doubt, the need for good quality water is increasing enormously day after day, especially in those health crises that afflict the green planet (Earth) from time to time. UN organizations; such as ESCWA and the WHO, have urged governments around the globe to provide clean water as crucial measure in avoiding the spread of pandemics (https://www.unescwa.org/sites/www.unescwa.org/files/escwa-covid-19-economic-cost-arab-region-en.pdf). By monitoring these ponds for many years, as an important principle of ecological restoration, maintaining a healthy environment, and avoiding future environmental risks (Yasseen and Al-Thani 2013), observations and results of many studies have come to a conclusion that these ponds could create many pollution risks to the ecosystem in the State of Qatar (Abulfatih *et al.* 2002; Mohieldeen and Al-Marri 2016; Elobaid *et al.* 2018; Al-Thani and Yasseen 2020). This issue has attracted a significant number of biologists, naturalists, agriculturists, environmentalists, planners, and decision-makers, to conduct comprehensive studies to look at the consequences of having such ponds on human health (Figure 4), which includes microbes, parasites, bad odor, vermin, and elevate the groundwater polluted with various kinds of abiotic and biotic factors (Al-Naimi 2002; Al-Thani 2002; Elhag 2002; Kardousha 2002; Sweileh 2002; Elobaid *et al.* 2018; Al-Thani and Yasseen 2020).

Moreover, serious ideas and suggestions have been introduced, and some measures have been taken that such wastewater might be useful after conducting comprehensive bioremediation and phytoremediation processes. As in Qatar's vision 2030, and passing through important international events (political and sport), the country has taken a number of measures to adopt a clean energy strategy, develop modern technologies to optimize the use of water to reduce the loss of desalinized water, improve the air quality, recycling waste as well as increasing the green spaces around the country.

Practical measures and case studies

Lessons should be learned from the previous experiences with old ponds before construct new lagoons remote of residential areas of Doha city with modern features to avoid pollution from inflicting the people's lives. These include studying the biodiversity and implementing the practical measures to construct new lagoons, and suggesting successful remediation processes. Two main important steps have

Figure 4. The biodiversity of these ponds encompasses most of the domains of life.

Figure 5. The old ponds were drained gradually from 2014 till 2020.

Figure 6. Restoration was carried out in some parts of the country and the ultimate objective is increasing green spaces.

been taken, **first:** draining the old ponds (Figure 5), treating the soil at the bottom of these ponds, building some temporary basins to evaporate the water to prevent leakage into groundwater, and reestablishing and restoring the area by encouraging the cultivation of native plants that normally live in that area, as well as microorganisms like green algae. Currently, the main objective of such projects is to maintain water sources, and in the near future, plans are concentrated on removing pollutants and recycling heavy metals and reducing the dissipation of water to keep the ecosystem safe and increase the green spaces around the country (Figure 6). Such efforts need a careful selection of those living organisms that proved successful in phytoremediation and bioremediation, **second:** conducting serious efforts to establish new successful lagoons remote of residential areas. In fact, the State of Qatar has allocated large sums for these projects and recruited researchers from all over the world to contribute to such promising projects.

One good example can be given here; the Karaana Lagoon, located about 60 km southwest of Doha city. This lagoon covers about 4 km^2, and it was receiving about 60,000 m^3 of wastewater (treated or untreated) per day, and this caused a contamination of the groundwater, producing foul odors and creating safety risks during transporting and storing of wastewater. However, in November 2019, the reclamation and rehabilitation projects were completed with modern technology to store and treat wastewater. More details can be found at: https://www.gulf-times.com/story/647730/Reclamation-rehabilitation-of-Al-Karaana-Lagoon-co. Figure 7 shows the new lagoon of Karaana, which could be a future alternative source of water for various purposes, including agricultural activities. The newly created lagoons should be treated with care, and a series of investigations should be carried out to determine their environmental impact on human health and wildlife.

Obtaining knowledge about the wild life (flora and fauna) at the old ponds is a prerequisite for future plans to construct new lagoons (Yasseen and Abu-Al-Basal 2008), so we aim by this review to put forward the previous experiences regarding the biodiversity at these ponds, and the possible roles played by the native plants, including aquatic plants and, cyanobacteria and algae, especially those related to the bioremediation and phytoremediation activities. So, the article discusses the analysis of the bioremediation and phytoremediation processes of aquatic native plants and microorganisms, and the practical methods to get clean water for various purposes; irrigation and domestic uses. Therefore, the following topics are discussed: (1) the biodiversity and ecology of flora and fauna, and the chemical contents at wastewater ponds, before drying and disappearing; (2) the problems and plans will be discussed with the possible solutions to keep the environment clean and safe from pollution; as a prerequisite of successful restoration and to sustain the ecosystem at these newly created lagoons; (3) the possible modern biotechnologies and innovative solutions to tackle the pollution problems including the

Figure 7. Part of the lagoon Karaana. This site needs a lot of effort to cultivate native plants (aquatic and terrestrial), with some species of green algae to phytoremediate the wastewater. The treatment station can be seen on the other side of the lagoon.

phytoremediation and phycoremediation methods that might be implemented using aquatic plants and algae to remediate wastewaters; and (4) activation of the monitoring system.

Biodiversity

Native plants

Specific locations at these ponds were studied periodically, and in each location, two major ecological zones were surveyed: the shallow littoral zone and wetland zone. Native plants were identified according to the knowledge of the flora of the Arabian Peninsula, supported by the herbarium specimens at the University of Qatar and some publications about the flora of Qatar (Abdel-Bari 2012). Many native plants (about 35 species of monocot and dicot) are found flourished at these two vegetation zones. Table 1 shows that most of these plants are found at wetland zone of both ponds, and only small number of plants were adapted at littoral zone which might be good candidates for phytoremediation of wastewater. The possible role of most of these plants in phytoremediation processes at polluted soils in Qatar has been recently discussed (Al-Sulaiti *et al.* 2013; Yasseen 2014; Al-Thani and Yasseen 2020). The presence of a high density of reeds (*Phragmites australis*) and perhaps other aquatic plants at these ponds is surely to play important roles in water purification (Figures 2 and 3).

Cyanobacteria and algae

Cyanobacteria and photosynthetic protista (such as algae and *Euglena*) occupy mostly the littoral zone, and their distribution is highly controlled by the quality of water, which differs from site to site. These living organisms contain photosynthetic pigments of various types, which have a very important biological contribution to trophic levels of the ecosystem. Also, microscopic living organisms such as ciliates, flagellates, amoeba-like protozoa, rotifers, and crustaceans, are frequently encountered in the littoral zones. The main Photosynthetic genera found in these ponds are listed in Table 2.

The above results revealed some differences between the two ponds, the most dominant genera in the untreated pond are: *Chlorella*, *Oscillatoria*, and *Spirulina*, while the treated pond has other genera, in addition to *Chlorella*; *Anacystis* and *Spirogyra*

Table 1. The presence of native plants at two vegetation zones in the two ponds on the outskirts of Doha city, Qatar.

	Un-treated pond		Treated pond	
Plant groups	Littoral zone	Wetland zone	Littoral zone	Wetland zone
Monocot	*Phragmites australis*, *Sporobolus ioclados*,	*Aeluropus Lagopoides*, *Chloris virgata*, *Cymbopogon commutatus*, *Juncus rigidus*, *Lasiurus scindicus*, *Polypogon monspeliensis*, *Sporobolus ioclados*, *Stipagrostis plumosa*,	*Juncus rigidus*, *Phragmites australis*, *Sporobolus ioclados*, *Typha domingensis*,	*Aeluropus Lagopoides*, *Chloris virgata*, *Cymbopogon commutatus*, *Cynodon dactylon*, *Juncus rigidus*, *Lasiurus scindicus*, *Polypogon monspeliensis*, *Sporobolus ioclados*, *Stipagrostis plumosa*, *Typha domingensis*,
Dicot	*Tamarix ramosissima*,	*Aizoon canariense*, *Anabasis setifera*, *Arnebia hispidissima*, *Cressa cretica*, *Euphorbia granulata*, *Fagonia* spp., *Herniaria hemistemon*, *Launea nudicaulis*, *Malva parviflora*, *Portulaca oleracea*, *Pulicaria crispa*, *Salsola baryosma*, *Solanum elaeagnifolium*, *Spergula fallax*, *Suaeda aegyptiaca*, *Suaeda vermiculata*, *Tamarix ramosissima*, *Tetraena qatarensis*, *Tetraena simplex*, *Tribulus terrestris*, *Urospermum picroides*,	*Rumex dentatus*, *Tamarix ramosissima*,	*Aizoon canariense*, *Amaranthus Viridis*, *Anabasis setifera*, *Arnebia hispidissima*, *Cressa cretica*, *Euphorbia granulata*, *Fagonia* spp., *Herniaria hemistemon*, *Launea nudicaulis*, *Malva parviflora*, *Portulaca oleracea*, *Pulicaria crispa*, *Salsola baryosma*, *Solanum elaeagnifolium*, *Spergula fallax*, *Suaeda aegyptiaca*, *Suaeda vermiculata*, *Tamarix ramosissima*, *Tetraena qatarensis*, *Tetraena simplex*, *Tribulus terrestris*, *Urospermum picroides*,

Abulfatih 2002.

Table 2. Photosynthetic phyla and genera encountered in these ponds at various locations.

