Phycoremediation: A Green Technology to Combat Environmental Pollution

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ABSTRACT:

Industrialization and urbanization have led to severe exploitation of natural resources causing havoc to the environment. There are numerous ways to tackle the problems of environmental pollutions however, these generate threats to the mother nature. Phycoremediation or microalgae treatment is one of the very effective ways to combat the problems caused by other physical and chemical means. This green approach has gained popularity in the recent years for treating various types of environmental wastes. This chapter highlights the significance of phycoremediation in various sectors (industrial and domestic waste water treatment, carbon and heavy metal sequestration and the like) and how this approach could be utilized in battling environmental pollution very effectively and precisely considering the safety of the environment.

Keywords: Phycoremediation, microalgae, environmental pollution, carbon sequestration, waste water treatment.

I. INTRODUCTION:

The world today is witnessing severe environmental pollution issues due to rapid growth in population, industrialization and urbanization which heavily impacting our ecosystem services. Every year, huge quantities of solid and liquid waste are generated worldwide of which only a small portion is recycled back, and the rest is discarded or left untreated, that gives rise to cascade of problems for people and the environment. There has always been a major concern in the society regarding waste water treatment before its safe discharge into the environment especially in developing countries like India. As we know that waste water can be a reliably used for irrigation purpose in agriculture it becomes extremely necessary to identify such cost-effective treatment techniques that are environmentally sustainable and require minimal inputs and infrastructure. Waste water treatment methods are categorized into primary, secondary, and tertiary. First treatment involves temporarily storing waste in a container to settle heavy materials at the bottom the while lighter material like oil, grease, and solids float on the upper level. Secondary treatment is mainly applicable for microorganisms in a well-maintained environment. Whereas tertiary treatment is applied in addition to primary and secondary treatment. However, as compared to biological treatment, both physical and chemical treatment are highly expensive. Moreover, in chemical method, there is a rise in conductivity, total dissolved matter and pH of the treated water which makes biological treatment the most efficient and sustainable one. The biological method involves incorporation of microorganisms to disintegrate chemicals present in waste water while enhancing the utility of the remaining residues to produce value-added compounds like biofuels and biopolymers. One of the recent technologies to control pollution is the or the use of algae (micro or macroalgae) or phycoremediation to remove or biotransform pollutants and other toxins (including xenobiotics) from waste water. Algae are an excellent sink for carbon dioxide and thus can efficiently reduce the carbon footprint [1],[2]. As they are ubiquitous in nature and highly well adapted to a wide range of habitats; they are broadly categorised as macroalgae, microalgae, and marine algae. Microalgae are very much rich in biodiversity and because of their well adaptation in diverse environments, they are potential candidates, for waste water treatment and biofuel production [3],[4],[5]. Refence [6] stated that due to improper treatment of waste water and faecal sludge a whole lot of diseases spread and is responsible for development of antimicrobial resistance. In addition to that, nutrient removal using microalgae is one of the useful tertiary waste water treatment strategies to eradicate NO_3^-, PO_4^{3-} and ammonium [7]. Microalgae effectively removes heavy metals, hydrocarbons, and pesticides from waste water with various treatment mechanisms that include including biosorption, bioaccumulation, biotransformation, decay, and assimilation [8],[9],[10]. In recent years, with the help of molecular and functional genomic approaches, scientists have developed different algal strains for treating waste water, by increasing their photosynthetic effectiveness, flexibility and potential to detoxify pollutants. [11],[12]. There are certain advantages with phycoremediation over other standard physiochemical oxidation or reduction. Some of which include low operational costs, easy acclimatization of N and P into algal biomass, eliminating the need for sludge handling and oxygenation of effluent before its discharge into water body. Furthermore, this process is ecofriendly and algal can be recycled as fertilizer without generating any secondary contaminant [13]. Some of the widely used microalgae treatment of different waste waters are *Botryococcus* sp., *Phormidium* sp., *Scenedesmus* sp., *Chlorella* sp., and Chlamydomonas sp.

