Review

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Review

Phycoremediation and Cyanoremediation of Polluted Seawater in the Arabian Gulf and Associated Risks to Human Health

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Abstract: Cyanobacteria play a crucial role in marine ecosystems as primary producers of food and oxygen for various organisms while helping remove waste and toxic substances from the environment. They are essential to the carbon cycle and help regulate the climate. These marine autotrophs also aid in the absorption of essential elements and support diverse life forms. They help degrade organic compounds including petroleum hydrocarbons as well as heavy metals. Fluctuations in cyanobacteria populations can indicate ecosystem health, influencing both human well-being and wildlife. Their significance also extends to potential technological advancements, thus providing valuable resources for fields such as pharmacology, medicine, health care, biofuels, cosmetics, and bioremediation. However, some species produce toxins that pose risks to human health and marine organisms. Consequently, cyanobacteria are a major focus of research aimed at preserving and improving marine ecosystems-especially given the environmental damage caused by past and potential future conflicts. This review highlights their roles in phycoremediation and other industrial and biotechnological applications with a particular focus on the Arabian Gulf region.

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1. Introduction

Plankton are living organisms found in the sea and other large bodies of water drifting with the currents. They are generally divided into two main groups: phytoplankton and zooplankton. Phytoplankton include a variety of organisms such as cyanobacteria (blue-green algae), microscopic green algae (Chlorophyta), diatoms, dinoflagellates, coccolithophores, and cryptophytes. In contrast, zooplankton are heterotrophic and consist of small crustaceans, protozoans, other microscopic organisms, and the larval stages of larger animals like fish and jellyfish. Phytoplankton are photosynthetic and thus they are typically found in the

Upper layers of marine and freshwater environments. However, only a few studies have examined phytoplankton diversity along the coastal waters and pools of the Rawdahs in Qatar. Cyanobacteria inhabit a wide range of aquatic environments including freshwater pools, brackish water, sewage from human activities, and seawater in the Arabian Gulf [1–4]. Certain cyanobacteria genera-such as *Anabaena*, *Anacystis*, *Lyngbya*, *Oscillatoria*, and *Spirulina*-can indicate environmental quality, especially in polluted areas. This article focuses primarily on cyanobacteria and explores their roles in remediating petroleum hydrocarbons, heavy metals, nitrogen fixation, industrial biotechnological applications, health issues, and their contributions to bloom formation.

1.1. Roles of Phytoplankton in Marine and Freshwater Ecosystems

The roles of these autotrophs have been well-documented in many studies, reports, and monographs as follows: First, phytoplankton are primary producers and perform photosynthesis to

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generate organic matter. During this process, CO_2, water, and nutrients are converted into carbohydrates, oxygen (O_2), and other essential organic compounds. These compounds serve as the primary food source for most zooplankton, which in turn supports higher trophic levels including fish, mammals, and other heterotrophs [5,6]. The oxygen produced by phytoplankton is also crucial for sustaining life, not only in seawater but also globally [7]. Second, phytoplankton help maintain the global carbon cycle; CO_2 is absorbed by marine autotrophs to synthesize organic matter, which becomes embedded in the ocean floor after these organisms die. This process helps maintain the carbon balance and regulate the global climate [8]. Third, phytoplankton are involved in nutrient cycling in the marine environment. Phytoplankton absorb essential elements such as nitrogen and phosphorus, which becomes part of their biomass. This biomass is then consumed by heterotrophic organisms. After these organisms die, the nutrients are released back into the seawater and become available for other marine life [9]. Fourth, these organisms are a good source of food for a variety of marine heterotrophic organisms such as zooplankton, small fish, and even large whales. Therefore, the health of phytoplankton has a direct effect on these organisms and the overall productivity of the marine ecosystem [10,11]. Fifth, these phytoplankton influence climate change by producing chemicals such as dimethyl sulfide, which lead to the formation of clouds. These clouds can reduce the amount of sunlight reaching the surface of seawater, affecting temperature and climate patterns [12]. Sixth, phytoplankton are adapted to a variety of environmental conditions, and thus they can support diverse marine ecosystems and enhance their resilience [13–15]. Seventh, these marine autotrophs might be used as indicators of environmental conditions. Many factors can affect phytoplankton such as temperature, light, nutrients, and pollution. Thus, changes in phytoplankton populations might be a consequence of changes in environmental conditions. Therefore, shifts in phytoplankton populations can be considered indicators of the health of the ecosystem [5,16]. Finally, phytoplankton are sources of useful compounds used in medicine and pharmacology. Recent findings revealed that phytoplankton are sources of bioactive substances and secondary metabolites, including toxins, which can be valuable to pharmaceutical, nutraceutical, and biotechnological industries [17].

