

PHYCOREMEDIATION: A GREEN TECHNOLOGY TO COMBAT ENVIRONMENTAL POLLUTION

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.

Author

Dr. Geetashree Bora
Maryam Ajmal Women's College of
Science and Technology
Hojai, India.
geetashreess22@gmail.com

I. INTRODUCTION

Today, the global community is confronting significant environmental pollution challenges, driven by the rapid expansion of population, industrialization, and urbanization. These factors are profoundly affecting the provision of ecosystem services. Annually, vast amount of solid and liquid wastes are produced worldwide, with only a limited portion being subject to recycling, while the majority is either disposed of improperly or remains untreated. These situations lead to a series of issues that impact both people and the environment. Concerns about wastewater treatment, particularly in developing nations like India, have always been prominent in society, particularly with regards to its safe discharge into the environment. Recognizing the potential of wastewater for agricultural irrigation, it becomes imperative to identify cost-effective treatment approaches that are environmentally sustainable and require minimal resources and infrastructures. Wastewater treatment techniques are typically categorised into primary, secondary, and tertiary stages. Primary treatment involves temporally containing wastewater to allow heavy metals to settle at the bottom. While lighter substances such as oil, grease and solids float to the surface. Secondary treatment primarily focuses on the role of microorganisms within a well-maintained environment. Tertiary treatment is employed in conjunction with primary and secondary processes. However, compared to biological treatment methods, both physical and chemical methods tend to be more costly. Furthermore, chemical treatment can lead to an increase in conductivity, total dissolved solids, pH levels in the treated water, making biological treatment the most efficient and sustainable option. The biological approach utilizes microorganisms to break down chemicals present in wastewater while enhancing the utilization of the remaining residues to produce value-added compounds such as biofuels and biopolymers. One of the recent pollution control technologies involves the use of algae, be it microalgae or macroalgae, known as phycoremediation, to eliminate or transform pollutants and other toxins, including xenobiotics from wastewater. Algae serve as an effective carbon dioxide sink, making them valuable for reducing carbon footprints [1], [2]. Their widespread presence in nature and remarkable adaptability to diverse habitats classifies them into three broad categories: macroalgae, microalgae, and marine algae. Microalgae, with their rich biodiversity and adaptability to various environments, are promising candidates for wastewater treatment and biofuel production [3], [4], [5]. Reference [6] highlights that improper wastewater and faecal sludge treatment contribute to the spread of diseases and development of antimicrobial resistance. Additionally, microalgae-based nutrient removal stands out as a beneficial tertiary wastewater treatment method for eliminating nitrate, phosphate, and ammonium [7]. Microalgae effectively removes heavy metals, hydrocarbons, and pesticides from wastewater through various mechanisms including biosorption, bioaccumulation, biotransformation, decay, and assimilation [8]. [9]. [10]. In recent years, scientists have harnessed molecular and functional genomics approaches to enhance different algal strains for wastewater treatment, enhancing their photosynthetic efficiency, adaptability, and pollutant detoxification capabilities [11], [12]. Phycoremediation offers distinct advantages compared to standard physiological oxidation or reduction processes. These advantages include cost-effectiveness, the ease of nitrogen and phosphorus into algal biomass, the elimination of the need for sludge management, and the absence of the requirement efflux oxygenation before its release into water bodies. Moreover, this method is environmentally friendly, allowing algae to be recycled as fertilizer without generating any secondary contaminants [13]. Some commonly utilized microalgae for treating various types

of wastewater include *Botryococcus* sp., *Phormidium* sp., *Scenedesmus* sp., *Chlorella* sp., and *Chlamydomonas* sp.

In the recent years, pollution has become a predominantly localized issue, with certain pollutants not only persisted in the environment but also manipulate atmospheric and climatic conditions. In the light of these developments, environmental management has emerge as a more pressing global concern, with significant emphasis placed on waste generation and disposal practices waste generation and disposal practices, particularly the handling of hazardous waste. Consequently, there is a growing need of extensive research in the field of biological approaches 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 typically classified into three main categories: solid, liquid or gas. Solid waste commonly includes items such as trash, garbage, rubbish, refuse, broken glass, cans, plastics, paper, battery casings and nylon [14]. Liquid wastes, often referred to as effluents, encompass agricultural runoff water, domestic wastewater, and discharged wastewater from industrial processes [15]. Gaseous waste, on the other hand include greenhouse gas emissions and waste gases produced by sources such as stack, lime dust, asbestos dust, cement factories, stone crushing excavation activities, acid fumes and cigarette fumes [15].