In the recent years, pollution has become a primarily localized problem as some of the pollutants not only persisted in the environment but also manipulate atmospheric and climatic conditions. In the light of which management of environment has become a more serious global issue, with a great deal of attention to be given to waste generation and disposal practices, more specifically hazardous waste disposal. Therefore, much research on biological approaches is needed to develop highly efficient biotechnological and advanced tools for effective waste management.

II. WASTE GENERATION AND ITS GLOBAL IMPACT

Nearly every year a huge amount of waste is generated across the globe, of which only a small portion is recycled while most of it remains untreated or dumped which impose hazardous health effects on people and the environment. Wastes are categorized into solid, liquid or gas. Commonly referred Solid wastes are trash, garbage, rubbish, refuse, broken glass, cans, plastics, paper, battery casings and nylon [14]. Liquid wastes, largely referred to as effluents, are comprised of agricultural runoff water, domestic wastewater, and discharged wastewater from industrial processes [15]. Greenhouse gas emissions and waste gases from stack, lime dust, asbestos dust, cement factories, stone crushing excavation activities, acid fumes and cigarette fumes are all categorised under gaseous waste [15].

A. Solid Wastes:

Majority of solid waste are composed of municipal garbage, industrial and agricultural wastes, mining and mineral wastes, construction, and demolition wastes, medical and radioactive (nuclear)wastes, human and animal excreta [16]. Solid waste from household, industries and markets leads to generation of huge levels of pollution, specifically in the form of methane gas and CO_2 emissions. Although physical and mechanical means like recycling, incineration, landfilling, etc. are widely used measures, waste processing/transformation by biological and chemical means remain the ultimate choice for sustainable technology development and successful waste management.

B. Liquid Wastes:

Liquid wastes comprise of industrial effluents in the form of black water, sullage and wastewaters from commercial establishments: black water in the form of domestic sewage contains human excreta including urine and faeces. It is estimated that approximately 80% of wastewater is released into the environment without treatment globally. Therefore, ecofriendly sustainable technologies is in demand for effective disposal of liquid wastes.

C. Gaseous Wastes:

A wide range of gaseous waste in the form of atmospheric pollutants generated predominantly due to anthropogenic activities. The most prominent of which are greenhouse gases such as CO2, methane and chlorofluorocarbons, in addition to oxides of nitrogen (NOx), oxides of sulphur and carbon monoxide. These gaseous waste components are quite hazardous and often lead to severe atmospheric pollution and destroy terrestrial and aquatic environments through precipitation. Thus, it becomes a matter of concern to manage these gaseous wastes although physical treatment processes like filtration are available and widely used. In this aspect advanced research is needed for developing effective treatment technologies.

D.Toxic Wastes:

Coming to the harmful toxic wastes, their treatment remains a great challenge in overall safety of the environment. The occurrence of toxic contaminants like heavy metals, pesticides, plastics, etc. poses a major threat to the environment. While various physical, chemical and biological treatment methods are available, all these processes lead to buildup of toxic elements in the environment which eventually results in bioaccumulation and biomagnification. Hence, the world today seeks for development of some successful remediation technologies which could lead to biotransformation processes, where toxic constituents are converted into safe, disposable non-toxic forms. Therefore, efficient waste and recycling management plans need to be developed to sustain environmental, economic and social development principles [17] (Fig. 1).

