Phycoremediation Technology: A Global prospective

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1 Introduction

Water crisis is realized as one of the major issues and global threat, even though sufficient water and land resources are available (CA 2007). According to United Nations World Water Development Report (2014), more than two million tons of sewage, agricultural, and industrial wastes is dumped untreated into lakes, rivers, and other waterbodies in developing countries that is eventually polluting the usable water supply. Almost all waterbodies globally are highly polluted because of release of various industrial as well as domestic wastewaters. This untreated wastewater provides various organic and inorganic nutrients such as nitrogen (N) and phosphorus (P), for the autotrophs which in turn leads the process of eutrophication in waterbodies (Schindler et al. 2008).

The art of utilization of algae (macro- or microalgae) in removal, biotransformation, or mineralization of various nutrients, heavy metals, and xenobiotics from wastewater and carbon dioxide from waste air (Olguin and Sanchez-Galvan 2012) is known as phycoremediation. During this treatment, carbon, nitrogen, phosphorus, and other salts are used by algae as nutrients, from the wastewater or air as the case may be. Other pollutants and xenobiotics are even taken care of by the organisms by various cellular mechanisms. This is an eco-friendly process as there is no secondary pollution if the biomass produced is harvested for utilization (Mulbry et al. 2008). Literature reveals that algal bioremediation (phycoremediation) technology is highly relevant and has immense potential for future applications in various waste removal strategies. In the past few decades, extensive research has been made in algal biotechnological advancement and has successfully established the

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S. K. Gupta, F. Bux (eds.), *Application of Microalgae in Wastewater Treatment*,
https://doi.org/10.1007/978-3-030-13913-1_1

system of wastewater remediation using algae, microalgae in particular, in reduction of an array of organic, inorganic nutrients, and some highly toxic chemicals (Beneman et al. 1980; Thomas et al. 2016).

The agents of phycoremediation, algae, are photosynthetic organisms, capable of growing in extremely harsh and difficult environments. In addition, there are various research reports on microalgal sequestration of various heavy metals in their cell walls through process of adsorption or ion exchange, as a means of bioremediation of heavy metals (Priyadarshani et al. 2011). While microalgae are microscopic, macroalgae are visible to naked eye. Phycoremediation can serve many purposes such as (i) utilization of nutrients from wastewater; (ii) transformation, degradation, or removal of xenobiotics; (iii) remediation of acidic and metal rich wastewaters; (iv) CO_2 sequestration; and (v) biosensor-based detection of toxic compounds (Gani et al. 2015). By taking in carbon dioxide from the atmosphere and giving out oxygen through photosynthesis, not only they purify the air, but their interplay with the pollutants reduces the load from entering the waterbodies. However, it is still a challenge to develop and optimize processes to treat industrial effluent as well as to restore polluted rivers and lakes through the process of phycoremediation. In addition, there are various research reports on microalgal sequestration of various heavy metals in their cell walls through process of adsorption or ion exchange, as a means of bioremediation of heavy metals (Priyadarshani et al. 2011).

As algae are emerging as a potential biofuel candidate due to its productivity and other beneficial characteristics, successful pilot-/field-scale trials are now coming into existence. These production systems for biofuels can be exploited for phycoremediation to make it more profitable and eco-friendly. Such approach will help in making the biofuel technology economically feasible. In the recent day, technological advancement has explored the scope of microalgae to mitigate various hazardous pollutants in the environments. Moreover, phycoremediation strategy coupled with energy production is well established; however algal biofuel technology is not feasible commercially because of higher energy inputs. Additionally, modification in the cultivation system, harvesting systems, extraction technology, and biomass utilization approaches (biochemical and thermochemical) could be adopted to cope with sustainability issue via an integrated/biorefinery approach as demonstrated in Fig. 1. Let us discuss the various important issues of phycoremediation in details starting from cultivation itself.