Photosynthetic phyla			
Cyanobacteria	Chlorophyta	Ochrophyta	Euglenozoa
*Anabaena** *Anacystis****, *Lyngbya***, *Oscillatoria****, *Spirulina***,	*Chlorella****, *Chlorogonium***, *Oedogonium**, *Scenedesmus****, *Spirogyra****, *Zygnema****,	Various genera of Diatoms***,	*Euglena* (a photosynthetic flagellate)***,

*Treated pond, **Un-tretaed pond, ***both ponds, Abulfatih 2002.

were encountered. However, some peculiarities were noticed regarding the presence of some genera at either of the two ponds. For example, *Chlorogonium*, *Lyngbya*, and *Spirulina* were found only in the untreated pond; on the other hand, *Anabaena* and *Oedogonium* were found only in the treated pond. Changes in the presence of these genera should be monitored regularly since some genera of algae and cyanobacteria might be considered as a sign of pollution, while the presence of *Oedogonium* in many ponds has been considered as a sign of good quality water (Yasseen *et al.* 2001).

Bacteria

There is a great deal of information in the literature addressing the microbiology of wastewater. Sewage discharge has highly important impacts on human health because it can spread pathogenic bacteria and viruses. Fortunately, the bacteria that grow in the intestinal tract of diseased humans are not likely to be found in the favorable wastewater environment for their growth and reproduction. Although many pathogenic organisms are removed by natural die-off during the wastewater treatment processes, sufficient numbers can remain to cause a threat to any downstream use involving human contact or consumption (Rheinheimer 1992). The microorganisms of natural waters are extremely diverse. The number and types of bacteria present will depend on the presence and the amounts of organic matter, toxic substances, and salinity, in addition to environmental conditions such as pH, temperature, and aeration (Toranzos and McFeters 1997). The largest numbers of heterotrophic forms will exit on the bottom and banks of these ponds, where organic matter predominates.

The bacterial analysis of the wastewater collected from the edges of these ponds has generally indicated the presence of coliform bacteria throughout the year. However, slight fluctuations in the counts of bacteria have been encountered from month to month and from site to site.

Table 3. The most common invertebrates found at the major ponds near Doha city.

Phylum	Group	Species	General characteristic	Presence at ponds
Annelida	Clitellata	*Enchytraeus* sp.	White worm	Present
Annelida	Clitellata	*Tubifex* sp.	Tubificid annelids, In the sediments	Present
Arthropoda	Arachnida	*Lycosa* sp.	Wolf spiders	Present
Arthropoda	Arachnida	*Lycosa* sp.	Nursery web spiders	Present
Arthropoda	Branchiopoda	*Daphnia* sp.	Water fleas	Rare
Arthropoda	Hexanauplia	*Cyclopoid* sp.	Small planktonic animals‡	Present
Arthropoda	Hexanauplia	*Cyclops* sp.	Single large eye; either red or black	Not found at untreated pond
Arthropoda	Hexanauplia	*Harpacticoid* sp.	Very short pair of first antennae	Prominently present
Arthropoda	Insecta	*Adesmia* sp.	Genus of beetles	Rare
Arthropoda	Insecta	*Aedes* sp.	Mosquitoes, muscoid flies	Present
Arthropoda	Insecta	*Anacridium* sp.	Genus of grasshoppers	Rare
Arthropoda	Insecta	*Anaphosia* sp.	Moths in the family Erebidae	Rare
Arthropoda	Insecta	*Cataglyphis* sp.	Desert ants	Present
Arthropoda	Insecta	*Coenagrionidae* sp. (not identified)	Narrow-winged damselflies	Present
Arthropoda	Insecta	*Formicidae* sp. (not identified)	Formicine ants	Present
Arthropoda	Insecta	*Nezara* sp.	Nezara a plant-feeding stink bug	Rare, not found at untreated pond
Arthropoda	Insecta	*Truxalis* sp.	Grasshoppers in Africa, Iberian Peninsula, and Asia	Rare, not found at untreated pond
Arthropoda	Ostracoda	*Podocopa* sp. (not identified)	Long endopod	Present
Gastrotricha	Chaetonotida	*Chaetonotida* sp. (not identified)	Butterflyfishes, Bottle - like shape	Not found at untreated pond
Mollusca	Bivalvia	*Sphaeriidae* sp. (not identified)	Small freshwater bivalve mollusks	Present
Nematoda	Phasmida	*Phasmid* sp. (not identified)	Stick insects, Walking sticks	Present
Platyhelminthes	flatworms	*Catenula* sp.	Acoelomates	Present
Platyhelminthes	Planarian	*Planaria* sp.	Non- parasitic flatworms, Freshwater triclads	Not found at untreated pond
Rotifera	Monogononta	*Monogononta* sp. (not identified)	Reduced corona, and has a single gonad	Not found at untreated pond

Elhag 2002. ‡First antennae shorter than the length of the head and thorax, and uniramous second antennae. The main joint lies between the fourth and fifth segments of the body.

Even the wastewater from the discharged pipeline at the treated pond coming directly from the water treatment plants contained some coliform bacteria. Further analysis revealed some other bacilli and Gram-negative bacteria as: (1) *Aeromonas hydrophila*: found in water and causes watery diarrhea and infects wounds; (2) *Pseudomonas aeruginosa*: found in water and causes skin irritation, ear and eye illness; (3) *Klebsiella pneumoniae*: found in rich organic matters and carbohydrates but not in human feces; (4) *Chromobacterium violaceum*: found in the moist subsoil surface and in water, which leads to the inflammation of wounds; (5) *Escherichia coli* (*E. coli*): its presence in water and soil is an indication of water pollution by human waste. Other bacterial species are also found in soil and water, including Gram-positive bacteria, such as *Streptomyces*, *Bacillus*, and *Macrococcus*. It is interesting to report that coliform bacteria are not found in the groundwater, and therefore monitoring of these sites should be maintained and continued regularly to check the level of pollution in that area.

Fauna

Invertebrates and vertebrates were investigated, and such a study could offer important information about the health of the habitat. For example, parasites at these ponds were studied (Kardousha 2002), and their role was discussed in terms of pollution status at these ponds (Al-Thani and Yasseen 2020). The untreated ponds were rich with *Ascaris lumbricoides* eggs, while the treated ponds were free of these eggs. Moreover, fecal debris of some visitor cattle (camels, sheep, and goats) and other inhabitant animals at the treated ponds contained eggs of *Trichostrongylus* sp., *Fasciola hepatica*, and *Capillaria* sp., as well as other nematodes. The relative presence of the different groups of fauna might give an indication of pollution and stresses at these ponds. Invertebrates are the most important components in the ecology of these ponds, as they support secondary production and interlink the different pathways of food webs. Table 3 shows the invertebrate species found at these ponds during one year of investigation (Elhag *et al.* 2002), and these species belong to seven phyla: Annelida, Arthropoda, Gastrotricha, Mollusca, Nematoda, Platyhelminthes, and Rotifera, the largest group among those phyla was Arthropoda; and the classes of Insecta and Arachnida occupied mostly the damp and drier parts of the ponds, while the rest groups were mainly aquatic. Kardousha (2016) further investigated the aquatic macroinvertebrates at the treated pond land, and his survey has come to report 24 species, many of which have been recorded for the first time.

These new records belong to the groups: Phylum: Rotifera: (*Asplanchna* sp.), Phylum: Arthropoda: Order: Notostraca: (*Triops longicaudatus*, adult stage); Order: Hemiptera, *Anisops* sp. (Adult stage); *Sigara striata* (Adult and Larvae stages); Order: Coleoptera: *Neoporus* sp. (Adult and Larvae stages), *Haliplus* sp. (Adult stage), *Laccobius* sp. (Adult and Larvae stages), *Hydrophilus* sp. (Larvae stage), *Stenopelmus* sp. (Adult stage); Order: Odonata: *Anisopteran* (species among the infraorder Anisoptera), (Larvae stage); Order: Diptera: *Chironomus* sp. (Larvae), *Brachydeutera* sp.

Table 4. The most common vertebrates found at the major ponds near Doha city.

Group	English name	Species	Status	Presence: Season & Ponds
Amphibians	Green toad	*Bufo viridis*	Endemic	All year, Treated
Birds	Ringed plover	*Charadrius dubius*	Migrant	Winter, Treated
Birds	Reef Heron	*Egretta gularis*	Resident	All year, Treated
Birds	Crested larks	*Galerida cristata*	Visitor	All year, Both
Birds	Black-winged stilt	*Himantopus himantopus*	Migrant	Spring, Winter, Both
Birds	Gray shrike	*Lanius excubitor*	Migrant	Spring, Both
Birds	Slender- bill gull	*Larus genei*	Visitor	Winter, Both
Birds	Stooty gull	*Larus hemprichii*	Visitor	Winter, Both
Birds	Godwit	*Limosa lapponica*	Migrant	Winter, Both
Birds	White wagtail	*Motacilla alba*	Visitor	All year, Treated
Birds	House sparrow	*Passer domesticus*	Visitor	All year, Both
Birds	Greater flamingo	*Phoenicopterus ruber*	Resident	All year, Both
Birds	Water rail	*Rallus aquaticus*	Resident	All year, Both
Birds	Caspian tern	*Sterna caspia*	Migrant	Winter, Treated
Birds	Palm dove	*Streptopelia senegalensis*	Visitor	All year, Both
Birds	Little grebe	*Tachybaptus ruficollis*	Resident	All year, Both
Birds	Sandpiper	*Tringa stagnatilis*	Migrant	Winter, Both
Fishes	Nile Tilapia	*Oreochromis niloticus*	Endemic	All year, Treated
Mammals	Camel	*Camelus dromedarius*	Visitor	All year, Treated
Mammals	Cheesman's gerbil	*Gerbillus cheesmani*	Endemic	All year, Treated
Mammals	Baluchistan gerbil	*Gerbillus nanus*	Endemic	All year, Treated
Mammals	Lesser gerboa	*Jaculus jaculus*	Endemic	All year, Both
Mammals	Cape hare	*Lepus capensis*	Endemic	All year, Treated
Mammals	Ethiopian hedgehog	*Paraechinus aethiopicus*	Endemic	All year, Treated
Reptiles	Fringed -toed sand lizard	*Acanthodactylus boskianus*	Endemic	All year, Treated
Reptiles	Jayakari's agama	*Agama flavimaculata*	Endemic	All year, Both
Reptiles	Arabian desert gecko	*Banopus tuberculatus*	Endemic	All year, Both
Reptiles	Rate snake	*Coluber ventromaculatus*	Endemic	All year, Treated
Reptiles	Keeled rock gecko	*Cyrtopodion scabrum*	Endemic	All year, Un-treated
Reptiles	Short nose desert lizard	*Mesalina brevirostris*	Endemic	All year, Both
Reptiles	Dhab	*Uromastyx microlepis*	Endemic	All year, Both

Kardousha 2002.

pupa (Larvae stage), *Ephydra* sp. pupa (Larvae stage). More details can be found in Kardousha (2016).