- 1. Solid Wastes:** The bulk of solid waste consists of municipal garbage, industrial and agricultural wastes, mining and mineral wastes, construction, and demolition wastes, medical and radioactive (nuclear) wastes, as well as human and animal excreta [16]. Solid waste originating from household, industries and markets contribute significantly to pollution, particularly through the release of methane gas and CO₂ emissions. While physical and mechanical methods like recycling, incineration, and landfilling are commonly employed practices, waste processing and transformation through biological and chemical methods are the preferred choices for achieving sustainable technology advancements and effective waste management.
- 2. Liquid Wastes:** Liquid wastes encompass industrial effluents categorised as black water, sullage and wastewater generated by commercial establishments. Back water, a component of domestic sewage, contains human excreta including urine and faeces. Globally, it is estimated that around 80% of wastewater is discharged into the environment without undergoing any treatment. Hence, there is a growing demand for environmentally friendly and sustainable technologies to facilitate efficient disposal of liquid wastes.
- 3. Gaseous Wastes:** A wide array of gaseous waste, primarily stemming from human activities, gives rise to atmospheric pollutants. Among these, the most notable include greenhouse gases like CO₂, methane, and chlorofluorocarbons, as well as nitrogen oxide (NO_x), sulphur oxide, and carbon monoxide. These gaseous waste components pose significant hazards, often resulting in severe atmospheric pollution and causing damage to

terrestrial and aquatic environments through precipitation. Consequently, there is a growing concern regarding the management of these gaseous even though physical treatment methods such as filtration are available and widely employed. To address this concern, advanced research is essential for the development of effective treatment technologies.

- Toxic Wastes:** When addressing the issue of harmful toxic wastes, their proper treatment remains a significant challenge in ensuring overall environmental safety. The presence of toxic contaminants like heavy metals, pesticides, plastics, and more poses a substantial threat to the environment. While there are various physical, chemical, and biological treatment methods available, all these processes can result in the accumulation of toxic elements in the environment, ultimately leading to bioaccumulation and biomagnification. Consequently, there is a global pursuit of developing successful remediation technologies that can facilitate biotransformation processes, converting these toxic constituents into safe, non-toxic forms of disposal. Hence, the imperative lies in the development of efficient waste and recycling management strategies to uphold environmental, economic, and social development principles [17] (Figure 1).

