Review

Not peer-reviewed version

Comparative Phycoremediation Potential of Micro-Green Algae and Dinoflagellates in Coastal and Inland Qatar

Roda F. Al-Thani and Bassam Taha Yasseen *

Posted Date: 23 June 2025

doi: 10.20944/preprints202506.1825.v1

Keywords: blooms; biotic agents; dinoflagellates; metabolic pathways; micro-green algae; phycoremediation; toxins

Review

Comparative Phycoremediation Potential of Micro-Green Algae and Dinoflagellates in Coastal and Inland Qatar

Al-Thani, R. F. and Yasseen, B. T. *

Department of Biological and Environmental Sciences, College of Arts and Sciences, Qatar University, Doha, Qatar

* Correspondence: bassam_tahaa@yahoo.co.uk

† Current address: 8 James Court, Dunstable Road, Luton, UK, LU4 0HN

Abstract: The Arabian Gulf, bordered by major energy-producing nations, harbors diverse microalgal communities with strong potential for bioremediation of environmental pollutants, particularly petroleum hydrocarbons. This review evaluates two key microalgal groups—micro-green algae and dinoflagellates—highlighting their distinct physiological traits and ecological roles in pollution mitigation. Dinoflagellates, including *Prorocentrum* and *Protoperidinium*, have demonstrated hydrocarbon-degrading abilities but are frequently linked to harmful algal blooms (HABs), marine toxins, and bioluminescence, posing ecological and health risks. The toxins produced by these algae can be hemolytic or neurotoxic and include compounds such as azaspiracids, brevetoxins, ciguatoxins, okadaic acid, saxitoxins, and yessotoxins. In contrast, micro-green algae such as *Oedogonium* and *Pandorina* are generally non-toxic, are seldom associated with HABs, and are typically found in clean freshwater and brackish environments. Some species, like *Chlorogonium*, indicate pollution tolerance, while *Dunaliella* has shown promise in remediating contaminated seawater. Both groups exhibit unique enzymatic pathways and metabolic mechanisms for degrading hydrocarbons and remediating heavy metals. Due to their respective phycoremediation capacities and environmental adaptability, these algae offer sustainable, nature-based solutions for pollution control in coastal, estuarine, and inland freshwater systems, particularly in mainland Qatar. This review compares their remediation efficacy, ecological impacts, and practical limitations to support the selection of effective algal candidates for eco-friendly strategies targeting petroleum-contaminated marine environments.

Keywords: blooms; biotic agents; dinoflagellates; metabolic pathways; micro-green algae; phycoremediation; toxins

---

1. Introduction

The Arabian Gulf, Gulf of Oman, and Arabian Sea (Figure 1) constitute a geographically and ecologically significant marine corridor influenced by extreme environmental conditions, including high salinity, elevated sea surface temperatures, and seasonal nutrient-rich upwelling. These stressors shape the structure, diversity, and adaptive strategies of local microalgal communities. Among these, phytoplankton—photosynthetic microorganisms inhabiting the euphotic zone—play a foundational role in marine ecosystems by driving primary production, regulating nutrient cycles, and supporting food web stability.

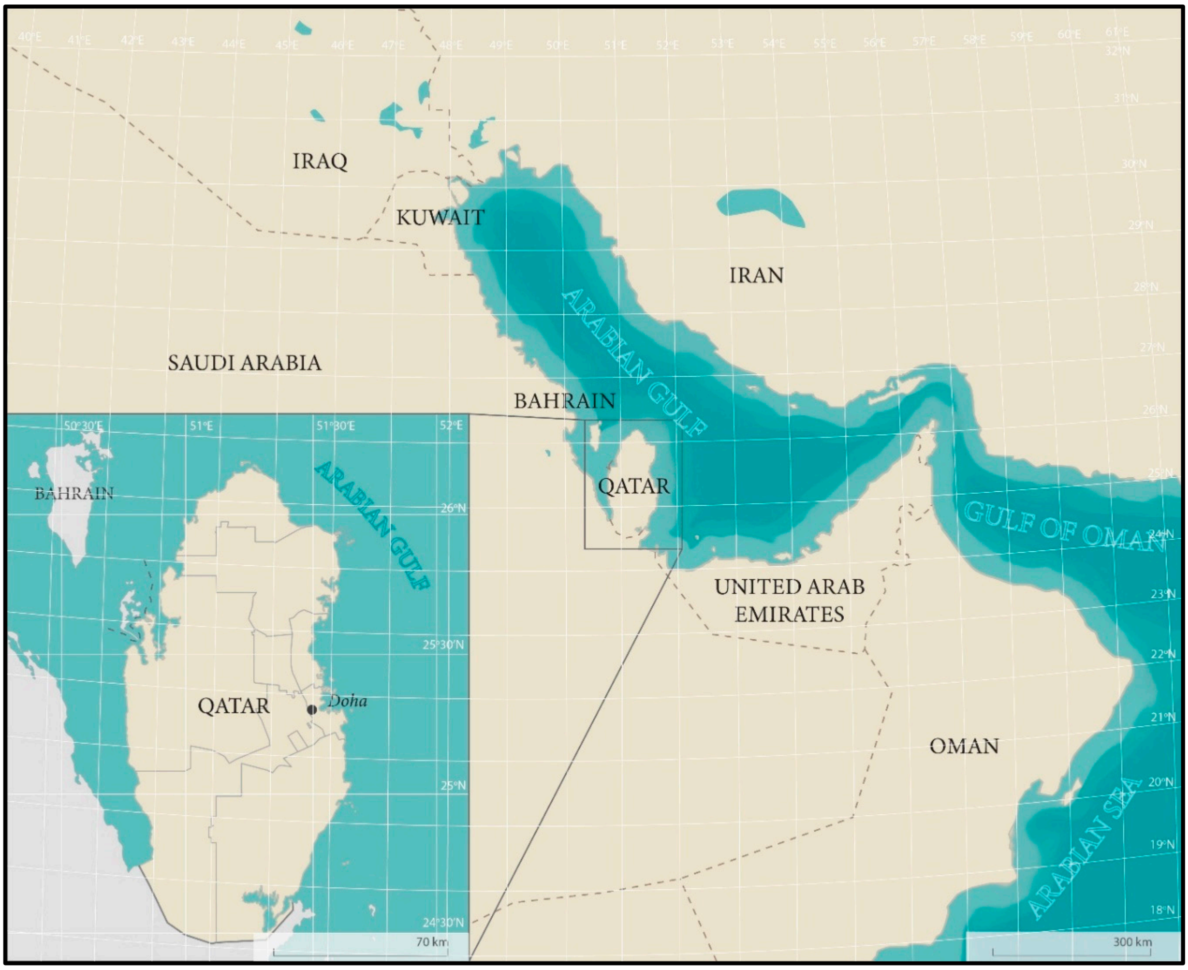

Figure 1. Map of the Arabian Gulf showing the Gulf of Oman and the Arabian Sea, with an inset map of Qatar.

In recent decades, however, escalating anthropogenic pressures—particularly from oil and gas operations—have severely impacted the marine environment. Hydrocarbon contamination has emerged as one of the most pressing environmental threats in the region, especially in semi-enclosed basins like the Arabian Gulf, where water circulation is limited and pollutant accumulation is intensified. The situation is further aggravated by geopolitical events such as the Iran–Iraq War (1980–1988), the Gulf War (1990–1991), and the Iraq War (2003), which contributed to industrial water pollution through large-scale oil spills and operational discharges [1,2]. In combination with climate change, increasing energy demands, and ongoing regional conflicts, these stressors have introduced persistent, carcinogenic, and neurotoxic organic pollutants into the marine environment, threatening biodiversity, food security, and public health [3]. Against this backdrop, there is increasing global interest in the role of marine autotrophs in environmental remediation and biotechnological innovation. Phytoplankton and other photosynthetic marine microorganisms have shown promise in mitigating aquatic pollution through mechanisms such as phytoremediation, phyco-remediation, and cyano-remediation [4]. These approaches utilize the natural metabolic pathways of autotrophs to absorb, transform, or sequester pollutants in an eco-friendly and sustainable manner. While previous research has concentrated largely on cyanobacteria, diatoms, seaweeds, seagrasses, and certain mangrove species, more recent efforts have turned toward underexplored groups such as green microalgae (Chlorophyta), dinoflagellates, and silicoflagellates **[5–7**].

In addition to their promising roles in remediation, micro-green algae (Chlorophyta) and dinoflagellates are also recognized for producing a wide spectrum of bioactive compounds—ranging from lipids and carotenoids to phycobiliproteins and phenolic substances—which exhibit significant antioxidant, antimicrobial, anticancer, antiviral, and neuroprotective properties [8]. These bio-actives

 doi:10.20944/preprints202506.1825.v1

have garnered interest for their potential in developing novel therapeutics targeting diseases such as Alzheimer's, HIV/AIDS, and COVID-19 [9].

This review specifically evaluates the bioremediation potential of Chlorophyta and dinoflagellates with respect to petroleum hydrocarbon and heavy metal pollution, emphasizing the ecological contrast between inland micro-green algae prevalent in Qatar's terrestrial environments and marine dinoflagellates dominant in the coastal waters of the Arabian Gulf. By synthesizing recent findings on their physiological adaptations, metabolic pathways, and ecological functions, this article provides a comparative analysis of these two algal groups and assesses their viability as sustainable biotechnological agents for marine pollution control and regional ecosystem restoration.

2. Characteristics and Roles of Microalgae in Marine Environments

Microorganisms, including bacteria, fungi, and algae, play a crucial role in the bioremediation of oil and gas pollutants by transforming them into less harmful or beneficial compounds for humans, flora, and fauna. Among these, algae—particularly micro-green algae—have demonstrated superior efficacy owing to their environmental sustainability, economic viability, and distinctive physiological and metabolic traits [10–12]. These features confer a competitive advantage over other microbial groups in degrading petroleum hydrocarbons and detoxifying heavy metals [13]. First, the rapid growth rate of algal cells, along with their high biomass production, may enable the removal of pollutants from water [8]. Second, micro-green algae's high biomass production can be used to generate significant amounts of valuable byproducts, bioactive agents, biofuels, and feedstocks [14,15]. Third, remediation of pollutants using micro-green algae is a cost-effective and eco-friendly method [16–18]. Fourth, microalgae require fewer resources to remediate wastewater in both water and soil [11]. Fifth, these phytoplankton have shown a remarkable ability to absorb heavy metals and metabolize organic compounds [19]. The cell wall plays a crucial role in the biosorption process, as its composition— which is rich in polysaccharides, proteins, and lipids—enhances the adsorption of contaminants [20]. Biosorption, a mechanism for heavy metal uptake, involves the reversible and rapid physicochemical binding of molecules or ions from the aqueous phase to functional groups on the surface of biological materials. A wide range of biosorbents have been identified, including living organisms such as algae, fungi (e.g., yeast), and bacteria, as well as non-living sources like agricultural waste and biopolymers [21]. Moreover, phytoplankton cells can actively uptake and store heavy metals within vacuoles or bind them to cell structures, which leads to a reduction in their availability in contaminated environments such as seawater and soil [22]. A sixth feature is that the metabolic pathways of organic components involve the degradation and/or transformation of certain types of petroleum hydrocarbons into less toxic compounds [23,24]. Notably, these microalgae produce oxygen and reactive oxygen species, which can enhance the breakdown of hydrocarbons. They also produce extracellular enzymes that facilitate the degradation of organic pollutants, such as polycyclic aromatic hydrocarbons (PAHs) [25]. Additionally, some microalgae can secrete phenolic compounds that aid in the degradation of petroleum hydrocarbons in marine sediments [26]. Certain species of microalgae can directly metabolize hydrocarbons as a carbon source. For example, certain green microalgae, such as *Dunaliella*, possess enzymatic systems capable of degrading and metabolizing a range of hydrocarbons, including PAHs and petroleum-based compounds [17,27]. These compounds are transformed into less toxic substances or useful metabolites that contribute to the metabolic pathways of these marine autotrophs [27–29]. Recent studies suggest that diatoms and bacteria work synergistically to degrade organic components present in wastewater from oil and gas activities [30]. Bacteria initiate the primary breakdown of hydrocarbons, while microalgae contribute to the subsequent stages through a series of metabolic reactions, ultimately leading to the production of valuable metabolites [31]. Although diatoms alone cannot fully degrade petroleum hydrocarbons, their association with bacteria enables the complete degradation of these compounds. The resulting metabolites are then funneled into central metabolic pathways, including the Krebs cycle, fatty acid biosynthesis, and amino acid interconversion. Vo et al. [32] highlighted the potential of using bacteria–microalgae associations to remediate organic pollutants in industrial wastewater. These relationships can take various forms, involving interactions and mechanisms that facilitate the production of diverse bioactive agents. Vo et al.'s study supports recent findings suggesting that modern biotechnological approaches can enhance the efficiency of microalgae, such as Chlorophyta, diatoms, and dinoflagellates. In natural environments, genetic interactions between microalgae and associated bacteria may occur via horizontal gene transfer (HGT), potentially enhancing the capacity of microalgae to remediate organic compounds [32]. Notably, Al-Thani and Yasseen [33,34] reported that HGT can occur between microorganisms and native plants, conferring mutual benefits. Such advantageous roles of HGT have been observed in numerous instances [35,36]. For example, microbes have acquired genes from plant biosynthetic pathways, which may have contributed to the evolutionary development of various organisms [37]. These gene transfers have been associated with traits such as antibacterial activity [38], the emergence of specific adaptations in extremophilic eukaryotes [39], and the ability of endophytes to assist plants in remediating contaminated soils, possibly through the transfer of genes that enhance plant resilience [40]. Finally, a seventh feature of microalgae is that they can interact synergistically with bacteria and fungi to facilitate the remediation of petroleum hydrocarbons. The oxygen generated by microalgae through photosynthesis may enhance the bacterial metabolic activity involved in the degradation of organic pollutants [10,11,32].