Also, these ponds embrace vertebrates of various groups (Table 4), and these living organisms found wastewater as a good refuge for their survival in the middle of the desert.

Many inhabitant animals, such as frogs, reptiles (spiny-tailed lizard, agamas, lizards, common snakes), and many birds were found around these ponds (Jennings 1981; Kamel and Madkour 1984; Mohammed 1988; Kingdon 1990; Oldfield and Oldfield 1994; El-Sherif and Al-Thani 2000).

The above documentation of flora and fauna around these ponds is essential for any future plans to construct new lagoons with modern criteria. The reported information is considered as a prerequisite for successful ecological restoration (Yasseen and Al-Thani 2013), and facilitate future efforts of phytoremediation projects (Yasseen 2014). By demolishing the old ponds without serious studies, the natural records of the aquatic habitats in Qatar, including the ecophysiological aspects of wildlife, will be lost, leaving little hope to regain the required information for future plans for ecological restoration projects (Yasseen and Abu-Al-Basal 2010; Yasseen 2011; Al-Thani and Yasseen 2020).

Phytoremediation and phycoremediation: perspectives of water sources

By increasing the standard of life and well-being in Qatar, concurrent with the fast expansion of the urban, industrial, and agricultural areas, more quality water is needed. The major development in various aspects of life in Qatar puts great serious responsibility on the decision-makers to make substantial efforts to construct more desalinization plants and store water in strategic reservoirs to support the people's need at emergencies, and create treated wastewater ponds and engineered wetlands (Al-Sulaiti *et al.* 2013; Al-Thani and Yasseen 2020). These efforts should be accompanied by abandoning of untreated wastewater ponds and other ponds that do not meet the international standards and guidelines to avoid any negative impacts of wastewater on human health and economy (Abulfatih *et al.* 2002). Worldwide water treatment engineers and biologists have started promising efforts to solve the problem of water scarcity by adopting innovative methods and using aquatic macrophytes and/or hydrophytes for water purification, where they planted different kinds of reed, rush, and hyacinth plants in natural and artificial wetlands and lagoons to reduce pollution risk by absorbing of heavy metals and metabolizing the organic components, and moreover, by applying modern biotechnology and genetic engineering techniques (Todorovics *et al.* 2005; Yan *et al.* 2020). Some studies were conducted to look at the chemical composition, organic, and inorganic components, of wastewater at the ponds around Doha city, and such wastewater produced mainly by anthropogenic activities; sewages and factories. Regarding the inorganic components-heavy metals in particular-Sweileh (2002) determined some of these elements in wastewater and sediment samples of some ponds on the outskirts of Doha city. The main heavy metals found at these ponds were in the order: Mn > Cu > Cr > Pb > Ni. However, Hg and Cd levels were close or below the limits of detection for the method adopted. Polychlorinated biphenyls (PCBs) were the main organic compounds found at these ponds, in addition to many other organic components (Al-Naimi 2002).

Industrial wastewaters (IWWs), on the other hand, from oil and gas activities were analyzed in some effluents, the data of Al-Sulaiti *et al.* (2013) indicated that metals found in the discharged IWW of crude oil and in sediments where oil was spilled are Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, V, Zn (Osuji and Onojake 2004; Yasseen 2014), other trace elements might be found as well. The analysis of elements in wastewater from gas activities include: Al, As, Ba, Cd, Co, Cr, Cu, Fe, Hg, K, Mn, Ni, Mo, Pb, Zn, and possibly others were present at low concentrations, these elements might nevertheless pose a real threat to public health in the long run (unpublished data). Other studies have investigated the petroleum hydrocarbons of IWW, which included: Total Petroleum Hydrocarbons (TPH), and Polycyclic Aromatic Hydrocarbons (PAHs). These IWWs are produced during oil and gas activities, and some interesting unpublished data showed that other organic components such as MEG (mono-ethylene glycol) and KHIs (kinetic hydrate inhibitors) that are added to wastewater during these activities might have had negative impact on the growth of plants when irrigated with such wastewater (Al-Thani and Yasseen 2020). Also, other organic components of various origins might be found among such wastewaters, and these included: BTEX (Benzene, Toluene, Ethylbenzene, and Xylene) and benzo[a]pyrene; B*a*P. More organic compounds are also found among the wastewaters, such as chlorinated solvents, explosives, DDT (Dichlorodiphenyltrichloroethane), cyanides, and dioxins (by-products of some industrial processes such as herbicide production and paper bleaching). Other organic components might be found in wastewaters, such as pesticides, fungicides, and insecticides. These compounds are dangerous to public health and introduce toxins when they enter the food-chain directly or indirectly via animal meat. For example, PAHs and PCBs are persistent compounds and recognized as carcinogenic (Ben Chekroun *et al.* 2014). Recent publications (Al-Thani and Yasseen 2020) have discussed the possible risk implications of having such wastewater used in agricultural purposes, whether by forced (when no better options available) or voluntarily (ignorance of risks) actions, and might lead to disastrous consequences on human health, as well as damage to cattle and livestock. Therefore, here we investigate the possible mechanisms operating at these ponds by native plants and microorganisms, and describe promising aquatic native plants and algae that proved efficient in remediation processes.

Many plants listed in Table 1 have shown a great deal of efficiency in removing and/or degrading heavy metals and organic matters, respectively. These plants include: *Aeluropus lagopoides*, *Amaranthus viridis*, *Cynodon dactylon*, *Euphorbia granulata*, *Fagonia* spp., *Juncus rigidus*, *Malva parviflora*, *Phragmites australis*, *Polypogon monspeliensis*, *Portulaca oleracea*, *Rumex dentatus*, *Salsola baryosma*, *Solanum elaeagnifolium*, *Sporobolus ioclados*, *Stipagrostis plumosa*, *Suaeda aegyptiaca*, *Suaeda vermiculata*, *Tamarix ramosissima*, *Tetraena qatarensis*, and *Typha domingensis* (Table 5).

Other plant species were also found at these ponds, and have not been tested at phytoremediation processes, and these plants should be studied to find out whether these plants can be used by phytoremediation, these plants include: *Aizoon canariense*, *Anabasis setifera*, *Arnebia hispidissima*, *Chloris virgata*, *Cressa cretica*, *Cymbopogon commutatus*, *Herniaria hemistemon*, *Lasiurus hirsutus*, *Launea nudicaulis*, *Pulicaria crispa*, *Spergula fallax*, *Tetraena simplex*, *Tribulus terrestris* and *Urospermum picroides*.

On the other hand, adopting phycoremediation methods have succeeded to remove, degrade, and render organic and inorganic components produced during various industrial and anthropogenic activities, such as agricultural practices, fuel use, industrial discharges, and domestic effluents. The case studies of this review showed that members of four major divisions of algae and cyanobacteria, such as Chlorophyta, Cyanophyta (cyanobacteria), Euglenophyta, and Ochrophyta; Heterokontophyta (diatoms), found in these ponds are considered as good candidates for phycoremediation (Yasseen 2014), and the presence of some species of algae and cyanobacteria at aquatic environments have been used to evaluate the status of water pollution (Palmer 1980; Sen *et al.* 2013; http://www.walpa.org/waterline/june-2012/algae-can-function-as-indicators-of-water-pollution/).

Some differences were found between ponds receiving wastewaters from different sources (Yasseen *et al.* 2001; Abulfatih 2002), as shown in Table 2. In fact, the most common genera encountered at many locations around the ponds under investigation were: *Anacystis*, *Chlorella*, Diatoms (various species), *Euglena*, *Oscillatoria*, *Scenedesmus*, *Spirogyra*, and *Zygnema*. However, some others rarely encountered in these ponds include the following genera: *Anabaena*, *Chlorogonium*, *Lyngbya*, *Oedogonium*, and *Scenedesmus*. Multiple articles from around the world have reported that these genera have the potential to clean water by removing and/or metabolizing many types of pollutants and impurities (Al-Hafedh *et al.* 2014). Over the last five decades, studies have shown that many algae species proved efficient in solving the problem of pollution by bioremediation processes of organic components and heavy metals (Walker *et al.* 1975a; Marella *et al.* 2016; Kaur *et al.* 2018; Upadhyay *et al.* 2019). For example, Walker *et al.* (1975b) isolated an alga, *Prototheca zopfi*, which proved capable degrading various types of crude oil and aromatic compounds. Cerniglia *et al.* (1980) showed that many cyanobacteria and algae species have the potential to oxidize naphthalene, and in the recent years, many authors, such as Ben Chekroun and Baghour (2013), Ben Chekroun *et al.* (2014), and Blažo Lalević *et al.* (2019), offered basic information about phycoremediation of waters and soils, and adopting modern biotechnologies to develop transgenic algae to deal with pollution at aquatic environments. Moreover, other important roles these organisms might play at aquatic environments include: (1) photosynthesis; (2) nitrogen fixation; (3) protein supplements to the human diet; (4) provide essential nutrients like carotenoids, vitamins, minerals, fertilizers, and oil; (5) source of medicinal components; (6) producing toxins; (7) food for

Table 5. Many Qatari native plants at wastewater ponds involved in phytoremediation of petroleum hydrocarbons and heavy metals with the cooperation of various microorganisms.