1.2. Disadvantages of Phytoplankton

Despite their roles in maintaining the marine ecosystem and sustaining marine life, phytoplankton face numerous threats and can sometimes have negative impacts on the ecosystem. While phytoplankton provide many benefits, such as producing oxygen and serving as a primary food source, they can also have negative effects, i.e., harmful algal blooms. In fact, phytoplankton might have negative impacts under certain environmental conditions. For example, some algae such as dinoflagellates and cyanobacteria can proliferate and lead to harmful blooms. These blooms produce toxins that are harmful to marine life, humans, and other marine animals such as fish and shellfish [18,19]. Oxygen depletion can also occur when dead phytoplankton decompose-this process consumes significant amounts of oxygen. As a result, oxygen levels in seawater can become very low (hypoxia), thus creating 'dead zones' where there is insufficient oxygen to sustain fish, shellfish, corals, and other aquatic organisms [20–22]. The dense presence of phytoplankton in the sea can also affect water quality and clarity, thus potentially impacting other photoautotrophs such as seagrasses and seaweeds. These organisms may decrease water transparency, which in turn affects the penetration of visible light that supports photosynthesis and ultimately influences the growth of marine autotrophs [23], this ultimately decreases marine biodiversity [24,25]. Furthermore, the presence of phytoplankton in seawater, oceans, and other bodies of water can either mitigate climate change or exacerbate its effects depending on variations in temperature, salinity, and other environmental factors [26]. While the positive roles of phytoplankton have been discussed above, their negative impacts can result from temperature changes that disrupt the recycling of nutrients from deep water to the surface. The greenhouse effect might negatively impact phytoplankton productivity, partly due to the increase in sea surface temperature. A decline in phytoplankton can lead to higher levels of CO_2 in the atmosphere, thus exacerbating the greenhouse effect and worsening climate change. In contrast, an overabundance of phytoplankton can cause blooms that reduce sunlight and oxygen penetration in the water, thus disrupting aquatic ecosystems [27].

The impact of phytoplankton on the economy and human life is another negative factor that requires attention. Harmful algal blooms can adversely affect fisheries and water treatment facilities- particularly in countries that rely on seawater for their livelihoods such as the Arab countries in the Arabian Gulf region. For example, toxins produced by certain phytoplankton species can cause the closure of shellfish beds, thus leading to economic losses. Furthermore, the Arabian Gulf States have recently initiated programs to store water in strategic reservoirs for use during crises and emergencies. Allowing phytoplankton to thrive could compromise seawater desalination and the treatment of industrial wastewater [28] because these phytoplankton might negatively impact desalination [4,28–30]. The Government of Qatar has started a precautionary program that stores water in strategic reservoirs for use during crises and emergencies [28].

2. Methods and Mechanisms of Phycoremediation

Phytoplankton including cyanobacteria can remediate seawater from pollutants, e.g., heavy metals and organic components such as petroleum hydrocarbons [31–33]. The following are the most common methods and mechanisms reported for phycoremediation: First, Extracellular polymeric substances (EPSs) are high-molecular-weight natural polymers secreted by various microorganisms, including microalgae. These polymers are produced through the metabolic activity of complex biological communities known as biofilms, which form protective layers around these microorganisms [34]. EPSs, along with biofilms, play a crucial role in enhancing the resilience of native plants and crops by providing protection against environmental stresses, including drought and salt stress [35,36]. EPS can degrade persistent organic pollutants via complexation [37]. Second, extracellular biosorption is the ability of biological materials to accumulate heavy metals from wastewater through metabolic and/or non-metabolic pathways or as a property of certain types of inactive microbial materials [38]. Third, intracellular bioaccumulation is a metabolic mechanism in which intracellular accumulation of metalloids such as antimony, arsenic, boron, and silicon occur through passive or active transport channels across plasma membranes using metabolic energy [39,40]. Fourth, compartmentalization refers to the separation of the cell's protoplast into distinct compartments, which contain compounds or heavy metals that could potentially damage the cell's active machinery. This separation helps protect the cell by isolating harmful substances and preventing their negative effects. Algal cells may use a similar method to avoid the harmful impacts of heavy metals or toxic organic compounds. Some algae species may compartmentalize heavy metals from the cytoplasm into vacuoles and cell walls. Certain transporters at the plasma membrane regulate the movement of heavy metals and facilitate their transport into vacuoles, thus preventing them from interfering with key cellular components such as chloroplasts, mitochondria, and the nucleus. This mechanism is an important strategy for reducing environmental stress including petroleum hydrocarbons and heavy metals [41,42]. Fifth, biomethylation occurs in living organisms when a methyl group is attached to one or two heavy atoms through a carbon atom. This process refers to the formation of volatile and non-volatile methylated compounds of metals and metalloids [43]. Sixth, **enzymatic reduction** can be employed by various living organisms, such as microalgae, to mitigate negative impacts on human health [32]. Notably, some organic compounds produced or used during industrial processes may have toxic, carcinogenic, or mutagenic effects. Several methods such as membrane filtration, ion exchange, photochemical oxidation, and nanotechnological approaches can be used to address these concerns. Living organisms including microalgae may play a role in enzymatic processes through the action of enzymes like reductases [44]. Seventh, volatilization is the process of converting a chemical substance from a solid or liquid state into a gaseous or vapor state. Yan et al. [45] briefly discussed this mechanism and noted that many plants can convert elements such as arsenic (As), mercury (Hg), sulfur (S), and selenium (Se) into gaseous forms and release them into the air through transpiration. Phytoplankton including micro-algae can also carry out this mechanism [46,47]. During the last five years, studies suggested that some Qatari

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native plants can volatilize these elements from polluted soils because these elements are very common in the industrial wastewater of gas activities [4,48,49].

