Environmental Science and Pollution Research (2022) 29:40373–40383
https://doi.org/10.1007/s11356-022-19636-7

REVIEW ARTICLE

The use of algae for environmental sustainability: trends and future prospects

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Received: 27 July 2021 / Accepted: 5 March 2022 / Published online: 24 March 2022

Abstract

Algae are photosynthetic prokaryotic or eukaryotic ubiquitously found group of organisms. Their enormous potentiality in coping up with various environmental crises has been well documented. Algae have proven to be ideal for biomonitoring of water pollution and help in removing the pollutants with their process of bioremediation apart from the production of eco-friendly sources of energy. Industries like food and pharmaceuticals are exploiting algae for producing several value-added products. The agricultural sector is also highly benefited from microalgae, as they are the good promoters of crop growth. The CO_2-removing potential of algae proves to be an asset in fighting climate change. Moreover, the relatively easy and inexpensive methods of sampling and culturing of algae make them more popular. In this paper, we review the sustainable application aspects of algae in various areas like pollution control, energy production, agriculture, and fighting climate change. Critical discussions have been made on the recent trends and advances of algal technologies indicating future prospects.

Keywords Algae · Biofuels · Biomonitoring · Bioremediation · Agriculture · Climate change

Introduction

Algae are thallophytic in nature; the body is not organized into true stems, leaves, and roots. Algae may be solitary or live in colonies. Their primitive vegetative bodies lack the vascular system which makes them dependant on water all the time (Likens 2009). They are ubiquitously found in a wide range of habitats, from soil to water. No extremities bound them and can be found in cold to warm, alkaline to acidic conditions (Likens 2009). Most of the algae possess chlorophyll-a, which makes them the primary producers and principal basis of food webs on earth (Likens 2009).

For decades *Spirulina* sp. and *Aphanizomenon* sp. are consumed as a food source by humans (Spolaore et al. 2006). Even having such historical background of the use of microalgae by humans, the applications of microalgae is still new and unexplored (Spolaore et al. 2006; Milledge 2011). Algae are being investigated for their beneficial aspects to both humans and the environment. They have been recognized as a very good bioindicator of water pollution (Briggs 1985). In addition, to monitor water pollution and predict future consequences, algae can also perform bioremediation to remove the pollutants from water bodies (Edwards et al. 2013; Dixit and Singh 2015). Algae are also being used in the field of sustainable energy. For instance, biofuels like biodiesel, biomethane, and bioethanol have been successfully produced from algae (Chisti 2007; Rahman et al. 2017). Anaerobic digestion has been implicated with algae in microbial fuel cells to produce electricity (Rashid et al. 2013; Gajda et al. 2015; Fasahati et al. 2017). Algal biomass also possesses various bioactive compounds which can help to facilitate the production of value-added products for food and pharmaceutical industries (González Del Campo et al. 2013).

The contribution of algae in agriculture is untold as they are the biological promoters of crop growth. Specifically, microalgae promote the growth of beneficial bacteria, improve soil organic carbon contents, make atmospheric

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Responsible Editor: Philippe Garrigues

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nitrogen available to the soil, produce growth hormones, and prevent plant diseases (Fogg 1949; Karthikeyan et al. 2007; Swain et al. 2017). The photosynthetic rates of algae are ideal for trapping CO_2, thereby removing the excess CO_2 from the atmosphere. Mass cultivation of algae has been proving beneficial in controlling climate change (Haoyang 2018; Toochi 2018; Adeniyi et al. 2018; Anguselvi et al. 2019). To date, a few numbers of review articles are available focusing algal driven solutions to individual environmental issues like pollution, energy demand, climate change, etc. (Gouveia and Oliveira 2009; Haoyang 2018; Rajakumari and Ridhanya 2021). However, no comprehensive and exclusive review is available. Hence, this review article put a beam on the research advancements on algal technology with regard to environmental sustainability. Different applications of algae for environmental sustainability are illustrated in Fig. 1.