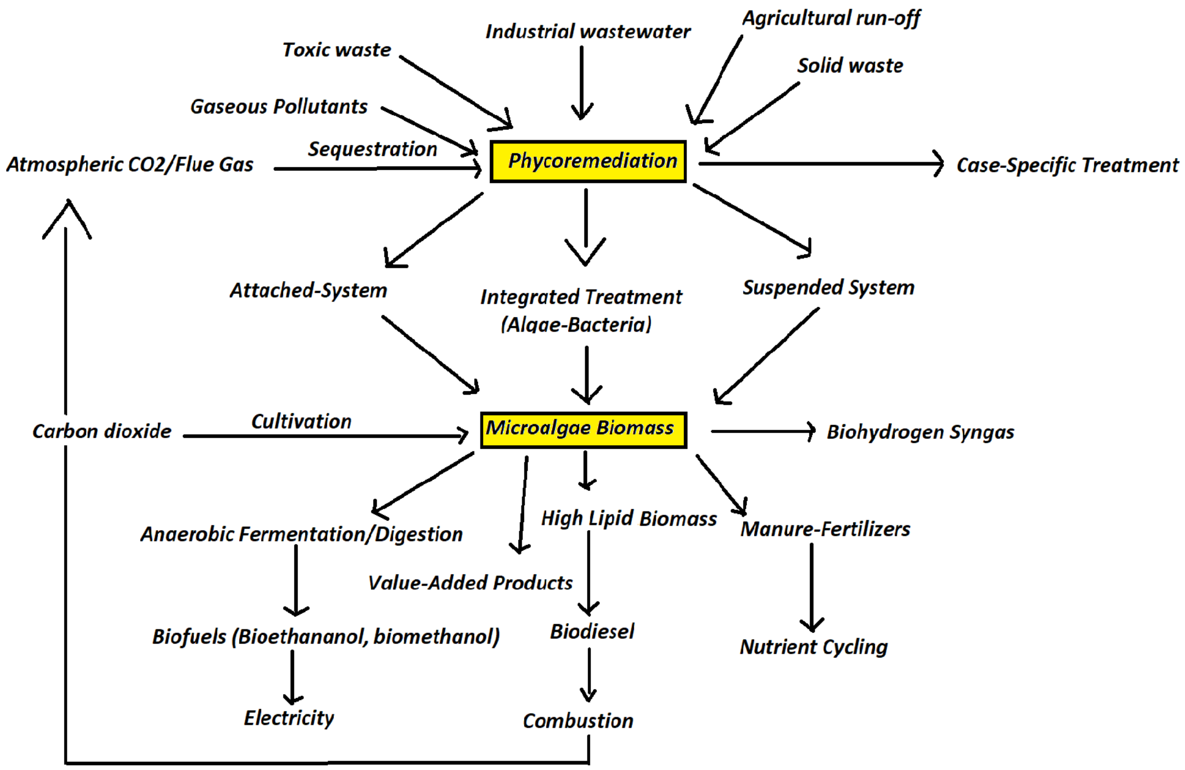

Fig.1 Microalgae and Environmental Sustainability

III. CONVENTIONAL BIOREMEDIATION AND PHYCOREMEDIATION: A COMPARISON

Bioremediation, in broader sense, refers to the treatment of environmental wastes using living agents like microorganisms, plants and animals. Whereas, phycoremediation is a recently identified unique terminology to represent the biological process of using algae as a source to mitigate environmental pollution. Phycoremediation offers certain vital advantages over conventional bioremediation (Table 1) [18]. Wastewater provides ideal habitat for bacterial growth; however, inorganic nutrients such as nitrogen and phosphorus are not completely removed/degraded by bacteria, and which is why it becomes the main cause of eutrophication in freshwater ecosystems. Amongst biological methods, Activated Sludge process (ASP) and biofilm systems are the most widely used tertiary treatment methods in wastewater treatment plants. However, these processes consume more energy (ASP, 1.3–2.5 MWh per million gallons (MG) of wastewater, and biofilm systems, 0.8–1.8 MWh per MG) when compared to that of algal ponds (0.4–1.4 MWh MG-1 d-1) [19], [20]. Moreover, ASP requires 1 kWh of electricity to remove 1 kg of biochemical oxygen demand (BOD). In contrary to this, photosynthetic oxygenation requires no energy inputs to remove BOD and in addition, produces enough algal biomass to generate methane gas that in turn produces 1 kWh of electric power [20], [21].