2.1. Advantages of Microalgae

A recent review on phytoplankton in the Arabian Gulf highlighted numerous beneficial roles of diatoms [7]. As autotrophic marine organisms, microalgae offer a wide array of benefits across diverse sectors, including environmental, nutritional, and industrial domains. New technologies have been used to identify biologically active substances such as proteins, lipids, polysaccharides, pigments, and vitamins in microalgae. Additional ingredients for value-added products are expected to be discovered. Other important biochemicals, biomaterials, and biofuels have also been reported. All these components play crucial roles in various sectors of human life [41,42]. Microalgae offer several environmental advantages: (1) the reduction of atmospheric CO_2 through carbon sequestration, thus contributing to climate change mitigation; (2) a significant role in global oxygen production via photosynthesis; (3) the efficient use of aquatic environments to synthesize valuable bioactive compounds while compensating for oxygen depletion during oxidative processes such as respiration, thereby conserving arable land for food crop cultivation; and (7) the purification of water bodies through the removal of pollutants and industrial waste, including heavy metals, organic contaminants, and excess nutrients such as nitrogen and phosphorus [43–45]. In terms of bioactive agent production, microalgae, as marine autotrophs, play a vital role in the production of a wide array of bioactive compounds, with applications across multiple sectors, including health, nutrition, and pharmaceuticals. These organisms synthesize high-value components such as proteins, essential amino acids, and long-chain omega-3 fatty acids (e.g., DHA and EPA), offering a sustainable, non-animal source of these crucial nutrients. Additionally, microalgae are rich in vitamins and antioxidants, contributing to their health-promoting potential. Notably, certain species produce pigments such as astaxanthin, beta-carotene, and phycocyanin, which are widely recognized for their potent anti-inflammatory and antioxidant properties and are commonly used in functional foods and dietary supplements [41,46,47]. Microalgae also provide industrial advantages, including value-added products derived from algae that are applicable in the energy sector, agriculture, and pharmacology. These products include biodiesel, bioethanol, biogas, biodegradable plastics, cosmetics, fertilizers, and pharmaceuticals [46–50]. Moreover, economic advantages include the high productivity of microalgae when cultivated under optimal environmental conditions. Moreover, certain microalgae are excellent candidates for high oil production, making them valuable for both biofuel and nutraceutical applications. Notably, nutraceuticals offer a wide range of applications; they can promote general well-being, support specific health conditions, and aid in the prevention and management of diseases. These products can be used as dietary supplements, functional foods, and even in pharmaceutical formulations to help treat heart disease, enhance cognitive function, improve digestive health, and support cancer therapies [51–53]. Beyond what is described here, other

 doi:10.20944/preprints202506.1825.v1

studies have recently reported even more details about the advantages of marine autotrophs including plants, seagrass, seaweeds, and microalgae [5–7].

2.2. Disadvantages of Microalgae

Al-Thani and Yasseen [24] observed that certain green algae species were found exclusively in polluted ponds, others in treated clean ponds, and some in both habitats. These findings indicate that micro-green algae can occupy diverse ecological niches and may exert both beneficial and adverse effects. Notably, *Oedogonium* and *Pandorina* are exclusively associated with clean fresh water and unpolluted water, suggesting their potential as a bioindicator of water quality. In contrast, a significant number of dinoflagellates can be found in both clean and contaminated seawater, and their presence may serve as an indicator of pollution or eutrophication [54]. A high diversity and abundance of dinoflagellates can signal potential water quality issues. Certain species are capable of rapid population growth, resulting in phenomena known as red tides or harmful algal blooms (HABs) [55–57]. During these events, the water may appear red, brown, or other colors (Figure 2) due to the dense proliferation of these microalgae.

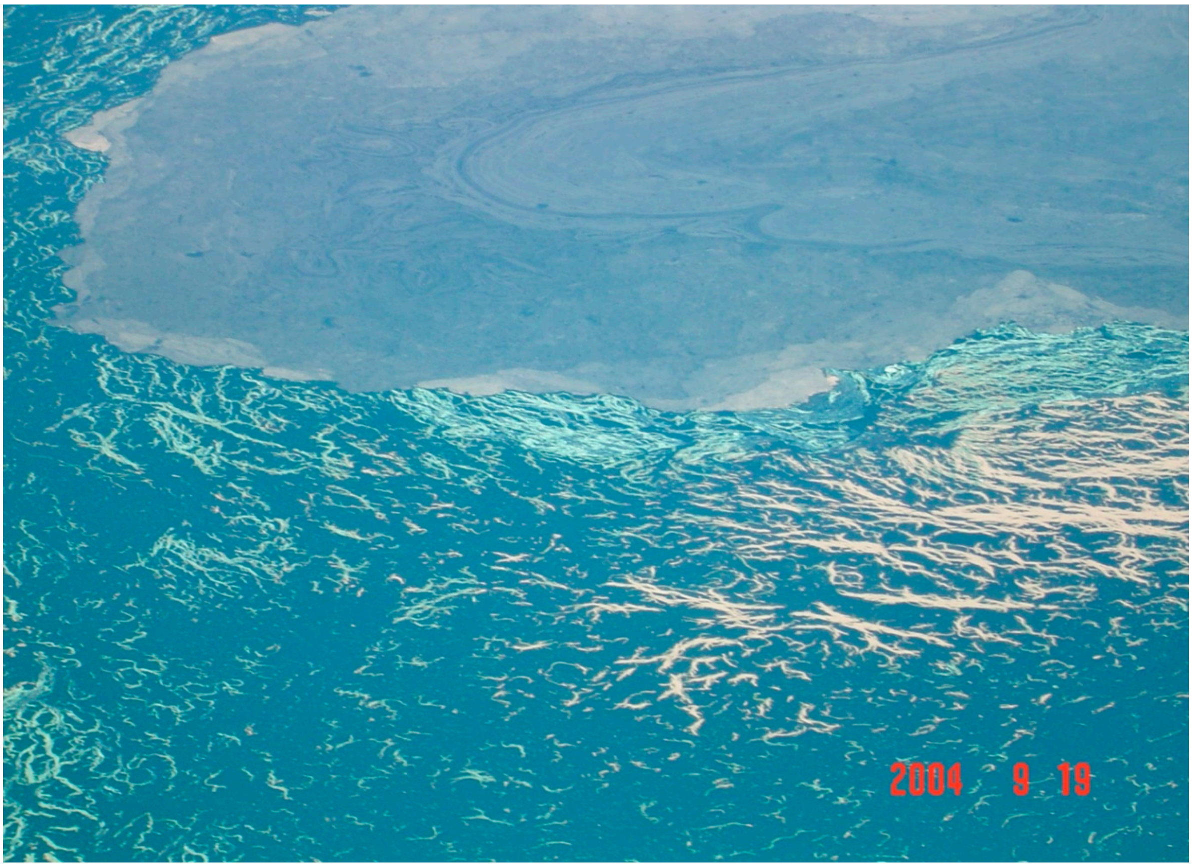

Figure 2. Blooms resulting from a substantial increase in microalgae, including dinoflagellates (File S1) [6].

These blooms are often triggered by increased pollution and nutrient runoff and can have harmful effects on marine life—such as fish kills (Figure 3)—as well as on human health [58]. Certain dinoflagellates produce potent toxins. These include azaspiracid, brevetoxins, ciguatoxins, okadaic acid, saxitoxin, yessotoxins, and possibly others [59]. One study reported about 100 dinoflagellate species, and diatoms produce a variety of toxins that pose a food safety risk when accumulated in shellfish, fish, and other seafood, potentially leading to food poisoning outbreaks [7]. These toxins may accumulate in the food chain, causing significant symptoms of illness in humans who consume contaminated seafood, including paralytic shellfish or diarrhetic shellfish poisoning.

Figure 3. Fish kills: an adverse effect of dinoflagellate blooms and other microalgae on marine life (File S1) [6].

Azaspiracids are a group of marine polyether toxins that were initially linked to the dinoflagellate *Protoperidinium*, although subsequent research has suggested that the true source may be other marine microorganisms, such as bacteria or symbiotic protists. As a relatively recent addition to the family of marine biotoxins, azaspiracids have gained attention due to their potent toxicity and their implications for food safety. They are primarily known for their hepatotoxic effects. However, the most reported symptoms in humans arise from gastrointestinal distress and include nausea, vomiting, diarrhea, abdominal cramps, and stomach pain. In addition to these symptoms, affected individuals may also experience headache and dizziness. Laboratory studies have further revealed that azaspiracids can exert cytotoxic and neurotoxic effects, raising concerns about possible long-term health impacts and the need for continued monitoring of seafood contamination.

Brevetoxins are marine neurotoxins produced by *Karenia brevis*, a species not recorded along the Qatari coast of the Arabian Gulf but found in the Gulf of Mexico and potentially in other coastal regions. These brevetoxins are a family of cyclic polyether compounds that can cause neurotoxic shellfish poisoning, leading to a range of health effects, including neurological symptoms, gastrointestinal distress, and respiratory problems [60–62].

Ciguatoxins, a potent, naturally occurring group of toxins, are heat-stable, lipid-soluble polyether compounds toxins produced by the dinoflagellate species *Gambierdiscus toxicus*, among others, that grow on coral reefs and cause ciguatera fish poisoning in humans. The toxins enter the food chain when herbivorous fish consume these algae, which are then transferred to larger predatory fish, where they accumulate in their bodies [63–65]. These toxins may affect transport carriers and disrupt normal neurological processes [66,67].

Okadaic acid (OA) is a fatty acid and a potent marine biotoxin with complex effects on the digestive tract, often causing gastrointestinal discomfort [68,69]. It is produced by several species of dinoflagellates, including *Dinophysis*, *Prorocentrum*, and *Phalacroma* [70]. These genera are among the dinoflagellates recorded in the Arabian Gulf around the Qatari coasts, where about 15 species belonging to these genera have been reported. OA accumulates in marine sponges and shellfish, and

 doi:10.20944/preprints202506.1825.v1

when humans consume shellfish contaminated with these dinoflagellates, it can lead to diarrhetic shellfish poisoning, which is characterized by symptoms such as abdominal pain, diarrhea, and vomiting [71,72].

Saxitoxin, a powerful alkaloid neurotoxin produced by certain species of dinoflagellates and cyanobacteria, is the primary cause of paralytic shellfish poisoning. Dinoflagellate genera such as *Alexandrium* and *Gymnodinium* are well-known producers of this toxin. Saxitoxin exerts its effects by blocking voltage-gated sodium channels, thereby disrupting the transmission of nerve impulses. This interference with sodium ion flow across cell membranes impairs normal nerve and muscle function, potentially leading function, potentially leading to paralysis and other serious neurological effects [73,74].

Yessotoxins are a group of lipophilic, sulfur-bearing polyether toxins related to ciguatoxins. They are produced by various dinoflagellates, most notably *Gonyaulax spinifera* and *Protoceratium reticulatum* [75], which are found along the Qatari coasts in the Arabian Gulf. These toxins accumulate in shellfish and can negatively affect marine life [76]. While yessotoxins may not have a significant impact on humans, they have demonstrated toxicity in mice [77].

2.3. Chlorophyta: A Focus on Micro-Green Algae

Freshwater algae in Qatar have been documented through research monographs, case studies, and specialized courses in phycology and photosynthetic organisms. These studies have primarily focused on seagrasses, seaweeds, cyanobacteria, and diatoms. However, other phytoplankton, including micro-green algae and dinoflagellates, require further discussion regarding their roles in polluted marine and freshwater environments. For instance, Abulfatih et al. [78] reported several genera of green algae, including *Chlamydomonas*, *Oedogonium*, *Spirogyra*, and *Volvox*. Additional genera such as *Chlorella*, *Chlorogonium*, *Scenedesmus*, and *Zygnema* have been identified in subsequent studies [79]. Notably, *Oedogonium* and *Pandorina* (Figure 4) are found exclusively in the freshwater lakes of Rawdahs and well areas in Qatar and the Arabian Peninsula [78,80]. In contrast, green microalgae such as *Chlamydomonas*, *Chlorella*, and *Chlorococcum* are restricted to polluted lakes. Some genera, including *Chlamydomonas*, *Scenedesmus*, *Spirogyra*, and *Zygnema*, thrive in both freshwater and polluted environments. Some of these micro-green algae are found in the seawater as well (**File S2**).

Despite these findings, few studies have examined phytoplankton diversity along Qatar's coastline and within the pools of Rawdahs. Establishing a baseline to identify algae species in both pristine and polluted seawater is essential. However, research indicates a greater diversity of green algae species in the Arabian Gulf's seawater, particularly among the seaweeds along the Qatari coast [5]. Table 1 shows some of the main genera of micro-green algae found in the fresh and brackish waters around the Qatari peninsula, as well as their roles in the remediation of petroleum hydrocarbons and production of bioactive agents such as biofuels, biochar, antibacterial products, nutritional components (**File S3**), pigments, phenolic compounds, and other components. Notably, these genera are rarely found in the Arabian Gulf, while macro-green algae have been recorded in the Arabian Gulf as hypersaline-tolerant algae [5].

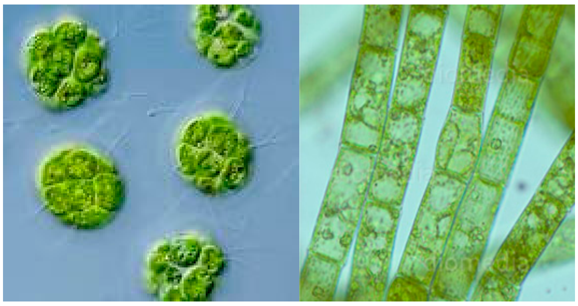

Figure 4. Micro-green algae (*Pandorina*, left, and *Oedogonium*, right) observed under high power of a light microscope. These algae are commonly found in the freshwater of certain pools and Rawdahs around Qatar.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 23 June 2025 doi:10.20944/preprints202506.1825.v1

2.4. Dinoflagellates

This group belongs to the division *Dinoflagellata* (Figure 5) and consists of unicellular aquatic organisms with two dissimilar flagella, exhibiting characteristics of both plants and animals. While most species are marine, some inhabit freshwater environments (File S1). As a key component of phytoplankton, dinoflagellates play a crucial role in the remediation of pollutants such as petroleum hydrocarbons and heavy metals. Additionally, they contribute to the production of bioactive agents and the formation of HABs, which can have toxic effects on marine life and humans. These roles have been extensively documented in various studies, reviews, and monographs [13,81–84]. Table 2 presents the dinoflagellate genera recorded along the Qatari coast and in the waters of the Arabian Gulf, highlighting their trophic modes, potential roles in the remediation of petroleum hydrocarbons, and other bioactive functions.

Table 1. Micro-green algae recorded in the freshwater pools and soil around the Qatari peninsula and their roles in phycoremediation and production of bioactive agents [5–7,85].