Algae in environment sustainability

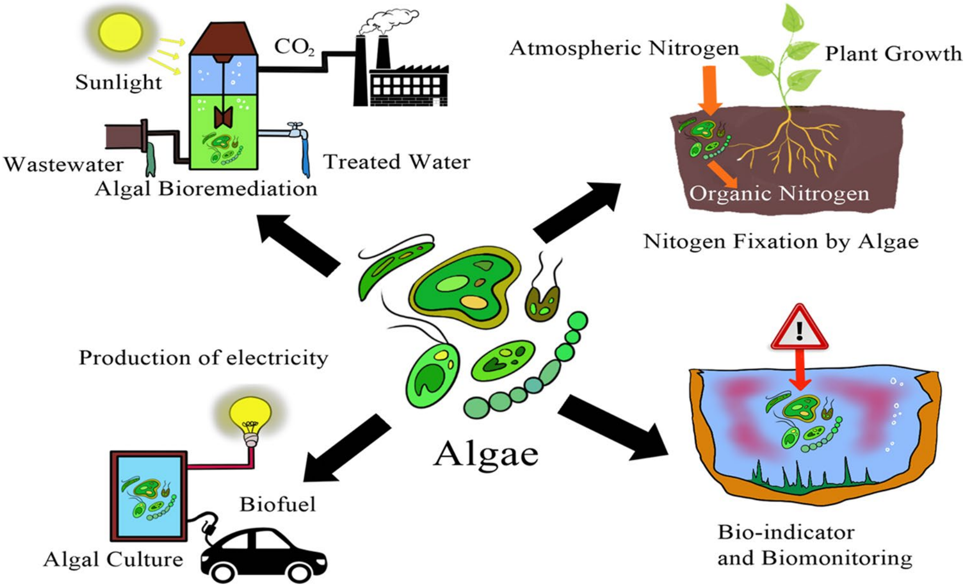
The unique relationship of algae with their aquatic habitat makes them one of the best bioindicators of water pollution. Besides, to report and predict the consequences of pollution, algae also help in dealing with the pollution by their process of bioremediation. For a sustainable source of energy, oil and algal biomass is being utilized in producing carbon–neutral biofuels. In addition, algal biomass is a rich source of value-added products that encourages us to minimize our dependence on synthetic and nonbiodegradable compounds that ultimately benefits the environment.

Algae as a bioindicator for biomonitoring

Biological indicators or bioindicators are those organisms whose presence reflects the environmental conditions (Laitat 1994). According to Karr and Chu (1999), we are dependent on the prediction and identification of anthropogenic activities in the biological systems to protect biological resources. Therefore, the data collected from indicator organisms can be utilized to evaluate certain degrees of environmental impacts and their possible threat to other living organisms. Biomonitoring becomes an essential application of biological feedback for the assessment of environmental change. For a sustainable approach in environmental monitoring, it has become essential to reduce the use of chemical indicators and to adopt and increase the use of bioindicators (McCormick and Cairns 1994).

In an aquatic ecosystem, algae are one of the most important groups and are proven to be an essential component of biological monitoring programs. They are well suited for the assessment of water quality because of their nutrient needs and very short life cycles. The rapid reproduction makes them ideal indicators of short-term environmental impacts. Algae are directly affected by physical and chemical factors because they are the primary producers of aquatic ecosystems. The benefits of using algae as a bioindicator include their sensitivity towards pollutants and ready accumulator of pollutants into their thallus. Algal metabolism is sensitive to environmental disturbances and responds quickly both in species density and composition to a wide range of water conditions. For instance, increasing the acidity of water in presence of acid-forming chemicals discharged from industrial areas may affect the density and composition of algae

Fig. 1 Applications of algae in environment sustainability



differently. However, some algal genera can tolerate these water conditions (Omar 2010). A list of algal species associated with biomonitoring of water is provided in Table 1.

Periphytopnic algae are widely used as a biological monitoring tool for water quality. They are sensitive to various environmental conditions, which are detected in their species composition, density, chlorophyll content, enzyme activity, and ash-free dry mass (AFDM) (Briggs 1985; Newman et al. 1985; Cosgrove et al. 2004). Diatoms have also been abundantly used for monitoring water quality. Diatoms provide multiple indicators of environmental change with precise data in comparison to zoological and chemical assessments (Round 1991).

In England, five algal species were selected as bioindicators of river pollution. In heavily polluted rivers, algal species *Stigeoclonium tenue* was observed in the downstream region, whereas species *Gomphonema parvulum* and *Nitzschia palea* appeared dominant at the mid polluted zone and species *Chamaesiphon* and *Cocconeis* were reported to thrive in the unpolluted parts of the stream (Butcher 1949). Later, the species *Gomphonema* and *Navicula accomoda* were also noted as good indicators of sewage water pollution (Archibald 1972). Diatoms like *Gyrosigma attenuatum* and *Amphora ovalis* were observed to be affected by higher contents of organics in water (Patrick 1948).