Table 1 Phycoremediation and Bioremediation: A comparison

Phycoremediation	Conventional bioremediation (Bacterial treatment)
Algal strains are capable of growing in multiple modes of nutrition such as autotrophic, heterotrophic and mixotrophic and remove wide range of pollutants	Mainly remove organic load
Less energy consumption	High energy consumption
Construction and maintenance costs are typically less	High construction and maintenance costsnhgth
Highly suitable for liquid biofuel production such as ethanol and biocrude/ biodiesel, which are truly carbon-neutral	Bacterial biomass usually undergoes anaerobic digestion
The technology is robust, and the algae can withstand high range of pH	The systems are very sensitive to pH ranges
Certain phycoremediating strains can be used as biofertilizers	Usually strains/consortia used here do not serve as biofertilizers
Highly environment-friendly as the organisms are capable of mitigating CO2	In fact, CO2 is released into the atmosphere during growth of the bacterial systems

IV. PHYCOREMEDIATION AS A TECHNOLOGY

In order to mitigate the problem of environmental pollution, various reactor have been designed and utilized using microalgae. A wide variety of treatment systems have been constructed that comprised of suspended algal systems, attached system, or closed systems. Amalgamation of this technology with other sustainable technologies can even lead to more fruitful results.

A.Photo-Bioreactors:

One of the widely used reactors are Photo-bioreactors which are usually closed cultivation systems characterized fully regulated parameters to attain the maximum benefits. This reactor offers significant advantages over conventional reactors in terms of reduced contamination risk, no CO_2 losses, feasible cultivation conditions, hydrodynamics and temperature control system and flexible technical design [22]. In addition to these benefits, it also provides higher areal productivities and the prevention of water loss by evaporation [23]. Different types of reactors such as tubular, vertical column and flat panel have been developed. To choose the optimal type of PBRs, it is mandatory to understand the major phenomena limiting According to the performance of microalgal cells such as light availability, nutrient supply including CO_2, right type of photo reactors is designed [24]. Although they can be used in wastewater treatment, it has some major drawbacks including investment and operational costs which limits their usage for wastewater treatment

B. Open Pond Treatment Systems:

When it comes to microalgae and biofuels more often it is found that open treatment systems are more efficient as they are less expensive and not so difficult to scale up. However, if they are cultivated for high value products, closed systems are more frequently used. In addition to that, most closed systems when operated indoors with artificial lighting, generates high energy costs. One classic example of an open pond system is a high-rate algal pond (HRAP). The idea of the HRAP was first developed in the mid-1950s by Oswald and co-workers and since then it has been in market in various countries [20], [25]. The design consists of a primary settlement lagoon with a shallow (0.2–0.6 m depth) meandering open channel and a motorized paddle wheel propels the effluent to prevent settling [26]. Velocities at which most ponds are operated rages from 10 to 30 cm/s which is quite low and this helps to avoid deposition of algal cells [20], 27]. HRAPs are very handy and easy to operate because of their simplicity as compared to conventional technologies such as activated sludge treatment methods. This design has an added advantage of serving two purposes: 1) secondary wastewater treatment and 2) algal biomass production. It is a blend of intensified oxidation ponds and an algal reactor. Here both algae and bacteria symbiotically help each other. HRAPs are supremely effective in eliminating organic matter, slowing down bacterial contamination. Wastewater treatment in HRAPs not only allows a substantial reduction organic matter but equally effective in reducing nitrogen and phosphorus. In addition to that, HRAPs provide a more efficient wastewater treatment method by taking care of other parameters such as bacteria load, BOD and even toxic nutrients [20], [28].

