First edition published 2024
by CRC Press
2385 NW Executive Center Drive, Suite 320, Boca Raton FL 33431

and by CRC Press
4 Park Square, Milton Park, Abingdon, Oxon, OX14 4RN
CRC Press is an imprint of Taylor & Francis Group, LLC

ISBN: 9781032438856 (hbk)
ISBN: 9781032439815 (pbk)
ISBN: 9781003369738 (ebk)

DOI: 10.1201/9781003369738

Typeset in Times
by Deanta Global Publishing Services, Chennai, India

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marine green organisms. Additionally, factors such as the age, size, and metabolic rate of the organism can also affect the degree of bioaccumulation (Cao et al., 2015).

The mechanisms of bioaccumulation in marine green organisms are complex and can have significant impacts on the health of marine ecosystems and the organisms that rely on them. Understanding these mechanisms is important for developing effective strategies to mitigate the risks associated with exposure to toxic substances in the marine environment (Mondragón et al., 2023).

2.6.2 Nutrient Removal

Marine green algae can absorb excess nutrients such as nitrogen and phosphorus, which are often present in high concentrations in marine environments due to human activities such as agricultural runoff and wastewater discharge. By removing these excess nutrients, the algae can help reduce the risk of harmful algal blooms and improve water quality (Ramanan et al., 2015).

Green marine plants, including seaweeds, seagrasses, and other aquatic plants, play a critical role in removing nutrients from marine ecosystems (Ramanan et al., 2015). There are several mechanisms through which green marine plants remove nutrients, including the following.

2.6.2.1 Uptake by Roots or Thallus

Seagrasses and some species of seaweeds have specialized structures called roots that allow them to take up nutrients from the sediment and the water column. The roots of seagrasses and some seaweeds can also release oxygen, which can create an aerobic zone around the plant that enhances nutrient uptake. In addition to roots, some species of seaweeds have a thallus that can directly absorb nutrients from the water. The uptake of nutrients by green marine plants can reduce the concentration of these nutrients in the surrounding water, which can help prevent eutrophication and harmful algal blooms (Mantri et al., 2020).

2.6.2.2 Adsorption

Green marine plants, particularly seaweeds, have a large surface area relative to their volume, which makes them efficient at adsorbing nutrients from the water column. Seaweeds have specialized structures on their surface, such as hairs or ridges, which increase their surface area and enhance nutrient uptake. Once nutrients are adsorbed onto the surface of the seaweed, they can diffuse across the cell membrane and into the plant (El-Said et al., 2018).

2.6.2.3 Sedimentation

As green marine plants take up nutrients, they incorporate them into their tissues. Over time, this can lead to the accumulation of nutrients in the plant biomass, which can then sink to the bottom of the ocean when the plant dies or sheds its leaves. This process is known as sedimentation, and it can help remove nutrients from the water column and store them in the sediment. Seagrasses, for example, can accumulate large amounts of carbon and nutrients in their root systems, which can help stabilize sediments and prevent erosion (Green et al., 2016; Zhang et al., 2019).

2.6.2.4 Assimilation

Green marine plants can assimilate nutrients into their tissues and use them for growth and metabolism. This process is particularly important for nitrogen, which is a key limiting nutrient in many marine ecosystems. As green marine plants take up nitrogen, they can incorporate it into their biomass and transfer it to higher trophic levels in the food web. Seagrasses, for example, can assimilate nitrogen into their leaves and stems, which can then be consumed by herbivores and ultimately support higher-level predators (Sutherland and Craggs, 2017).

Green marine plants play an important role in removing nutrients from marine ecosystems through a combination of these mechanisms. By reducing the availability of nutrients in the water, they help to maintain the balance of the ecosystem and prevent harmful algal blooms and other negative impacts of nutrient pollution (Zhan et al., 2017).

2.6.2.5 Heavy Metal Removal

Marine green algae can also absorb and remove heavy metals from the water. Heavy metals such as mercury, lead, and cadmium are toxic to marine life and can accumulate in the tissues of aquatic organisms. Green algae can absorb these metals and store them in their tissues, reducing the concentration of heavy metals in the water and reducing the risk of toxicity to marine organisms (Danouche et al., 2021; Abioye et al., 2020).

Marine organisms such as algae, bacteria, and some types of shellfish have been found to have the ability to remove heavy metals from seawater. The mechanisms through which they do this can vary depending on the organism and the specific metal being removed, but two common mechanisms are adsorption and biomineralization.