Table 1 List of algal species utilized for their biomonitoring potential

Algal species	Reference
Amphora ovalis	(Patrick 1948)
Anabaena sp.	(Carlson 1977)
Chlorococcus sp.	(Carlson 1977; Harun et al. 2010)
Cladophora glomerata	(Al-Homaidan et al. 2021)
Gyrosigma attenuatum	(Patrick 1948)
Cryptogamia sp.	(Parus and Karbowska 2020)
Cystoseiria sp.	(Parus and Karbowska 2020)
Dinobryon sp.	(Carlson 1977)
Enteromorpha intestinalis	(Al-Homaidan et al. 2021)
Euglena viridis	(Palmer 1969)
Gomphonema parvulum	(Butcher 1949)
Microcystis sp.	(Carlson 1977)
Nitzschia palea	(Palmer 1969)
Nostoc sp.	(Carlson 1977)
Oscillatoria limosa	(Palmer 1969)
Oscillatoria tenuis	(Palmer 1969)
Pseudokirchneriella subcapitata	(Vernouillet et al. 2010)
Sargassum furatum	(Lourenço et al. 2019)
Sargassum sp.	(Ho and Bantoto-Kinamot 2021)
Scenedesmus obliquus	(Gouveia and Oliveira 2009)
Scenedesmus vacuolatus	(Neuwoehner and Escher 2011)
Scenedesmus quadricauda	(Palmer 1969)
Spirulina maxima	(Gouveia and Oliveira 2009)
Stigeoclonium tenue	(Butcher 1949)
Ulva sp.	(Parus and Karbowska 2020)

Blue-green algae like *Oscillatoria* and *Phormidium*, diatoms like *Synedra* and *Navicula*, and green algae like *Chlamydomonas* and *Euglena* were reported to have good tolerance to organic pollution (Palmer 1969). Dell'Aglio et al. (2017) utilized the redox potential curves of respiration and photosynthesis of a green algae *Scenedesmus* sp. for biomonitoring of pollution caused by toxic drugs in water bodies. Their studies revealed *Scenedesmus* sp. as an efficient biomonitoring tool for toxic drug pollution in an aquatic environment. Two green algae, *Enteromorpha intestinalis* and *Cladophora glomerata*, were used to measure heavy metal pollution in Wadi Hanifah stream, Saudi Arabia. Concentrations of manganese (Mn), arsenic (As), zinc (Zn), copper (Cu), cadmium (Cd), and lead (Pb) were measured from the dried biomass of these two algal species. The study showed *E. intestinalis* as an excellent indicator of Mn, As, and Zn while species *C. glomerata* indicated Cu, Cd, and Pb pollution (Al-Homaidan et al. 2021).

Like their freshwater counterparts, marine algae are also being utilized as biomonitoring agents of water pollution. A brown algae *Sargassum furcatum* with its associated amphipods were utilized for the indication of petroleum hydrocarbon pollution in the marine ecosystem of São Sebastião Channel of south-eastern Brazil (Lourenço et al. 2019). In the Black Sea of Turkey, marine algae were used to assess the heavy metal pollution and their accumulation in the algal thallus. Species *Cryptogamia*, *Cystoseira*, and *Ulva* were reported to accumulate copper, cadmium, iron (Fe), lead, zinc, and thallium (Tl) into their thallus indicating heavy metal pollution (Parus and Karbowska 2020). Similarly, four red algal species, *Corallina panizzoi*, *Antithamnion cruciatum*, *Ceramium panizzoi*, and *Porphyra umbilicalis* were assessed to measure heavy metals like nickel, copper, manganese, cobalt (Co), lead, and cadmium in the Black Sea coast of Samsun, Turkey (Arici and Bat 2016).

Recently, Cd concentration in the thalli of three brown algae species i.e., *Sargassum* sp., *Padina* sp., and *Turbinaria* sp. from North Bais Bay were studied (Ho and Bantoto-Kinamot 2021). Their study showed that *Sargasum* sp. contained the highest concentration of Cd which ranged from 2.14 to 4.45 mg kg^{-1} followed by *Padina* sp. (2.2 to 3.4 mg kg^{-1}) and *Turbunaia* sp. (2.36 to 2.76 mg kg^{-1}). They concluded brown algae as an effective bio-indicators of marine Cd contamination.

In crux, the algal diversity in polluted water indicates its usefulness as a bioindicator. The resistant algal species can be further explored for their possible use in the field of bioremediation.