C. Attached Systems/Sloping Pond Technology:

The concept of immobilization of microalgae was introduced by de la Noue and his [20], [29], [30]. In general, immobilization is achieved by either growing microalgae entrapped in a matrix or on attached systems. By using mechanical pressure such as suction or scraping, algae growing on the surface can be harvested. In addition to that remaining algal colonies adhered on the surface can be used as inoculum for the next batch of growth making the process a semi-continuous system of culturing microalgae [20], [31], [32]. As per reference [33], a novel algal biofilm membrane photo-equipped with solid carriers and a submerged membrane module was developed in which *Chlorella vulgaris* was attached for treatment of secondary effluent. This method is quite effective which makes it preferable for harvesting the biomass. In the recent years, a more robust form is developed that makes use of a cost-effective sloping pond, where attached and suspended systems both are combined for effluent treatment. The idea is to create a turbulent flow while the algal suspension flows through sloping surfaces. The process is kept in circulation if sufficient incidence of radiation is present. For the remaining hours, the suspension is stored in tanks provided with aeration [20], [34]. This prevents the deviations (from the hydrodynamic balance) from affecting the efficiency. [20],[35]. Another successful method was developed by reference [36]. The technology consists of an algal turf that is created by growing benthic macroalgae/microalgae to be used as a scrubber of CO_2, nutrients and pollutants which also generates biomass production.

D. Integration of Algal Treatment System into Other Conventional Biotreatment Systems:

Microalgal treatment has a tremendous future as this method is highly cost-effective and hence can be easily integrated as part of the existing secondary/tertiary treatment systems [18], [20]. However, the integration depends on the quality of the wastewater being treated. According to [37], the efficiency of nutrient removal can be very high when bacterial and algal systems are integrated. The process is highly useful when the wastewater contains high organic load and toxic heavy metals (Fig. 2).

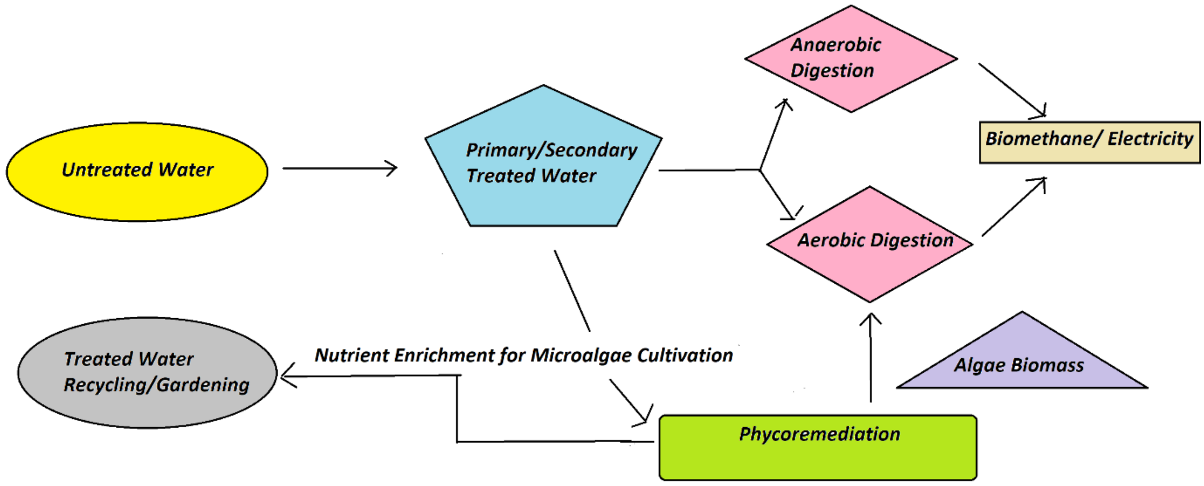

Fig. 2 Flowchart of Phycoremediation Process

V. MECHANISM

Flocculation, sedimentation, and rhizo-filtration are some of the general methods by which algae eliminate contaminants [38], [39], [40], [41]. Microalgae in their unicellular bodies are very effective in accumulating and assimilating heavy metals, plant nutrients, organic and inorganic contaminants, pesticides, and radioactive substances [41], [42]. This adds up to many profits, in terms of enhancing the water quality and affording a convenient and economical alternative compared to other methods. The biochemical approach of cleaning environmental pollution includes cations and anion exchange, absorption, precipitation, and oxidation/reduction, [41], [43]. [44], [45], [46], [47].