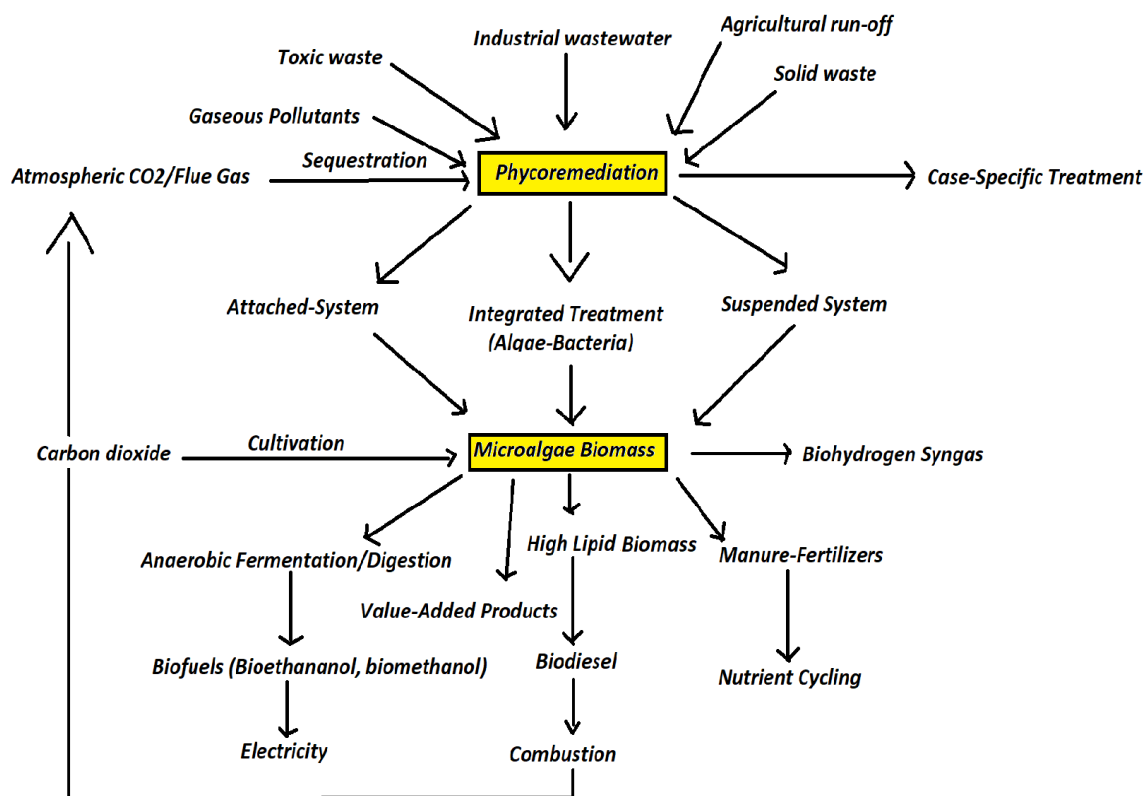


Figure 1: Microalgae and Environmental Sustainability

III. CONVENTIONAL BIOREMEDIATION AND PHYCOREMEDIATION: A COMPARISON

Bioremediation, in broader context, refers to the process of treating environmental wastes using living agents such as microorganisms, plants and animals. In contrast, phycoremediation is a recently coined term that specifically describes the biological utilization of algae to address environmental pollution. Phycoremediation presents several key advantages over traditional bioremediation methods (Table 1) [18]. Wastewater serves as an ideal habitat for bacterial growth; however, bacteria don not fully remove or degrade inorganic nutrients such as nitrogen and phosphorus, making them a primary driver of in freshwater ecosystems.

Among biological approaches, Activated Sludge process (ASP) and biofilm systems are widely employed tertiary treatment methods in wastewater treatment plants. Nevertheless, these processes consume more energy with ASP requiring 1.3–2.5 MWh per million gallons (MG) of wastewater, and biofilm systems, requiring 0.8–1.8 MWh per MG, compared to algal ponds, which demand 0.4–1.4 MWh MG⁻¹ d⁻¹ [19], [20]. Furthermore, ASP necessitates 1 kWh of electricity to remove 1 kg of biochemical oxygen demand (BOD). In contrast, photosynthetic oxygenation demands no energy inputs to remove BOD and, additionally, generates sufficient algal biomass to produce methane gas, subsequently, yielding 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 costs
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 CO ₂	In fact, CO ₂ is released into the atmosphere during growth of the bacterial systems

IV. PHYCOREMEDIATION AS A TECHNOLOGY

To address the issue of environmental pollution, different types of reactors have been developed and employed, employing the microalgae as a key component. Diverse treatment systems have been established, including suspended algal systems, attached system, and closed systems. Combining this technology with other sustainable approaches can yield even more beneficial outcomes.

1. Photo-Bioreactors: Photo-Bioreactors are widely employed reactors, typically closed cultivation systems distinguished by precisely controlled parameters to maximise their benefits. These reactors offer several advantages over conventional counterparts, including reduced contamination risk, prevention of CO₂ losses, feasible cultivation conditions, well-controlled hydrodynamics and temperature system, and adaptable technical design [22]. Furthermore, they result in higher areal productivities and help prevent water loss through evaporation [23]. various types of photo-bioreactors, such as tubular, vertical column and flat panel have been developed. To select the most suitable PBR type, it is essential to understand the key factors that limit microalgal cells performance, such as light availability, nutrient supply (including CO₂), and specific requirements for photo-reactor designs [24].