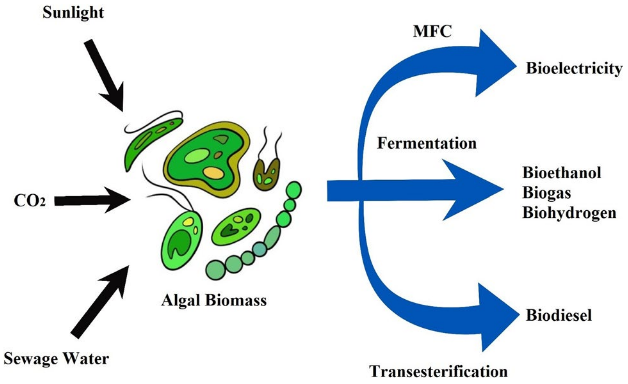


Fig. 2 Production of bioenergy with algal biomass using various methods

Energy production by algae

The world is facing a major crisis in energy production with increasing population and demand for energy. The use of fossil fuels on a larger scale increased the CO_2 levels and other greenhouse gases in the atmosphere. Thus, there is an urgent need for renewable and environment-friendly fuel to fulfill the world's energy demand (Schenk et al. 2008). To meet the demand, algae can be used as the major source of biofuel due to their safe, noncompetitive, and rapid growth. Moreover, algae can be utilized to produce electricity. Various methods for the production of bioenergy from algae were illustrated in Fig. 2.

Production of biofuel from algae

Algal cells contain a wide range of fatty acids, carbohydrates, lipids, and proteins. The oil content of microalgae can be 20–50%, but it has been observed that in some species it can go up to 80% (Metting 1996; Spolaore et al. 2006). The oil-rich species are considered ideal to produce biofuels that can substitute fossil fuels like diesel, kerosene, and gasoline. Being carbon neutral, the algal biofuels are ideal for the environment and economic sustainability (Chisti 2007; Slade and Bauen 2013). Algae associated with the production of biofuel are enlisted in Table 2.

Rutz and Janssen (2007) put forward some standard methods like sedimentation, flocculation, filtration, flotation, or electrophoresis for harvesting microalgae to produce biodiesel. The production of biodiesel is generally done with the methods like pyrolysis, micro-emulsification, and transesterification (Demirbas 2009; Musa 2016; Akubude et al. 2019). Among all these methods; transesterification is most widely used to produce biodiesel from microalgae (Xu et al. 2006; Koberg et al. 2011). Apart from biodiesel production; microalgae are also used for generating bio-hydrogen by photobiological process (Fedorov et al. 2005; Kapdan and Kargi 2006), bio-methane by anaerobic digestion (Spolaore et al. 2006; Heaven et al. 2011), bioethanol by fermentation (Fu and Dexter 2007; Choi et al. 2010), and liquid oil by thermal liquefaction (Banerjee et al. 2002; Miao and Wu 2004; Xu et al. 2006).

Pradana et al. (2017) successfully cultivated microalgae *Nannochloropsis* sp., *Botryococcus braunii*, and *Arthrospira platensis* at different regions of Indonesia to produce biodiesel. Gouveia and Oliveira (2009) screened microalgae, *Chlorella vulgaris*, *Spirulina maxima*, *Nannochloropsis sp.*, *Neochloris oleoabundans*, *Scenedesmus obliquus*, and *Dunaliella tertiolecta* for the production of biodiesel. The freshwater algal species *Neochloris oleoabundans* and marine *Nannochloropsis* sp. had the highest oil content of 29% and 28.7%, respectively (Gouveia and Oliveira 2009). Rahman et al. (2017) successfully synthesized biodiesel from species *Spirulina maxima* by using the transesterification process.

Studies showed that both biodiesel and bioethanol could be extracted from algae simultaneously by removing lipids from the algal biomass for fermentation (Dragone et al. 2010). The extracted lipids gave 60% bioethanol in concentration compared to dried biomass without lipid extraction. Harun et al. (2010) extracted lipids from *Chlorococcus* sp. and fermented