Genus	Remediation of petroleum hydrocarbons and heavy metals	Other possible roles	References
Chlamydomonas	Demonstrates activity in remediation processes of petroleum hydrocarbons	Promising microalgae for production of bioactive agents such as biofuels, biofertilizers, and other various products	[86]
Chlorella	Demonstrates activity in remediation processes of petroleum hydrocarbons	Promising candidate for producing bioactive agents	[25,87,88]
Chlorococcum	Needs testing; possible role in phycoremediation of various organic components	Possible production of bioactive agents such as biofuels and other valuable products	[25,89]
Chlorogonium	Needs testing; possible role in phycoremediation of various organic components and heavy metals	Needs investigation; its presence in freshwater lakes might be a sign of high levels of nutrients and pollution	[90]
Dunaliella	Efficient in remediating heavy metals such as Cd, Co, Cu, and Zn	Possible resistance mechanism against heavy metal pollution	[13,91]
Oedogonium	Removes heavy metals from water and soil; possible role in remediation of organic components	May convert the biomass of this alga into biochar via a pyrolysis process	[92]
Pandorina	Possible role in remediation of organic components; needs testing	Needs investigation into the bioactive agents produced by activity	[85,93]
Scenedesmus	Efficient in removing petroleum hydrocarbons and heavy metals such as Cd, Cr, and Cu	Potential source of novel bioactive compounds such as antibacterial and nutritional components; possible candidate for	[94–97]

doi:10.20944/preprints202506.1825.v1

		biotechnological applications	
Spirogyra	Efficient in absorbing oil components as compared to some herb plants; remediates mine drainage	Produces various types of bioactive components	[98–100]
Volvox	Possible role in remediating wastewater and heavy metals; needs more confirmation	May produce bioactive agents such as biofuels	[13,101,102]
Zygnema	No scientific evidence; needs testing	May produce bioactive compounds such as pigments and phenolic compounds with various roles	[103,104]

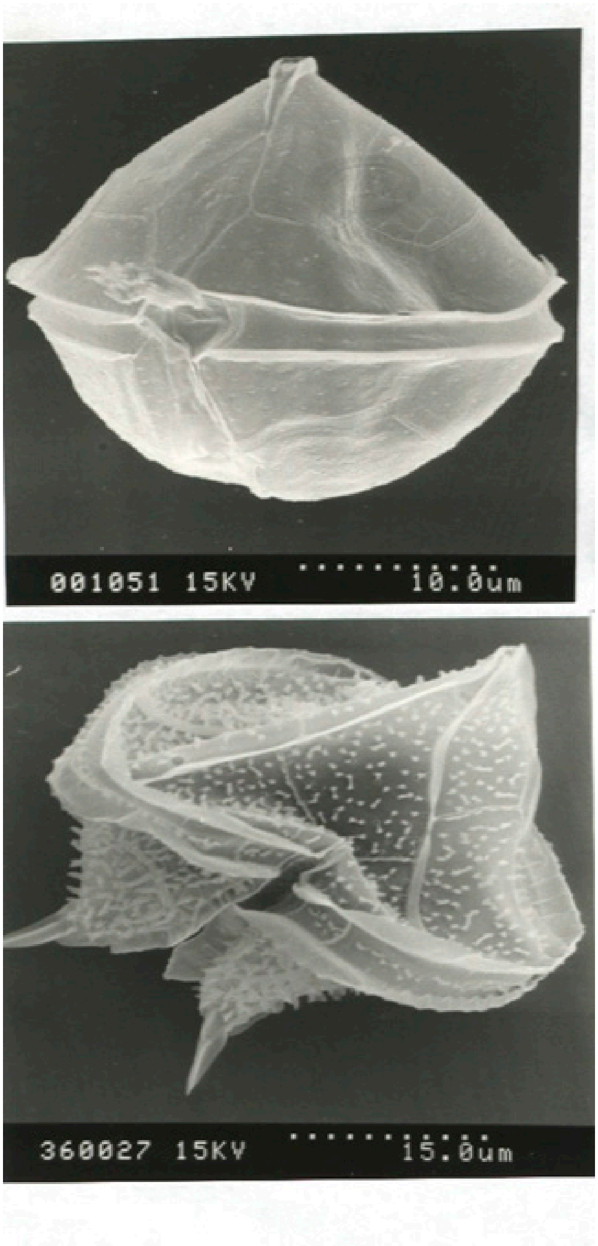

Figure 5. Three-dimensional image of some dinoflagellates, more species can be found in File S1.

Table 2. Dinoflagellate species recorded in the Arabian Gulf around the Qatari peninsula and their roles in phycoremediation and production of bioactive agents [5–7,105,106].

Genus	No. of recorded species	Remediation of organic and inorganic components	Other features and possible roles	References
Alexandrium	Not known	Needs testing	Mixotrophic mode; it is a well-known genus for its bloom-forming behavior and potential to produce toxins	[107,108]
*Amphidinium**	Not known	Shows possible role in remediation of petroleum hydrocarbons	Diverse range of trophic modes: producing bioactive compounds, serving in pharmaceutical applications, acting as food source for other marine organisms, and contributing to harmful algal blooms (HABs)	[84,100,109,111]
Ceratium	53	Needs testing and confirmation	Mixotrophic mode, harmless and non-toxic in nature, found in predators and prey in the ecosystem; fish kills result from depleting oxygen levels caused by blooms; high nitrogen levels compared to phosphorus encourage their growth; some species produce HABs	[112–114]
Ceratocorys	1	Needs testing	Autotrophic mode, no data available; further investigation is needed regarding its ability to absorb heavy metals, remove excess nutrients such as nitrogen and phosphorus, and degrade organic compounds	[115,116]
Dinophysis	6	Needs testing; some indications are promising	Mixotrophic mode; might produce diarrhetic toxins; possible role in production of bioactive agents	[84,117,118]
Diplopsalis	1	Possible remediation of heavy metals	Heterotrophic mode; the presence of some dinoflagellates showed a significant positive correlation with heavy metals; some species produce HABs; possible toxic impact on marine life; its presence might be a sign of pollution	[119–121]

*Exuviaella***	2	Needs testing	Little information about its role in phycoremediation; possible toxic impacts on marine life	[10,84]
*Glenodinium***	1	Little information about its role in phycoremediation, needs investigation	More investigations are needed regarding its role in the production of bioactive agents and HABs	[122,123]
*Gonyaulax***	12	Possible role in remediation of oil and gas components	Some toxins are produced within the cells	[124,125]
*Gymnodinium**	1	Possible role in remediation of oil and gas components	Nitrogen shortage might have negative effects on growth and toxin production; fatty acids synthesis was stimulated and anti-oxidant defense systems were upregulated; produces HABs that might cause toxic effects on marine organisms	[126–128]
Hemidinium	1	Needs testing	Heterotrophic; might produce HABs; needs testing for bioactive agents	[129]
Histioneis	1	Needs testing	Heterotrophic; further investigation needed to show production of HABs and bioactive agents	[130]
Noctiluca	1	Needs testing	Heterotrophic; produces HABs; might produce some bioactive agent during bloom production	[131–133]
Ornithocercus	2	Needs confirmation	Heterotrophic; further investigation needed to show and confirm the production of HABs and bioactive agents	[123,130,134]
*Oxytoxum****	6	Needs information and confirmation via testing	No indication of production of HABs and bioactive agents	[115,135]
Peridinium	2	Good indications of remediation roles; needs testing and confirmation	Mixotrophic mode; HABs were found with the presence of *Peridinium umbonatum*	[136]
*Phalacroma**	6	Needs testing	Might produce HABs and bioactive agents	[137]
*Podolampas***	3	Little information but	Little data available; needs further information	[138]

		needs further investigation		
*Prorocentrum***	3	Could be a candidate to remediate petroleum hydrocarbons and heavy metals, more studies are needed	Might produce HABs that could be toxic to marine life and fish; associated bacteria could help this dinoflagellate to resist and remediate petroleum hydrocarbons and heavy metals	[139,140]
Protopreidinium	41	Possible role in remediation of petroleum hydrocarbons, need to be monitored	Heterotrophic, non-toxic blooms consume other microalgae such as diatoms and dinoflagellates	[90,141,142]
Pseudophalacroma	1	No studies on remediation processes; needs testing	Heterotrophic; might produce HABs and bioactive agents	[138]
Pyrocystis	5	No studies; needs further testing	Autotrophic; needs investigation; might produce HABs and bioactive agents	[143,144]
*Pyrophacus***	1	No studies; needs further testing	Needs investigation; might produce HABs and bioactive agents	[6,7]
Triadinium	2	No studies; needs further testing	Autotrophic; needs investigation; might produce HABs and bioactive agents	[84]

*Some species are autotrophic; others are heterotrophic. **This genus exhibits phago-trophy, direct engulfment of large, small, and dead cells, and some exhibit an autotrophic mode. ***Heterotrophic, cannibalistic, and showing some remnant of photosystems.

2.5. Silicoflagellates

Silicoflagellates are a small group of unicellular, photosynthetic algae classified within the class Dictyochophyceae Silva, 1982 and the order Dictyochales Haeckel, 1894. They are characterized by their intricate siliceous skeletons, which consist of hollow rods joined at triple junctions to form distinctive three-dimensional structures. Along the coast of Qatar in the Arabian Gulf, only two species have been recorded, belonging to the genera *Dictyocha* and *Mesocena* (Table 3), as reported by Dorgham and Al-Muftah [105]. While some silicoflagellates are known to form blooms, their potential role in the remediation of petroleum hydrocarbons and heavy metals associated with oil and gas activities remains largely unexplored. Like many other microorganisms, silicoflagellates merit further research for their potential application in bioremediation [7,8].

Table 3. Two silicoflagellates species recorded in the Arabian Gulf around the Qatari peninsula.

Genus	No. of species	Remediation of organic and inorganic components	Other possible roles	References
Dictyocha	1	Needs testing	Produces blooms	[145,146]
Mesocena	1	Needs testing	Needs investigation	[147]

3. Microalgae Metabolism in Petroleum Hydrocarbon Remediation

Most algae are photosynthetic microorganisms capable of metabolizing a broad spectrum of organic pollutants, particularly those associated with oil and gas activities [11]. Different algal groups exhibit diverse photosynthetic efficiencies, primarily due to variations in their photosynthetic pigments. These pigments—such as chlorophylls, carotenoids, and phycobilins—absorb light at different wavelengths, thereby influencing the overall effectiveness of photosynthesis [148]. In addition to pigment variation, structural differences among algae may significantly impact the uptake and metabolism of various pollutants [149]. Furthermore, Yasseen and Al-Thani [150] suggest that the morphological and structural traits of wild plants and microorganisms could serve as valuable resources for modern gene technology.

Microalgae, as photosynthetic microorganisms, are highly effective in metabolizing a wide range of organic pollutants and remediating heavy metals from oil and gas activities [151]. They employ various mechanisms such as absorption, accumulation, and metabolic transformation to reduce contaminants to non-toxic levels. In the process, microalgae also produce numerous biologically active substances, including biofuels, anticancer agents, and cosmetic ingredients, along with valuable compounds such as proteins, lipids, polysaccharides, pigments, and vitamins [5,6,41]. Their efficiency is attributed to features such as a high surface-area-to-volume ratio, rapid metabolic rates, and broad availability in marine environments. Moreover, microalgae play a significant role in environmental remediation through mechanisms including direct degradation, biosorption, bioaccumulation, and the indirect stimulation of microbial consortia [152]. They can remove various contaminants, such as heavy metals and organic pollutants, from wastewater. This is achieved through biosorption, where pollutants bind to the algal surface, or through bioaccumulation, where contaminants are stored within vacuoles. Additionally, microalgae can enhance the activity of surrounding microbial communities, facilitating a more comprehensive breakdown of pollutants. Micro-green algae can contribute to hydrocarbon remediation through various methods and mechanisms. One such mechanism is photosynthetic oxygenation, whereby green algae produce oxygen through photosynthesis, which can be utilized by bacteria to mineralize PAHs originating from various sources. Notably, consortia of microalgae and bacteria can cooperate to degrade organic compounds using the oxygen generated via photosynthesis. PAHs are toxic to multiple ecosystems, including marine, freshwater, and terrestrial environments. Their harmful effects include mutagenic and carcinogenic impacts on living organisms, including humans. These effects may result from covalent interactions between PAHs and biomolecules such as RNA and proteins. Such interactions can negatively affect the endocrine system (e.g., the thyroid gland) and the reproductive and immune systems [26]. Wichmann et al. [28] have described algal hydrocarbon metabolism, including carbon partitioning capacities, the localization and size of precursor pools, environmental effects on flux distribution, and limiting factors affecting efficient (heterologous) hydrocarbon production.

A second relevant mechanism is biosorption, whereby hydrocarbons adhere to the algal cell wall components, including algaenans, proteins, lipids, and polysaccharides, providing multiple binding sites for hydrocarbon adsorption [153–155]. As non-polar surfaces, cell walls offer good sites for this method. In fact, this method is a primary step for biodegradation, a process which microorganisms can carry out. This method is a passive process by which biological materials, whether living or dead, adsorb pollutants such as petroleum hydrocarbons through physical and/or chemical interactions [156,157]. While it is not a metabolic process, it plays a critical supporting role in the remediation of hydrocarbon-contaminated environments. The mechanisms of biosorption can be achieved by adsorption, ion exchange complexation, and precipitation. Factors such as biomass type, pH, temperature, hydrocarbon type, and the presence of surfactants might enhance hydrocarbon solubility and uptake [158–161]. Another mechanism through which micro-green algae contribute to hydrocarbon remediation is bioaccumulation, which involves two primary mechanisms. The first is the uptake and sequestration of substances within non-metabolically active organelles, such as vacuoles. The second involves the uptake of compounds followed by their metabolic transformation. Heavy metals, for example, can be stored in vacuoles without undergoing metabolic alteration [162,163]. In contrast, organic constituents of petroleum hydrocarbons may either be sequestered in vacuoles or cell walls, or otherwise metabolized into less toxic compounds or into useful metabolites that contribute to various physiological and biochemical functions [29]. These metabolites can enter central metabolic pathways, including the Krebs cycle, fatty acid biosynthesis, and amino acid metabolism [23,24]. Enzymatic degradation plays a key role in these processes, involving enzymes such as oxygenases, peroxidases, and others that facilitate the breakdown of petroleum hydrocarbons. Some micro-green algae demonstrate high tolerance to hydrocarbon toxicity, while others can utilize petroleum hydrocarbons as a carbon source under specific environmental conditions [10,164]. Recent work by Abu-Tahon et al. [165] has explored the efficiency of microorganisms, including microalgae, in degrading various pollutant compounds such as hydrocarbons, dyes, pesticides, pharmaceutical wastes, and anthropogenic pollutants like polychlorinated biphenyls. Over the past five years, numerous studies and review articles have examined the mechanisms employed by native plants, seagrasses, seaweeds, microalgae such as diatoms, and cyanobacteria in the Arabian Gulf region, particularly in Qatar. These works have detailed the biochemical pathways, reactions, and methods involved in the transformation of toxic petroleum hydrocarbons and anthropogenic compounds into useful metabolites or less harmful substances [23,24,166]. Notably, the above reports have shown that some micro-green algae such as *Chlamydomonas*, *Nannochloropsis*, and *Scenedesmus* may be able to remediate organic compounds such as carbamazepine; pharmaceutical wastes such as sulfamethoxazole, triclosan, and trimethoprim; and most petroleum hydrocarbons [86,167,168]. Over the last decade, numerous studies have demonstrated that various native plants and crops—such as *Chloris gayana*, *Hordeum vulgare*, *Medicago sativa*, *Phragmites australis*, *Sporobolus ioclados*, and *Typha domingensis*—are effective in remediating industrial wastewater and polluted soil and water [169]. Yasseen [170] provides further details, discussions, and an expanded list of plants capable of remediating petroleum hydrocarbons and heavy metals. Other studies have been conducted to investigate the role of microorganisms from various groups such as bacteria, fungi, and algae in remediating petroleum hydrocarbons and heavy metals [171]. The mechanisms for biodegradation depend on many microbial enzymes such as oxidoreductases, hydrolases, peroxidases, oxygenases, proteases, lipases, and lacquers. Modern biotechnologies such as genetic engineering have been applied to improve the efficiency of the bioremediation, phytoremediation, and phycoremediation of pollutants [165]. Given this context, micro-green algae provide a sustainable, nutrient-rich, and eco-friendly solution for applications in food, feed, biofuel, and environmental management.