While photo-reactors can be applied to wastewater treatment, there are notable drawbacks, primarily related to their investment and operational costs, which restricts their utilization in this context.

2. Open Pond Treatment Systems: When considering the cultivation of microalgae and biofuels, it is often observed that open treatment systems tend to be more efficient due to their lower costs and ease of scalability. However, closed systems are more commonly utilized when cultivating microalgae for high-value products. It is worth noting that most closed systems, especially those operated indoors with artificial lighting, tend to incur high energy costs.

A classic example of an open pond system is a high-rate algal pond (HRAP), a concept first developed in the mid-1950s by Oswald and colleagues and subsequently implemented in various countries [20], [25]. The HRAP design includes primary settlement lagoon with a shallow meandering open channel (0.2–0.6 m deep), and a motorized paddle wheel is used to prevent settling of the effluent [26]. The flow velocities in these ponds typically range from 10 to 30 cm/s, which is relatively low and this helps prevent the deposition of algal cells [20], [27]. HRAPs are known for their simplicity and ease of operation as compared to conventional technologies like activated sludge treatment methods. This design offers the added advantage of serving two purposes: 1) secondary wastewater treatment and 2) algal biomass production. It combines features of intensified oxidation ponds and an algal reactor, with algae and bacteria symbiotically supporting each other.

HRAPs are highly effective in removing organic matter, and reducing bacterial contamination. They not only substantially decrease organic matter but also effectively reduce nitrogen and phosphorus in wastewater. Additionally, HRAPs provide an efficient

wastewater treatment method by addressing other parameters such as bacteria load, Biological Oxygen demand (BOD), and even toxic nutrients [20], [28].

- 3. Attached Systems/Sloping Pond Technology:** The concept of immobilization of microalgae was first introduced by de la Noue and his colleagues [20], [29], [30]. Generally, microalgae immobilization is achieved either by cultivating them entrapped within a matrix or using attached systems. Algae growing on surfaces can be harvested by employing mechanical pressure methods like suction or scraping. Furthermore, the remaining algal colonies adhered to the surface can serve as an inoculum for the subsequent growth, making the process a semi-continuous microalgae cultivation system [20], [31], [32].

According to reference [33], a novel algal biofilm membrane equipped with solid carriers and a submerged membrane module was developed for the treatment of secondary effluent, with *Chlorella vulgaris* attached to it. This method has proven to be highly effective, making it a preferable approach for biomass harvesting. In the recent years, a more robust variant has been developed that utilizes a cost-effective sloping pond where both attached and suspended systems are combined for effluent treatment. The concept involves creating turbulent flow as algal suspension passes through sloping surfaces. The process remains in circulation when there is sufficient incident radiation. During other hours, the suspension is stored in tanks equipped with aeration, effectively preventing deviations from the hydrodynamic balance that could impact efficiency [20], [34],[35].

Another successful method was developed as outlined in reference [36]. The technology involves the cultivation of benthic macroalgae/microalgae to create an algal turf, which functions as a scrubber for CO₂, nutrients and pollutants while also generating biomass production.

- 4. Integration of Algal Treatment System into Other Conventional Biotreatment Systems:** The prospects of microalgal treatment are quite promising due to significant cost-effectiveness, making it readily adaptable as an integral component within existing secondary and tertiary treatment systems [18], [20]. Nevertheless, the feasibility of integration hinges upon the quality of the wastewater under consideration. As indicated by reference [37], the efficiency of nutrient removal can be notably high when combining bacterial and algal systems. The approach proves particularly advantageous when dealing with wastewater characterised by high organic loads and presence of toxic heavy metals (Fig. 2).