2 Different Algal Systems Used for Bioremediation

The cultivation systems for algal biomass production coupling with remediation of wastewater are basically open systems and closed systems (photobioreactor). Other than the suspension culture, attached cultivation is also frequently implemented both in open systems and closed systems. Among these, open pond (raceway ponds) algae culturing and turf scrubbers are the most popular systems for algae cultivation. On the other hand, the closed systems for algae cultivation (photobioreactors) have more

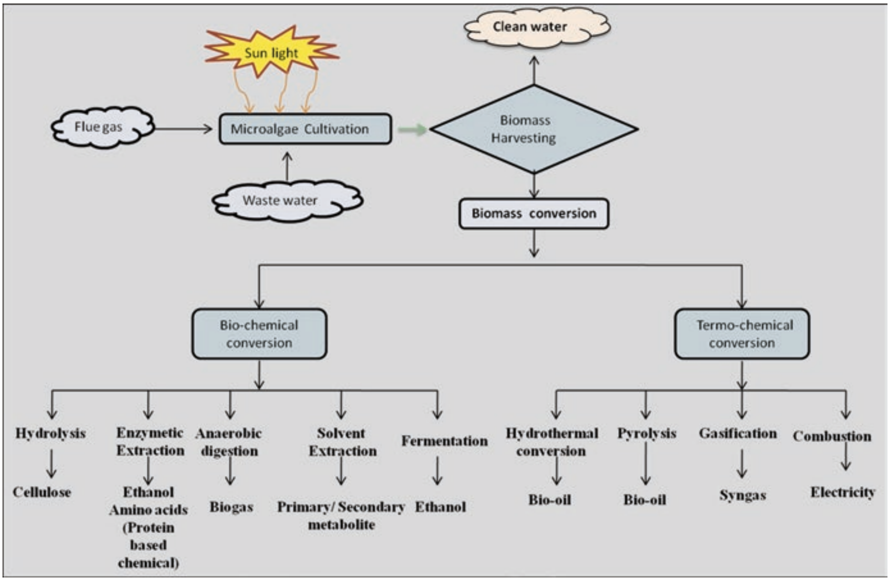

Fig. 1 Integrated biomass conversion flow chart

diversity based on its shapes and configurations of the bioreactor. The most frequently used closed systems for algae cultivation are tubular, bubble column, airlift, and flat panel (Richardson et al. 2012). The algae employed in these systems may act in monoculture, consortia, or natural assemblage of algal community. However, other two modes are considered more sustainable than monoculture mode.

2.1 Open and Closed Culture Systems

Open ponds for algae cultivation are the oldest and simplest form of cultivation systems for microalgae biomass production (Handler et al. 2012). In the past decade, stabilization ponds have been found to be used for the treatment of urban wastewater (Caldwell 1946); however to be more efficient, it requires a lot of land. In general high rate algal ponds (HRAPs) are shallow-type open raceway system with a single or multiple loops, and to obtain a water velocity of 0.15–0.3 m/s, it uses paddle wheel (Park et al. 2011). The depth of the systems is in between 0.2 and 0.4 m (sometimes up to 1 m) where CO_2 can be added in a sump of about 1.5 m depth. It is found that high rate algal ponds reduce the surface needed in comparison to stabilization ponds by a factor of 5 (Picot et al. 1992) and achieving a three-fold improvement in biomass productivity with a yield from 10 ton/year/ha (Craggs et al. 2011). As compared to activated sludge systems, the capital costs and operational costs are significantly reduced in case of HRAPs (Craggs et al. 2011).

On the other hand in photobioreactor, microalgae can be cultivated in axenic and controlled conditions, and there is significant increase in the volumetric productivities compared to open systems of algae cultivation. Earlier research found that *Chlamydomonas reinhardtii* cultivation using wastewater in photobioreactor produced better biomass and lipid (+144% and +271%, respectively), and removal rates of N and P (+38% and +15%, respectively) were found compared to flasks culture (Kong et al. 2010). However, the closed culturing systems demand significantly higher cost than open systems of algae cultivation which is approximately ten times high (Davis et al. 2011). For keeping axenic cultures and to grow fragile strains which produce potent bioactive molecules, closed systems are very much useful. However, in case of wastewater medium having a huge diversity of microorganisms, this precious advantage is lost in closed system. Moreover, the volumetric productivity does not counterbalance the high cost of photobioreactor for treatment of urban or agricultural wastewater for algae production.