	Chemicals involved				
Plant species	Organic	Inorganic	microorganisms involved	Mechanism adopted	References
Aeluropus littoralis	TPHs, PAHs	–	Heterotrophic bacteria in the rhizosphere	Accumulations of PAHs by adsorption and diffusion	Alavi *et al.* 2016; Rafiee *et al.* 2017
Amaranthus viridis	TPHs	As, Cd, Cr, Cs, Cu, Hg, Ni, Pb, Zn	*Fusarium* spp. (TPHs)	Phytoextraction	Mellem 2008; Abubakar *et al.* 2014a; Ziarati and Alaedini 2014; Mohsenzadeh and Chehregani Rad 2015
Cynodon dactylon	Organic compounds	As, Cd, Co, Cr, Cs, Cu, Ni, Pb, Se, Zn	White-rot-fungus, unspecified soil microbes	Phytoextraction, Phytostabilization, Phytodegradation, Phytovolatilization, Rhizofiltration, Rhizodegradation	Oh *et al.* 2014; Mustapha *et al.* 2018
Euphorbia granulata	–	Cd, Cr, Cu, Pb, Zn	Not specified	Phytoextraction (Heavy metals),	Jiménez *et al.* 2011; Husnain *et al.* 2013
Fagonia spp.	–	Al, Cu, Fe, Ni, Pb, V, saline soils	Not specified	Phytoextraction (Heavy metals)	Bu-Olayan and Thomas 2009; Naz *et al.* 2010
Juncus rigidus	PAHs, various IWWs	Al, Cd, Cr, Cu, Fe, Hg, Mn, Ni, Pb Zn	degrading bacteria, *Pseudomonads*, Endophytic bacteria, possibly others	Immobilization and exclusion at root system, Denitrification for organic components	Smialek *et al.* 2006; Zhang *et al.* 2012; Bhatia and Goyal 2014; Syranidou *et al.* 2017
Malva parviflora	Crude oil	Mn, Cd, Cu, Fe, Cr, Ni, Pb, Zn	Microbes and fungi role are possible	Phytoextraction (Heavy metals)	El-Rjoob and Omari 2009; Suchkova *et al.* 2014
Phragmites australis	PAHs, various IWWs	As, Ba, Cd, Co, Cr, Cu, Fe, Hg, Mn, Mo, Ni, Pb, Se, Zn	Various microbes in the soil; hydrocarbons degrading bacteria	Phytoextraction (Heavy metals), Exclusion of metals in the root system	Nie *et al.* 2011; Kleche *et al.* 2013; Oliveira *et al.* 2014; Cicero-Fernández et al., 2016; Bello *et al.* 2018; Rezania *et al.* 2019; Fahid *et al.* 2020
Polypogon monspeliensis	TOG	Hg, Zn	Rhizosphere microorganisms	Phytoextraction, Hyperaccumulation, Exclusion mechanism, Detoxification	Farzamisepeher *et al.* 2013; Ouni *et al.* 2016; Farzamisepehr and Nourozi 2018; García-Mercado *et al.* 2019
Portulaca oleracea	Bisphenol derivatives	As, Cd, Cr, Fe, Ni, Pb, Zn	Soil microbes could have a role	Phytoextraction; heavy metals, Exclusion of metals in the root system, Organic compounds metabolized	Tiwari *et al.* 2008; Okuhata *et al.* 2013; Tandon *et al.* 2014; Hammami *et al.* 2016; Yadegari 2018
Rumex dentatus	Carbosulfan & carbofuran	Ni	Not specified	Phytostabilization, Phytoextraction, Metabolize insecticides	Romeh 2016; Sajad *et al.* 2019a, 2009b
Salsola baryosma	–	Cd, Co, Cr, Fe, Mn, Ni, Pb, V, Zn	Not specified	Phytoextraction; heavy metals, Exclusion mechanisms	Al-Khateeb and Leilah 2005; Dragovic *et al.* 2014
Solanum spp.	PAHs	Cd- Cu, Zn, Pb	Rhizobacteria, Soil microbes	Phytoextraction (Heavy metals)	Xu *et al.* 2012; Varun *et al.* 2015; Yu *et al.* 2015; Kundan *et al.* 2017; Zia-ur-Rehman *et al.* 2017; Khalid *et al.* 2019
Sporobolus ioclados	Petroleum hydrocarbons	Heavy metals and saline soils	Soil microbes	Hyperaccumulation	Yasseen 2014; Al-Thani and Yasseen 2020
Stipagrostis plumosa	Petroleum hydrocarbons,	No record	No record	Not specified	Jahantab *et al.* 2018
Suaeda spp.	No record	Cd, Mn, Pb	Soil microbes could have a role	Not specified	Zhang *et al.* 2018
Tamarix spp.	PAHs	Cd, Cu, Fe, Mn, Ni, Pb, Zn	Not specified	Phytoextraction (Heavy metals)	Al-Taisan 2009; Betancur-Galvis *et al.* 2012; Suska-Malawska *et al.* 2019
Tetraena qatarensis	Anthropogenic wastewater	Cd, Cr, Cu, Fe, Ni, Zn	Not specified	Phytoextraction, Phytostabilization	Abdel-Bari *et al.* 2007; Usman *et al.* 2019; Observation by authors*
Typha domingensis	Organic components	Al, As, B, Cd, Co, Cr, Cu, Fe, Hg, Mn, Mo, Ni, Pb, Zn	Soil microbes, Rhizosphere	Phytostabilization, Rhizofiltration, Phytoextraction, Thiol induction & Metal binding	Chandra and Yadav 2010; Yasseen 2014; Bonanno and Cirelli 2017; Anning and Akoto 2018

IWW: Industrial Wastewater, TPHs: Total Petroleum Hydrocarbons, PAHs: Polycyclic Aromatic Hydrocarbons, TOG: Total Oil and Grease. *observation by authors after visiting some wastewater ponds at the outskirts of Doha.

zooplanktons; (8) mutualistic relationship with some living organisms; (9) production of antioxidants; and (10) source of biodiesel (Table 6).

All autotrophic micro-algae at these ponds around Doha city (Tables 2 and 6) have been reported widely to have phycoremediation roles, except *Anacystis* and *Zygnema*; these genera were not shown to have any phycoremediation activities, and further investigation is needed to look at the possibility of having any role in purification of wastewaters at these ponds and at IWW of oil and gas. Among those genera listed in the above tables, two interesting genera, although rarely encountered; need to discuss their roles,

Table 6. Many cyanobacteria and algae thrived at the wastewater habitats to play various ecological roles and phycoremediation actions of pollutants.

Algal species	Main roles at ecosystem	Phycoremediation	References
Anabaena	Produces toxins; dangerous to humans and animals, Nitrogen fixation	Remove heavy metals, and other pollutants	Azarpira *et al.* 2014; David Noel and Rajan 2014, Kaur *et al.* 2018
Chlorella	Protein supplement to the human diet, provide essential nutrients like carotenoids, vitamins, mineral content and oil	Remove nutrients, organic pollutants & heavy metals: B, As	Mamun *et al.* 2012; Mitra *et al.* 2012; Ben Chekroun *et al.* 2014; Bansal *et al.* 2018; Sunday *et al.* 2018; Kaur *et al.* 2018
Chlorogonium	Mutualistic relationship with some toads	Remove pollutants and nutrients	Tumlison and Trauth 2006; Lee *et al.* 2015; https://en.wikipedia.org/wiki/Chlorogonium
Diatoms	Responsible for over 40 % of photosynthesis in the world's oceans, food for zooplankton	Remove nutrients and pollutants from wastewater ponds, Water purification	Marella *et al.* 2016; Marella *et al.* 2020a, b
Euglena	Carrying on photosynthesis,	Remove pollutants, Heavy metals,	Sengar *et al.* 2011; https://en.wikipedia.org/wiki/Euglena
Lyngbya	Produces toxins; result in acute dermatitis with a pruritic rash vesicle formation; skin irritations,	Remediates the pollutants from some industrial effluent	David Noel and Rajan 2014; Sunday *et al.* 2018
Oedogonium	Treat effluents rich in COD, BOD, Fixation of heavy metals in fresh water ecosystems,	Remove heavy metals & dyes,	Gupta and Rastogi 2008; 2009; Tabinda *et al.* 2019; Kaur *et al.* 2018
Oscillatoria	Carrying on photosynthesis, Natural production of butylated hydroxytoluene; an antioxidant, food additive and industrial chemical, .	Remove heavy metals,	Babu and Wu 2008; Sunday *et al.* 2018; Kaur *et al.* 2018
Scenedesmus	Carrying on photosynthesis, provide oxygen for the bacterial breakdown of organic matter and thereby help to destroy other harmful substances, a potential source of biodiesel,	Remove organic pollutants & heavy metals: Cd, Cr, Cu	Peña-Castro *et al.* 2004; Ben Chekroun *et al.* 2014; Ballén-Segura *et al.* 2016; Bansal *et al.* 2018; Sunday *et al.* 2018; Kaur *et al.* 2018 https://www.britannica.com/science/Scenedesmus
Spirogyra	Freshwater inhabitant, source of natural bioactive compounds of medical uses,	Remove heavy metals; As, Cd, Co, Hg, Pb	Nirmal Kumar and Oommen 2012; Kumar *et al.* 2015; Kaur *et al.* 2018
Spirulina	Source of healthy food, Medicinal uses of its products,	Remove heavy metals: As, Hg, Pb, others	Al-Dhabi 2013; Sunday *et al.* 2018; Kaur *et al.* 2018; Seghiri *et al.* 2019

BOD: Biochemical Oxygen Demand, COD: Chemical Oxygen Demand.

these are *Anabaena* spp. (treated pond) and *Spirulina* spp. (untreated pond). *Anabaena* spp. are filamentous plankton cyanobacteria that grow in spirally coiled filaments.