2.6.2.5.1 Adsorption Or: Adsorption of Heavy Metal Ions

Adsorption is the process by which a substance (in this case, a heavy metal ion) is attracted and adheres to the surface of another substance (such as the cell surface of an organism). Many marine organisms have cell surfaces that contain functional groups (such as carboxyl, hydroxyl, or amino groups) that can bind to heavy metal ions. This process is often selective, meaning that different organisms may be able to remove different types of heavy metals. Once the metal ions are bound to the organism's surface, they can be removed from the seawater through sedimentation (settling to the bottom) or filtration (Cheng et al., 2019).

2.6.2.5.2 Biomineralization

Biomineralization is the process by which organisms form minerals within their tissues. Some marine organisms have the ability to precipitate heavy metals into biominerals such as carbonates, sulfides, or phosphates. This process can be a detoxification mechanism to prevent the metal ions from accumulating in the organism's tissues, or it can be a way to sequester the metals in a form that is less toxic to the environment. For example, some types of bacteria can produce sulfide minerals that can bind and remove heavy metal ions from seawater (Cheng et al., 2023).

2.7 ABILITIES OF MARINE GREENS IN REMEDIATION OF CONTAMINANTS

Algae play an important role in returning an environment that has been altered by various contaminants to its original state (Singhal et al., 2021). Phycoremediation is an algal-based emerging technology applied to remove various pollutants from water (Abioye et al., 2020). It is a low-cost, eco-friendly, and easily manageable remediation strategy. In this technique, algae are used as agents of remediation, and so far, a number of algae have been identified with high potential to detoxify various kinds of pollutants, such as nutrients, heavy metals, radionuclides, herbicides, and pesticides (Shackira et al., 2022). Both micro- and macroalgae are widely exploited to detoxify various contaminants from water bodies. Algae are a source of green energy, serve as a sink for CO_2, and are also a rich resource of economically important components, making phycoremediation a promising technology. Even though the detailed mechanism behind the phycoremediation technique is yet to be unraveled, processes like biosorption, accumulation, degradation, volatilization, and complexation have been proved to be operating in most of the species (Shackira et al., 2022).

This process can be carried out easily without disturbing human life or the environment during conduction and transportation. In algae-based bioremediation, algae fix carbon dioxide, release oxygen by photosynthesis, and increase biological oxygen demand in contaminated water (Singhal et al., 2021). They are highly adaptive, i.e., they can grow autotrophically, heterotrophically, or mixotrophically in the environment depending on the availability of substrate and light. Algae absorb

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TABLE 2.1
Classification of Phaeophyta

Domain	Eukaryota
Kingdom	Protista
Phylum	Heterokontophyta (has chlorophyll a and c)
Class	Phaeophyceae (has pigment fucoxanthin)
Order	Laminarales, Fucales, Ectocarpales, Dictyotales
Family	Fucaceae
Genus	*Fucus*
Species	*serratus*, *distichus*, *vesiculosus*, *spiralis*

Source: Mlblevins, https://biologywise.com/phaeophyta-brown-algae, 2009.