In conclusion, petroleum hydrocarbons undergo a series of biochemical transformations that result in either detoxification—often through sequestration in vacuoles—or integration into central metabolic routes. After uptake, they are commonly oxidized by monooxygenases or dioxygenases, forming intermediates such as fatty acids, which are then assimilated into pathways like the Krebs cycle, fatty acid biosynthesis, and amino acid metabolism. These processes can yield useful metabolites such as acetyl-CoA, succinate, pyruvate, and various amino acid precursors, which support cellular growth and energy production.

 doi:10.20944/preprints202506.1825.v1

Dinoflagellates are a group of unicellular protists found in both marine and freshwater environments, where they play diverse ecological roles and can gain competitive advantages in polluted marine settings. They perform photosynthesis to convert sunlight into energy-rich organic compounds and serve as a foundational part of the marine food web. Many of these organisms contain chlorophylls *a* and *c2*, along with other pigments such as carotenoids, including peridinin, diadinoxanthin, diatoxanthin, and β-carotene.

Dinoflagellates exhibit three trophic modes—photosynthetic, heterotrophic, and mixotrophic—that enhance their ecological versatility, particularly in polluted environments [172–174]. Photosynthetic dinoflagellates harness solar energy through chlorophyll and accessory pigments to produce organic matter via photosynthesis. In oil-contaminated waters, this capability contributes to photo-enhanced hydrocarbon degradation. Light-driven photolysis can break down hydrocarbon molecules, and the reactive oxygen species generated during photosynthesis can oxidize hydrocarbons, aiding in their detoxification. These organisms may also assimilate dissolved organic compounds derived from partially degraded petroleum, integrating them into the microbial loop. Heterotrophic dinoflagellates, which lack photosynthetic machinery, obtain nutrients by ingesting particulate matter, including crude oil droplets and oil-contaminated prey such as bacteria or smaller protists. Once internalized, hydrocarbons may be enzymatically metabolized or compartmentalized in vacuoles, allowing the dinoflagellates to tolerate otherwise toxic environments. Through this process, they also contribute to the vertical transfer of hydrocarbons when these marine organisms die and sink, as well as to horizontal transfer, which involves the movement of hydrocarbons across the water surface, either between organisms or from one area to another within marine food webs, thereby influencing their distribution and potential biodegradation by other organisms. On the other hand, mixotrophic dinoflagellates combine autotrophic and heterotrophic nutrition, enabling them to adapt to the varying light and nutrient conditions typical of oil-contaminated habitats. This flexibility allows them to survive and remain metabolically active in environments where either light or organic matter is limited. Furthermore, mixotrophs can secrete extracellular enzymes that initiate the breakdown of complex hydrocarbon compounds outside the cell, facilitating subsequent uptake and metabolism. Their ability to degrade aliphatic hydrocarbons is well documented, although their efficiency in degrading PAHs—which are more persistent and toxic—is comparatively limited. Beyond individual metabolic capacities, dinoflagellates often form mutualistic relationships with hydrocarbon-degrading bacteria. These consortia enhance the overall degradation process by combining algal photosynthetic oxygen production with bacterial enzymatic pathways. Such interactions are especially valuable in oxygen-limited conditions, such as deeper water columns or stratified environments affected by oil spills. This symbiosis accelerates the breakdown of petroleum hydrocarbons and contributes to the detoxification and recovery of polluted marine and freshwater systems [115]. In general, both autotrophic and heterotrophic dinoflagellates contribute to the degradation of these pollutants and can influence the impact of oil spills. Their efficiency varies depending on the species, environmental conditions, and the nature of the petroleum hydrocarbons involved. Field studies have confirmed the presence and activity of hydrocarbon-tolerant dinoflagellate species in oil-polluted environments. Notably, genera such as *Amphidinium*, *Diplopsalis*, *Gonyaulax*, *Peridinium*, *Prorocentrum*, and *Protoperidinium*, along with other species listed in Table 2, have been identified in the Arabian Gulf, a region heavily impacted by petroleum activities. All these genera need to be tested for their potential role in the remediation of various types of pollutants. These dinoflagellates demonstrate not only tolerance to hydrocarbon contamination but also active participation in biogeochemical processes that mitigate pollution levels.

In recent years, dinoflagellates have garnered increasing attention for their potential role in the bioremediation of petroleum hydrocarbons and heavy metals. Although traditionally overshadowed by bacteria and fungi in environmental remediation research, emerging studies have revealed that dinoflagellates possess unique metabolic and enzymatic mechanisms that enable them to interact with and degrade hydrocarbon pollutants [7]. Enzymatic systems such as monooxygenases and dioxygenases facilitate the oxidation of hydrocarbons, transforming these compounds into less toxic intermediates or allowing their sequestration within intracellular vacuoles [7,175].

4. Comparative Analysis of Micro-Green Algae and Dinoflagellates

Comparing micro-green algae and dinoflagellates reveals differences across several key aspects, including general characteristics, photosynthetic mechanisms, ecological roles, bioremediation potential, production of bioactive compounds, and their impact on marine environments through toxic effects. Despite these differences, both groups play vital roles in aquatic ecosystems, contribute to biotechnology applications, and form integral components of aquatic food webs. Table 4 summarizes the distinguishing features of these two groups.

Although the micro-green algae discussed in this review are not commonly found in the seawater of the Arabian Gulf, their presence in inland freshwater bodies such as lakes and pools in Qatar may inspire further research into their potential applications in industrial wastewater treatment. Such investigations could contribute to broader environmental efforts aimed at restoring polluted terrestrial and marine ecosystems. Future research may not only help mitigate the impacts of toxic organic and inorganic contaminants but also support the rehabilitation of degraded land and water resources, thereby contributing to the availability of clean water for various purposes, including agricultural irrigation and potentially even potable use [24]. Recent studies have highlighted the significant role of algae in remediating water polluted by anthropogenic and industrial activities [24,166,170]. Several species of macroalgae identified in recent years have shown great potential for the phycoremediation of contaminated seawater [5,6].

Table 4. Comparative characteristics of micro-green algae and dinoflagellates.

Characteristics	Micro-green algae	Dinoflagellates
Classification	Protista, Chlorophyta	Protista, Dinoflagellata
Habitat and ecology	Freshwater and marine; base of food chain; oxygen producers; stable in their habitat	Mostly marine, some freshwater; primary producers and predators; key in marine food webs; produce blooms and show bioluminescence
Cell type	Cellulosic cell wall	Complex cell wall with some cellulose; layered system of membranes, vesicles, and plates
Photosynthetic pigments	Chlorophylls *a* and *b*, giving appearance of green color with some carotenoids and xanthophylls; efficient in light absorption	Chlorophylls *a* and *c*, various types of carotenoids and xanthophylls like peridinin, giving a golden-brown color; less efficient in light absorption
Trophic mode	Autotrophic	Autotrophic, heterotrophic, mixotrophic
Human health	Low impact unless contaminated; largely safe	High, many cause HABs, mostly toxic cause fish kills
Toxin production	Rarely produce harmful toxins	Many are toxics, producing number of toxins*
Bioactive agents	Produce bioactive agents such as pharmaceuticals, nutraceuticals, cosmetics, and biotechnology uses	Highly used in marine pharmacology, neurotoxicology, and biotechnology
Environmental impact	Mostly safe, stable, and commercially useful, especially for nutrition and renewable energy	Harmful blooms, marine toxins, and bioluminescence

*See the text.

 doi:10.20944/preprints202506.1825.v1

Dinoflagellates, though rare in Qatari inland environments such as pools and freshwater bodies, are present in the seawater of the Arabian Gulf. While their use in irrigation water production is limited, these marine microorganisms possess considerable potential in environmental and biotechnological applications. They are known to produce a wide array of bioactive compounds with relevance to the health, industrial, and ecological sectors. In addition, dinoflagellates contribute to the removal and metabolism of both inorganic and organic pollutants and serve as sensitive bioindicators of marine pollution, particularly that associated with oil and gas activities. Through their diverse physiological and biochemical processes, dinoflagellates can significantly influence human health, environmental sustainability, and economic stability. Notably, their increased abundance is often a response to oil and gas pollution, and this proliferation under such conditions may lead to a range of ecological and biochemical effects. First, the proliferation of dinoflagellates may lead to the production of potent marine toxins, both hemolytic and neurotoxic,-that could have a negative impact on public health and fisheries [58]. These neurotoxins are known as brevetoxins, which are a suite of ladder-like polycyclic ether toxins that can cause serious illnesses in humans, such as paralytic or neurotoxic shellfish poisoning [61]. A second possible effect is the synthesis of bioactive secondary metabolites, including anticancer, antiviral, and inflammatory agents [176]. Third, dinoflagellate proliferation results in photosynthesis, a process that produces oxygen, which encourages the degradation of petroleum hydrocarbons, while at the same time reducing carbon dioxide, thus mitigating climate change due to the ill effects of modern technology [177]. Fourth, dinoflagellates have a symbiotic association with corals, providing them with important nutrients such as amino acids, glucose, and glycerol, which give corals energy and help build the coral structure. Conversely, dinoflagellates receive protection and access to waste products such as carbon dioxide, nitrogen, and phosphorus, which are needed for vital activities such as photosynthesis and biosynthesis of various metabolites such as amino acids and fatty acids. Also, the association between dinoflagellates with microorganisms such as bacteria may strongly influence reef health and biodiversity, in addition to facilitating the degradation of petroleum hydrocarbons [178]. Finally, a fifth effect of dinoflagellates is that they can be a tool for environmental monitoring and bioremediation [125].

5. Conclusions

In recent years, a third strategy—centered on environmental and genetic interventions—has gained prominence for enhancing the ability of autotrophs to adapt to diverse conditions and contribute to pollution mitigation. Over the past two decades, biological approaches have shown considerable promise in addressing contamination from heavy metals and organic pollutants in wastewater across various sectors. A growing body of research emphasizes the synergistic relationships between autotrophs and microorganisms, particularly bacteria and fungi, in confronting complex environmental challenges such as pollution from the oil and gas industry. These partnerships function as integrated systems, with bacteria initiating the breakdown of complex petroleum hydrocarbons and heavy metals, and autotrophs—especially microalgae like green algae, diatoms, and dinoflagellates—further metabolizing or sequestering the byproducts into less harmful forms or storing them in non-functional organelles like vacuoles to reduce toxicity.

This review considers autotrophs and heterotrophs together because, independently, their capacity to remediate petroleum hydrocarbons is limited. Effective bioremediation typically depends on cooperation with microbial communities [10]. In regions such as Qatar, the intrusion of polluted seawater inland and the discharge of untreated sewage into pools and lakes exacerbate environmental degradation. Petroleum hydrocarbons and other human-derived contaminants threaten soil and water quality [24,40,179–181]. Nonetheless, microalgae in aquatic environments and native vegetation on land, in collaboration with microbes, can help degrade these harmful substances and support ecological resilience. However, these organisms may also accumulate heavy metals, potentially leading to toxic buildup. Regular environmental monitoring is therefore crucial to ensure that metal concentrations remain within internationally accepted safety thresholds. Achieving a

 doi:10.20944/preprints202506.1825.v1

sustainable balance between leveraging biological remediation and maintaining ecological safety is essential for long-term environmental health.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org.

Acknowledgments: The author would like to thank Qatar University for supporting the publication of this scientific article. Thanks, are also due to Nada Abbara for her assistance in designing the map of Qatar and the graphic abstract.