3. Biodiversity and Functions of Cyanobacteria

The Arabian Gulf (also known as the Gulf) is a semi-enclosed sea bordered by eight countries: Iran, the United Arab Emirates, the Kingdom of Saudi Arabia, Qatar, Kuwait, Iraq, Oman, and the Kingdom of Bahrain (Figure 1). Six species of benthic algae were first reported in the mid-nineteenth century with additional reports in the 20th century and beyond including those by John and Al-Thani [50]. Notably, data from many studies [4,51–53] using general morphology, microscopic examinations, and modern techniques revealed 17 cyanobacteria (blue-green algae) genera.

Figure 1. Map of the Arabian Gulf region and its bordering countries.

Further discussions will explore the potential roles of these genera in the phycoremediation of oil and gas components as well as other pollutants resulting from anthropogenic activities. The monograph by Rizk et al. [52] reported only two cyanobacteria genera with four species in the Arabian Gulf near the Qatari peninsula: *Calothrix* spp., and *Oscillatoria* spp. However, in 1986, Dorgham and Al-Muftah [51] identified 11 species, and the current number of cyanobacteria species recorded in the seawaters around Qatar has since increased to 26 species. This rise is attributed to the identification of additional species in seawater, brackish water pools, and industrial wastewater of anthropogenic origin. The increase was noted in studies by Al-Khelaifi [53] and Al-Muftah [54] as shown in Table 1.

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Table 1. Cyanobacteria species found at the coastal line of Qatari peninsula, features, and roles.

Species	Family	Features	Roles	References
Amphanizomenon sp.	Aphanizomenonaceae	Unicellular organisms that consolidate into linear (non-branching) chains called trichomes. Inhabits freshwater lakes and can cause dense blooms	Fixes nitrogen, remediates petroleum hydrocarbons, produces anticancer agents, and develops blooms; produces toxic metabolites such as hepatotoxins, neurotoxins, and cytotoxins	[55–57]
Anabaena spp. (2 species)	Nostocaceae	Found in all types of water, including rivers, streams, lakes, and ponds; filamentous, cylindrical, barrel-shaped, or spherical	Fixes nitrogen, remediate crude oil, water extracts have anticancer activity against breast cancer, forms symbiotic relationships with some plants; produces neurotoxins; forms blooms	[58–60]
Calothrix spp. (3 species)	Rivulariaceae	Found in marine, fresh waters, and terrestrial environments; grow in high-salinity conditions, and form relationships with the roots of plants like rice, tomato, and wheat. Form a black, slick surface on rocks and mud and produce a gelatinous outer layer to prevent drying	Fixes nitrogen possible remediation of industrial wastewater, Calothrixins are produced; used to cure many diseases including cytotoxicity in cancer; *Aplysiatoxins might be produced that cause serious health issues including* various dermatitis and promoting tumors	[61,62]
Chroococcus sp.	Chroococcaceae	Unicellular ovoid or rod-shaped	Uses large amounts of atmospheric CO_2	[63–65]

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Species	Family	Features	Roles	References
		organisms, irregular to roughly spherical in shape, forming colonies with gelatinous texture, found in water reserves.	for photosynthesis; produces O_2. These were some of the first organisms to use water as source of electrons and hydrogens for photosynthesis which enables the evolution of other organisms Remediation of polluted water and soil is very possible; do not fix nitrogenand might produce anticancer agents.	
Croococcidiopsis sp.	Chroococcidiopsidaceae	Unicellular with survival in extreme environments; salinity and desiccation, high antioxidant, develop thick mucilage envelopes.	Fixes nitrogen, it resists very extreme environments (e.g. endurance to a Mars-like environment), phycoremedes wastewater and contaminated soil, might be used as food and oxygen producers at the space; Mars as example,	[66–68]
Dermocarpella sp.	Dermocarpellaceae	Gram-negative, thickened ovoid aggregate uniquely exhibits polarity; motile baeocytes result from multiple fission of apical cell; undergo binary and multiple fission	Needs to be tested for nitrogen fixation, might have toxic impact at the ecosystem. Possible role in phycoremediation	[53,69,70]
Euhalothece sp.	Cyanobacteriaceae	Unicellular, halophilic, not pathogenic, not known to produce toxins. High concentration of mycosporine-like	Needs to be tested for nitrogen fixation; primary producer in hypersaline environments; strong antioxidant and some oxidant	[70,71]

		amino acids, carotenoid-binding proteins, and C-phycocyanin subunits	compounds protect its cellular machinery from UV-induced oxidative stress; it has β-car. and Zea-dependent ROS scavenging systems to help cells cope with salt stress, helps in biotechnology applications; possible role in phycoremediation	
Geitlerinema sp.	Coleofasciculaceae	Filamentous, thin, delicate thallus, bright blue-green, violet or brown; has motile trichomes, active oxygenic and anoxygenic, rich in proteins and phycobiliproteins, contains polyphosphates, starch, and carboxysomes	Fixes nitrogen, oxygenic and anoxygenic photosynthetic capabilities, biomass feedstock, produce biofuels, produce pro-inflammatory cytokines and adhesion molecules, develop glucocorticoid-resistant asthma, increase the phagocytic ability of monocytes, possible role in phycoremediation	[70,72,73]
Geminocystis sp.	Geminocystaceae	Small, spherical cells, found in colonies, photosynthetically adapted to aquatic environments, can be found in freshwater ecosystem	Needs to be tested for nitrogen fixation, can adjust the wavelengths of light they absorb by remodeling photosynthetic antenna-possible role in phycoremediation	[71,74]
Lyngbya sp.	Oscillatoriaceae	Filamentous, non-branched or pseudo-branched; macroscopic layered or stratified and brownish-colored sheaths; musty or foul odor, cell division occurs crosswise with reproduction by	Fixes nitrogen, rich source of marine natural products; produces extracellular sunscreen scytonemin, indole alkaloid, source of food of some grass carp, forming	[75,76]