These species occur as toxic water blooms (Rastogi *et al.* 2015), and are colored gray to blue-green or even green when free-floating as in treated ponds. They might produce dangerous alkaloid compounds, which are toxic to animals and humans (https://www.mass.gov/info-details/microcystis-and-anabaena-algae-blooms). This could cause a lot of health problems in nervous and respiratory systems, and even cancer (https://www.sciencedirect.com/topics/earth-and-planetary-sciences/anabaena).

Moreover, Richer *et al.* (2015) have concluded that air-borne neurotoxins produced by cyanobacteria in biological soil crusts might have caused a lot of inhalation difficulties for the people at the desert and military personnel during wars and training. However, these species have efficient nitrogen-fixing abilities, and can form symbiotic relationships with the roots of certain plants, such as *Cycas* and *Azolla* (Ray *et al.* 1978; Van Hove and Lejeune 2002; https://en.m.wikipedia.org/wiki/Anabaena; https://biology-boom.com/anabaena-for-b-s-only-scientific-classification/). *Spirulina*, on the other hand, is a microscopic and filamentous cyanobacterium that has been used as safe, functional food, and it has long been recognized as a dietary supplement since it is an excellent choice when tackling some nutritional issues related to human health (Karkos *et al.* 2011). However, some concerns have been raised, that such cyanobacteria might have a negative impact on such an aquatic system related to the production of neurotoxic substances (https://www.superfoodly.com/spirulina-chlorella-side-effects-benefits/).

Many microbial species are found in these ponds, and the most abundant are coliform bacteria. However, other species are found that might be an indication of pathogenicity and/or as a normal flora (Al-Thani 2002). Some reports concluded the presence of some of these bacteria in the soil contaminated with petroleum hydrocarbons; these include; *Bacillus megaterium*, *Pseudomonas* spp., and *Enterobacter cloacae* (Unpublished data).

Phytoremediation of organic components

The degradation of organic compounds has been addressed actively over the last three decades (Trapp and Karlson 2001), the cooperation of microorganisms (bacteria, fungi, and algae) with plants has resulted into novel successes to degrade and/or remove pollutants of various kinds from the soil, water, and air. In fact, a huge number of articles have discussed the methods and metabolic pathways to detoxify and metabolize these compounds inside plant tissues, and these have been referred to as the Green Liver Model (Sandermann 1994; Burken 2003; Campos *et al.* 2008; Yasseen 2014). Some details of these metabolic pathways were given elsewhere (Al-Thani and Yasseen 2020). However, Table 5 shows the native and aquatic plants at wastewater ponds in Qatar that proved efficient in degrading these organic compounds, and such a list could be useful when scientists and engineers construct Phyto-Engineered Wetlands (PEW). Regarding the degradation of PCBs (Figure 8); as these components are very common at those ponds around Doha city, these compounds can be degraded by some microbes in the soil and/or in the plant tissues (Petruzzelli *et al.* 2012), and some reports have shown that at least four phytoremediation methods and one bioremediation method can transform these compounds into useful metabolites and/or to less toxicity.

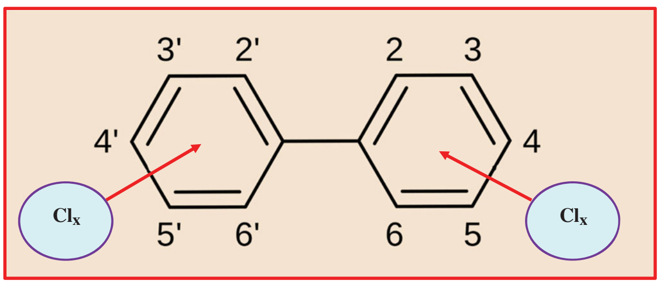

Figure 8. The general structure of PCBs, the number of chlorine atoms varies from one to ten to replace the hydrogen atoms in the biphenyl to give as many as 209 different chemical compounds (Lee and Fletcher 1990).

These methods (phytoextraction, rhizofiltration, phytovolatilization, and phytotransformation) are adopted by many plants, whereas rhizoremediation is used by some associated microbes (Van Aken *et al.* 2010; Yasseen and Al-Thani 2013; Yasseen 2014).

Figure 9 summarizes the role of microorganisms (anaerobic and aerobic bacteria) and possibly fungi and plants in the degradation of PCBs. The first steps are partial removal of some chlorine atoms from one of the rings of biphenyl by the dehalogenase enzyme released from anaerobic bacteria into the contaminated soil or into the aqueous medium around the bacteria. The consequent steps of the biphenyl pathway are catalyzed by series of enzymes released from aerobic bacteria, and the function of enzymes involved has been explained elsewhere (Ohtsubo *et al.* 2004), which end in useful metabolites like succinyl Co-A or acetyl Co-A; the intermediates that play major role in TCA cycle. Other metabolites, however, are formed either of less toxicity

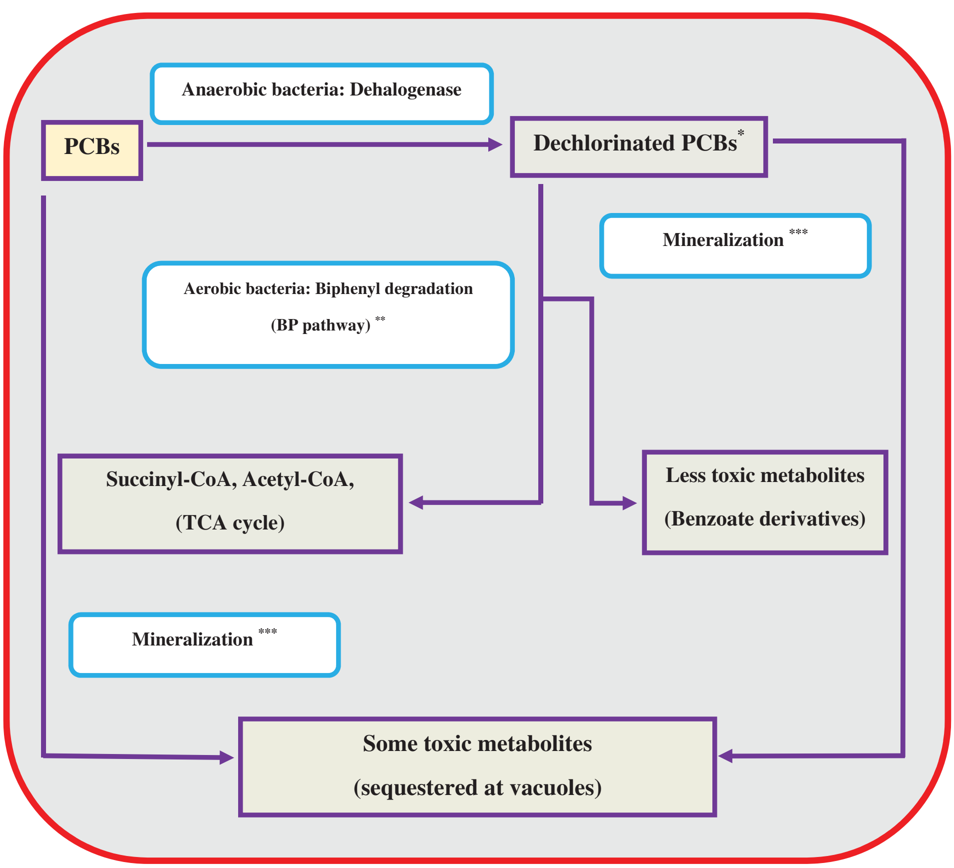

Figure 9. Diagram showing the main pathway for PCBs degradation in microorganisms and plant tissues. *partially, less than 5 Cl atoms, no chlorines in one ring, **BP pathway is series of reactions carried out by a group of aerobic bacteria (like *Pseudomonas* sp. and *Azoarcus evansii*), ***Mineralization in soil science is the decomposition of the chemical compounds in organic matter, by which the nutrients in those compounds are released in soluble inorganic forms that may be available to plants. Also, it is achieved by some microorganisms (fungi) and plants. (https://en.wikipedia.org/wiki/Mineralization_%28biology%29).

(benzoate derivatives) or even toxic compounds with chlorine atoms. The latter compounds might be sequestered at the vacuoles of native plants carrying out phytoremediation actions (Van Aken 2008), as an avoidance mechanism to keep the active machinery sites of the cells away from any negative impact of toxic compounds.