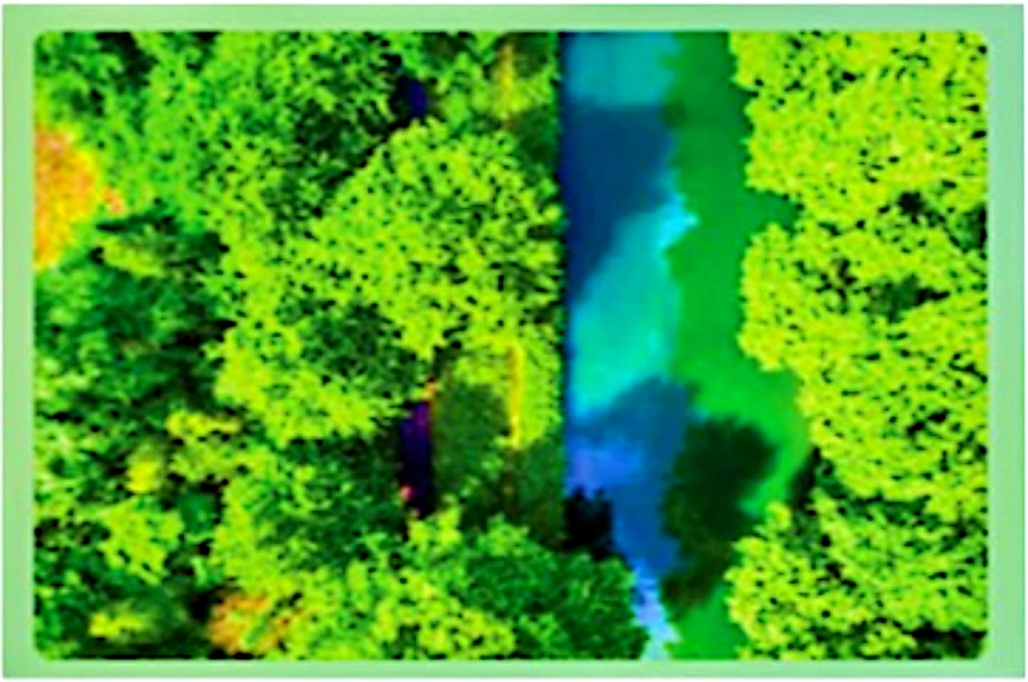

FIGURE 2.2 Green algae (*Chlorophyta*) (Becker, 2013)

Carbohydrates, lipids, and oils found in higher plants make up the bulk of the reserves. The earliest known forms of plant life on Earth were probably green algae (Freitas and Loverde-Oliveira, 2013).

2.4.1 *Chlorophyta* Classification

The taxonomic class Chlorophyta has its roots in the kingdom Plantae. It could be a reference to a group under the kingdom Plantae that contains all known types of green algae. Chlorophyta and Charophyta are two separate phyla that were initially considered to be one giant group of green algae species (charophytes) (Cremen et al., 2019).

Green algae species that do well in salt water are called chlorophytes (members of the *Chlorophyta*), whereas their freshwater counterparts are called charophytes (i.e., belonging to *Charophyta*). Yet, chlorophytes can thrive in a wide variety of environments. Both freshwater and saltwater environments host these organisms. Some chlorophytes are adapted to survive in extreme conditions, such as species found in deserts, hypersaline areas, and polar regions (Cremen et al., 2019).

According to the original taxonomic system, the genus *Chlorophyta* contains over 7000 recognized species of green algae. By the second definition of taxonomy, only about 4300 species belong to the *Chlorophyta*, while the rest are now called charophytes (Cormaci et al., 2014). *Chlorophyta* is a division of kingdom Plantae that includes all green algae categorized into classes such as *Bryopsidophyceae*, *Chlorophyceae*, *Cladophorophyceae*, *Charophyceae*, *Dasycladophyceae*, *Klebsormidiophyceae*, *Prasinophyceae*, *Pleurastrophyceae*, *Trentepohliophyceae*, *Ulvophyceae*, *and Zygne* (Cormaci et al., 2014). According to more recent taxonomies, such as that of Leliaert et al. (2012), charophyte algae are distinct from chlorophytes and instead are classified as *Streptophyta* within the *Viridiplantae* (together with the embryophytes). It is important to stress, however, that new ways of classifying organisms will inevitably emerge as more research is conducted on a wider range of species (Cremen et al., 2019).

2.5 THE RED ALGAE (*RHODOPHYTA*)

The red color of these algae comes from the pigments phycoerythrin and phycocyanin, which obscure the presence of other pigments like chlorophyll a (no chlorophyll b), beta-carotene, and a variety of xanthophylls (Brawley et al., 2017). Flax seed starch and floridoside are the primary reserves; true starch, like that found in higher plants and green algae, is absent. Long-chained polysaccharides including cellulose, agar, and carrageenan are employed to build the walls. There are a number of unicellular forms from different origins, and more complex thalli are built up of filaments (Qiu et al., 2015) (Figure 2.3).

Red algae called coralline algae dot the ocean floor and secrete calcium carbonate onto their cell surfaces (*Corallina officinalis*). Bone regeneration therapy has made use of these corallines. The term *Corallina officinalis* refers to the old practice of using coralline algae as a vermifuge (Yoou et al., 2017).