A. Cation/anion exchange:

According to Upadhyay et al., 2019, presence of certain functional groups on the algal cell-wall (–COOH, –OH, -NH2, –SH, aromatic, carboxyl, alkyl and amide) provides negative charge which facilitates metal adsorption (cations) and absorption. Ths phenomenon provides a strong metal cation binding site which are involved in metal exchange through the ion-exchange mechanism. This method of heavy metal removal from aquatic systems seems to be quite effective which has a strong possibility of eliminating and recovering metals from waste water [41], [48].

B. Absorption:

Waste water contains too many inorganic ions and heavy metals. Assimilation property of microalgae help the inorganic ions to get converted to organic N. here inorganic nitrogen translocates into the cytoplasm of cells. Nitrite and nitrate reductase which reside in the cytoplasm, conduct redox reactions converting inorganic N to NH_4, This NH_4 is then absorbed into the cytoplasm [41], [47]. Phosphorus is a chief component of macromolecules which is consumed as $H_2PO_4^-$ and HPO_4^{2-} during algal metabolism. microalgae effectively transform inorganic phosphate into organic compound phosphorylation. Metal ions are absorbed by algal biomass. This increases electronegativity and lowers ionic radii of the cell [41], [49].

C. Precipitation:

Presence of microalgae in sewage secrete various chemicals, of which organic acids and secondary metabolites are very prominent. These components substantially drop down the surrounding pH, and facilitates the precipitation of toxic contaminants which further reduces inorganic P [41], [50]. At low pH, cell wall are bound with protons. These leaves no space for metal cations to bind. Consequently, pH rises and increases the number of negatively charged sites, due to which metal cations are adsorbed on the cell surface, which ultimately reduces their bioavailability [41], [51].

VI. PHYCOREMEDIATION OF VARIOUS WASTES

A. Domestic Wastewater Treatment

Waste water generated from home and commercial institutions are referred to as domestic waste water. In general, high levels of organic matter, pathogenic microbes, nutrients and toxic compounds are present in untreated domestic water which serves as an ideal medium for microalgae as it contains high concentrations of all necessary nutrients necessary for its growth. These microalgae offer a low-cost and effective way to get rid of excess nutrients and other impurities which forms the basis of secondary or tertiary waste water treatment. In general, microalgae are cultivated in facultative or aerobic high-rate ponds to be used in municipal wastewater [20], [26]. Some of the important microalgae found suitable for domestic wastewater treatments are *Scenedesmus dimorphus, Nostoc muscorum, Anabaena variabilis, Plectonema* sp., *Oscillatoria* sp., *Phormidium* sp., *Spirulina* sp., *Chlorella pyrenoidosa, Euglena* sp. [41], [52]. It has been found that the microalgal biomass generated during the process has huge commercial applications wherein high value commodities can be produced in the process.

B. Industrial Wastewater Treatment

a) Mining/Metallurgy Industry: According to Kalin et al. 2006, leaching of metals from mining industries into the soil or groundwater possess severe environmental impacts thus polluting various ecosystems. The list of various metallurgy industries includes chrome plating industry, other electroplating plants, goldsmith workshops, steel industries, etc. Till recent yers, conventional technologies such as ion exchange, lime precipitation were used. However, they are found to be less effective for treating such wastes. Furthermore, these technologies are highly costly which limits their use. Use of microalgae is one of the novel approaches. Hyperaccumulating/hypersequestering capabilities of microalgae have been thoroughly studied in the last few decades [41], [53], [54]. These microalgae have special characteristics of tolerance to extreme temperature, chemical composition with predominance of high value-added products, quick sedimentation behaviour in addition to capacity to remove nutrients more efficiently [41], [55].

b) Food Industry: One of the fastest growing industries in the world is the food processing industry which has worldwide global market in terms of increasing economy. Water is an inevitable component of food processing, tons of portable water is utilized, which in turn give rise to huge amounts of wastewater, in addition to the water being used for washing and cleaning purposes. The effluent has a high range of COD and contains lots of total organic carbon, nitrogen, and phosphate, which may cause serious environmental issues. although conventional biological treatment systems using microorganisms (bacterial systems) are often used to reduce parameters such as COD, microalgae are considered as a more potential alternative due their high rates of nutrient removal that have been reported with monocultures of cyanobacteria such as *Spirulina* [56], [57] and *Phormidium* [58] grown on effluents from dairy industries. In one report published by reference [42], microalgae have been used the treatment of wastewater in food-processing industry. According to their report, they obtained a total reduction in COD and BOD of 70.68% and 61.11% respectively. Consecutively, there was a significant reduction in TOC at 76.66%. the said report proves the efficiency of phycoremediation over conventional methods.