Phytoremediation of inorganic components

Looking at Table 5, most plants at the ponds around Doha city proved efficient in removing heavy metals from aquatic environments of different sources. The heavy metals mentioned above were found in wastewater of anthropogenic activities and also as major components of IWW of oil and gas operations. By surveying the native plants at the Qatari habitats, many aquatic plants or those adapted at aquatic life can be used to remove heavy metals from polluted waters. These plants include: *Amaranthus viridis*, *Cynodon dactylon*, *Juncus rigidus*, *Malva parviflora*, *Phragmites australis*, *Portulaca oleracea*, *Salsola baryosma*, *Tamarix* spp., *Tetraena qatarensis*, and *Typha domingensis*, and other plants with potential to remediate these trace elements also need to be investigated. However, the monitoring system should be activated to avoid high toxic trace elements entering the food chain of humans and domestic animals. Plants at aquatic ecosystems have different abilities, mechanisms, and strategies to deal with heavy metals (Bai *et al.* 2018), and the following are the main variables affecting their accumulation in plant tissues and mobilization around the rhizosphere of plants: (1) plant species (Carvalho and Martin 2001; Prasad and Freitas 2003), (2) presence of microorganisms; such as plant growth-promoting rhizobacteria (PGPR) (Kaushal and Wani 2016; Ma *et al.* 2016), (3) rhizosphere environment (Wenzel 2009; Tangahu *et al.* 2011; Dotaniya and Meena 2015; Guo *et al.* 2019), (4) the concentration of elements, (5) pattern of behavior and mobility of heavy metals (Carvalho and Martin 2001; Jung 2008; Violante *et al.* 2010; Yabanlı *et al.* 2014). However, once heavy metals are available around the environment of the plant's root, there are at least three phytoremediation techniques adopted by plants to deal with excessive levels of toxic heavy metals at the rhizosphere and inside the plant tissues (Tangahu *et al.* 2011).

Methods of phytoremediation

The following mechanisms are adopted by the Qatari aquatic plants, and associated and adjacent microorganisms to achieve the remediation methods; bioremediation, phytoremediation and phycoremediation.

Phytoextraction, this mechanism is often referred to as phytomining (McIntyre 2003; Nkrumah *et al.* 2018). It is the uptake of heavy metals by the root system, and then translocation to the shoot system (stems and leaves). This technique is appropriate for plants with high vegetative biomass and not edible for humans and livestock (Epstein 1983; Van Epps 2006). After harvesting these plants, they can be utilized in gaining energy and for various industrial activities providing that metals in their products are recycled (Lasat 2000; Al-Thani and Yasseen 2020). Using edible plants and crops might put the ecosystem at real risk when these heavy metals enter the food chain, causing a lot of disturbances and disruptions in the ultrastructure of plant tissues and metabolic pathways, respectively (Mehrag 1993; Arif *et al.* 2016; Kumar and Aery 2016). Many plant species listed in Table 5 might be good candidates for such a method, and these included: *Amaranthus viridis*, *Cynodon dactylon*, *Euphorbia granulata*, *Fagonia* spp., *Malva parviflora*, *Phragmites australis*, *Polypogon monspeliensis*, *Portulaca oleracea*, *Solanum* spp., *Tamarix* spp., *Tetraena qatarensis*, and *Typha domingensis*.

Rhizofiltration, this mechanism is similar to phytoextraction. However, it relies on the efficiency of root systems to remove contaminants, especially trace elements. Ideally, water culture and sand culture techniques are the recommended practical methods for plant cultivation using such mechanism. Later on, the method can be exploited widely in fields (Yasseen 2014). Aquatic plants and those that can grow at wetland habitats are good candidates for a rhizofiltration approach. The plants that adopt such a method to clean up wastewater should have a dense root system, high biomass production, and be tolerant to heavy metals. The groundwater or wastewater containing contaminants is pumped on the surface to irrigate the growing plants, and when the roots are saturated with contaminants, they can be harvested and disposed of, or the accumulated metals in the root systems can be extracted and utilized in industry. The most encouraging and promising candidate for such a mechanism is *Typha domingensis* (https://en.wikipedia.org/wiki/Typha_latifolia), and there may be others that have the ability and capacity to accumulate heavy metals at their rhizosphere and inside root tissues. This mechanism has been adopted successfully in many other plants, some species of which are found at the Qatari habitats like *Brassica* spp., *Helianthus annuus* and some grasses (Nanda Kumar *et al.* 1995; Yadav *et al.* 2011; Abubakar *et al.* 2014b).

Phytostabilization is a technique used by plants to immobilize heavy metals, either in the soil or inside the plant root (Ibrahim *et al.* 2013). Normally, plants immobilize heavy metals at the following sites: (1) absorption and accumulation in the root tissues, (2) adsorption onto roots, and (3) precipitation at the rhizosphere zones. Thus, reducing the toxic levels of heavy metals in the soil can be achieved either by taking up and accumulating them in the roots, providing that the transport of these metals from the root system (underground) to the shoot system (aboveground) is at the lowest rate (McGrath and Zhao 2003; Yabanlı *et al.* 2014), or these heavy metals are insolubilized (stabilized) in the soil after some exudates are secreted from the plant roots and/or from microorganisms, such as bacteria, to prevent their uptake and protect and keep the food chain away from their toxic impacts (Chen *et al.* 2017; Mishra *et al.* 2017). Early reports (Jing *et al.* 2007) have concluded that bacteria at the rhizosphere might affect the trace elements mobility and availability by releasing some chemicals and agents causing changes in redox and soil characteristics, such as acidification and phosphate solubilization, thereby enhancing the phytoremediation processes. This technique is appropriate for leafy vegetables and fruit plants, as their leaves and fruits are edible and suitable for the consumption of man and livestock.

Phytovolatilization is another technique adopted by plants to clean soils and waters from contaminants. The absorbed organic and inorganic substances are transformed into less toxic components and then volatilized through the transpiration stream. Few studies have been done to recognize heavy metals that are volatilized by native plants, at least three heavy metals [Arsenic (As), Mercury (Hg), and Selenium (Se)] were found converted to gaseous species within the plant and released into the atmosphere (Terry *et al.* 2000; Carvalho and Martin 2001; Sakakibara *et al.* 2007; Tangahu *et al.* 2011; Yasseen 2014; Muthusaravanan *et al.* 2018). IWW produced from industrial gas activities, that is rich of As and Hg, could be purified using some aquatic native plants such as: *Amaranthus viridis*, *Cynodon dactylon*, *Juncus rigidus*, *Phragmites australis*, *Polypogon monspeliensis*, *Portulaca oleracea*, and *Typha domingensis*. These plants proved efficient in phytoremediation of both elements or at least either of them, and they might use the volatilization technique to phytoremediate IWW and providing that monitoring system is active since some of these plants are edible at livestock. Other aquatic plants listed in Table 5 could be appropriate for IWW of industrial oil and anthropogenic activities.

Phytotransformation, on the other hand, is one of the main mechanisms carried out by many plants to degrade organic compounds into simpler or useful metabolites. The organic contaminants are absorbed and/or metabolized externally or internally. Externally, such actions might take place after plants secrete some metabolites to boost the growth of the associated microorganisms; which carry out the degradation processes, or, the plant exudates contain a mixture of enzymes that catalyze the breaking down of these components. If the degradation was partial, the small units then absorbed by plants and become part of the plant metabolism as it grows, and in the end, they become incorporated into the plant tissues (Al-Thani and Yasseen 2020). Internally, the absorption of organic components depends upon the molecular weight; low molecular weights can be easily accessed, while the high molecular weight compounds can enter by adherence mechanism, which described elsewhere (Singh *et al.* 2012). Some reports have discussed the metabolic pathways of degradation of organic components of oil and gas activities (Sandermann 1994; Kvesitadze *et al.* 2009; Ndimele 2010). Some plants among the flora of Qatar might be good candidates for such a mechanism; these include *Cynodon dactylon*, *Cyperus conglomeratus*, and *Typha domingensis* (Mustapha *et al.* 2018). Other native aquatic plant species might be involved in such methods, such as *Phragmites australis* (unpublished data).

At a wide practical scale, much preparations are required for a successful method, and these include the following: (1) the economic feasibility, (2) the financial capabilities, (3) the goodwill of decision-makers and scientists, (4) the candidates of plants, and the microorganisms to support the plants, and (5) adopting modern biotechnology to improve the efficiency of the existing aquatic plants and introduce transgenic plants proved efficient in rhizofiltration (Yan *et al.* 2020).

Possible modern and innovative approaches

The time has come for utilizing phytoremediation techniques at such a huge volume of IWW to remove heavy metals and to degrade and metabolize organic components. So, instead of continuing pumping and dumping such wastewater deep in the earth and exposing the groundwater to pollution risks, new strategies are being implemented by adopting innovative methods and modern biotechnologies in treating wastewater. Here, one important approach is the use of transgenic aquatic plants, algae, and bacteria to remove toxic and environmentally damaging organic and inorganic ingredients, and convert them into beneficial materials and purify the ecosystem from any dangerous agents (Yasseen 2014; Yan *et al.* 2020). The following discussion is dedicated to looking at the measures that should be taken into account when dealing with the current strategies and remediation approaches at the engineered wetlands: (1) the basic information is the first practical step; the chemical and physical analyses should be done to determine the quality and quantity of pollutants at wastewater ponds; the follow-up of such water bodies by monitoring any changes in these parameters can be considered as a prerequisite for successful ecological restoration and maintaining healthy environment (Yasseen and Al-Thani 2013). Recent assessments have suggested that pollution is predicted to worsen by time, a situation that might have a great threat on health, the economy, and wildlife (Elobaid *et al.* 2018; Al-Thani and Yasseen 2020); (2) careful selection of the appropriate remediators (microorganisms: algae, fungi, and bacteria); and plants (a remediator: any living organism that can be used in remediation), which means that the selected organism should be active and efficient in dealing with particular contaminants (Alkorta *et al.* 2004). For example, *Amaranthus viridis*, *Phragmites australis*, *Typha domingensis*, and perhaps others, can be used in phytoremediation of wastewater produced from gas fields, as these native plants are good candidates for remediating As and Hg metals; the elements found abundantly in the wastewater of gas activities (Table 5). So, because of such high content of these two very toxic metals at gas wastewater; it was estimated that such wastewater is ten-times more toxic than that discharged from oil activities (Jacobs *et al.* 1992; Veil *et al.* 2004). Other native and aquatic plants, and even crops could be used successfully to remediate wastewater from other sources, such as anthropogenic activities and from other sources, including those at oil fields (Al-Thani and Yasseen 2020; Yan *et al.* 2020); (3) the bio-remediators (plants, algae) contributed at phytoremediation and phycoremediation methods should be harvested and then involved in various industrial and agrobiotechnology activities as shown in Figure 10, thereby, heavy metals and any other toxic components are recycled