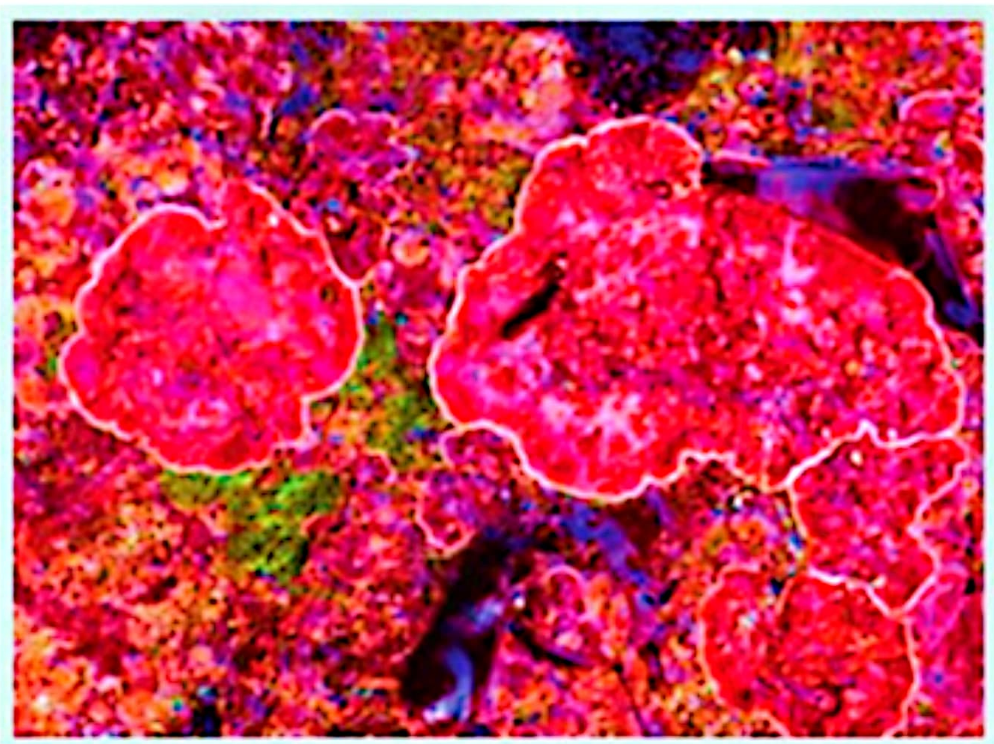

FIGURE 2.3 Red algae (*Rhodophyta*) (Freese and Lane, 2017)

nutrients like carbon, phosphate, and heavy metals from wastewater and produce new biomass, which is useful in the generation of bioenergy (Priya et al., 2022).

This can increase their chances of survival in harsh climates (Singhal et al., 2021) Microalgae can absorb many pollutants during photosynthesis in water (Nithin et al., 2020) Microalgae increase oxygen concentration in water, which increases the growth of several degraders, and oxygen production also decreases the need for external aeration, which is required for aerobic biodegradation. In association with heterotrophic microorganisms, microalgae can perform the degradation of several complex pesticides (the complexity of a pesticide depends on its chemical structure) (Chen and Wang, 2020).

Microalgae, mainly green algae belonging to the genera *Selenastrum*, *Scenedemus*, or *Chlorella*, have been demonstrated to be effective in the degradation of polycyclic aromatic hydrocarbons, such as naphthalene, phenanthrene, and pyrene (Ghosal et al., 2016), and in the immobilization of metals. The mechanisms enabling microalgae to remove toxic compounds, thus reducing their bioavailability and toxicity, mainly rely on the production of exopolysaccharides, which can mediate the uptake of contaminants on the cell surface and/or their complexation into less bioavailable forms (Casillo et al., 2021). Contaminants attached to the membrane or cell wall exopolysaccharides (depending on the microalgal taxa) can remain adherent or can be internalized and chelated by molecules belonging to the phytochelatin classes (Kaur and Reddy, 2019).

The possibility of exploiting the activity of microalgae for the degradation of aromatic compounds such as naphthalene was reported almost half a century ago. More recently, Lei et al. (2002) reported pyrene degradation ranging from 34% to 100% during seven days of treatment using green microalgae (*Chlamydomonas*, *Chlorella*, *Scenedesmus*, *Selenastrum*) or cyanophytes (*Synechocystis*). Similarly, other studies revealed that *Skeletonema costatum* and *Nitschia* sp. were effective in the removal of phenanthrene and fluoranthrene (Hong et al., 2008).

In addition, the green microalga *Chlorella vulgaris* displayed high potential in the remediation of waters contaminated by crude oil, with a bioremediation efficiency between 88% and 94% (Nweze and Aniebonam, 2009). Das and Deca (2019) identified *Chlorella vulgaris* BS1 as capable of degrading 98% of petroleum hydrocarbons at initial concentrations of 115 mg L^{-1} from water in 14 days (Al-Hussieny et al., 2020). It was also reported by Al-Hussieny et al. (2020) that five cyanophytes, namely, *Westiellopsis prolifica*, *Anabaena variabilia*, *Oscillatoria pranceps*, *Phormidium mucicola*, and *Lyngbya digueti*, were capable of reducing the concentrations of different hydrocarbon compounds from oil refinery waste waters by between 24% and 92%.