For microalgae culturing in attached cultivation, immobilized microalgae are fixed on a supporting material, and that is immersed in the nutrients medium. However, there are few comparisons of wastewater treatment for suspended and attached algal systems (Kesaano and Sims 2014). It needs more research on certain factors which affect growth, nutrient mass transport, selection of species, algal-bacterial mutualistic interactions, and upscaling of laboratory research. The attached cultivation systems have provided promising results with certain wastewaters. It has been reported that use of dairy manure for cultivation of benthic algae in an attached cultivation system would require 26% less land area for equivalent nitrogen uptake compared to the conventional corn/rye rotation process (23% for phosphorus) (Wilkie and Mulbry 2002). In addition, biofilm rotating disk reactor is one of the efficient attached cultivation system for microalgae cultivation using wastewater with better biomass productivity. Earlier studies reveal that biomass productivities between 20 and 31 g/m^2/day with nutrient reduction rates as high as 14.1 g/m^2/day for nitrogen and 2.1 g/m^2/day for phosphorus (Christenson and Sims 2012). Using rotating biological contactor-based photobioreactor, an average biomass productivity of 20.1 ± 0.7 g/m^2/day was obtained over a period of 21 weeks without reinoculation (Blanken et al. 2014). These reactors provide better surface area to volume ratio in comparison to HRAPs.

2.2 Use of Monoculture and Consortia

Microorganisms usually exist in nature as part of organized communities and consortia, which gain benefits from cohabitation to keep invaders away, tackle risk of contamination, and simultaneously improve productivity and product diversity. In contrary, most of the cultivation trials are attempting a monoculture of selected species with advantageous traits. Promising genera/species/strains with specialized characters are generally employed under algal technology either as monocultures or consortia or as natural community depending upon the purpose. When the intention is biological manufacturing, i.e., to harvest high-value items from mass cultivation of biological organisms, axenic monocultures are mainly used (Mcneil et al. 2013). But, such monocultures are highly prone to contamination and losses. They require controlled conditions, high degree of sophistication hence, and higher throughput for the cultivation.

Controlled, symbiotic co-cultures possess features to overcome these bottlenecks, and co-cultures have shown improvements in yields of biomass, lipids (Yen et al. 2014), and high-value products (Dong and Zhao 2004). Maintaining axenic cultures has also proved as expensive and labor intensive, given the recurrent problem of contamination by bacteria, viruses, protozoa, fungi yeast, fungi, and microplasma (Langer 2008). Moreover, parasites or grazers can outcompete the working cell culture and influence production outputs and cell health.

With a wide range of thallus organization, algae could be found in a diverse habitat ranging from fresh to marine environments. Some commonly studied species for phycoremediation include *Botryococcus*, *Chlamydomonas*, *Chlorella*, *Phormidium*, *Haematococcus*, *Spirulina*, *Oscillatoria*, *Dunaliella*, *Desmodesmus*, *Arthrospira*, *Nodularia*, *Nostoc*, *Cyanothece*, *Scenedesmus*, etc. (Dubey et al. 2015; Rawat et al. 2011). Different species of algae possess different phycoremediation attributes such as growth rates, photosynthesis, total biomass production, biotransformation of certain molecule, faster uptake of certain heavy metal or nutrient, etc. Therefore, a mixture (consortia) of selected algal species will show a better performance than any individual species. Different species with distinct attributes and without any antagonistic effects could be taken together to form a functionally distinct community. However, for the formation of consortia, the screening of various traits of each constituent monoculture is necessary, as each species bear distinct inherent traits to make it superior than others. Association of eukaryotic algae with other organisms like bacteria, yeast, or cyanobacteria may be beneficial in production outputs. So, symbiotic/synergistic/mutualistic association of organisms in artificial co-cultures may produce marketable products and allow a biorefinery mode of production (Markou and Nerantzis 2013; Gebreslassie et al. 2013). A mixture of microorganisms possessing different metabolic activities and adapted to various environmental conditions develops a healthy biological system that can operate under different nutrient loads and environmental conditions (Johnson and Admassu 2013; Boonma et al. 2014). Moreover, cooperative interactions can be established between the microorganisms integrating the consortia, which can increases nutrient uptake rates (Renuka et al. 2013).