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Species	Family	Features	Roles	References
		hormogonium formation; found in high alkaline water	blooms, possible remediation of heavy metals, petroleum hydrocarbons	
Leptolyngbya sp.	Lyptolyngbyaceae	Filamentous cells divide by symmetrical crosswise binary fission, produce hormogonia, tolerate severe environmental conditions, have antioxidant activity, scavenge free radicals, act as an iron-chelating agent; applications in food and pharmaceuticals; high in lipids	Some species fix nitrogen, phycoremediation of contaminated of water and soil, phycoremediation petroleum hydrocarbons	[77–79]
Merismopedia sp.	Microcystaceae	Found in fresh and salt water, ovoid or spherical, arranged in rows and flats, forming rectangular colonies held together by a mucilaginous matrix; non-nitrogen fixing bacteria	Not fixing nitrogen; remediation efficiency needs to be tested; produces lipopolysaccharides; can cause skin irritation and gastrointestinal distress	[80]
Species	**Family**	**Features**	**Roles**	**References**
Microcystis wesenbergii	Microcystaceae	Single cell; cells are small (a few micrometers in diameter) and spherical or hemispherical; cells are light blue-green in color, but appear brown or dark due to the presence of gas-filled vesicles; forms colonies surrounded by a thick mucilage; colonies begin spherical but become irregular over time	Does not fix nitrogen; possible pollution remediation; freshwater forms harmful bloom and hepatotoxins such as microcystin and cyanopeptolin; communities are often a mix of toxin-producing and nonproducing isolates; scum formation with pollution	[6,81,82]
Nodularia spumigera	Aphanizomenonaceae	Form solitary filaments or groups of filaments; unipolar, straight or curved; yellowish, olive-green, or blue-green	Fixes nitrogen and forms blooms; can be toxic to ecosystems and water quality; possible	[79,83,84]

		in color; reproduced by the formation of hormogonia, filament breakage, akinetes, salinity and temperature stress reduce toxin production	remediation of pollutants, produces nodularin (liver toxin) and beta-methylamino-L-alanine (nerve toxin), stress might affect toxin production	
Nostoc linekia	Nostocaceae	Cylindrical, barrel-shaped, or spherical, thick cell wall; peptidoglycan, various pigments (chlorophyll, phycocyanin, and phycoerythrin); found in a variety of environments, grows symbiotically with plants providing nitrogen	Fixes nitrogen and remediates petroleum hydrocarbons	[80,85,86]
Oscillatoria spp. (3 species)	Oscillatoriaceae	Filamentous; form bright blue-green mats; motile with a slow rhythmic oscillation motion	Fixes nitrogen, remediates sewage wastewater and crude oil polluted water; heavy metals are eliminated	[80,87–89]
Phormidium sp.	Oscillatoriaceae	Has curved trichomes and unbranched filaments; cells divide crosswise perpendicular to the long axis of the trichome; cells are isodiametric; cells of the filament ended with rounded or pointed apical cells	Fixes nitrogen, remediates petroleum hydrocarbons and heavy metals	[90]
Richelia sp.	Nostocaceae	Filamentous trichomes; heterocystous associated within the cell membrane and cell wall of diatoms; exist as an epiphyte and an endophyte	Fixes nitrogen, possible remediation of industrial wastewater, nitrogen fixing	[91,92]
Stanieria sp.	Dermocarpellaceae	Coccoid sessile on shells or epiphytic on algae, and other cyanobacteria,	Needs to be tested for nitrogen fixation, potential bioremediation of	[93–95]

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Species	Family	Features	Roles	References
		coccoid microfossils, PTB-microbialite, and Permian Triassic. Boundary; calcified sheaths of the extant unicellular endospores are used for identification; anoxia is favorable to preservation of *Stanieria* as fossils	petroleum hydrocarbons	
Synechococcus sp.	Synechococcaceae	Unicellular, spherical, ellipsoidal, rod-shaped, marine environments and fresh water; motile without flagellates; it moves by oscillating its cell surface and grows in a wide range of light intensities; prefers neutral to slightly alkaline pH; contains phycoerthrin, cell wall is peptidoglycan and polysaccharides; can tolerate long periods without nutrient supply	Some species fix nitrogen; remediates petroleum hydrocarbons such as kerosene and other oil and gas compounds	[79,96]
Trichodesmium erythraeum.	Microcoleaceae	Found in tropical and subtropical oceans; straight or curved individual filaments, form spherical aggregates and large blooms; the red pigments responsible for the color of the red sea	Fixes nitrogen and carbon while undergoing photosynthesis; the close physical contact between genetically identically cells allows cell specialization; metabolizes some organic compounds and related components	[97–100]