References

1. Al-Imarah, F.J.M.; Hantoosh, A.A.; Nasir, A.M. Petroleum hydrocarbons in water and sediments of northwest Arabian Gulf 1980-2005. *AEHMS*. **2007**. *10*, 335-340. https://doi: 10.1080/14634980701513200.
2. Freije, AM. Heavy metal, trace element and petroleum hydrocarbon pollution in the Arabian Gulf: Review. J. *Assoc. Arab Univ. Basic Appl. Sci*. **2015**, *17*, 90-100. https://doi:10.1016/j.jaubas.2014.02.001.
3. Li, X.; Shen, X.; Jiang, W.; Xi, Y.; Li, S. Comprehensive review of emerging contaminants: Detection technologies, environmental impact, and management strategies. *Ecotoxicol. Environ. Saf.* **2024**, *116420*. https://doi.org/10.1016/j.ecoenv.2024.116420.
4. Ben Chekroun, K.; Sanchez, E.; Baghour, M. The role of algae in bioremediation of organic pollutants. *Int. Res. J. Public Environ. Health* **2014**, *1*, 19–32.
5. Al-Thani, R.F.; Yasseen, B.T. Methods using marine aquatic photoautotrophs along the Qatari coastline to remediate oil and gas industrial water. *Toxics* **2024**, *12*, 625. https://doi.org/10.3390/toxics12090625.
6. Al-Thani, R.F.; Yasseen, B.T. Cyanoremediation of polluted seawater in the Arabian Gulf: Risks and benefits to human health. *Processes* **2024**, *12*, 2733. https:// doi.org/10.3390/pr12122733.
7. Al-Thani, R.F.; Yasseen, B.T. The role of phytoplankton in phycoremediation of polluted seawater: Risks, benefits to human health, and a focus on diatoms in the Arabian Gulf. *Water* **2025**, *17*, 920. https://doi.org/10.3390/w17070920.
8. Das, N.; Chandran, P. Microbial degradation of petroleum hydrocarbon contaminants: An overview. *Biotechnol. Res. Int.* **2011**, 941810. https://doi.org/10.4061/2011/941810.
9. Eze, C.N.; Onyejiaka, C.K.; Ihim, S.A.; Ayoka, T.O.; Aduba, C.C.; Ndukwe, J.K.; Nwaiwu, O.; Helen Onyeaka, H. Bioactive compounds by microalgae and potentials for the management of some human disease conditions. *AIMS Microbiol.* **2023**, *9*, 55–74. https://doi.org/10.3934/microbiol.2023004.
10. Dell' Anno, F.; Rastelli, E.; Sansone, C.; Brunet, C.; Ianora, A.; Dell' Anno, A. Bacteria, fungi, and microalgae for the bioremediation of marine sediments contaminated by petroleum hydrocarbons in the omics era. *Microorganisms* **2021**, *9*, 1695. https://doi.org/10.3390/microorganisms9081695.
11. Abdelfattah, A.; Ali, S.S.; Ramadan, H.; El-Aswar, E.I.; Eltawab, R.; Ho, S.-H.; Elsamahy, T.; Li, S.; El-Sheekh, M.M.; Schagerl, M.; Kornaros, M.; Sun, J. Microalgae-based wastewater treatment: Mechanisms, challenges, recent advances, and prospects. *Environ. Sci. Ecotechnol*. **2023**, *13*, 100205. https://doi.org/10.1016/j.ese.2022.100205.
12. Flayyih, A.H.; AL Magdamy, B.A. Phytoremediation of petroleum hydrocarbon by micro green algae: A review. *J. Biotechnol. Res. Center* **2024**, *18*. https://doi.org/10.24126/jobrc.2024.18.2.805.
13. Chugh, M.; Kumar, L.; Shah, M.P.; Bharadvaja, N. Algal bioremediation of heavy metals: An insight into removal mechanisms, recovery of by-products, challenges, and future opportunities. *Energy Nexus* **2022**, *7*, 100129. https://doi.org/10.1016/j.nexus.2022.100129.
14. Bora, A.; Rajan, A.S.T.; Ponnuchamy, K.; Muthusamy, G.; Alagarsamy, A. Microalgae to bioenergy production: Recent advances, influencing parameters, utilization of wastewater – A critical review. *Sci. Total Environ.* **2024**, *946*, 174230. https://doi.org/10.1016/j.scitotenv.2024.174230.
15. Da Rosa, M.D.H.; Alves, C.J.; dos Santos, F.N.; de Souza, A.O.; Zavareze, E, da-R.; Ernani Pinto, E.; Noseda, M.D.; Ramos, D.; de Pereira, C.M.P. Macroalgae and microalgae biomass as feedstock for products applied to bioenergy and food industry: A brief review. *Energies* **2023**, *16*, 1820. https://doi.org/10.3390/en16041820.

16. Saini, S.; Gill, J.K.; Kaur, J.; Saikia, H.R.; Singh, N.; Kaur, I.; Katnoria, J.K. Biosorption as environmentally friendly technique for heavy metal removal from wastewater. In *Fresh Water Pollution Dynamics and Remediation*; Qadri, H., Bhat, R., Mehmood, M., Dar, G., Eds.; Springer: Singapore; 2020. https://doi.org/10.1007/978-981-13-8277-2_10.
17. Touliabah, H.E.; El-Sheekh, M.M.; Ismail, M. M.; El-Kassas, H. A review of microalgae-and cyanobacteria -based biodegradation of organic pollutants. *Molecules* **2022**, *27*, 1141. https://doi.org/10.3390/molecules27031141.
18. Devi, A.; Verma, M.; Saratale, G.D.; Saratale, R.G.; Ferreira, L.F.R.; Mulla, S.I.; Bharagava, R.N. Microalgae: A green eco-friendly agent for bioremediation of tannery wastewater with simultaneous production of value-added products. *Chemosphere* **2023**, *336*, 139192. https://doi.org/10.1016/j.chemosphere.2023.139192.
19. Mahlangu, D.; Mphahlele, K.; De Paola, F.; Mthombeni, N.H. Microalgae-mediated biosorption for effective heavy metals removal from wastewater: A review. *Water* **2024**, *16*, 718. https://doi.org/10.3390/w16050718.
20. Soto-Ramírez, R.; Lobos, M.-G.; Córdova, O.; Poirrier, P.; Chamy, R. Effect of growth conditions on cell wall composition and cadmium adsorption in *Chlorella vulgaris*: A new approach to biosorption research. *J. Hazard. Mater.* **2021**, *411*, 125059. https://doi.org/10.1016/j.jhazmat.2021.125059.
21. Shrestha, R.; Ban, S.; Devkota, S.; Sharma, S.; Joshi, R.; Tiwari, A.P.; Kim, H.Y.; Joshi, M.K. Technological trends in heavy metals removal from industrial wastewater: A review. *Environ. Chem. Eng.* **2021**, *9*, 105688. https://doi.org/10.1016/j.jece.2021.105688.
22. Sarma, U.; Hoque, M.E.; Thekkangil, A.; Venkatarayappa, N.; Rajagopal, S. Microalgae in removing heavy metals from wastewater – An advanced green technology for urban wastewater treatment. *J. Hazard. Mater.* **2024**, *15*, 100444. https://doi.org/10.1016/j.hazadv.2024.100444.
23. Al-Thani, R.F.; Yasseen, B.T. Phytoremediation of polluted soils and waters by native Qatari plants: Future perspectives. *Environ. Pollut.* **2020**, *259*, 113694. https://doi.org/10.1016/j.envpol.2019.113694.
24. Al-Thani, R.F.; Yasseen, B.T. Perspectives of future water sources in Qatar by phytoremediation: Biodiversity at ponds and modern approach. *Int. J. Phytoremediat.* **2021**, *23*, 866-889. https://doi.org/10.1080/15226514.2020.1859986.
25. Hamouda, R.A.; Alhumairi, A.M.; Saddiq, A.A. Simultaneous bioremediation of petroleum hydrocarbons and production of biofuels by the micro-green alga, cyanobacteria, and its consortium. *Heliyon* **2023**, *9*, e16656. https://doi.org/10.1016/j.heliyon.2023.e16656.
26. Satpati, G.G.; Gupta, S.; Biswas, R.K.; Choudhury, A.K.; Kim, J.-W.; Davoodbasha, M.A. Microalgae mediated bioremediation of polycyclic aromatic hydrocarbons: Strategies, advancement, and regulations. *Chemosphere* **2023**, *344*, 140337. https://doi.org/10.1016/j.chemosphere.2023.140337.
27. Mohsenpour, S.F.; Hennige, S.; Willoughby, N.; Adeloye, A.; Gutierrez, T. Integrating micro-algae into wastewater treatment: A review. *Sci. Total Environ.* **2021**, *752*, 142168. https://doi.org/10.1016/j.scitotenv.2020.142168.
28. Wichmann, J.; Lauersen, K.J.; Kruse, O. Green algal hydrocarbon metabolism is an exceptional source of sustainable chemicals. *Curr. Opin. Biotechnol.* **2020**, *61*, 28–37. https://doi.org/10.1016/j.copbio.2019.09.019.
29. Dey, S.; Samanta, P.; Ghosh, A.R.; Banerjee, S.; Sen, K. State-of-the-art microalgae-based bioreactor wastewater treatment for the elimination of emerging contaminants: A mechanistic review. *Cleaner Water* **2024**, *2*, 100027. https://doi.org/10.1016/j.clwat.2024.100027.
30. Koedooder, C.; Stock, W.; Willems, A.; Mangelinckx, S.; De Troch, M.; Vyverman, W.; Sabbe, K. Diatom-bacteria interactions modulate the composition and productivity of benthic diatom biofilms. *Front. Microbiol.* **2019**, *10*, 1255. https://doi.org/10.3389/fmicb.2019.01255.
31. Thompson, H.F. Investigating Relationships Between Hydrocarbonoclastic Bacteria and Micro-Algae. Ph. D. Thesis, Heriot-Watt University, School of Engineering & Physical Science, UK, 2017.
32. Vo, T.P.; Danaee, S.; Chaiwong, C.; Pham, B.T.; Poddar, N.; Kim, M.; Kuzhiumparambil, U.; Songsomboon, C.; Pernice, M.; Ngo, H.H.; Ralph, P.J.; Vo, P.H.N. Microalgae-bacteria consortia for organic pollutants remediation from wastewater: A critical review. *J. Environ. Chem. Eng.* **2024**, *12*, 114213. https://doi.org/10.1016/j.jece.2024.114213.

33. Al-Thani, R.F.; Yasseen, B. T. Biological soil crusts and extremophiles adjacent to native plants at Sabkhas and Rawdahs, Qatar: The possible roles. *Front. Environ. Microbiol.* **2018**, *4*, 55–70. https://doi.org/10.11648/j.fem.20180402.13.
34. Al-Thani, R.F.; Yasseen, B.T. Solutes in native plants in the Arabian Gulf Region and the role of microorganisms: Future research. *J. Plant Ecol.* **2018**, *11*, 671–684. https://doi.org/10.1093/jpe/rtx066.
35. Wiedenbeck, J.; Cohan, F.M. Origins of bacterial diversity through horizontal genetic transfer and adaptation to new ecological niches. *FEMS Microbiol. Rev.* **2011**, *35*, 957–976.
36. Huang, J. Horizontal gene transfer in eukaryotes: The weak link model. *Bioessays* **2013**, *35*, 868–875.
37. Bode, H.B.; Müller, R. Possibility of bacterial recruitment of plant genes associated with the biosynthesis of secondary metabolites. *Plant Physiol.* **2003**, *132*, 1153–1161.
38. Vinayamohan, P.G.; Pellissery, A.J.; Venkitanarayanan, K. Role of horizontal gene transfer in the dissemination of antimicrobial resistance in food animal production. *Curr. Opin. Food Sci.* **2022**, *47*, 100882. https://doi.org/10.1016/j.cofs.2022.100882.
39. Schönknecht, G.; Chen, W.-H.; Ternes, C.M.; Barbier, G.G.; Shrestha, R.P.; Stanke, M.; Bräutigam, A.; Baker, B.J.; Banfield, J.F.; Garavito, R.M.; Carr, K.; Wilkerson, C.; Rensing, S. A.; Gagneul, D.; Dickenson, N.E.; Oesterhelt, C.; Lercher, M.J.; Weber, A.P.M. Gene transfer from bacteria and archaea facilitated evolution of an extremophilic eukaryote. *Sci.* **2013**, *339*, 1207–1210. doi. 10.1126/science.1231707.
40. Yasseen, B.T; Al-Thani, R.F. Endophytes and halophytes to remediate industrial wastewater and saline soils: Perspectives from Qatar. *Plants* **2022**, *11*, 1497. https:// doi.org/10.3390/plants1111149.
41. Dolganyuk, V.; Belova, D.; Babich, O.; Prosekov, A.; Ivanova, S.; Katserov, D.; Patyukov, N.; Sukhikh, S. Microalgae: A promising source of valuable bioproducts. *Biomolecules* **2020**, *10*, 1153. https://doi.org/10.3390/biom10081153.
42. Gurreri, L.; Rindina, M.C.; Luciano, A.; Lima, S.; Scargiali, F.; Fino, D.; Mancini, G. Environmental sustainability of microalgae-based production systems: Roadmap and challenges towards the industrial implementation. *Sustain. Chem. Pharm.* **2023**, *35*, 101191. https://doi.org/10.1016/j.scp.2023.101191.
43. Ahmad, A.; Ashraf, S.S. Harnessing microalgae: Innovations for achieving UN Sustainable Development Goals and climate resilience. *J. Water Process Eng.* **2024**, *68*, 106506. https://doi.org/10.1016/j.jwpe.2024.106506.
44. Parida, P.K.; Selvi, G.A.; Vinodhini, S.M.; Reddy, M. B. Carbon sequestration by terrestrial, aquatic, and marine biodiversity, Chapter 13. In *Impact of Societal Development and Infrastructure on Biodiversity Decline*; 2024. IGI Global Platform. https://doi.org/10.4018/979-8-3693-6950-0.ch013. pp. 215-245.
45. Hosny, S.; Elshobary, M.E.; El-Sheekh, M.M. Unleashing the power of microalgae: A pioneering path to sustainability and achieving the Sustainable Development Goals. *Environ. Sci. Pollut. Res.* **2025**. https://doi.org/10.1007/s11356-025-35885-8.
46. Dutta, S.; Kataki, S.; Banerjee, I.; Pohrmen, C.B.; Jaiswal, K.K.; Jaiswal, A.K. Microalgal biorefineries in sustainable biofuel production and other high-value products. *New Biotechnol.* **2025**, *87*, 39–59. https://doi.org/10.1016/j.nbt.2025.02.007.
47. Silva, M.; Geada, P.; Pereira, R.N.; Teixeira, J.A. Microalgae biomass–A source of sustainable dietary bioactive compounds towards improved health and well-being. *Food Chem. Adv.* **2025**, *6*, 100926. https://doi.org/10.1016/j.focha.2025.100926.
48. Kukreja, S.; Thakur, K.; Salaria, N.; Goutam, U. Changing Trends in Microalgal Energy Production- Review of Conventional and Emerging Approaches. *J. Pure Appl. Microbiol.* **2017**, *11*, 993–1007. https://doi.org/10.22207/JPAM.11.2.42.
49. Moshood, T.D.; Nawanir, G.; Mahmud, F. Microalgae biofuels production: A systematic review on socioeconomic prospects of microalgae biofuels and policy implications. *Environ. Chall.* **2021**, *5*, 100207. https://doi.org/10.1016/j.envc.2021.100207.
50. Siddiki, Y.-A.; Mofijur, M.; Kumar, P.S.; Ahmed, S.F.; Inayat, A.; Kusumo, F.; Badruddin, I.A.; Yunus Khan, T.M.; Nghiem, L.D.; Ong, H.C.; Indra Mahlia, T.M.I. Microalgae biomass as a sustainable source for biofuel, biochemical and biobased value-added products: An integrated biorefinery concept. *Fuel* **2022**, *307*, 121782. https://doi.org/10.1016/j.fuel.2021.121782.