The important factors for stability of consortia are the initial inoculum size of constituent species, duration of log phase of each species, carrying capacities, non-allelopathy (toxin/antibiotic nonproducing) features, and maintenance of their original features in the consortia (Patel et al. 2017). The distinct features of the constituent species could be nitrogen fixation, luxury uptake of phosphates, heavy metal detoxification, high CO_2 sequestration, easy harvesting feature, etc. In such consortia, while the nitrogen fixers will alleviate nitrogen limitation, phosphates from anthropogenic sources will help to enhance their growth, and heavy metal detoxifying strains such as *Chlorella* can provide a better growth condition. This means, both cyanobacteria and green algae as constituent in consortia may provide a successful functional community. More diverse community means a higher stability and more biomass production (Cardinale 2011). Even if open ponds are inoculated with different algal species, high degree of contamination by pathogens is a possibility which leads to change in the original community structure. But at the same time, the inherent diversity and interaction within the consortia protect the individuals from pathogen or high light intensity. Therefore, the structural diversity and functional stability of consortia help in decreasing overall throughput and increasing the sustainability of the phycoremediation.

3 The Agents with Special Attributes

Owing to rapid industrialization and rapid growth of human population, resulting environmental degradation is very alarming. To deal with such situation, we need to follow unique approaches. Among various strategies for waste mitigation, today by means of algal strains with special characteristics, the nutrient removal has been shown to be more efficient. They possess various desired attributes like extreme temperature tolerance, producing high-value molecules, quick sedimentation behavior, mixotrophic growth potential, etc. A *Phormidium* sp. that was isolated from polar environment is capable of removing nutrients more efficiently than a community of green algae at temperatures below 10 °C. This strain was appropriate for wastewater treatment in cold climates during spring and autumn (Tang et al. 1997). On the other hand, *Phormidium bohneri* is a high-temperature alga for treating wastewater in addition to its quick sedimentation behavior (Talbot and De la Noüe 1993).

Some marine seaweed, green macroalgae, and their alginate derivatives show high affinity for various metal ions (Mani and Kumar 2014). Alginate plays a vital role in metal biosorption process by brown algae. So, there should be an attempt by scientist and industries to make the microalgal technology more eco-friendly and cost-effective by focusing specific uses. It can meet most of the problems and lead toward global sustainability.

3.1 Cyanophycean as Bioremediators

The cyanobacteria are able to fix atmospheric N_2, catalyze the cycling of various nutrient elements, purify soil and water by discouraging growth of pathogenic microbes, and decompose organic substances. They could remediate heavy metals and detoxify pesticides and other xenobiotics to promote soil and water reclamation. They contribute to agriculture by improving soil quality and promoting plant growth by production of enzymes, vitamins, hormones, and other bioactive compounds (Higa and Wididana 1991). The restored soil fertility, land reclamation, nutrient cycling, and reduced agrochemical uses not only contribute to agricultural sustainability but also provide environmental protection and pollution prevention (Shukia et al. 2008). Some researcher found that the evolution of greenhouse gases such as CH_4 from the soils of various ecosystems is minimized to a great extent by the association of methanotrophs and cyanobacteria (Tiwari et al. 2015). It may be noted that CH_4 is 28 times more potential GHG than CO_2 (IPCC Fifth Assessment Report 2014 (AR5)).