This table shows advantages and disadvantages for each. Al-Khelaifi [53] provided a better understanding of cyanobacterial biodiversity along the Qatari coastline using modern techniques. The main species reported include *Croococcidiopsis* sp. (25.0%), *Dermocarpella* sp. (3.6%), *Euhalothece* sp. (7.1%), *Geitlerinem* sp. (21.4%), *Geminocystis* sp. (7.1%), *Leptolyngbya* sp. (3.6%), *Oscillatoria* sp. (3.6%), *Stanieria* sp. (10.7%), and *Synechococcus* sp. (10.7%). The study also incorporated genotypic analysis to assess local diversity, thus providing a consistent reference for future comparative studies, biotechnological applications, and monitoring efforts. These species comprised about 93% of the total cyanobacteria identified in the seawater of the Arabian Gulf near Qatar as well as in pools of brackish water and industrial anthropogenic wastewater. These species play significant roles in the aquatic ecosystem, thus engaging in a variety of activities that can be classified into two main types: (a) positive activities and (b) negative activities. Both types of activities include the following:

3.1. Nitrogen fixation

This is a light-regulated process that involves the reduction of atmospheric nitrogen into ammonia facilitated by the nitrogenase enzyme complex (E) found in specialized cells called heterocysts. The reactions catalyzed by nitrogenase require ATP as a source of metabolic energy.

$$N_2 + 12ATP + 6e^- + 8H^+ \xrightarrow{E} 2NH_4^+ + 12ADP + 12Pi \quad (1)$$

These microorganisms can metabolize ammonium to produce amino acids, amides, and other nitrogenous compounds [101]. Two enzyme system operate in cyanobacteria: glutamine synthetase (GS) and glutamate synthase or glutamine oxoglutarate aminotransferase (GOGAT) system. The first one synthesizes glutamine from glutamate and NH_4, while the second one synthesizes glutamate from glutamine:

$$\text{Glutamate} + NH_4 \xrightarrow{GS} \text{Glutamine} \quad (2)$$

Glutamine is converted to glutamate through a process called deamination which is catalyzed by phosphate-activated glutaminase. This reaction produces NH_4.

$$\text{Glutamine} \xrightarrow{GOGAT} \text{Glutamate} + NH_4 \quad (3)$$

Other groups of enzymes are found in cyanobacteria that involve NH_3 in ammonia assimilation such as alanine dehydrogenase, asparagine synthetase, aspartate dehydrogenase, and aspartase [102,103]. Additionally, heterocysts import carbohydrates from nearby vegetative cells along the filaments, which serve as a source of energy and reductants for nitrogen fixation. Notably, carbohydrate metabolism in heterocysts involves the oxidative pentose phosphate pathway to generate NADPH, which is necessary for the biosynthesis of nucleic acids, proteins, and other essential compounds [104]. To protect nitrogenase from oxygen inactivation, heterocysts create a microoxic environment (an environment with low oxygen levels). They achieve this by producing additional cell walls and extra polysaccharides that limit air diffusion. Furthermore, they upregulate heterocyst-specific respiratory enzymes and degrade photosystem II (the system responsible for oxygen production); their thylakoids are structurally different from those in vegetative cells [105].

Importantly, the number of heterocysts increases under nitrogen starvation conditions because they are more active in anaerobic environments where they fix atmospheric nitrogen. This is supported by studies on cyanobacteria found in the Qatari sabkhas where the soil is nitrogen-deficient [106–108]. Furthermore, polluted soils-particularly those contaminated with petroleum hydrocarbons and heavy metals-may also experience similar conditions of nitrogen deficiency [109]. Substantial evidence has been presented to support the argument that high concentrations of petroleum hydrocarbons increase the C:N ratio in soil and water, thus leading microorganisms such as cyanobacteria to activate the formation of heterocysts to enhance nitrogen fixation [110].