51. Khan, M.I.; Shin, J.H.; Kim, J.D. The promising future of microalgae: Status, challenges, and optimization of a sustainable and renewable industry for biofuels, feed, and other products. *Microb. Cell Fact.* **17**, 36 (2018). https://doi.org/10.1186/s12934-018-0879-x.
52. Gárate-Osuna, A.J.; Ambriz-Pérez, D.L.; Angel, V.-O.; Ballardo, D.U.S. Microalgae as a promising alternative for development of biorefineries: Main technological and economical challenges. *Arquivos de Ciências do Mar* **2022**, *55*, 369–412. https://doi.org/10.32360/acmar.v55iEspecial.78410.
53. Naik, B.; Mishra, R.; Kumar, V.; Mishra, S.; Gupta, U.; Rustagi, S.; Gupta, A.K.; Preet, M.S.; Bhatt, S.C.; Rizwanuddin, S. Micro-algae: Revolutionizing food production for a healthy and sustainable future. *J. Agric. Food Res.* **2024**, *15*: 100939. https://doi.org/10.1016/j.jafr.2023.100939.
54. Perkins, J.C.; Zenger, K.R.; Kjeldsen, S.R.; Liu, Y.; Strugnell, J.M. Assessment of dinoflagellate diversity using DNA metabarcoding reveals toxic dinoflagellate species in Australian coastal waters. *Mar. Pollut. Bull.* **2025**, *210*: 117319. https://doi.org/10.1016/j.marpolbul.2024.117319.
55. Pospelova, V.; Chmura, G.L.; Walker, H.A. Environmental factors influencing spatial distribution of dinoflagellate cyst assemblages in shallow lagoons of Southern New England (USA). *Rev. Palaeobot. Palynol.* **2004**, *128*, 7–34. https://doi.org/10.1016/S0034-6667(03)00110-6.
56. Song, Y.; Guo, Y.; Liu, H.; Zhang, G.; Zhang, X.; Thangaraj, S.; Sun, J. Water quality shifts the dominant phytoplankton group from diatoms to dinoflagellates in the coastal ecosystem of the Bohai Bay. *Mar. Pollut. Bull.* **2022**, *183*: 114078. https://doi.org/10.1016/j.marpolbul.2022.114078.
57. Herawati, E.Y.; Valina, R.; Dini, C.F.A.; Cahyani, V.; Handayani, M.P.; Khasanah, R.I.; Wiratno, E.N.; Samuel, P.D. Eutrophication, and distribution of dinoflagellates as an indicator of water quality in the Probolinggo Coast, East Java, Indonesia. *AACL Bioflux* **2023**, *16*, 2174–2184.
58. Wang, D.Z. Neurotoxins from marine dinoflagellates: A brief review. *Mar. Drugs* **2008**, *6*: 349–371. https://doi.org/10.3390/md20080016.
59. Botana, L.M.; Alfonso, A.; Vale, C.; Vilariño, N.; Rubiolo, J.; Alonso, E.; Cagide, E. The mechanistic complexities of phycotoxins: Toxicology of azaspiracids and yessotoxins. In *Advances in Molecular Toxicology* **2014**, *8*, 1–33. https://doi.org/10.1016/B978-0-444-63406-1.00001-5.
60. Naar, J.; Flewelling, L.; Lenzi, A.; Abbott, J.P.; Granholm, A.; Jacocks, H.M.; Gannon, D.; Henry, M.S.; Pierce, R.H.; Baden, D.; Wolny, J.; Landsberg, J.H. Brevetoxins, like ciguatoxins, are potent ichthyotoxic neurotoxins that accumulate in fish. *Toxicon* **2007**, *50*, 707–723. https://doi.org/10.1016/j.toxicon.2007.06.005.
61. Watkins, S.M.; Reich, A.; Fleming, L.E.; Hammond, R. Neurotoxic shellfish poisoning. *Mar. Drugs* **2008**, *6*, 431–455. https://doi.org/10.3390/md20080021.
62. Louzao, M.C.; Vilariño, N.; Vale, C.; Costas, C.; Cao, A.; Raposo-Garcia, S.; Vieytes, M.R.; Botana, L.M. Current trends, and new challenges in marine phycotoxins. *Mar. Drugs* **2022**, *20*, 198. https://doi.org/10.3390/md20030198.
63. Steidinger, K.A. Some taxonomic and biologic aspects of toxic dinoflagellates. In *Algal Toxins in Seafood and Drinking Water*; 1993; pp. 1–28. https://doi.org/10.1016/B978-0-08-091811-2.50006-X
64. Perkins, J.C.; Zenger, K.R.; Liu, Y.; Strugnell, J.M. Ciguatera poisoning: A review of the ecology and detection methods for *Gambierdiscus* and *Fukuyoa* species. *Harmful Algae* **2024**, *139*, 102735. https://doi.org/10.1016/j.hal.2024.102735.
65. Holmes, M.J.; Lewis, R.J. Reviewing evidence for disturbance to coral reefs increasing the risk of ciguatera. *Toxins* **2025**, *17*, 195. https://doi.org/10.3390/toxins17040195.
66. Darracq, M.A. Ciguatoxin. Encyclopedia of Toxicology, 3rd ed.; 2014; pp. 963–965. https://doi.org/10.1016/B978-0-12-386454-3.00712-0
67. L'Herondelle, K.; Talagas, M.; Mignen, O.; Misery, L.; Le Garrec R. (2020). Neurological disturbances of ciguatera poisoning: Clinical features and pathophysiological basis. *Cells* **2020**, 9, 2291. https://doi.org/10.3390/cells9102291.
68. Dietrich, J.; Grass, I.; Günzel, D.; Herek, S.; Braeuning, A.; Lampen, A.; Hessel-Pras, S. The marine biotoxin okadaic acid affects intestinal tight junction proteins in human intestinal cells. *Toxicol.* In Vitro **2019**, *58*, 150–160. https://doi.org/10.1016/j.tiv.2019.03.033.

69. Liu, Y.; Yuan, T.; Zheng, J.; Li, D.; Jiao, Y.; Li, H.; Li, R.; Yang, W. Exposure to okadaic acid could disrupt the colonic microenvironment in rats. *Ecotoxicol. Environ. Saf.* **2023**, *263*, 115376. https://doi.org/10.1016/j.ecoenv.2023.115376.
70. Henigman, U.; Mozetič, P.; Francé, J.; Knific, T.; Vadnjal, S.; Dolenc, J.; Kirbiš, A.; Biasizzo, M. Okadaic acid as a major problem for the seafood safety (*Mytilus galloprovincialis*) and the dynamics of toxic phytoplankton in the Slovenian coastal sea (Gulf of Trieste, Adriatic Sea). *Harmful Algae* **2024**, *135*, 102632. https://doi.org/10.1016/j.hal.2024.10263.
71. Valdiglesias, V.; Prego-Faraldo, M.V.; Pásaro, E.; Méndez, J.; Laffon, B. Okadaic acid: More than a diarrheic toxin. *Mar. Drugs* **2013**, *11*, 4328–4349. https://doi.org/10.3390/md11114328.
72. Sosa, S.; Tubaro, A. Okadaic acid and other diarrheic toxins: Toxicological profile. In *Marine and Freshwater Toxins*; Gopalakrishnakone, P., Haddad V., Kem, W., Tubaro, A., Kim, E., Eds.; Springer, Dordrecht, 2015. https://doi.org/10.1007/978-94-007-6650-1_4-.
73. Wiese, M.; D'Agostino, P.M.; Mihali, T.K.; Moffitt, M.C.; Neilan, B.A. Neurotoxic alkaloids: saxitoxin and its analogs. *Mar. Drugs* **2010**, *8*, 2185–2211. https://doi.org/10.3390/md8072185.
74. Akbar, M.A.; Yusof, N.Y.; Yusof, M.; Tahir, N.I.; Ahmad, A.; Usup, G.; Sahrani, F K.; Bunawan, H. Biosynthesis of saxitoxin in marine dinoflagellates: An omics perspective. *Mar. Drugs* **2020**, *18*, 103. https://doi.org/10.3390/md18020103.
75. Paz, B.; Daranas, A.H.; Norte, M.; Riobó, P.; Franco, J.M.; Fernández, J.J. Yessotoxins, a group of marine polyether toxins: An overview. *Mar. Drugs* **2008**, *6*, 73–102. https://doi.org/10.3390/md20080005.
76. Nieves, M.G.; Díaz, P.A.; Araya, M.; Salgado, P.; Rojas, R.; Quiroga, E.; Pizarro, G.; Álvarez, G. Effects of the toxic dinoflagellate *Protoceratium reticulatum* and its yessotoxins on the survival and feed ingestion of *Argopecten purpuratus* veliger larvae. *Mar. Pollut. Bull.* **2024**, *199*, 116022. https://doi.org/10.1016/j.marpolbul.2023.116022.
77. Aune, T.; Sørby, R.; Yasumoto, T.; Ramstad, H.; Landsverk, T. Comparison of oral and intraperitoneal toxicity of yessotoxin towards mice. *Toxicon* **2002**, *40*, 77–82. https://doi.org/10.1016/S0041-0101(01)00192-1.
78. Abulfatih, H.A.; Abdel-Bari, E.M.; Alsubaey, A.; Ibrahim, Y.M. Vegetation of Qatar. Scientific and Applied Research Center (SARC), University of Qatar, Doha, Qatar. 2001.
79. Abulfatih, H. A.; Al-Thani, R.F.; Al-Naimi, I.S.; Swelleh, J.A.; Elhag, E.A.; Kardousha, M.M. Ecology of wastewater ponds in Qatar. Scientific and Applied Research Centre (SARC), University of Qatar, Doha, Qatar. 2002.
80. Yasseen, B.T.; Abulfatih, H.A.; Nasher, A.K.; Abid, K.Y.; Al-Mofti, M.B. Preliminary assessment of pollution due to faulty sewage system in north of Sana,a, Republic of Yemen. *Dirasat.* **2001**, *28*, 89–96.
81. Weis, J.S. *Marine Pollution*. Oxford, University Press, 2015.
82. Marella, T.K.; Pacheco, I.Y.L.; Parra, R.; Dixit, S.; Tiwari, A. Wealth from waste: Diatoms as tools for phycoremediation of wastewater and for obtaining value from the biomass. *Sci. Total Environ.* **2020**, *724*, 137960. https://doi.org/10.1016/j.scitotenv.2020.137960.
83. Marella, T.K.; Saxena, A.; Tiwari, A. Diatom mediated heavy metal remediation: A review. *Bioresour. Technol*. **2020**, *305*, 123068. https://doi.org/10.1016/j.biortech.2020.123068.
84. Paniagua-Michel, J.; Banat, I.M. Unravelling diatoms' potential for the bioremediation of oil hydrocarbons in marine environments. *Clean Technol*. **2024**, *6*, 93–115. https://doi.org/10.3390/ cleantechnol6010007.
85. Walters, C.; Steyn, M.; Ndlela, L.; Nocanda, X.; Moloi, M.; Oberholster, P. Phycoremediation of industrial wastewater: review of algae consortia. *Int. J. Environ. Sci. Technol.* **2025**, *22*: 6209–6224. https://doi.org/10.1007/s13762-024-06130-5.
86. Bellido-Pedraza, C.M.; Torres, M.J.; Llamas, A. The microalgae *Chlamydomonas* for bioremediation and bioproduct production. *Cells* **2024**, *13*, 1137. https://doi.org/10.3390/cells13131137.
87. Kalhor, A.X.; Movafeghi, A.; Mohammadi-Nassab, A.D.; Abedi, E.; Bahrami, A. Potential of the green alga *Chlorella vulgaris* for biodegradation of crude oil hydrocarbons. *Mar. Pollut. Bull.* **2017**, *123*, 286–290. https://doi.org/10.1016/j.
88. Fang, Y.; Cai, Y.; Zhang, Q.; Ruan, R.; Ting Zhou, T. Research status and prospects for bioactive compounds of *Chlorella* species: Composition, extraction, production, and biosynthesis pathways. *Process Saf. Environ. Prot.* **2024**, *191*, 345–359. https://doi.org/10.1016/j.psep.2024.08.114.