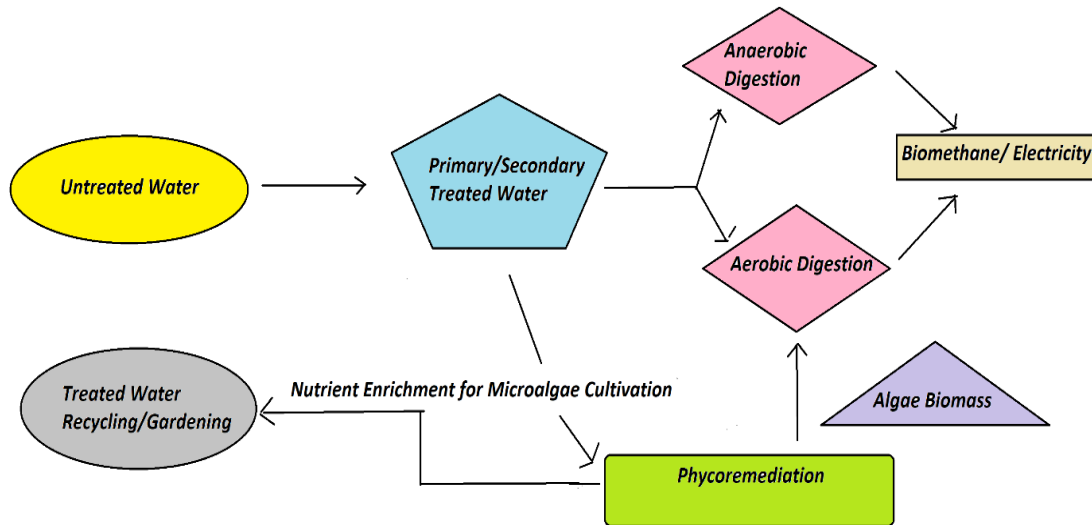


Figure 2: Flowchart of Phycoremediation Process

V. MECHANISM

Flocculation, sedimentation, and rhizo-filtration represent some of the commonly employed methods through which algae are capable of removing contaminants [38], [39], [40], [41]. Microalgae, in their unicellular forms, exhibit remarkable effectiveness in accumulating and assimilating a wide range of substances, including heavy metals, plant nutrients, organic and inorganic contaminants, pesticides, and even radioactive substances [41], [42]. This capability leads to numerous advantages in terms of improving water quality and providing a convenient and cost-effective alternative compared to other techniques. The biochemical strategies for addressing environmental pollution encompass cations and anion exchange, absorption, precipitation, as well as oxidation and reduction processes [41], [43], [44], [45], [46], [47].

- 1. Cation/Anion Exchange:** As stated by Upadhyay et al. in 2019, the presence of specific functional groups on the algal cell-wall, including $-\text{COOH}$, $-\text{OH}$, $-\text{NH}_2$, $-\text{SH}$, aromatic, carboxyl, alkyl and amide groups, imparts a negative charge that facilitates adsorption and absorption of metal cations. This phenomenon creates robust binding sites for metal cations, which participate in metal exchange through an ion-exchange mechanism. This approach for removing heavy metals from aquatic systems appears highly effective and holds significant potential for eliminating and recovering metals from waste water [41], [48].
- 2. 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].

- 3. Precipitation:** The existence of microalgae in sewage results in the release of various chemicals, with organic acids and secondary metabolites being particularly noteworthy. These components lead to a significant decrease in the local pH level, which, in turn, promotes the precipitation of toxic contaminants and a subsequent reduction in reduces inorganic P level [41], [50]. In addition of low pH, cell wall become saturated with protons leaving minimal space for metal cations to bind. Consequently, the pH level rises, creating more negatively charged sites on the cell surface. This, in turn, leads to the adsorption of metal cations onto the cell surface, ultimately reducing their bioavailability [41], [51].