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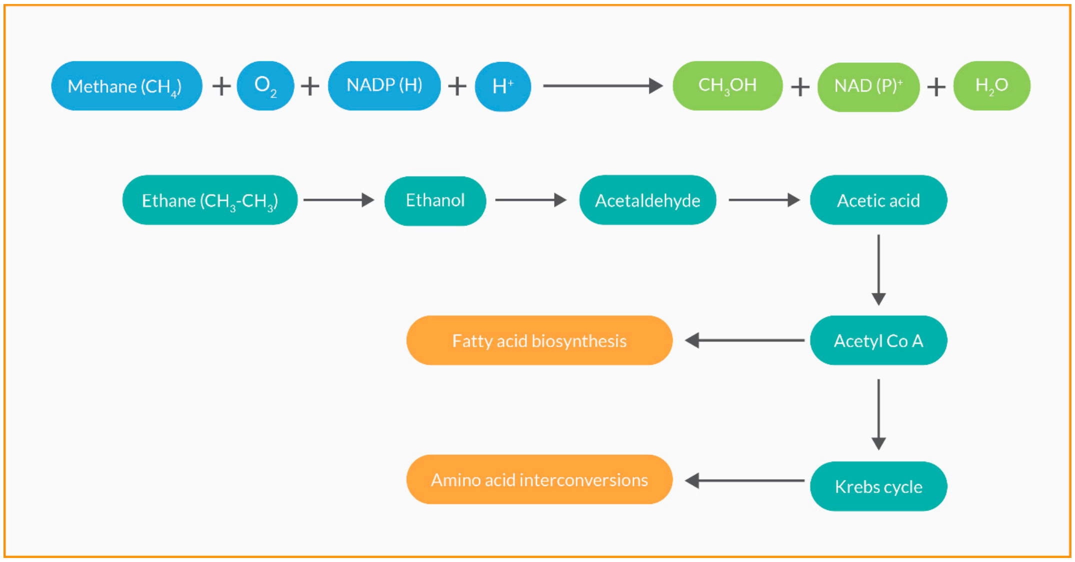
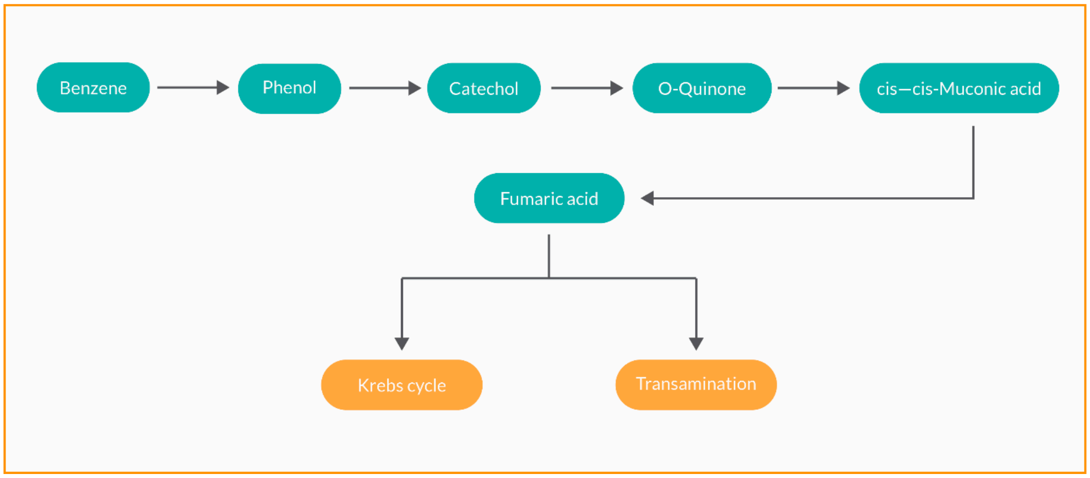
3.2. Phycoremediation (Cyanoremediation) of Oil and Gas Components

Many cyanobacteria species can utilize crude oil as a source of carbon and energy [111]. This capability has been discussed in numerous studies, which outlines the metabolic pathways involved in the breakdown of petroleum hydrocarbons by various organisms including bacteria, cyanobacteria, and algae [28,75]. The complete degradation of these compounds leads to the formation of useful metabolites such as acetyl Co-A and fumaric acid. These species participate in the Krebs cycle, fatty acid biosynthesis, and amino acid interconversions [4,30,89]. As discussed in these reports, the degradation of organic compounds occurs during various industrial activities related to oil, gas, and other anthropogenic processes. The following are some examples of these processes performed in microorganisms including cyanobacteria:

3.2.1. Alkane Degradation



3.2.2. Aromatic Compound Degradation



The above processes offer degradation of organic petroleum hydrocarbons. However, in some cases, microorganisms or plants might not able to complete the degradation of organic compounds, which make some these compounds less toxic as reported by Sandermann [112] who demonstrated the transformation of organochlorine pesticides and the hydroxylation of 2,4-D is followed by conjugation with glucose and malonyl residues and subsequent deposition in vacuoles [28].

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Another example was reported by Ohtsubo et al. [113] and Van Aken [114] who explained the degradation of polychlorinated biphenyls (PCBs) which result in useful metabolites like succinyl Co-A or acetyl Co-A. Other metabolites are less toxic and can be sequestered in the vacuoles to keep the metabolic machinery safe for plants and the adjacent and/or associated microorganisms [4]. These reactions are crucial in metabolic pathways because they convert toxic compounds into beneficial metabolites. Importantly, these reactions-along with the phycoremediation of petroleum hydrocarbons and heavy metals are important from two key perspectives: positive potential and possible negative impacts [30,49]. On the positive side, this process can degrade organic petroleum hydrocarbons, thus preventing these harmful substances from entering the food chain [79]. However, there are significant challenges to consider. Some cyanobacteria species, while metabolizing petroleum hydrocarbons and removing heavy metals, may also accumulate these toxic metals within their cells. This accumulation could pose risks to ecosystems and wildlife because incomplete detoxification of petroleum hydrocarbons might lead to harmful side effects [4]. Additionally, many species of cyanobacteria are consumed by fish and other marine living organisms. If these organisms accumulate heavy metals or toxic compounds then it could seriously disrupt the food chain, thus leading to broader ecological consequences [115]. Early studies also indicated that some autotrophic organisms can absorb pollutants, thus unintentionally introducing some toxic metals and other organic components into the food web [28,116–118]. This highlights the challenge of ensuring that heavy metals and other toxic substances are prevented from entering the food chain because this could harm ecosystem and threaten human health.