The oxygen released by cyanobacteria during photosynthesis creates an aerobic environment in the rhizosphere, simultaneously reduces the methane genesis, and enhances the aerobic methane oxidation (Prasanna et al. 2002). As cyanobacteria minimizes methane flux without compromising the productivity of the flooded rice field, the cyanobacteria could be employed as a practical option for minimizing global warming potential and enhancing nitrogen fixation potential of paddy fields (Prasanna et al. 2002). Increased diversity of cyanobacteria, methanotrophs, and other organisms in the wet crop fields promotes higher production and reduced CH_4 emissions (Singh 2015). Furthermore, the cyanobacterial N fixation resulting in reduced fertilizer use makes the land restoration cost-effective, sustainable, and safer (Pandey et al. 2014) which also conserves the diversity of methanotrophs and CH_4 consumers. However, the cyanobacterial genetic and metabolic engineering in the future are expected to make the phycoremediation more effective in mitigating environmental pollution and empowering global sustainability.

3.2 Role of Algae for Detoxification of Organic Pollutants and Heavy Metal

The extensive occurrence of various toxic pollutants like heavy metals and other hazardous contaminants in the environment is a serious concern today. Several removal methods have been proposed and implemented in an eco-friendly manner to address various environmental pollution issues. Recent study by Oregon State University reveals that the marine plants and seaweeds in shallow coastal ecosystems can give a major role in increasing the effects of ocean acidification. Moreover, researchers found that seaweed, green macroalgae, and their alginate derivatives show high affinity for various metal ions (Mani and Kumar 2014). It is know that alginate plays a significant role in metal biosorption by brown algae. The potential of microalgae to perform well at very low levels of contaminants without producing toxic sludge is easy to culture and maintain. Furthermore, microalgae have a very good binding affinity (because of its relatively high specific surface area and net negative charge) and also appropriate remediation strategies (Suresh Kumar et al. 2015). Some earlier studies on potential of microalgae for bioremediation of heavy metals are noted in Table 1. There is still need of research that leads to the development of new bioremediation technologies which use algae in engineered systems to mitigate toxic organic pollutants for a green environment.

Table 1 Some studies on algal application for bioremediation of heavy metals (Priyadarshani et al. 2011)

Microalgae	References	Metal studied
Tetraselmis chuii	Ayse et al. (2005)	Cu
Spirulina (Arthrospira) Platensis	Arunakumara et al. (2008)	Pb
Spirogyra sp., *Nostoc commune*	Mane et al. (2011)	Se
Anabaena variabilis, *Aulosira* sp., *Nostoc muscorum*, *Oscillatoria* sp., and *Westiellopsis* sp.	Parameswari et al. (2010)	Cr(VI), Ni (II)
Spirogyra hyalina	Nirmal Kumar and Cini (2012)	Cd, Hg, Pb, As, and Co
Scenedesmus bijuga, *Oscillatoria quadripunctulata*	Ajayan et al. (2011)	*Cu*, *Co*, *Pb*, *Zn*
Scenedesmus acutus, *Chlorella vulgaris*	Travieso et al. (1999)	*Cd*, *Zn*, and *Cr*
Spirulina platensis	Garnikar (2002)	*Cu*, *Hg*, and *Pb*
Chlorella minutissima	Singh et al. (2011)	*Cr(VI)*

3.3 Exploiting Harmful Algal Blooms (HABs)

Algal blooms are generally a resultant of nutrient enrichment of aquatic bodies. Bloom is a state of higher productivity and is desired most of the times in man-engineered systems. However, when such blooms in nature comprise harmful cyanobacteria, it becomes an environmental concern because of their toxins which compromise the safety of water usage (Smith and Daniels 2018). Owing to incidence of various illnesses in livestock and human form algal toxins, there is a worldwide attention on harmful algal blooms which are characterized by very fast growth and biomass accumulation of one or several species of algae (Chen et al. 2016). The management challenges these blooms pose are a thorough understanding of the aquatic food web dynamics, community ecology, and the links with other ecosystems, along with the socioeconomic welfare and the administrative issue (Qin et al. 2015; Sun et al. 2015; Brooks et al. 2016). Thus, short-term management strategies of bloom control and eradication and reducing their harmful effects can lead to unseen damages to aquatic ecosystems and thereby significant socioeconomic losses (Ahlvik and Hyytiäinen 2015). On the other hand, a thorough understanding of the toxicological potential of HABs (Brooks et al. 2016) particularly of costal ecosystems is required for our safeguard and a successful management of the algal blooms. Therefore, there is an urgent need to improve our understanding of the toxicological potential of HABs (Brooks et al. 2016), especially for coastal ecosystems (Halpern et al. 2008).