Table 2 Algal species associated with the production of biofuels

Algal species	Oil content (%)	Reference
Arthrospira platensis	35.31	(Pradana et al. 2017)
Botryococcus braunii	43.06	(Pradana et al. 2017)
Chlorella vulgaris	14–56	(Gouveia and Oliveira 2009; de Godos et al. 2012)
Chlorococcus sp.	38	(Carlson 1977; Harun et al. 2010)
Dunaliella tertiolecta	60–67	(Gouveia and Oliveira 2009)
Nannochloropsis sp.	28–30	(Pradana et al. 2017)
Neochloris oleoabundans	7.6–40.3	(Gouveia and Oliveira 2009)
Scenedesmus obliquus	35–55	(Gouveia and Oliveira 2009)
Spirulina maxima	4–9	(Gouveia and Oliveira 2009)

them to produce bioethanol. However, little work has been done on the production of biomethane from microalgae using the anaerobic digestion method. Golueke et al. (1957) digested algal species *Chlorella* and *Scenedesmus* from wastewater ponds that produced 0.25–0.50 L CH4/g at 11 days of retention time at an incubated temperature of 35–50 °C. These studies proved microalgae as an excellent choice for sustainable biofuel production. However, advanced and affordable technologies are yet to develop. Along with biofuel production, microalgae are associated with various food and pharmaceutical products, tools for phycoremediation, bio-fertilizers, etc. Industries are fronting complications in escalating the processes (Saad et al. 2019). One of the most crucial challenges is the screening of the microalgal strains with a higher lipid-producing ability and modifying them through genetic and metabolic engineering for rapid growth and lipid production (Saad et al. 2019).

Production of electricity from algae

Algal biomass is suitable for energy conversion technologies, which include anaerobic digestion or microbial fuel cell (MFC). These MFC are interesting renewable energy technology where photosynthetic organisms are used to generate electricity (Strik et al. 2008; González Del Campo et al. 2013). Electrons generated from the algal biomass are moved to the external circuit to produce electricity (Rosenbaum et al. 2010; Wang et al. 2010). Normally pure organic compounds like glucose, acetate, and cysteine are used as substrates at the anode, but wastewater can also be used as a substrate (Rodrigo et al. 2007; Martin et al. 2010). Rashid et al. (2013) selected *Scenedesmus* sp. as a suitable substrate in MFC due to its high lipid content and potential nutrient source for microbes at the anode. It produced a much higher power density than any other reported substrates. Algal biomass served as both waste management and power generation. Similar experiments were also done by Strik et al. (2008) where a mixture of algal species was taken as a substrate in MFC for electricity generation. Gajda et al. (2015) connected an algal photobioreactor with an MFC to manufacture a continuous power generator system. The bioreactors can continuously supply the algal biomass which served as a substrate. Fasahati et al. (2017) utilized brown algae *Laminaria japonica* for the production of electricity using anaerobic digestion. Thus, algal biomass is a promising way for the sustainable production of electricity.

Algae as the potential candidate for bioremediation

Algae are being well utilized for the bioremediation of water pollutants and the process is known as phytoremediation. Water pollutants include inorganic nutrients including heavy metals, several organic compounds (hydrocarbons, polychlorinated biphenyls, insecticides, and detergents), and radioactive isotopes (Dixit and Singh 2015). Table 3 enlists some algal species which are used for their bioremediation abilities,

Microalgae use several mechanisms for the bioremediation of pollutants while enhancing their tolerance to detoxify or degrade the pollutants. For example, they transform the heavy metals into sulfides, which make these metals insoluble and consequently lowering toxicity and availability (Edwards et al. 2013). Another mechanism is the absorption of toxicants into their biomass (Mehta and Gaur 2005). They do so because of their large surface:volume ratio, presence of metal-binding groups on their surface, and the efficient metal uptake and storage systems (Rajamani et al. 2007). Microalgae can take part in the bioremediation of acidic wastewater by generating alkalinity via nitrate assimilation, especially from acid mine drainage (Das et al. 2009). Studies also documented the efficacy of microalgae and cyanobacteria in the degradation of organic chemicals including pesticides, phenolic compounds, tributyltin, naphthalene, bisphenol, and other hydrocarbons (Joseph and Joseph 2001; Todd et al. 2002; Barton et al. 2004; Hirooka et al. 2005; Singh and Walker 2006). Figure 3 Illustrates different processes of bioremediation utilized by algae in controlling various organic and inorganic pollutants.

Microalgae in the removal of inorganic pollutants

Microalgae remove nitrogen and phosphorous from water as these elements are beneficial for their growth and development. Besides, they are capable of degrading inorganic pollutants like heavy metals. Microalgae insolubilize the heavy metals by converting them into sulfides and making them unavailable (Phang et al. 2015). It was observed that when the cyanobacterium *Synechococcus leopoliensis*, green alga *Chlamydomonas reinhardtii*, and red alga *Cyanidioschyzon merolae* were exposed to cadmium, they detoxified the heavy metal by converting it into cadmium sulfide (Edwards et al. 2013). Similarly, the red alga *Galdieria sulphuraria* converted 90% of Hg (II) into metacinnabar (βHgS) within 20 min of exposure (Kelly et al. 2007). Gong et al. (2011) found that a microalgae *Chlorella vulgaris* could accelerate the aggregation of nickel oxide which reduces its valency to zero.