One promising species for mitigating this issue is ***Lyngbya*** **sp.,** which has shown potential for removing heavy metals and breaking down the organic compounds found in crude oil and gas [75,76]. However, careful action and monitoring are required when employing cyanobacteria and other phytoplankton in industrial processes. It is essential to extract and contain these toxic substances, thus preventing them from re-entering the ecosystem. Methods such as bio-cycling and agro-botanical recycling could help manage the biomass of these organisms and ensure their safe use without disrupting ecosystems [49]. Integrating phytoplankton into projects designed to address pollution from industrial wastewater and oil and gas spills is a promising biological strategy. Success in this approach relies on effective monitoring systems and recycling processes driven by advances in biotechnology. Such systems would help limit the harmful effects of toxic substances produced by energy-related activities. By adopting innovative technologies, we can reduce environmental damage, improve the sustainability of energy production, and enhance waste management practices. Other species of cyanobacteria should be tested to explore the possibility of using them in large-scale projects aimed at protecting the marine environment in the Gulf region. A major challenge in the Gulf is the limited availability of freshwater for agriculture and domestic use due to the absence of natural freshwater sources such as rivers, lakes, or springs. Al-Thani and Yasseen [4] suggested industrial wastewater be an alternative water source in the future, given the ongoing production of oil and gas, political instability, accidents, and military exercises. Substantial efforts have been made to construct strategic reservoirs and desalination plants to meet the population's needs during emergencies [28,30,119].

3.3. Source of Industrial Biotechnological and Health Applications

The search for novel compounds extracted from cyanobacteria has gained significant attention due to their potential in healthcare [120,121], biofuels [122], cosmetics [123], bioremediation [85], etc. Notably, these extracts have demonstrated a range of bioactive properties such as anti-inflammatory, anticancer [121], antibacterial, antiparasitic, antidiabetic, antiviral, antioxidant, anti-aging, and anti-obesity. This makes them promising candidates for drug development.

Considerable progress has been made with several compounds demonstrating notable antitumor activity. Of these, calothrixin and its derivatives have shown promise in cancer treatment [94,124]. Of note, more than 50% of cultivated cyanobacteria are used to extract bioactive compounds with properties that can treat various and serious health issues [59]. Recent findings by Bouyahya et al. [125] revealed that various phytochemicals exhibit significant anticancer effects, e.g., secondary

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metabolites such as flavonoids, phenolic acids, terpenoids, and tannins. Specific compounds with proven anticancer efficacy such as lyngbyastatin, curacin A, kalkitoxin, and cryptophycin have been identified in cyanobacterial extracts from numerous species. However, petroleum hydrocarbon pollution in seawater may negatively impact the ability of cyanobacteria to produce bioactive chemicals including those with anticancer properties. Limited information and research are available on this topic. Further investigation is needed to clarify the impact of extreme environmental conditions such as exposure to crude oil, gas, and heavy metals, on the efficacy of cyanobacteria in producing anticancer compounds [126]. More details can be found in recent publications regarding the roles of these phytoplankton to treat disease [17, 125. 127].

3.4. Bloom Formation

Blooms in water bodies such as lakes, rivers, or oceans refer to large populations of microalgae such as diatoms, dinoflagellates, and cyanobacteria that cause the water to appear colored, e.g., red, or brown (Figure 2). These blooms often have septic or musty odors and can make the water look murky, discolored, or covered in scum.

Figure 2. A bloom caused by a substantial increase in cyanobacteria and dinoflagellate populations [54].

Such algal blooms can produce toxins such as toxic secondary metabolites that affect animals and humans; children are especially at risk [128]. Hu [129] found that the common freshwater cyanobacteria *Microcystis* rapidly proliferates to form heavy algal blooms on the water surface, especially under severe environmental condition like pollution. Notably, the massive *Microcystis* blooms not only destroy ecosystems but can also deteriorate the water quality to produce toxins threatening public health. Furthermore, these blooms might be seen at the oceans and seas and/or under polluted conditions of water bodies. For example, Teikari et al. [130] found that toxic *Nodularia spumigena* thrived under high salinity in the Baltic Sea. Over decades of wars, military exercises, and accidents during crude oil transport, the Gulf is under serious anthropogenic disturbances that ended in substantial increase in the cyanobacteria and dinoflagellates that produce toxins from these blooms

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and kill marine organisms potentially impacting the food chain [131]. Al-Muftah et al. [132] reported seven toxic components produced by these microalgae including paralytic shellfish toxins (PSTs), diarrhetic shellfish toxin (DST), amnesic shellfish toxin (AST), cyclic imines (CIs), and polyether-lactone toxins. These toxins cause harmful effects on human health and marine animals [133] including fish (Figure 3).

Figure 3. Fish kills result from blooms caused by cyanobacteria and dinoflagellates [54].

Cyanobacterial blooms can significantly harm humans, animals, and ecosystems [134]. These negative impacts include the production of cyanotoxins, which can lead to various health issues such as skin rashes, eye irritation, vomiting, diarrhea, fever, and chronic diseases (such as cancer). Blooms also negatively affect water quality thus threatening aquatic organisms. Climate change may also exacerbate anthropogenic eutrophication in water bodies worldwide, thus further contributing to these harmful effects. However, cyanobacterial blooms may offer certain positive aspects. For instance, Hassanshahian et al. [135] reported a significant number of microorganisms,

including cyanobacteria, isolated from blooms of many genera such as *Phormidium* spp., *Oscillatoria* spp., *Aphanothece* sp., *Dactylococcopsis* sp., and some strains of *Halothece* and *Synechocystis*. Such blooms can degrade petroleum hydrocarbons like n-alkanes. Moreover, Hamouda et al. [79] found that the blue-green alga *Synechococcus* sp., along with its consortium, can grow and degrade hydrocarbons such as kerosene. Zeng et al. [136] discussed methods for removing cyanobacteria from polluted water bodies and highlighted the advantages and disadvantages of mitigating large-scale water bodies, including seawater. They reported that while physical methods can be effective, they tend to be expensive. Biological methods, though effective for long-term control, may be slow and unsuitable for responding to sudden blooms such as those that occurred following wars in the Arabian Gulf. Although chemical methods work more quickly, they can cause secondary negative impacts such as killing non-target organisms and contributing to secondary pollution.