Research on algal bloom for exploring its potential has given rise to conversion of the biomass into commercial products and as natural renewable bioresources (Kim et al. 2015). Moreover, the natural ones, in comparison to culture biomass which are photoautotrophic, need a lower cost of raw material input. Further, the occasion of bloom formation can be exploited for the purpose of phycoremediation. For this purpose, we simply have to feed the existing bloom with wastewater. The bloom remediates the wastewater at a much faster rate due to high population density of the algae. In this context, Sahoo (2010) found that nutrient uptake rate is much faster when fed to a denser algal population than low density population. In case of planned cultivation program, also a bloom is desired but at the cost of artificial nutrient inputs. So, the natural bloom can explored for phycoremediation purpose. However, a proper management plan needs to be in place which takes care of wastewater input and harvest of the bloom biomass so that the ecological balance is maintained. Pandhal et al. (2018) worked on harvesting of natural bloom and reported an improved ecosystem functioning in response to maximum rate of harvesting. The biomass of natural algae blooms could offer an abundant feedstock for conversion into various biofuel products like bio-oil, biochar, biodiesel, and so on. As the eutrophication and bloom ordinarily is damaging to the local ecosystems as well as economy, the utilization of this abundant waste biomass would provide a feedstock for green bioenergy while still mitigating the environmental burdens (Zeng et al. 2013).

3.4 Bioremediation of Soil Using Algae-Bacteria Consortia

There is a global concern for environmental impacts of soil contamination. Bioremediation of such areas is a high-priority research topic for researchers worldwide. A consortium of microorganisms could be employed for such purpose. Consortia are generally symbiotic community of microalgae, cyanobacteria, and other associated aerobic or anaerobic microorganisms. They synergistically neutralize various toxic, organic, and inorganic pollutants. Microalgae and bacteria complement each other, and the synergy results in better remediation efficiency. Oxygen, and electron acceptor from algal photosynthesis, helps the degradation of organic matter by heterotrophic bacteria, and in turn, algae get their CO_2, nutrients, and other stimulatory substances from bacteria (Subashchandrabose et al. 2011).

Comparing to chemical technologies, the bioremediation processes involving algae-bacteria consortia techno-economically feasible self-sustaining approach (Bose and Das 2013). The effect that is obtained from the algae-bacteria synergy is hardly possible from employing any single species of (Escobar et al. 2008). In comparison to monoculture, consortia are very robust, are resistant against invasion, can bear environmental stress, and can maintain a more stable community. This ensures more stability in their growth and production. Chemical substances on their cell surface acting sometimes as allelochemicals help in enhanced bacterial degradation of wastes (Luo et al. 2014).

Bioremediation by such approach not only minimizes the material inputs in terms of energy, nutrients, and CO_2, but it produces biomass as by-product which could be utilized for various purposes (biofuel or biomaterial). Some valuable elements can even be recovered from the biomass. Such bioremediation process is sometimes more efficient in treatment of hazardous chemicals. Algae, because of their sensitivity, can serve as bioindicators to identify contamination, genotoxicity, and ecotoxicity in sediment as well as in soil (Bose and Das 2013). Taking the help of modern molecular techniques, selected consortia can provide better results for waste remediation and side by side produce some desired metabolites. Further improvements could be achieved by application of computation biology in addition to experimental biology by getting more insight into the algal-bacterial interaction at both molecular and metabolic levels.

4 Genetic Engineering and Phycoremediation

Research advancement on algal biotechnology is exploring the method like recombinant DNA technique to create constructs for both prokaryotes and eukaryotes that may replicate and possess novel research utility. It can also be applied to modification of algal metabolic pathways to targeted cellular activities of the photosynthetic cells by manipulating enzymatic, transport, and various important regulatory functions.