Marine microalgae–bacteria interactions remain to be further investigated to clarify the processes involved in hydrocarbon degradation as well as their actual potential to enhance bioremediation yields in bio-based approaches for the reclamation of contaminated marine sediments (Thompson et al., 2017).

2.8 CONCLUSION

In conclusion, the ability of marine green algae to remediate contaminants in marine environments is a promising area of research. While the effectiveness of algae-based remediation methods can vary depending on the type of contaminant, the species of algae, and the environmental conditions, there is significant potential for algae-based remediation methods to be used as a low-cost and environmentally friendly method for improving water quality and protecting marine ecosystems.

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Marine Greens

Environmental, Agricultural, Industrial and Biomedical Applications

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CRC Press
Taylor & Francis Group

2.3 THE BROWN ALGAE (*PHAEOPHYTA*)

Phaeophyta (Figure 2.1) are a group of brown algae that include fucoxanthin, beta-carotene, and chlorophyll a and c. These algae, which are typically found in the ocean, are the most complex of all (Ali et al., 2017). The size of Phaeophyta can vary widely, from the micrometer scale to several meters. At most, they have a length of about 30 meters (Hakim and Patel, 2020)

Brown algae, or Phaeophyta, are a type of autotrophic, multicellular organism that belongs to the Chromophyta division The xanthophyll pigment fucoxanthin is present in them, along with the chlorophylls a and c. So, those that belong to the Phaeophyta group tend to be a unique shade of greenish brown (Remya et al., 2022). For Phaeophyta to thrive in the ocean's depths, the brown pigment is crucial. Most Phaeophyta live in saltwater; however, there are a select few that thrive in freshwater (Al-Homaidan et al., 2021). The majority of Phaeophyta are found in temperate zones of the northern hemisphere, while a few species can be found in tropical seas. As of now, scientists have identified between 1500 and 2000 different types of brown algae (Al-Homaidan et al., 2021).

2.3.1 Phaeophyta Classification

The classification of Phaeophyta is shown in Table 2.1.

2.4 THE GREEN ALGAE (*CHLOROPHYTA*)

Green algae, or Chlorophyta (Figure 2.2), are also commonly referred to as seaweed. Several species can be found on land, but they are much more commonly associated with water. Single-cell and multicellular forms, colonies, and coenocytic (one large cell) organisms are all possible. Chlorophyta convert sunlight into starch, which is then used as an energy reserve in the cells (Polle et al., 2014).

Chlorophylls (a and b) in the same ratio as in "higher" plants provide the green color, together with beta-carotene (a yellow pigment) and other xanthophylls (yellowish or brownish pigments).

FIGURE 2.1 Brown algae (*Phaeophyta*) (Mlblevins, 2009)

Dulse (*Palmaria palmata*) and carrageen moss (*Chondrus crispus* and *Mastocarpus stellatus*) are two of the best-known edible red algae (Johnston et al., 2014).

It's true that there are many kinds of algae, and one of them is red. *Kappaphycus* and *Betaphycus* are the primary sources for the carrageenan utilized in most processed food today. This includes many of our favorite dairy products like yogurt, chocolate milk, and reconstituted puddings. Agar is made from red algae like *Gracilaria*, *Gelidium*, and *Pterocladia* and is used as a microbial growth medium, in the food industry, and in biotechnology (Rahelivao et al., 2015).

2.6 MARINE GREENS AND CONTAMINATION

Green marine algae have been shown to be very good at cleaning up pollution in marine environments. The algae are able to absorb, change, and even break down contaminants because of their different metabolic and physiological processes (Chekroun and Baghour, 2013; Babaniyi et al., 2023). Marine green algae, which are also called seaweeds, have been shown to be effective at cleaning up heavy metals, organic pollutants, and excessive nutrients in marine environments. Some of the things that marine green algae can do to help get rid of these pollutants are described in the following subsections.