c) Paper/Pulp Industry: another important industry is paper production industry which leads to the generation of effluents with huge amounts of lignocellulosic derivatives [20], [59]. Every year paper mill releases chlorinated lignosulphonic acids, chlorinated resin acids, chlorinated phenols and chlorinated hydrocarbons in the effluent. In addition to that, highly toxic and recalcitrant compounds, dibenzo-p-dioxin and dibenzofuran, are also present in sufficient amount in some paper effluents. Reference [59] further reported that although physical and chemical processes are used, they are quite expensive to remove highmolecular-weight chlorinated lignins, colour, toxicants, suspended solids and COD. Moreover, their efficacy in removing BOD and low-molecular-weight compounds is also in question which is why the biological process is particularly used to remove the recalcitrant pollutants. In another studies, researchers have suggested that microalgae can be quite effective in removing colour and absorbable organic halides (AOX) [20], [60], [61]. *Chlorella, Ankistrodesmus* or *Scenedesmus* species are widely used to remove organic pollutants from pulp, paper mills and olive oil mills [62].

C. Carbon Sequestration

Rise in temperature and climate change results from rapid Industrialization and increasing transportation needs leads to enormous release of greenhouse gases, especially CO_2 and methane. In this regard, sequestration of CO_2 has become a global concern which researchers are constantly diving into finding an alternative to this problem. Earlier many physical and chemical methods have been suggested and tried, however, their cost and effectiveness have always been a question and which is why biological methods are preferred. Terrestrial plants are known to alleviate a good amount of CO_2 from the atmosphere; however, as the percentage of CO_2 is relatively small (0.036%) in the atmosphere, the use of terrestrial plants could not prove to be an economically feasible option. Moreover, discharge gases from heavy industries and enormous use of vehicles leads to significantly higher CO_2 levels than that is found in the atmosphere (10–20%). Therefore, some feasible strategies need to be developed based on the emissions mentioned above. Thus, phycoremediation has emerged as a potential option for fixation of CO_2. Research found that microalgal biomass consists of 40–50% carbon, which suggests that about 1.5–2.0 kg of CO_2 is required to produce 1 kg of biomass [20], [63]. Microalgae are very good autotrophs and conduct photosynthesis efficiently than that of C_4 plants, have faster proliferation rates, wider tolerance to extreme environments and are prone to intensive culturing techniques. These advantages have made microalgae, a superior choice for sequestration. It has been found that some microalgal species have CO_2 concentrations above 15%. One of such species is *Euglena gracilis*, in which the growth of this species was found to be higher with 5–45% concentrations of CO_2 [64]. There is one strain of *Chlorella* sp according to Maeda et al. (1995) report, which could grow in 100% CO_2, even though the maximum growth rate occurred at 10% concentration. Some other species like *Cyanidium caldarium* [65] are laboratory tested and can also be cultivated in pure CO_2 [66]. Brown in 1996 stated that the CO_2 supply not only serves as a good carbon source for microalgal growth but also simultaneously controls the pH of the culture. This is an added advantage. According to a report, the average efficiency of flue gas CO_2 capture in the biomass of algae was 70% [67], [68], [69]. Recently marine microalgal open farming has become another area of research to be considered which is of significant potential in global biological carbon sequestration.