The genetically modified algae produce higher yields of the primary metabolites as well as by-products (Snow and Smith 2012). They do so depending on the desired characters for which the genes are introduced. This is a product of synthetic biology which provides a superior feedstock (Tabatabaei et al. 2011). The introduction of DNA into algal cells is done through various routes such as artificial transposons, particle bombardment, agitation of a cell suspension in the presence of DNA and glass beads, electroporation, agrobacterium infection, viruses, and silicon carbide whiskers. Out of these all methods electroporation and particle bombardment are the best ones (Rismani-Yazdi et al. 2011).

By modification of genomic DNA, desirable traits can be incorporated in algae to make them survive and show improved performance in harsh conditions. Techniques like DNA sequencing, metagenomics, hybridization, and enhanced evolution are being employed as tools for this purpose (Dana et al. 2012). Non-transgenic methods could even be employed to develop improved algal strains (Tabatabaei et al. 2011; Flynn et al. 2010). When an improved trait is incorporated, normally a trade-off occurs to make some other traits unfavorable (Hall and Benemann 2011). The major challenges of genetic engineering which influences the global commercialization of algae are the lower growth rate and gene quality (Tabatabaei et al. 2011).

However, there is a need of suicide genes to control an accidental escape and occurrence of any dangerous algal strain which possess high risk to environment (Quinn and Davis 2015). Although the bioremediation concept using algae to degrade pollutants in situ has lately attracted a lot of public attention, introducing the “genetically engineered” algae into the environment to enhance the process is yet to be demonstrated with success.

5 Algal Omics in Phycoremediation

An in-depth understanding of the role of different factors related to metabolism, growth, function, and dynamics of the microbial communities of the contaminated site is required for a successful bioremediation application. Proteomics, transcriptomics, genomics, and metabolomics tools together are providing a crucial insight into interactions in microbial communities and the bioremediation mechanisms and understanding of toxicity. It also helps in predicting the risks associated with environmental toxicity and bioprospecting of value-added products. This "omics" technology has become highly helpful in producing a complete description of nearly all components within a biological entity. Further, the technique and related data processing activity have a great value in ecotoxicological research (Spurgeon et al. 2010). The different omic techniques are providing information about the microbes involved in soil bioremediation and their metabolic responses. In addition, algal omics technology has also been extensively applied to the examination of algal bioremediation (Merchant et al. 2007). This advance technology is helping to unlock the full potential of microalgae feedstocks for multiple uses, through utility in an array of industrial biotechnology, biofuel, and biomedical applications (Guarnieri and Pienkos 2015). Thus, algae are emerging as highly attractive microbial cell factories in producing wide array of algal bio-products. The omic concept can help in driving bio-product discovery and optimization in microalgal systems. Moreover, multi-omic analyses of algal biology are evolving as a potential tool for development of biocatalyst and offering a powerful path toward hypothesis-driven strain-engineering strategies for enhanced TAG biosynthesis (Arora et al. 2018).

6 Global Challenges

Global issues like rapid climate change because of global warming are the major threat to ecosystem health and sustainable human welfare. Moreover, several anthropogenic stresses are hampering our day-to-day activities and ecosystems equilibrium. Therefore, there is need of mitigation strategies to solve this serious issue related to environmental pollution. Among various mitigating strategies, phycoremediation is a powerful tool for addressing global changes. Microalgae possess effective CO_2sequestration capacity compared to other photosynthetic organisms. Furthermore, microalgae can use CO_2 from flue gases and produce several high-value products. Production of biofuel from microalgae is a very promising technology.

6.1 Changing Land Uses and Consumption Pattern

Microalgae cultivation is emerging as an important research and investment area these days, because of its wide potential for fuels, foods, animal feed, pharmaceuticals, industrial applications, and environmental benefits. In addition, microalgae promises many environmental benefits compared to existing waste treatment and fuel technology. However, there are certain issues to overcome for a feasible and sustainable wastewater management, emissions reduction, and land use changing pattern (Usher et al. 2014). Moreover, microalgae cultivation seems more advantageous owing to their high growth rates and option to use marginal land for cultivation, thereby minimizing competition with food production as compared to other bioenergy crops. However, large-scale algae cultivation could have significant impacts on global energy scenario and agricultural and land markets, leading to considerable changes in global resource demands and greenhouse gas emissions (Efroymson et al. 2016).