According to Perales-Vela et al. (2006), microalgae can produce phytochelatins to take part in the chelation of heavy metals and thus help in detoxification. Three genera of green algae *Rhizoclonium* sp., *Oedogonium* sp., and *Hydrodictyon* sp. are reported to accumulate vanadium (V) and arsenic (As) from wastewater into their biomass (Saunders et al. 2014). Similarly, *Spirogyra hyalina* was found to be useful

Table 3 Algae species having potential for bioremediation

Algal species	Inorganic pollutants	Organic pollutants	Reference
Chlamydomonas reinhardtii	Cd	—	(Edwards et al. 2013)
Chlorella vulgaris	Ni	—	(Gong et al. 2011)
Coelastrum reticulatum	—	Biophenols	(Nakajima et al. 2007)
Cyanidioschyzon merole	Cd	—	(Edwards et al. 2013)
Cylindrospermum stagnale	—	Proteinaceous ossein effluents	(Ameen et al. 2021)
Galdieria sulphuraria	Hg (II)	—	(Kelly et al. 2007)
Hydrodictyon sp.	V and As	—	(Saunders et al. 2014)
Microspora sp.	Fe and Cu	—	(Equeenuddin et al. 2021)
Oedogonium sp.	V and As	—	(Saunders et al. 2014)
Oscillatoria sp.	Pb, Zn, Fe, Co, and Cu	—	(Sheoran and Bhandari 2005)
Pseudokirchneriella subcapitata	—	Biophenols	(Nakajima et al. 2007)
Rhizodonium sp.	V and As	—	(Saunders et al. 2014)
Scenedesmus acutus	—	Biophenols	(Nakajima et al. 2007)
Scenedesmus obliquus	—	Halogenated phenols, p-cresol	(Papazi and Kotzabasis 2007; Papazi et al. 2012)
Scenedesmus quadricauda	—	Biophenols	(Nakajima et al. 2007)
Spirogyra hyaline	Cd, Pb, Hg, As, and Co	—	(Kumar and Oommen 2012)
Synechococcus leopoliensis	Cd	—	(Edwards et al. 2013)

in removing cadmium, lead, mercury, arsenic, and cobalt (Kumar and Oommen 2012). Dead biomass of *Arthrospira* sp. can detoxify chromium (Cr) by reducing Cr (IV) to Cr (III). In a study to remove acid wastewater derived from a mining site, the consortium of *Oscillatoria* sp. was found beneficial to remove sulfate and precipitate metals like Pb, Zn, Fe, Co, and Cu. Besides, the acidity of the water was reduced as the pH increased from 2.93 to 6.78 (Sheoran and Bhandari 2005). In *Microspora* sp. high metal accumulation potential was observed in the acid mine drainage system (AMD) of Malanjkhand copper mine. The alga was able to accumulate Fe and Cu from 0.95 to 9.14% and 1.74 to 3.66% respectively (Equeenuddin et al. 2021).

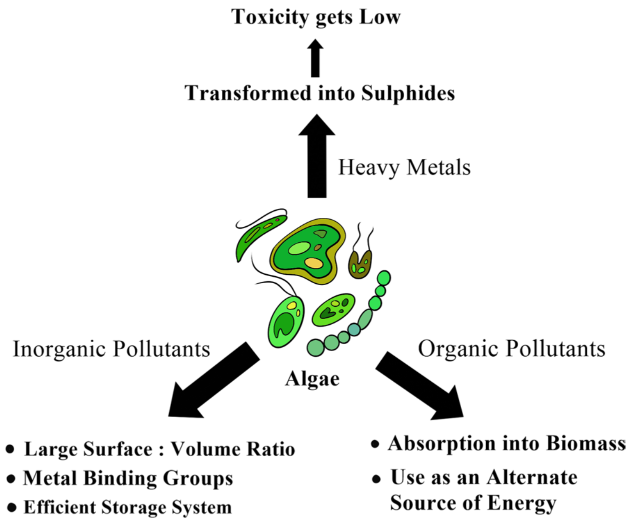


Fig. 3 Process used by microalgae in remediation of organic and inorganic pollutants