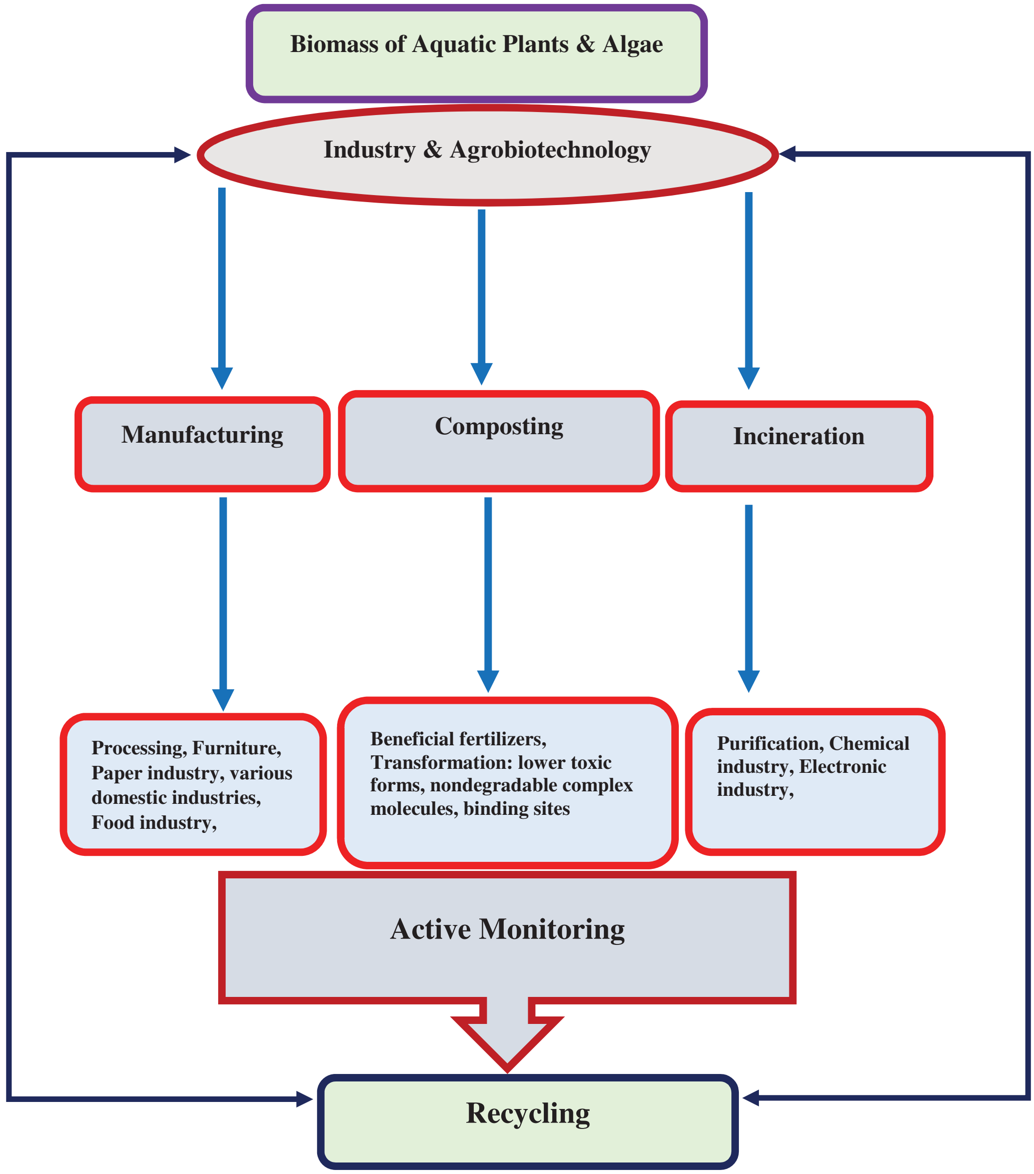

Figure 10. Industrial and Agrobiotechnological activities of bio-remediators followed by monitoring and recycling.

to keep them away from the food chain and ultimately maintaining the safety of ecosystem (Alkorta *et al.* 2004; Mudgal *et al.* 2010; Badr *et al.* 2012; Al-Thani and Yasseen 2020); (4) monitoring the whole system: water, living organisms (e.g., plants and algae) and any changes in environmental conditions and the chemical contents of remediators involved. Monitoring is a long term follow up program to ensure the success of any project (Al-Ansi *et al.* 2004), and such measures have been defined as collecting and analyzing data to make the required assessment and might involve modification in the plans and to conduct further amendments to solve any emerged problems (Yasseen and Al-Thani 2013; Davis 2017).

The outcomes of monitoring processes should be forwarded to the scientists and decision-makers to make further manipulations and measures to reach the solutions of the emerging problems and ensure the success of the whole remediation processes; (5) cultivation of inedible plants as the first option. Otherwise, the monitoring system must be sustainable and applicable (Al-Thani and Yasseen 2020); (6) continuous research in modern biotechnology and genetic engineering to develop active remediators to deal with the continuous accumulation of heavy metals and organic compounds.

Environmental pollution has emerged as a real and strong abiotic threat to the ecosystem in the modern industrialization era; a situation that needs contemporary and innovative approaches to reach successful solutions, and to eliminate pollutants of various kinds. Modern biotechnological techniques have topped up to develop transgenic plants and microorganisms to increase the efficiency and capacity to remediate contaminated soils, waters, and air. Unlike petroleum hydrocarbons and other organic components, heavy metal pollutants are immutable and do not degrade. Almost all organic compounds can be metabolized inside the plant tissues. Otherwise, microorganisms (algae, bacteria, fungi) can degrade these compounds in soils and waters. These organisms have different abilities to deal with pollutants, and the identification of efficient remediators is the first choice, followed by the monitoring system and recycling programs. However, three options to solve the problems of environmental stresses have been introduced in the last four decades; to increase the efficiency of plants, algae, and bacteria to remediate polluted soils and waters.

Environmental approach

Environmental manipulation has been considered as a traditional approach; this means changing the environment to become clean and suitable for humans, agriculture, and wildlife. Such approaches include techniques to enhance phytoremediation, such as the application of fertilizers and/or manures, surfactants, and tillage to the contaminated soils, while other methods cover natural attenuation and engineering techniques (Frick *et al.* 1999). In fact, the environmental approach strategy, in general, is based on the implementation of large scheme of: (a) irrigation with high -quality water, (b) conservation of existing agricultural lands, (c) reclamation methods such as constructing good drainage systems, (d) application of supplementary irrigation in lands of uncertain rainfall and not guaranteed, (e) conventional methods of soil remediation include digging through the contaminated soils (saline or/and polluted soils and waters), and remove the contaminants mechanically and transfer them to another sites. However, most of these methods have many drawbacks in terms of the applicability techniques, financial cost, ineffective, time consuming, and not guaranteed success (Liu *et al.* 2015; https://esemag.com/hazmat-remediation/heavy-metals-remediation/). Moreover, the soil after reclamation needs a lot of care and the treatment with fertilizers, especially those with high salinity levels. Thus, all the measures of the environmental approach might not be a workable and applicable option at Qatar lands and other countries at the Arabian Gulf region (Vidali 2001; DOE U. S. Department of Energy 2003; Van Epps 2006; Yasseen 2014; Al-Thani and Yasseen 2018a).