2.6.1 Bioaccumulation

Marine green algae can accumulate and store contaminants within their tissues. This process is referred to as bioaccumulation and is a key mechanism through which algae can remove contaminants from the water. Once the algae have accumulated the contaminants, they can be harvested or allowed to die and sink to the bottom of the ocean, removing the contaminants from the water (Henriques et al., 2015). Bioaccumulation is the process by which substances, such as nutrients, metals, or organic compounds, accumulate in the tissues of marine green organisms (Mao et al., 2023). This accumulation occurs because the organisms are exposed to these substances in their environment and cannot metabolize or eliminate them efficiently. The mechanism of bioaccumulation is a result of the concentration of these substances in the tissues of the organisms over time, often due to their inability to metabolize or eliminate them efficiently (Mao et al., 2023).

One mechanism of bioaccumulation in marine green organisms is through the process of uptake and retention. Marine green organisms, such as algae or seaweed, take up substances from the surrounding water or sediments through their cell membranes. Some substances can also be absorbed through the surface of the organism or through the ingestion of food particles. Once the substances are taken up by the organism, they can accumulate in the tissues over time, leading to increased concentrations (Gojkovic et al., 2015). The degree of uptake and retention depends on several factors, including the chemical properties of the substance, the characteristics of the organism, and the environmental conditions. For example, substances that are hydrophobic, meaning they have a low solubility in water, tend to accumulate more readily in the tissues of marine green organisms (Zhang et al., 2016; Aransiola et al., 2021). This is because the organisms have a high lipid content in their cell membranes, which can attract and retain hydrophobic substances (Zhang et al., 2016). Another mechanism of bioaccumulation in marine green organisms is through the food chain: marine green organisms, such as plankton, are often the base of the marine food web (El-Shoubaky and Mohammad, 2016). When they consume substances that are present in the water or sediments, these substances can accumulate in their tissues. When higher-level organisms, such as fish, consume the plankton, they can accumulate even higher concentrations of these substances in their tissues (El-Shoubaky and Mohammad, 2016). This process is known as biomagnification and can lead to high concentrations of toxic substances in top predators, such as sharks or marine mammals (Sun et al., 2020). The level of bioaccumulation depends on the chemical properties of the substance, the characteristics of the organism, and the environmental conditions. For example, the temperature, salinity, and pH of the surrounding water can affect the uptake and retention of substances in

2 Marine Greens
Abilities in Remediation of Contaminants

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2.1 INTRODUCTION

"Marine greens" refers to the vast and diverse ecosystem of marine algae or seaweeds that exist in oceans, seas, and other bodies of saltwater. Algae are a type of plant that can grow both in the water and on land (Wang et al., 2014). However, marine green algae are only found in saltwater. They play a significant role in marine ecology, as they serve as the primary food source for many aquatic organisms and provide important nutrients to the oceanic food chain (Cardol et al., 2008).

Marine green algae play a vital role in maintaining the health and balance of marine ecosystems. They serve as a primary food source for many aquatic animals, including fish, crustaceans, and other invertebrates, and are also consumed by larger marine mammals such as manatees and sea otters (Edison et al., 2016). Additionally, they produce significant amounts of oxygen through photosynthesis, which helps to maintain the oxygen balance in marine environments. The algae also absorb carbon dioxide from the atmosphere and store it, thereby reducing the amount of carbon in the atmosphere and mitigating the effects of climate change (Edison et al., 2016).

Marine green algae are an essential component of marine ecosystems, providing crucial nutrients, oxygen, and ecological balance. The biodiversity and variety of these algae are crucial to the well-being of numerous marine species and help mitigate the effects of climate change by reducing carbon dioxide in the atmosphere. The preservation and conservation of these species are crucial to maintaining the health of our oceans and by extension, the planet (Ghoneim et al., 2014). Therefore, this review proposes to look at the ability of marine greens to remediate contaminants.

2.2 TYPES OF MARINE GREENS

Seaweed is a common name for many types of marine algae. Although they look like aquatic plants and can reach lengths of more than 150 feet, seaweeds are not plants (Aravind et al., 2020). Instead, marine algae are a diverse group of organisms belonging to the Protista kingdom, specifically the brown algae (*Phaeophyta*), the green algae (*Chlorophyta*), and the red algae (*Rhodophyta*). Algae aren't really plants, but they do share some key characteristics with their plant counterparts. For photosynthesis, marine algae rely on chlorophyll in much the same way as land plants do. Seaweeds, like land plants, have cell walls (Wang et al., 2014). However, plants have crucial characteristics that seaweeds lack, such as a root system, an internal circulatory system, and the ability to generate seeds and flowers (RothSchulze et al., 2018).

DOI: 10.1201/9781003369738-3