VII. CARBON-NEUTRAL BIOFUELS FROM ALGAE FOR MITIGATION OF GLOBAL TEMPERATURE RISE

A. Replacement for Fossil Fuels:

Global climate change has currently become the most significant burning topic of the world. Researchers have been constantly working on the use of renewable, clean energy sources that can be substituted for fossil fuels which emits lesser amount of CO_2 than the fossil fuels. According to [70], because of depleting resources, the continued use of fossil fuels as a primary source of energy has now been declared unsustainable. Although there are several sources of renewable fuels available on earth, biofuels have become successful in capturing attention because of their increased sustainability, eco-friendly nature, and possibility of converting into a cheaper technology. biofuels derived from oil crops/other food crops are considered as first-generation biofuels. They are a potential renewable and carbon-neutral alternative to petroleum products but regrettably, these are unable to satisfy even a small fraction of the existing demand for transport fuels and hence require extensive land areas and enormous freshwater [71]. In addition to that, these may lead to food-versus-fuel conflict. In a similar way, commercialization of second-generation biofuels from lignocellulosic and other agricultural wastes faces huge challenges because of the unavailability/ seasonal availability of raw materials. Therefore, the entire responsibility falls on third generation biofuels using microorganisms which seems to be the only viable option. Microalgae are considered far better owing to the production of carbon-neutral fuels. Furthermore, microalgae generate higher oil production as compared to the oil produced by high yielding energy crops. Some of the important biofuels produced by microalgae are biomethane, biodiesel, biohydrogen, bioethanol, biobutanol, etc.

VIII. SAFETY AND ENVIRONMENTAL IMPACT OF PHYCOREMEDIATION

For any new technology to be introduced in the market, the safety and environmental impact must be thoroughly studied before full-scale implementation of the same. Phycoremediation or use of microalgae is a safe technology in which only photosynthetic oxygenic organisms are used which are non-pathogenic in general. Moreover, many of them exert antagonistic effects on other biological agents like bacteria and can get rid of bacterial loads [28]. If the toxicity levels of algal sludge are found to be higher than the required figure, the it is subjected to treatment before being disposed of. Unexpectedly, some algal species exhibit phycovolatilization, where toxic substances are converted to non-toxic ones [72]. In the context of environmental impact, phycoremediation exhibits far more positive attributes such as biological carbon sequestration, effective nutrient removal property and oxygenation by photosynthesis. Hence, it can be designated as an environmentally safe technology. Moreover, phycoremediated algal sludge is used as a plant growth promoter and a feed for aquatic organisms as it possesses zero adverse effects [73].

IX. CURRENT GLOBAL/NATIONAL SCENARIO

Phycoremediation has become a burning topic these days because of its increasing demand owing to its eco-friendly nature and for being a potential renewable resource. Globally several pilot-scale projects and commercial-scale trials are in the pipeline; many have been tested successfully as well. Undoubtedly, this green technology has become effective for the treatment of various types of wastewaters, starting from domestic sewage, agricultural waste substrates, agro-industrial wastewater, livestock wastewater to food-processing effluents and various other industrial wastes [74], [75], [76], [77]. Coming home, the first accomplishment in the aspect of commercialization of this approach has begun with the operation of the world's full-scale phycoremediation plant at SNAP Alginate Pvt. Ltd., India, [77]. Afterward, the India based Phycospectrum Environment Research Centre has been successful in installing full-scale plants in several industries all over the country and abroad. Some of the reputed industries such as Brintons Carpets, UK; Pacific Rubiales oil-drilling site, Colombia; KH Exports, India; Ranitec CETP, India; etc. have been successfully installed [18].

X. PROSPECTS

Looking at its greatest advantages like environmental sustainability, carbon credits benefits and creation of wealth from waste, phycoremediation technology is going to outshine conventional methods in near future. Moreover, the alarming rise in the prices and limited availability of fossil fuels, has created an urgent need for development of sustainable generation of biomass at an affordable price. This has in turn raise the hope of combining the integrated approach of waste remediation and generation of biomass by many biofuel industries. This approach shall help overcome biomass constraints, thus providing greater commercial gains. Moreover, appropriate policy amendments by the government for efficient management of environment and industrial waste shall certainly enable implementation of such green technologies with ease in the future.

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