Genetic approach

Manipulating the genetic code of plants (e.g., crops) and associated microorganisms have been considered as a future solution and to ease of the adverse impact of environmental stresses over the last five decades. Increasing crop production horizontally as well as vertically, is the main challenge facing mankind under severe drought and salinity. FAO estimates that an additional 200 million hectares of new cropland will be needed over the coming 10 years just to feed the new generations at tropics and subtropics. Finding a genuine solution to pollution problems is not too far from such an approach, methods of genetic manipulation have been introduced during the last ten years. This approach covered conventional breeding methods, such as the selection of desired traits and classic hybridization, though limited success has been achieved (Alkorta *et al.* 2004), and modern biotechnology and genetic engineering programs that have been considered as promising and more advanced methods, tissue culture technique was recognized as a prerequisite for those programs (Czakó *et al.* 2005). In fact, this technique has been used for two main purposes: (1) physiological studies, and (2) selection of lines. As far as pollution with IWW is concerned, studying physiological activities using the tissue culture technique could fulfill two main objectives: (a) more understanding at the mechanisms and metabolic activities related to the pollution stress and resistance of biotic and abiotic factors apart of the complexities and interferences at the whole plant level. This technique could be a successful approach for many physiological studies especially studying the signaling and biochemical pathways involved in the re-toxification of pollutants and resistance of plants to various types of stresses (Svoboda and Reenstra 2002; Hussain *et al.* 2012), (b) identification of traits, genes, and proteins at the cell levels for further follow up of modern research to develop transgenic plants with new traits to deal with particular environmental stress (e.g., heavy metals, petroleum hydrocarbons). The selection of lines, on the other hand, involves the development of transgenic plants after genetic engineering techniques have succeeded in inserting the desired gene (s) in the target plants. The selected lines are presumed to be genetic variants that, upon regeneration, the new living organism will express the selected characteristics and provide genetic material for improvement programs. Thus, tissue culture techniques offer many advantages: (1) all the cells at the tissue culture are exposed to same environmental conditions, (2) dismiss all the responses except those at the cell levels, (3) control the physical and environmental parameters, and the nutritional levels, (4) all cells at the tissue culture are genetically uniform, by regeneration they produce organized growth models, and the physiological and biochemical changes in response to pollution stress are purely associated with these cells, and (5) different cell patterns having different responses to pollution can be isolated for experimental comparisons. However, not all the trials and attempts have been successful, as there are some setbacks that need to be solved (Yan *et al.* 2020). For example, many physiological and metabolic activities found in the whole plant; like photosynthesis, transpiration, water absorption, ion transport and metabolism, gas exchange, and growth processes, cannot be portrayed when working using culture cells as test material. This is a major disadvantage, since the life of the whole plant is more complex than individual cells. However, Doran (2009) discussed the advantages and restrictions of using tissue culture techniques in phytoremediation activities, and offered a critical assessment of the applications and perspectives of such technique instead of whole plants in the research programs. The author has confirmed the arguments we put forward above, and concluded that trials using plant tissue cultures play an important role in phytoremediation research, as well as understanding the metabolic pathways of various types of pollutants. In fact, when a chemical is metabolized by individual plant cells, this is a clear indication that the parent plant has the ability to bio-transform such compounds. Moreover, tissue culture methods are a valuable approach when inserting the desired phytoremediation genes into

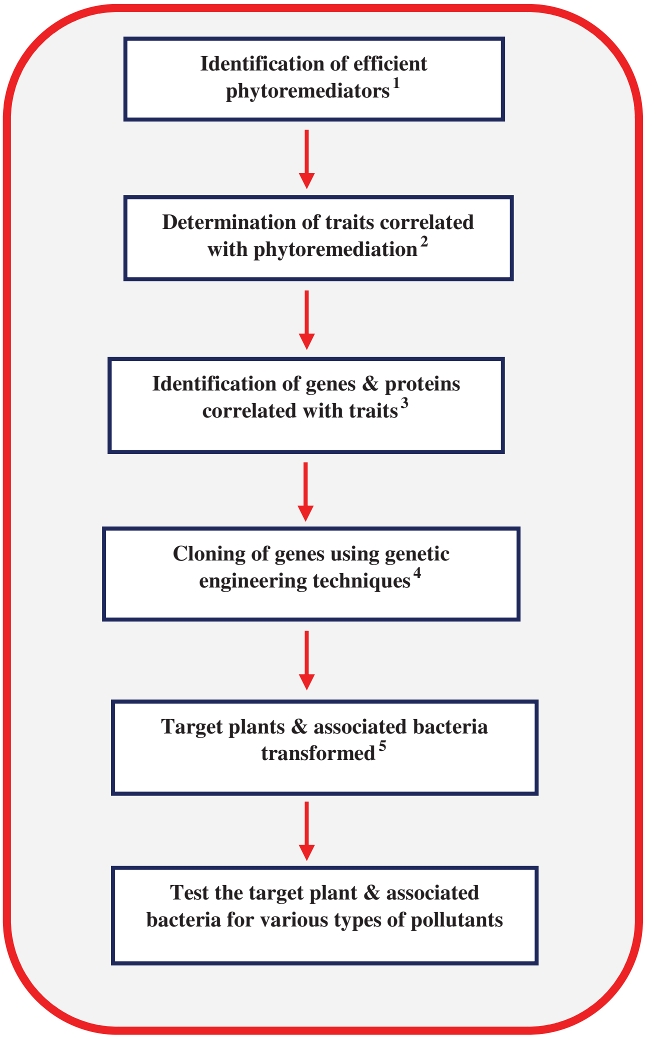

Figure 11. Modified theoretical diagram showing genetic engineering programs of aquatic plants and associated bacteria to remediate IWW.
[1]**: Plants:** Amaranthus viridis, Cynodon dactylon, Juncus rigidus, Phragmites australis, Polypogon monspeliensis, Portulaca oleracea, Typha domingensis, and possibly others. **Bacteria:** Gram-negative bacteria: Aeromonas hydrophilia, Pseudomonas aeruginosa, Klebsiella pneumoniae, Chromobacterium violaceum, Gram-positive bacteria: Streptomyces spp., Bacillus spp., and Macrococcus sp., and possibly others. **References:** Al-Qurainy and Abdel-Megeed 2009.
[2]**: Traits:** Biomass production, Well-developed roots, High growth rates, Highly-branched root system, Leaf greenness, Chlorophyll fluorescence, Non-consumable (non-edible), Easy harvestability, Resistant to metal accumulation, Accumulation of heavy metals, Metabolize petroleum hydrocarbons, Nitrate and phosphate removal, etc. **References:** Al-Qurainy and Abdel-Megeed 2009; Chen *et al.* 2019; https://www.drdarrinlew.us/metal-contaminated/characteristics-of-plants-used-for-phytoremediation-of-heavy-metals.html.
[3]**: Genes and Proteins, References:** Fulekar *et al.* 2009; Mudgal *et al.* 2010; Singh *et al.* 2012; Liu *et al.* 2015.
[4]: **Genetic engineering, References:** Kärenlampi *et al.* 2000; Ruiz *et al.* 2003; Alkorta *et al.* 2004; Mudgal *et al.* 2010; Van Aken *et al.* 2010; Azad *et al.* 2014; Yan *et al.* 2020.
[5]: **Transformation, References:** Gratão *et al.* 2005; Fulekar *et al.* 2009; Van Aken *et al.* 2010; Ben Chekroun and Baghour 2013; Yan *et al.* 2020.

target plant tissue, the callus, and then the developed transgenic plants might have great efficacity to remediate pollutants. Serious programs to develop transgenic phytoremediator plants and associated bacteria started in the last decade, the theoretical background was suggested by many authors, and Figure 11 shows a modified theoretical diagram for such programs.

Most of the native plants and the associated microbes reported at the ponds around Doha city are good candidates for modern biotechnology to develop transgenic plants and bacteria to remediate heavy metals and metabolize petroleum hydrocarbons (Yasseen 2014; Liu *et al.* 2015; Al-Thani and Yasseen 2018a, 2020; unpublished data).

Biological approach

A third approach has emerged over the past decade to solve the problems of pollution with heavy metals and organic components of wastewater of various sources. Recent works (Glick 2014; Hanin *et al.* 2016; Al-Thani and Yasseen 2018a, 2018b, 2020; Yan *et al.* 2020) have suggested such an approach as an environmentally friendly biological solution for many problems facing the ecosystem and human life in health, agriculture, and economy. Some important facts have emerged from the huge number of published articles about the cooperation between plants and associated microbes in dealing with harsh environmental issues: (1) Efficient phytoremediation actions always come from the cooperation of plants and associated microorganisms by beneficial interactions (Yasseen and Al-Thani 2013; Singh *et al.* 2016; Ojuederie and Babalola 2017), as such combined actions could confer adaptability to harsh environments of drought, salinity, and possibly pollution stresses (Al-Qurainy and Abdel-Megeed 2009; Yasseen *et al.* 2018); (2) Many mechanisms have been adopted by microorganisms to mitigate harsh abiotic stresses facing plants in general and crops in particular, the details of these mechanisms were discussed recently by Al-Thani and Yasseen (2018a); (3) Horizontal gene transfer (HGT) is possible between microorganisms and plants, this could lead to mutual beneficial activities and boosts the ecosystem to deal with harsh environment (Rosewich and Kistler 2000; Bode and Müller 2003; Al-Thani and Yasseen 2018b); (4) Plants might secrete exudates at the rhizosphere to stimulate and accelerate some metabolic pathways in microorganisms leading to degradation of petroleum hydrocarbons and/or immobilization of heavy metals (Chen *et al.* 2017; Mishra *et al.* 2017; Jin *et al.* 2019); (5) Modern biotechnology could improve, develop, and create transgenic microorganisms and plants to deal with polluted soils and waters (Kärenlampi *et al.* 2000; Ruiz *et al.* 2003; Gratão *et al.* 2005; Fulekar *et al.* 2009; Van Aken *et al.* 2010; Zeraatkar *et al.* 2016; Ojuederie and Babalola 2017).

Conclusion

On the path of finding a solution to the problem of water scarcity in countries suffering from desertification, such as the Arabian Gulf states; which are also rich in oil and gas resources. The current review discussed the promising perspectives of taking advantage of industrial wastewaters by adopting modern and innovative scientific means to get rid of pollutants in all their organic and inorganic forms. Also, by utilizing of the genetic bank of wild plants and their associated microorganisms and by adopting the scientific approaches to develop transgenic organisms, it is possible to increasing their efficiency in removing and/or metabolizing of these pollutants and producing quality water. Moreover, these activities reinforce the State's aspirations to develop and restore arid lands into green spaces creating new esthetic areas in the middle of the desert, and more importantly, to provide appropriate alternative water sources at conditions many countries are exposed, in terms of water scarcity for human uses and agricultural activities, and in anticipation of dangers that might result from unseen threats. These efforts cannot be completed without financial support of the governments and the aspirations of scholars and decision-makers.

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