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4. Bioactive Compounds in the Arabian Gulf

Approximately 71% of the Earth's surface is covered by water-most of which is saline. These marine environments contain largely untapped natural resources that can be exploited to obtain novel compounds with bioactive properties. Recent studies have shown that cyanobacteria and other microalgae produce numerous biologically active compounds that have potential applications in various fields including biotechnology, pharmacology, cosmetology, and biofuels [121]. These studies highlight the diverse properties of these bioactive compounds making them promising candidates for drug development and the treatment of various health conditions. The notable effects of these compounds include anti-inflammatory, anticancer, antibacterial, antiparasitic, antidiabetic, antiviral, antioxidant, anti-aging, and anti-obesity activities. These compounds are secondary metabolites, including flavonoids, phenolic acids, terpenoids, and tannins, which exhibit remarkable anticancer effects. The promising properties of these compounds have inspired scientists and research centers to investigate their industrialization for addressing human health issues.

For instance, Xu et al. [94] demonstrated that certain calothrixins, i.e., metabolites derived from cyanobacteria, were effective as anticancer and antimicrobial agents. Similarly, reviews by Bajpai et al. [137] and Karan and Aydin [138] discussed a range of biologically active and chemically diverse compounds with significant impacts on chronic diseases, including cancer. Qamar et al. [59] also reported that these compounds are efficient sources of bioactive secondary metabolites noting that over 50% of cyanobacteria are cultivated on commercial platforms for extracting bioactive compounds with anticancer activity; this plays a role in treating various diseases.

Finally, Bouyahya et al. [125] provided further support by reporting the presence of various phytochemicals and bioactive compounds with notable anticancer effects-particularly against leukemia and breast cancers. Additional applications were also noted such as the production of biofuels and cosmetics as summarized in Table 2.

Table 2. Key biotic activities of common cyanobacteria genera found in Qatar [59,79,139].

Genera	**Nitrogen fixation**	Phycoremediation	Production of agents		
			Anticancer	Biofuels	Cosmetics
Amphanizomenon	+	+	+: [40]	Needs test	P: [139,155]
Anabaena	+	+	+: [141].	+: [153]	+: [139,171]
Calothrix	+	P	+:[142]	VP: [154,155]	P: [139,175]
Chroococcus	-	VP	+: [63]	+: [156]	P: [176]
Croococcidiopsis	+	+	Needs test	+: [157]	P: [177]
Dermocarpella	Needs test	P	Needs test: [59]	P: [158]	Needs test
Euhalothece	Needs test	P	Needs test: [143]	P: [159]	P: [123]
Geitlerinema	+	P	+: [144]	+: [160]	P: [139,178]
Geminocystis	Needs test	P	P: [145]	P: [161]	P: [179]
Lyngbya	+	P	+: [146]	+: [162,163]	+: [139,180]
Leptolyngbya	Some +	+	P: [124,147]	+: [164,165]	P: [139,181]
Merismopedia	-	Needs test	P: [125,148]	P: [166]	P: [139,182]
Microcystis	-	P	P: [129]	+: [167]	P: [139,183]
Nodularia	+	P	P: [59]	+: [168]	P: [184]
Nostoc	+	+	+: [149,150]	+: [169]	+: [182,184,185]
Oscillatoria	+	+	+: [151,152]	+: [162]	+: [175]
Phormidium	+	+	+: [152]	+: [170]	+: [182,184,186]
Richelia	+	P	P: [124]	P: [171]	P: [10,187]
Stanieria	Needs test	+	+: [59]	+: [172]	P: [182,184]
Synechococcus	Some +	+	+: [59]	+: [173]	P: [176,182]
Trichodesmium	+	+	Needs test: [98]	+: [174]	P[178]

+: Positive, -: Negative, P: Possible, VP: Very possible.

These positive outcomes also highlighted a range of activities related to the contribution of various chemicals in treating different diseases. Analysis of the data in this table revealed several key findings about the roles that cyanobacteria play in both marine and freshwater environments around Qatar. For example, of 21 genera, approximately 13 were shown to be efficient in nitrogen fixation, while about 10 genera were effective in phycoremediation. In terms of bioactive agents for treating human diseases, producing biofuels, and manufacturing cosmetics, many of these cyanobacteria were found to be either active or promising candidates.

5. Conclusions

Future efforts in the Arabian Gulf should focus on harnessing the unique properties of marine organisms like cyanobacteria to advance biotechnological initiatives. These organisms hold great potential for remediating oil and gas pollution and can play a vital role in developing industrial infrastructure across health, energy, and environmental sectors. By leveraging their capabilities, the region can address environmental challenges while simultaneously fostering progress in critical areas that support the welfare of its people.

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