89. Gupta, P.K.; Ranjan, S.; Gupta, S.K. Phycoremediation of petroleum hydrocarbon-polluted sites: Application, challenges, and future prospects. In *Application of Microalgae in Wastewater Treatment*; Gupta, S.K., Bux, F., Eds.; Springer Nature Switzerland AG, 2019. https://doi.org/10.1007/978-3-030-13913-1_8.
90. Elgazali, A.; Althalb, H.; Elmusrati, I.; Ahmed, H.M.; Banat, I.M. (**2023**). Remediation approaches to reduce hydrocarbon contamination in petroleum-polluted soil. Microorganisms. 11:2577. https://doi.org/10.3390/microorganisms11102577.
91. Shafik, M. Phytoremediation of some heavy metals by *Dunaliella salina*. *Global Environ. Res.* **2008**, *2*, 1–11.
92. Mondal, A.K.; Hinkley, C.; Kondaveeti, S.; Vo, P.H.N.; Ralph, P.; Kuzhiumparambil, U. Influence of pyrolysis time on removal of heavy metals using biochar derived from macroalgal biomass (*Oedogonium* sp.). *Bioresour. Technol.* **2024**, *414*, 131562. https://doi.org/10.1016/j.biortech.2024.131562G.
93. Abioye, O.P. Biological remediation of hydrocarbon and heavy metals and contaminated soil. In *Soil Contamination, Open Tech*; Pascucci, S., Ed.; 2011. https://doi.org/10.5772/24938.
94. Rajasulochana, P.; Dhamotharan, R.; Murugesan, S.; Murthy A.R.C. Bioremediation of oil refinery effluent by using *Scenedesmus Obliquus*. *J. Amer. Sci.* **2009**, *5*, 17–22. http://www.americanscience.org.
95. Ishaq, A.; Peralta, H.M.M.; Basri, H. Bioactive compounds from green microalga – Scenedesmus and its potential applications: A brief review. *Pertanika J. Trop. Agric. Sci.* **2016**, *39*, 1–16.
96. Rajan, P.S.; Gopinath, K.P.; Arun, J.; Pavithra, K.G. Hydrothermal liquefaction of *Scenedesmus abundans* biomass spent for sorption of petroleum residues from wastewater and studies on recycling of post hydrothermal liquefaction wastewater. *Bioresour. Technol.* **2019**, 283, 36–44. https://doi.org/10.1016/j.biortech.2019.03.077.
97. Paramasivam, P.; Maniam, G.P. Removal of heavy metals from petroleum industry wastewater using indigenous microalgae *Scenedesmus* sp. *Key Eng. Mater.* **2024**, *974*, 25–30. https://doi.org/10.4028/p-LEdW39.
98. Shaheed, A.; Dashak, D.A.; Joseph, K.O. Assessment of total petroleum hydrocarbons (TPH) contamination with *Kyllina pumila* and *Spirogyra longata* around Nigerian national petroleum corporation (NNPC) Jos Depot's effluent water discharged point. *FUDMA J. Sci.* **2021**, *5*, 350–354. https://doi.org/10.33003/fjs.
99. Almeida, A.; Cotas, J.; Pereira L.; Carvalho, P.C.S. Potential role of *Spirogyra* sp. and *Chlorella* sp. in bioremediation of mine drainage: A review. *Phycol.* **2023**, *3*, 186–201. https://doi.org/10.3390/phycology3010012.
100. Guleria, S.; Chawla, P.; Relhan, A.; Kumar, A.; Bhasin, A.; Zhou, J.L. Antibacterial and photocatalytic potential of bioactive compounds extracted from freshwater microalgae species (*Spirogyra* and *Ocillatoria*): A comparative analysis. *Sci. Total Environ*. **2024**, *912*, 169224. https://doi.org/10.1016/j.scitotenv.2023.169224.
101. Cao, X.; Xiong, Y.; Lund, J. The effects of micro-algae characteristics on the bioremediation rate of Deepwater Horizon crude oil. *J. Emerg. Investig.* **2013**. http://creativecommons.org/licenses/ by-nc-nd/3.0/). (accessed on 25 March 2025).
102. Ameen, F.; Dawoud, T.; Alabdullatif, J.; Arif, I. CO_2 sequestration and biodiesel production from *Volvox aureus* a newly isolated green microalgal species from industrial wastewater. *Environ. Res.* **2023**, *221*, 115251. https://doi.org/10.1016/j.envres.2023.115251.
103. Han, J.W.; Yoon, M.; Lee, K.P.; Kim, G.H. Isolation of total RNA from a freshwater green alga, *Zygnema cruciatum*, containing high levels of pigments isolation of total RNA from a freshwater green alga, *Zygnema cruciatum*, containing high levels of pigments. *Algae* **2007** *22*, 125–129. Doi.10.4490/ALGAE.2007.22.2.125.
104. Arc, E.; Pichrtová, M.; Kranner, I.; Holzinger, A. Pre-akinete formation in *Zygnema* sp. from polar habitats is associated with metabolite re-arrangement. *J. Exp. Bot.* **2020**, *71*, 3314–3322. https://doi.org/10.1093/jxb/eraa123.
105. Dorgham, M.M.; Al-Muftah, A.M. Plankton studies in the Arabian Gulf. I. Preliminary list of phytoplankton species in Qatari waters. *Arab Gulf J. Sci. Res. Agric. Biol. Sci.* **1986**, *4*, 421–436.
106. Gallardo-Rodríguez, J.; Sánchez-Mirón, A.; García-Camacho, F.; López-Rosales, L.; Chisti, Y.; Molina-Grima, E. Bio-actives from microalgal dinoflagellates. *Biotechnol. Adv.* **2012**, *30*, 1673–1684. https://doi.org/10.1016/j.biotechadv.2012.07.005.
107. Olajire, A.A.; Essien, J.P. Aerobic degradation of petroleum components by microbial consortia. *J. Pet. Environ. Biotechnol.* **2014**, *5*, 195. https://doi.org/10.4172/2157-7463.1000195.

108. Montuori, E.; De Luca, D.; Penna, A.; Stalberga, D.; Lauritano, C. *Alexandrium* spp.: From toxicity to potential biotechnological benefits. *Mar. Drugs* **2023**, *22*, 31. https://doi.org/10.3390/md22010031.
109. Karafas, S.; Teng, S.T.; Leaw, C.P.; Alves-de-Souza, C. An evaluation of the genus *Amphidinium* (Dinophyceae) combining evidence from morphology, phylogenetics, and toxin production, with the introduction of six novel species. *Harmful Algae* **2017**, *68*, 128–151. https://doi.org/10.1016/j.hal.2017.08.001.
110. Durán-Riveroll, L.M.; Juárez, O.E.; Okolodkov, Y.B.; Mejía-Camacho, A.L.; Ramírez-Corona, F.; Casanova-Gracia, D.; Osorio-Ramírez, M. del C.; Cervantes-Urieta, V.A.; Cembella, A.D. Morphological and molecular characterization of the benthic dinoflagellate *Amphidinium* from coastal waters of Mexico. *Phycol.* **2023**, *3*, 305–324. https://doi.org/10.3390/phycology3020020.
111. Orefice, I.; Balzano, S.; Romano, G.; Sardo, A. *Amphidinium* spp. as a source of antimicrobial, antifungal, and anticancer compounds. *Life (Basel)* **2023**, *13*, 2164. https://doi.org/10.3390/life13112164.
112. Baek, S.H.; Shimode, S.; Han, M.-S.; Kikuchi, T. Growth of dinoflagellates, *Ceratium furca* and *Ceratium fusus* in Sagami Bay, Japan: The role of nutrients. *Harmful Algae* **2008**, *7*, 729–739. https://doi.org/10.1016/j.hal.2008.02.007.
113. De Zaburlín, N.M.; Vogler, R.E.; Molina, M.J.; Llano, V.M. Potential distribution of the invasive freshwater dinoflagellate *Ceratium furcoides* (Levander) Langhans (Dinophyta) in South America. *J. Phycol.* **2016**, *52*, 200–208. https://doi.org/10.1111/jpy.12382.
114. Nwankwegu, A.S.; Zhang, L.; Xie, D.; Ohore, O.E.; Li, Y.; Yang, G.; Yao, X.; Song, Z.; Yang, Q. Metabolites dynamics exacerbated by external nutrients inputs into a *Ceratium hirundinella*-dominated bloom in the Pengxi River, Three Gorges Reservoir, China. *Aquat. Toxicol.* **2023**, *258*: 106507. doi: DOI: 10.1016/j.aquatox.2023.106507.
115. Almeda, R.; Connelly, T.L.; Buskey, E.J. Novel insight into the role of heterotrophic dinoflagellates in the fate of crude oil in the sea. *Sci. Rep.* **2014**, *4*: 7560. https://doi.org/10.1038/srep07560.
116. Qadri, H.; Uqab, B.; Javeed, O.; Dar, G.H.; Bhat, R.A. *Ceratophyllum demersum*-An accretion biotool for heavy metal remediation. *Sci. Total Environ.* **2021**, *806*, 150548. https://doi.org/10.1016/j.scitotenv.2021.150548.
117. Reguera, B.; Riobó, P.; Rodríguez, F.; Díaz, P.A.; Pizarro, G.; Paz, B.; Franco, J.M.; Blanco, J. *Dinophysis* toxins: causative organisms, distribution, and fate in shellfish. *Mar. Drugs* **2014**, *12*, 394–461. https://doi.org/10.3390/md12010394.
118. Lim, C.C.; Yoon, J.; Renolds, K.; Gerald, L.B.; Ault, A.P.; Heo, S.; Bell, M.L. Harmful algal bloom aerosols and human health. *EBioMedicine* **2023,** *93*: 104604. https://doi.org/10.1016/j.ebiom.2023.104604.
119. Dale, B. Marine dinoflagellate cysts as indicators of eutrophication and industrial pollution: A discussion. *Sci. Total Environ.* **2001**, *264*, 235–240. 10.1016/S0048-9697(00)00719-1.
120. Aydin, H.; Yürür, E.E.; Uzar, S.; Küçüksezgin, F. Impact of industrial pollution on recent dinoflagellate cysts in Izmir Bay (Eastern Aegean). *Mar. Pollut. Bull.* **2015**, *94*: 144–152. https://doi.org/10.1016/j.marpolbul.2015.02.03.
121. Borbor-Cordova, M.J.; Torres, G.; Mantilla-Saltos, G.; Casierra-Tomala, A.; Bermudez, J.F.; Renteria, W.; Bayot, B. Oceanography of harmful algal blooms on the Ecuadorian coast (1997-2017): Integrating remote sensing and biological data. *Front. Mar. Sci.* **2019**, *6*. https://doi.org/10.3389/fmars.2019.00013.
122. Rodríguez-Palacio, M.C.; Crisóstomo-Vázquez, L.; Álvarez-Hernández, S.; Lozano-Ramírez, C. Strains of toxic and harmful microalgae, from waste water, marine, brackish, and fresh water. *Food Addit. Contamin. Part A* **2011**, *29*, 304–313. https://doi.org/10.1080/19440049.2011.596164.
123. Camenzuli, D.; Freidman, B. L. On-site and in situ remediation technologies applicable to petroleum hydrocarbon contaminated sites in the Antarctic and Arctic. *Polar Res.* **2015**, *34*: 24492. https://doi.org/10.3402/polar.v34.24492.
124. Prakash, A. Growth and Toxicity of a Marine Dinoflagellate, *Gonyaulax tamarensis*. *J. Fish. Res. Board of Canada* **2011**, *24*, 1589–1606. https://doi.org/10.1139/f67-131.
125. Li, Y.; Chen, B.; Yang, S.; Jiao, Z.; Zhang, M.; Yang, Y.; Gao, Y. Advances in environmental pollutant detection techniques: Enhancing public health monitoring and risk assessment. *Environ. Int.* **2025**, *197*: 109365. https://doi.org/10.1016/j.envint.2025.109365.
126. Flores-Chavarria, A.M.; Rodríguez-Jaramillo, C.; Band-Schmidt, C.J.; Hernández-Sandoval, F.E.; Núñez-Vázquez, E.; Bustillos-Guzmán, J.J. Effect of dissolved metabolites of the dinoflagellate *Gymnodinium*

 doi:10.20944/preprints202506.1825.v1

catenatum (Graham, 1943) on the white shrimp *Litopenaeus vannamei* (Boone, 1931): A histological study. *Heliyon* **2023**, *9*, e17018. https://doi.org/10.1016/j.heliyon.2023.e17018.

127. Shi, J.; Liu, Y.; Song, S.; Gu, H.; Li, C. Physiological and transcriptomic response of dinoflagellate *Gymnodinium catenatum* to nitrate deficiency. *Mar. Pollut. Bull.* **2024**, *208*, 117009. https://doi.org/10.1016/j.marpolbul.2024.117009.
128. Shi, J.; Liu, Y.; Xue, B.; Liang, Y.; Song, S.; Gu, H.; Li, C. Integrated physiological and transcriptomic analysis reveals mechanism of planktonic dinoflagellate *Gymnodinium catenatum* response to heat and cold stress. *Harmful Algae* **2025**, *147*, 102884. https://doi.org/10.1016/j.hal.2025.102884.
129. Hu, Z.; Liu, Y.; Deng, Y.; Tang, Y.Z. The notorious harmful algal blooms-forming dinoflagellate *Prorocentrum donghaiense* produces sexual resting cysts, which widely distribute along the coastal marine sediment of China. *Front. Mar. Sci.* **2022**. http://doi.org/10.3389/fmars.2022.826736.
130. Anderson, D.M.; Cembella, A.D.; Hallegraeff, G.M. Progress in understanding harmful algal blooms: paradigm shifts and new technologies for research, monitoring, and management. *Ann. Rev. Mar. Sci.* **2012**, *4*, 143–176. https://doi.org/10.1146/annurev-marine-120308-081121.
131. Song, J.; Bi, H.; Cai, Z.; Cheng, X.; He, Y.; Benfield, M.C.; Fan, C. Early warning of *Noctiluca scintillans* blooms using in-situ plankton imaging system: An example from Dapeng Bay, P. R. China. *Ecolog. Indic.* **2020**, *112*, 106123. https://doi.org/10.1016/j.ecolind.2020.106123.
132. Rameshkumar, P.; Thirumalaiselvan, P.S.; Raman, M.; Remya, L.; Jayakumar, R.; Sakthivel, M.; Tamilmani, G.; Sankar, M.; Anikuttan, K.K.; Menon, N.N.; Saravanan, R.; Ravikumar, T.T.; Narasimapallavan, I.; Krishnaveni, N.; Muniasamy, V.; Batcha, S.M.; Gopalakrishnan, A. Monitoring of Harmful Algal Bloom (HAB) of *Noctiluca scintillans* (Macartney) along the Gulf of Mannar, India using in-situ and satellite observations and its impact on wild and mari-cultured finfishes. *Mar. Pollut. Bull.* **2023**, *188*, 114611. https://doi.org/10.1016/j.marpolbul.2023.114611.
133. Xiaodong, L.; Weijing, L.; Fan, J.; Ziqin, C.; Yang, C.; Ziyang, W.; Tan, Y.; Jing, L.; Weicheng, W.; Chen Xinhua, C. The dinoflagellate *Noctiluca scintillans* in China: A review of its distribution and role in harmful algal blooms. *Mar. Pollut. Bull.* **2023**, *194*, 115415. https://doi.org/10.1016/j.marpolbul.2023.115415.
134. Ajani, P.A.; Brett, S.; Krogh, M.; Scanes, P.; Webster, G.; Armand, L.K. The risk of harmful algal blooms (HABs) in the oyster-growing estuaries of New South Wales, Australia. *Environ. Monitor. Assess.* **2012**, *185*, 5295–5316. https://doi.org/10.1007/s10661-012-2946-9.
135. Anderson, D.M.; Fachon, E.; Hubbard, K.; Lefebvre, K.A.; Lin, P.; Pickart, R.; Richlen, M.; Sheffield, G.; Van Hemert, C. Harmful algal blooms in the Alaskan Arctic: An emerging threat as the ocean warms. *Oceanogr.* **2022**, *35*, 130–139. https://doi.org/10.5670/oceanog.2022.121.
136. Laneve, G.; Bruno, M.; Mukherjee, A.; Messineo, V.; Giuseppetti, R.; Pace, R.; Magurano, F.; D'Ugo, E. Remote sensing detection of algal blooms in a lake impacted by petroleum hydrocarbons. *Remote Sens.* **2022**, *14*, 121. https://doi.org/10.3390/rs14010121.
137. Esqueda-Lara, K.; Hernández-Becerril, D.U. Two new species of the dinoflagellate genus *Phalacroma Stein* (Dinophyceae) from tropical Mexican Pacific. *Nova Hedwigia* **2017**, *105*, 301–312.
138. Haque, S.; Srivastava, N.; Pal, D.B.; Alkhanani, M.F.; Almalki, A.H.; Areeshi, M.Y.; Naidu, R.; Gupta, V.K. Functional microbiome strategies for the bioremediation of petroleum-hydrocarbon and heavy metal contaminated soils: A review. *Sci. Total Environ.* **2022**, *833*, 155222. https://doi.org/10.1016/j.scitotenv.2022.155222.
139. D'Costa, P.M.; Kunkolienkar, R.S.S.; Naik, A.G.; Naik, R.K.; Roy, R. The response of *Prorocentrum sigmoides* and its associated culturable bacteria to metals and organic pollutants. *J. Basic Microbiol.* **2019**, *59*. doi; 10.1002/jobm.201900244.
140. Khanaychenko, A.N.; Telesh, I.V.; Skarlato, S.O. Bloom-forming potentially toxic dinoflagellates *Prorocentrum cordatum* in marine plankton food webs. *Protistol.* **2019**, *13*, 95–125. https://doi.org/10.21685/1680-0826-2019-13-3-1.
141. Gribble, K.E.; Nolan, G.; Anderson, D.M. Biodiversity, biogeography, and potential trophic impact of *Protoperidinium* spp. (Dinophyceae) off the southwestern coast of Ireland. *J. Plankton Res.* **2007**, *29*, 931–947. https://doi.org/10.1093/plankt/fbm070.