Microalgae in remediation of organic pollutants

Cyanobacteria and microalgae have a very huge potential in removing organic pollutants from water bodies. It was found that nutrients in the form of carbon sources like glucose could increase the growth and capacity of microalgae in degrading organic pollutants (Megharaj et al. 1994; Tikoo et al. 1997; Papazi and Kotzabasis 2007; Papazi et al. 2012). For example, the growth and catabolic activity of *Scenedesmus obliquus* has increased the degrading ability of halogenated phenols in presence of glucose. Further investigation on *Scenedesmus obliquus* revealed that algae can even degrade p-cresol (toxic) and can utilize it as an alternate energy source(Papazi and Kotzabasis 2007; Papazi et al. 2012). Similarly, *Scenedesmus acutus*, *S. quadricauda*, *Coelastrum reticulatum*, and *Pseudokirchneriella subcapitata* were reported to metabolize biophenol (Nakajima et al. 2007). There are reports of cyanobacteria and microalgae in removing harmful insecticides and utilizing them as a source of phosphorous (Megharaj et al. 1994).

Inoculation of a consortium of several microalgae (*Chlorococcus*, *Anabaena cylindrica*, *Chlorella*, *Scenedesmus quadricauda*, and *Spirulina platensis*) into pond water containing wastewater has led to the removal of endocrine-disrupting pesticides like 17β-estradiol and estrone by involving the processes like bioabsorption and biodegradation (Shi et al. 2010). Dotto et al. (2013) demonstrated the usefulness of nanoparticles from *Spirulina* sp. in removing phenols by absorption. Along with pesticides, antibiotic contamination is a major problem in water bodies. Diatoms producing hydroxyl radicals can degrade these antibiotics efficiently. Studies showed that diatoms can produce such hydroxyl-radicals by bio-fenton process which can readily degrade tetracycline from wastewater (Pariyarath et al. 2021). In oceanic water, the presence of proteinaceous ossein effluents poses a serious threat to the marine ecosystem. Moreover, Ca- and Cl-rich compounds are very hard to remove and also have a strong odor (Das et al. 2011). Gelatin-producing industries are the major sources of this ossein. However, Ameen et al. (2021) came up with the strategy of using marine cyanobacterium *Cylindrospermum stagnale* to remove these pollutants. Their study documented that *C. stagnale* can degrade ossein effluents optimally when cultured with effluents and seawater in the ratio of 1:1.

Thus, utilizing the potentiality of microalgae for the treatment of organic and inorganic pollutants has become a major trend in recent times. Identification of new ideal species for the bioremediation process and the introduction of these algal species to the polluted sites can benefit in overcoming different levels of water pollution.

Cyanobacteria in nitrogen cycling and its fixation

The fixation of atmospheric nitrogen through specialized cells of cyanobacteria is termed as heterocysts and was first demonstrated by Fogg (1949) in *Anabaena cylindrica*. The fixed nitrogen becomes available to the plants and the other organisms in the surrounding environment when it is released in the form of polypeptides, free amino acids, ammonia, vitamins, and auxin like substances either by cell secretion or by microbial degradation (Subramanian and Shanmugasundaram 1986; Rana et al. 2012). It has been estimated that around 32 Tg of nitrogen is fixed by cyanobacteria annually, among which paddy fields are considered to be the most suitable habitat. Approximately 4 kg N ha^{-1} is supplied by cyanobacterial biomass in the rice ecosystem, and their N_2 fixing ability is widely studied (Vaishampayan et al. 2001). Asia being the largest rice producer depends mostly on cyanobacterial N_2 fixation.

Cyanobacterial species like *Anabaena iyengarii*, *A. fertilissima*, *Nostoc commune*, *N. ellipso-sporum*, and *N. linckia* have been reported with exceptional N_2-fixing ability (Pereira et al. 2009). Increased rice yields were recorded from India and Japan due to the inoculation of cyanobacteria (Vaishampayan et al. 2001). In wheat crops, in vitro inoculation of cyanobacteria has raised plant shoot/root length along with fresh and dry yield weight (Spiller and Gunasekaran 1990; Obreht et al. 1993). Soil inoculation with biofilms of *Anabaena* sp. increased nitrogen in wheat fields from 40% to 57.42% compared to control (Swarnalakshmi et al. 2013). Apart from rice and wheat, the cyanobacterial-induced nitrogen fixation has a wide scope in cotton, a variety of vegetables, and other food crops (Osman et al. 2010; Prasanna et al. 2016). In pea plants, two cyanobacteria *Nostoc entophytum* and *Oscillatoria augustissima* have great potential as biofertilizer as they can save 50% in chemical fertilizers and add nutritional value in pea seeds (Osman et al. 2010).