Topographic and soil constraints limit the land availability for algal cultivation system in raceway pond as the large shallow ponds require relatively flat terrain. In addition, the soil porosity/permeability will also affect the need for pond lining and sealing (Lundquist et al. 2010). Solar radiation is one of the important factors influencing growth of algae to achieve higher production all over the year with little seasonal variation. For this reason, the most suitable locations for algal cultivation are warm countries close to the equator where insolation is not less than 3000 h yr.^{-1} and with an average of 250 h month^{-1} (Necton 1990; Verween et al. 2011). So far, the most commercial microalgae production has occurred in low-latitude regions such as Israel, Hawaii, and Southern California.

6.2 Climate Change Phenomena

The global warming and climatic disturbance as a consequence of environmental pollution have emerged as an important issue around the globe. These issues have drawn the attention of environmental biologists, pathologists, eco-chemists, eco-toxicologists, and researchers from diverse fields. Moderation of climate change phenomena is one of the important incentives for the algal energy field in addition to control of global environmental pollution issues. The greenhouse gas (carbon dioxide, methane, and nitrous oxide) mediated global warming, and climate change appears to be seriously disturbing the natural world. The main source of energy in India is coal which is currently contributing around 54% of electricity need and may reach to around 70% in the future (Arora 2013). The other important energy source is crude oil, about 70% of which is consumed by automobiles. It is obvious that fuel requirements and associated pollution will increase with increasing living standard and expanding population.

The compatibility of cyanobacteria with predicted global climate change is expected to be positive as concluded from research on their in situ dynamics, evolutionary history, and ecophysiology (Paul 2008; Paerl and Huisman 2009). Many systems for algae cultivation and production continue to be developed for moderate and hot climates (e.g., USA, Europe, and Australia) (Pankratz et al. 2017). Recently, algae cultivation has explored for the use in fixation of CO_2, which is of higher interest in greenhouse gas mitigation and in biofuels production. Furthermore, algae may provide key to scientists to achieve a negative emissions technology and to produce electricity, biofuels, value chemicals, and protein while simultaneously removing substantial amounts of carbon dioxide from atmosphere and reducing deforestation. Oswald and Golueke (1960) initially conceptualized the idea of phycoremediation involving a large-scale system of dozens of large (40 ha) high-rate algal ponds. The harvesting of biomass was done by a simple flocculation-settling procedure. Anaerobic digestion of the concentrated algal sludge produced biogas (methane and CO_2). Microalgae are able to sequester CO_2 from the ambient media and also from soluble carbonates (Chanakya et al. 2012). Many stationary industries such as cement plants, thermal power plants, refineries and petrochemical plants, and fertilizer plants are the main source of CO_2 with high concentrations localized in the ambient environment (Mildbrandt and Jarvis 2010). Being environmental friendly and without any secondary pollution as in case of chemical methods of wastewater treatment, application of phycoremediation technology to the wastewater and gas is being thought of these days for carbon capture.

7 Conclusion

Phycoremediation is an eco-friendly solution with no secondary pollution conditioned prior to harvest and utilization of the algae biomass. It has immense potential for future applications in various waste removal strategies. However, phycoremediation is still in growing stage; there is a need to develop and optimize the processes to treat industrial effluent. To address the sustainability issues of wastewater treatment as well as resource recovery, modification in the cultivation system, harvesting systems, extraction technology, and biomass utilization approaches (biochemical and thermochemical) via an integrated/biorefinery approach is necessary. Genetic engineering, synthetic ecology (synthetic consortia), and omics approach of algae are futuristic approaches to optimize the phycoremediation technology. This simple technology has the ability to address the global issues of land use changes and global climate change.

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