142. Sathishkumar, R.S.; Sahu, G.; Mohanty, A.K.; Arunachalam, K.D.; Venkatesan, R. First report of *Protoperidinium steinii* (Dinophyceae) bloom from the coastal marine ecosystem – an observation from tropical Indian waters. *Oceanologia* **2021**, *63*, 391–402. https://doi.org/10.1016/j.oceano.2021.04.003.
143. Mitra, A. *Estuarine Pollution in the Lower Gangetic Delta: Threats and Management*. Springer, Cham, Switzerland, 2019. https://doi.org/10.1007/978-3-319-93305-4.
144. Perin, L.S.; Moraes, G.V.; Galeazzo, G.A.; Oliveira, A.G. Bioluminescent dinoflagellates as a bioassay for toxicity assessment. *Int. J. Mol. Sci.* **2022**, *23*, 13012. https:// doi.org/10.3390/ijms232113012.
145. Jochem, F.; Bebenerd, B. Naked *Dictyocha speculum*- A new type of phytoplankton bloom in the Western Baltic. *Mar. Biol.* **1989**, *103*, 373–379.
146. Prego, R.; Carballeira, R.; Pazos, Y.; Bao, R. Oceanographical context of the first bloom of the silicoflagellate *Octactis speculum* (Ehrenberg) recorded to cause salmon mortality in a Galician Ria: Was this bloom a rare event in the Iberian coast? *Toxins* **2023**, *15*, 435. https://doi.org/10.3390/toxins15070435.
147. Sanchez-Huerta, C.; Zhang, S.; Alahmari, M.; Humam, A.A.; Hong, P.Y. Remediation of petroleum hydrocarbons in contaminated groundwater with the use of surfactants and biosurfactants. *Chemosphere* **2025**, *376*, 144290. https://doi.org/10.1016/j.chemosphere.2025.144290.
148. Taiz, L.; Zeiger, E. *Plant Physiology*. 5th ed.; Sinauer Associates, Inc., Sunderland, 2010.
149. Patel, A.K.; Albarico, F.P.J.B.; Perumal, P.K.; Vadrale, A.P.; Nian, C.T.; Chau, H.T.B.; Anwar, C.; Wani, H.M.; Pal, A.; Saini, R.; Ha, L.H.; Senthilkumar, B.; Tsang, Y.-S.; Chen, C.-W.; Dong, C.-D.; Singhania, R.R. Algae as an emerging source of bioactive pigments. *Bioresour. Technol.* **2022**, *351*, 126910. https://doi.org/10.1016/j.biortech.2022.126910.
150. Yasseen, B.T.; Al-Thani, R.F. Wild plants in the Qatari peninsula are hidden gene bank for future research: Perspectives of desirable traits. In *Cutting Edge Research in Biology*, Vol. 8. B P International, 2023. https://doi.org/10.9734/bpi/cerb/v8/6473A. pp. 207–252.
151. El-Sheekh, M.M.; El-Kassas, H.Y.; Ali, S.S. Microalgae-based bioremediation of refractory pollutants: an approach towards environmental sustainability. *Microb. Cell Fact.* **2025**, *24*, 19. https://doi.org/10.1186/s12934-024-02638-0.
152. Barra, L.; Greco, S. The potential of microalgae in phycoremediation. In *Microalgae- Current and Potential Applications*; Aydin, S., Ed.; Intech Open, 2023. https://doi.org/10.5772/intechopen.1003212.
153. Allard, B.; Rager, M.-N.; Templier, J. Occurrence of high molecular weight lipids (C80+) in the trilaminar outer cell walls of some freshwater microalgae. A reappraisal of algaenan structure. *Org. Geochem.* **2002**, *33*, 789–801. https://doi.org/10.1016/S0146-6380(02)00029-3.
154. Dunker, S.; Wilhelm, C. Cell wall structure of coccoid green algae as an important trade-off between biotic interference mechanisms and multidimensional cell growth. *Front. Microbiol.* **2018**, *9*, 719. https://doi.org/10.3389/fmicb.2018.00719.
155. Stan, D.; Mirica, A.-C.; Mocanu, S.; Stan, D.; Podolean, I.; Candu, N.; El Fergani, M.; Stefan, L.M.; Seciu-Grama, A.-M.; Aricov, L.; Brincoveanu, O.; Moldovan, C.; Bocancia-Mateescu, L.-A.; Coman, S.M. Hybrid hydrogel supplemented with algal polysaccharide for potential use in biomedical applications. *Gels* **2025**, *11*, 17. https://doi.org/10.3390/gels11010017.
156. Silva, A.; Coimbra, R.N.; Escapa, C.; Figueiredo, S.A.; Freitas, O.M.; Otero, M. Green microalgae *Scenedesmus Obliquus* utilization for the adsorptive removal of nonsteroidal anti-inflammatory drugs (NSAIDs) from water samples. *Int. J. Environ. Res. Public. Health.* **2020**, *17*, 3707. https://doi.org/10.3390/ijerph17103707.
157. Alabssawy, A.N.; Hashem, A.H. Bioremediation of hazardous heavy metals by marine microorganisms: A recent review. *Arch. Microbiol.* **2024**, *206*, 103. https://doi.org/10.1007/s00203-023-03793-5.
158. Kanamarlapudi, S.L.R.K.; Chintalpudi, V.K.; Muddada, S. Application of biosorption for removal of heavy metals from wastewater. In *Biosorption*; Derco, J., Vrana, B., Eds.; Intech Open, Slovak University of Technology, Bratislava, Slovakia, 2018. https://doi.org/10.5772/intechopen.77315.
159. Elgarahy, A.M.; Elwakeel, K.Z.; Mohammad, S.H.; Elshoubaky, G.A. A critical review of biosorption of dyes, heavy metals, and metalloids from wastewater as an efficient and green process. *Cleaner Eng. Technol.* **2021**, *4*, 100209. https://doi.org/10.1016/j.clet.2021.100209.

160. Poonam, A.R.; Sharma, P.K. Biosorption: Principles, and applications. In *Advances in Civil Engineering and Infrastructural Development*; Gupta, L.M., et al., Eds.; Springer, Singapore, 2021; pp. 501–510. https://doi.org/10.1007/978-981-15-6463-5.
161. Pham, V.H.T.; Kim, J.; Chang, S.; Chung, W. Bacterial biosorbents, an efficient heavy metals green clean-up strategy: Prospects, challenges, and opportunities. *Microorganisms* **2022**, *10*, 610. https://doi.org/10.3390/microorganisms10030610.
162. Pradhan, B.; Bhuyan, P.P.; Nayak, R.; Patra, S.; Behera, C.; Ki, J.S.; Ragusa, A.; Lukatkin, A.S.; Jena, M. Micro-algal phycoremediation: A glimpse into a sustainable environment. *Toxics* **2022**, *10*, 525. https://doi.org/10.3390/toxics10090525.
163. Faruque, M.O.; Uddin, S.; Hossain, M.M.; Hossain, S.M.Z.; Shafiquzzaman, M.; Abdur Razzak, S. A comprehensive review on microalgae-driven heavy metals removal from industrial wastewater using living and nonliving. *J. Hazardous Mater. Adv.* **2024**, *16*, 100492. https://doi.org/10.1016/j.hazadv.2024.100492.
164. Tedesco, P.; Balzano, S.; Coppola, D.; Esposito, F.P.; de Pascale, D.; Renata Denaro, R. Bioremediation for the recovery of oil polluted marine environment, opportunities and challenges approaching the Blue Growth. *Mar. Pollut. Bull.* **2024**, *200*, 116157. https://doi.org/10.1016/j.marpolbul.2024.116157.
165. Abu-Tahon, M.A.; Housseiny, M.M.; Aboelmagd, H.I.; Daifalla, N.; Khalili, M.; Isichei, A.C.; Ramadan, A.; Abu El-Saad, A.M.; Seddek, N.H.; Ebrahim, D.; Ali, Y.H.; Saeed, I.K.; Rikabi, H.A.; Eltaib, L. A holistic perspective on the efficiency of microbial enzymes in bioremediation process: Mechanism and challenges: A review. *Int. J. Biol. Macromol.* **2025**, 308, 142278. https://doi.org/10.1016/j.ijbiomac.2025.142278.
166. Al-Thani, R.F.; Yasseen, B.T. Microbial ecology of Qatar, the Arabian Gulf: Possible roles of microorganisms. *Front. Mar. Sci.* **2021**, *8*, 697269. https://doi.org/10.3389/fmars.2021.697269.
167. Xiong, J.-Q.; Kurade, M.B.; Abou-Shanab, R.A.I.; Ji, M.-K.; Choi, J.; Kim, J.O.; Jeon, B.-H. Biodegradation of carbamazepine using freshwater microalgae *Chlamydomonas mexicana* and *Scenedesmus obliquus* and the determination of its metabolic fate. *Bioresour. Technol.* **2016**, *205*. https://doi.org/10.1016/j.biortech.2016.01.038.
168. Miazek, K.; Brozek-Pluska, B. Effect of PHRs and PCPs on microalgal growth, metabolism, and microalgae-based bioremediation processes: A review. *Int. J. Mol. Sci.* **2019**, *20*, 2492. https://doi.org/10.3390/ijms20102492.
169. Al-Sulaiti, M.Y.; Al-Shaikh, I.M.; Yasseen, B.T.; Ashraf, S.; Hassan, H.M. Ability of Qatar's native plant species to phytoremediate industrial wastewater in an engineered wetland treatment system for beneficial water re-use. *Qatar Foundation Annual Research Forum Proceedings*: 2013, EEO 010. https://doi.org/10.5339/qfarf.2013.EEO-010.
170. Yasseen, B.T. Phytoremediation of industrial wastewater from oil and gas fields using native plants: The research perspectives in the State of Qatar. *Central Eur. J. Exp. Biol.* **2014**, *3*, 6–23.
171. *Handbook of Biodegradable Materials*; Ali, A.M., Makhlouf, A.S.H., Eds.; Springer Nature Switzerland AG, 2023. https://doi.org/10.1007/978-3-031-09710-2_11221. (accessed on 7 May 2025).
172. Ismael, A.A. Succession of heterotrophic and mixotrophic dinoflagellates as well as autotrophic microplankton in the harbour of Alexandria, Egypt. *J. Plankton Res.* **2003**, *25*, 193–202. https://doi.org/10.1093/plankt/25.2.193.
173. Guo, Z.; Zhang, H.; Liu, S.; Lin, S. Biology of the marine heterotrophic dinoflagellate *Oxyrrhis marina*: Current status and future directions. *Microorganisms* **2013**, *1*, 33–57. https://doi.org/10.3390/microorganisms1010033.
174. Miao, W.; Wang, S.; Lin, T.; Yan, Y.; Bao, Z.; Zhang, D.; Jiang, Z.; Zhang, H. Interaction patterns and assembly mechanisms of dinoflagellates and diatoms in a coastal bay suffering from long-term eutrophication. *mSphere* **2024**, *9*, e0036624. https://doi.org/10.1128/msphere.00366-24.
175. Stepanova, A.Y.; Gladkov, E.A.; Osipova, E.S.; Gladkova, O.V.; Tereshonok, D.V. Bioremediation of soil from petroleum contamination. *Processes* **2022**, *10*, 1224. https:// doi.org/10.3390/pr10061224.
176. Bouyahya, A.; Bakrim, S.; Chamkhi, I.; Taha, D.; El Omari, N.; El Mneyiy, N.; El Hachlafi, N.; El-Shazly, M.; Khalid, A.; Abdalla, A.N.; Goh, K.W.; Ming, L.C.; Goh, B.H.; Aanniz, T. Bioactive substances of

doi:10.20944/preprints202506.1825.v1

cyanobacteria and microalgae: Sources, metabolism, and anticancer mechanism insights. *Biomed. Pharmacother.* **2024**, *170*, 115989. https://doi.org/10.1016/j.biopha.2023.115989.

177. Marella, T.K.; Bhaskar, M.V.; Tiwari, A. Phycoremediation of eutrophic lakes using diatom algae. In *Lake Sciences and Climate Changes*; Intech. Open: London, UK, 2016.
178. Voss, P.A.; Gornik, S.G.; Jacobovitz, M.R.; Rupp, S.; Dörr, M.; Maegele, I.; Annika Guse, A. Host nutrient sensing is mediated by mTOR signaling in cnidarian-dinoflagellate symbiosis. *Curr. Biol.* **2023**, *33*, 3634–3647. https://doi.org/10.1016/j.cub.2023.07.038.
179. Al-Thani, R.F.; Yasseen, B.T. Possible future risks of pollution consequent to the expansion of oil and gas operations in Qatar. *Environ. Pollut.* **2023**, *12*, 12–52. https://doi.org/10.5539/ep.v12n1p12.
180. Aloui, S.; Zghibi, A.; Mazzoni, A.; Elomri, A.; Triki, C. Groundwater resources in Qatar: A comprehensive review and informative recommendations for research, governance, and management in support of sustainability. *J. Hydrol. Reg. Stud.* **2023**, *50*, 101564. https://doi.org/10.1016/j.ejrh.2023.101564.
181. Al-Thani, R.F.; Yasseen, B.T.; Balakrishnan, P. Microorganisms and halophytes attracted to the northeast coast of Qatar for potential phytoremediation: A case study and analysis. *Int. J. Curr. Microbiol. Appl. Sci.* **2025**, *14*, 79–102. https://doi.org/10.20546/ijcmas.2025.1402.008.