Thus, the use of cyanobacteria to provide nitrogen in the crop field is not only cost-efficient but also serves as an alternative environment-friendly source compared to mineral fertilizer.

Potential use of algae in fighting climate change

In the present times, 80% of annual energy produced worldwide is generated from the combustion of fossil fuels. It has been estimated that more than 24 Gigatons (Gt) of CO_2 is emitted in this process of combustion (Lewis and Nocera 2006). In 2019, the atmospheric CO_2 reached 409.8 ± 0.1 ppm which was recorded to be the highest CO_2 level in over 800,000 years (Lindsey 2020). This accumulated atmospheric CO_2 has contributed substantially to global warming, climate change, and extinction of various species (Lewis and Nocera 2006; Battisti and Naylor 2009). Thus, the use of CO_2-free energy sources has become essential in controlling global warming. These sustainable sources of energy like solar energy may be promising, but the initial cost is very high, and they pollute the environment with lead and cadmium. There are also very few selected areas of the world, where wind and hydropower plants can be opted. Additionally, biofuels may be environment-friendly but they also release CO_2 and CH_4 during combustion (Haoyang 2018). However, algae thrive by removing the CO_2 and storing it into their biomass via photosynthesis at very faster rates. Thus, making them an ideal candidate for trapping CO_2. It has been estimated that 1 kg of algae uses around 1.87 kg of CO_2 daily. One acre of algae can utilize 2.7 tons of CO_2 every day (Anguselvi et al. 2019). Comparative studies found that a 25-year-old maple beech-birch forest only utilizes 2.18 kg of CO_2 daily, but the equal amount can be fixed by only 1.17 kg of algae (Toochi 2018). There are two major cultivation techniques of algae such as open-oceanic algal blooms and photobioreactors that can be utilized for trapping CO_2 from the atmosphere. Microalgae under the presence of a higher concentration of CO_2 from flue gas or soluble carbonate have significantly increased their CO_2 and biomass productivity (Yoo et al. 2010; Sydney et al. 2010; Kuo et al. 2017). Thus, cultivating algae for CO_2 trapping can be a promising approach in fighting global warming and climate change and reducing industrial pollution.

Open-oceanic algal blooms

Algae are abundant on the surface of the open ocean water making them ideal for CO_2 trapping; also, the ocean water provides enormous space for their growth. Algal blooms can be massively increased by adding iron (II) sulfate. This cultivation technique has been pictured to be the most promising because ocean water is the largest reservoir of algae and amount of CO_2 trapping is directly proportional to the number of algae that undergoes photosynthesis. Oceanic algal blooms are also very cost-efficient, as it only requires iron (II) sulfate and there is no need for constant maintenance (Haoyang 2018). The overabundant algal biomass can also be collected and utilized for the production of biofuels (Ghosh and Kiran 2017; Kumar et al. 2018; Nath et al. 2019). Ecologically, the overabundant algae on the ocean surfaces are consumed by shellfishes where the carbon contents of algal biomass are incorporated into the shells of the shellfishes as calcium carbonate (Haoyang 2018).

Photobioreactors

Photobioreactors are artificially made growth chambers having controlled nutrient levels and pH for the optimum growth of algae (Adeniyi et al. 2018). In comparison to oceanic algal blooms, photobioreactors have much more photosynthetic rates due to high algal concentrations per unit area. Nutrients like iron and magnesium and vitamins are added to the photobioreactors to increase the photosynthetic rate and to decrease the rate of evaporation. Photobioreactors can also utilize wastewater as a nutrient source making it an alternate approach to remove pollutants from water (Adeniyi et al. 2018). The only drawback is that the cost and maintenance of photobioreactors are high.

Thus, engineering interference is needed to manufacture more cost-efficient photobioreactors.

Conclusions

Algal biomasses represent a valuable source of environment-friendly strategies in overcoming some of the major environmental issues the world is facing today. Though research in this area has gained momentum in the last 3–4 decades, but many algal species have remained unattended. Therefore, scientific intervention is essential for identifying the biological potential of microalgae and their efficient application to facilitate the benefits to humankind and betterment of the planet earth.

Author contribution Original draft preparation, Amlan Roy; conceptualization, Nirmali Gogoi, Mohammad Farooq, Amlan Roy; supervision, review and editing of the manuscript, Nirmali Gogoi, Farishta Yasmin, Mohammad Farooq.

Data availability Not applicable

Declarations

Ethics approval and consent to participate Not applicable

Consent for publication Not applicable

Competing interests The authors declare no competing interests.

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