VI. PHYCOREMEDIATION OF VARIOUS WASTES

- 1. Domestic Wastewater Treatment:** Wastewater originating from residential and commercial establishments is commonly referred to as domestic wastewater. Typically, untreated domestic wastewater contains elevated levels of organic matter, pathogenic microorganisms, nutrients, and toxic compounds, making it an ideal medium for microalgae due to its rich nutrient content necessary for their growth. Microalgae offer a cost-effective and efficient means of removing excess nutrients and other impurities, forming the basis of secondary or tertiary wastewater treatment processes. Generally, microalgae are cultivated in facultative or aerobic high-rate ponds for use in municipal wastewater treatment [20], [26]. Several microalgae species have proven suitable for domestic wastewater treatments, including *Scenedesmus dimorphus*, *Nostoc muscorum*, *Anabaena variabilis*, *Plectonema* sp., *Oscillatoria* sp., *Phormidium* sp., *Spirulina* sp., *Chlorella pyrenoidosa*, *Euglena* sp. [41], [52]. Importantly the microalgal biomass generated during this process holds significant commercial potential, enabling the production of high value commodities.
- 2. Industrial Wastewater Treatment:**
 - Mining/Metallurgy Industry:** As per Kalin et al. in 2006, the leaching of metals from mining industries into the soil or groundwater possess significant environmental effects resulting pollution of various ecosystems. These metallurgy industries encompass a range of activities, including the chrome plating industry, other electroplating plants, goldsmith workshops, steel industries, and more. Until recent years, conventional technologies like ion exchange and lime precipitation were the primary methods employed for treatment. However, they the proven to be less effective in addressing such waste streams. Additionally, these technologies are associated with highly cost, limiting their widespread adoption. The utilization of microalgae represents a novel approach to tackle this issue. Hyperaccumulating/hyper sequestering abilities of microalgae have been extensively investigated in recent decades [41], [53], [54]. These microalgae possess unique attributes, including tolerance to extreme temperature, a chemical composition rich in high value-added products, rapid sedimentation behaviour, and enhanced nutrient removal capabilities [41], [55].

- **Food Industry:** One of the fastest-growing industries worldwide is the food processing industry, with a global market that significantly contributes to the growing economy. Water is an indispensable component of food processing, with vast amounts of potable water being used. Consequently, this leads to the generation of substantial volumes of wastewater, in addition to water being utilized for washing and cleaning purposes, which in turn give rise to huge amounts of wastewater, in addition to the water being used for washing and cleaning purposes. The effluent produced typically exhibits a wide range of Chemical Oxygen demand (COD) and contains significant levels of total organic carbon, nitrogen, and phosphate, posing potential environmental concerns.

While conventional biological treatment systems employing microorganisms (bacterial systems) are often employed to reduce parameters like COD, microalgae are emerging as a more promising alternative due to their reported high rates of nutrient removal. Monocultures of cyanobacteria such as *Spirulina* [56], [57] and *Phormidium* [58] grown on effluents from dairy industries, have shown impressive nutrient removal capabilities.

In a report published by reference [42], microalgae were utilized for the treatment of wastewater in the food-processing industry. According to their findings, a substantial reduction in the COD and BOD of 70.68% and 61.11% respectively, was achieved. Furthermore, there was a significant decrease in Total Organic Carbon (TOC) at 76.66%. This report provides compelling evidence of the efficiency of phycoremediation compared to conventional methods.

- **Paper/Pulp Industry:** The paper production industry is another significant sector that generates effluents containing substantial amounts of lignocellulosic derivatives [20], [59]. Annually, paper mills release effluents containing chlorinated lignosulphonic acids, chlorinated resin acids, chlorinated phenols, and chlorinated hydrocarbons. Furthermore, some paper effluents contain highly toxic and recalcitrant compounds, dibenzo-p-dioxin and dibenzofuran, in significant quantities. According to reference [59], physical and chemical processes, although used, are relatively expensive for the removal of high-molecular-weight chlorinated lignins, colorants, toxic substances, suspended solids, and COD. Additionally, their effectiveness in eliminating BOD and low-molecular-weight compounds is questionable, which is why the biological processes are particularly employed to address recalcitrant pollutants.

In other studies, researchers have suggested that microalgae can be highly effective in removing colorants and absorbable organic halides (AOX) [20], [60], [61]. Species like *Chlorella*, *Ankistrodesmus* or *Scenedesmus* are widely utilized to remove organic pollutants from pulp, paper mills, as well as olive oil mills [62].

3. **Carbon Sequestration:** The increase in temperature and climate, driven by rapid industrialization and growing transportation demands, results in the substantial release of greenhouse gases, particularly CO₂ and methane. Consequently, the sequestration of CO₂ has emerged as a global concern, prompting ongoing research into alternative solutions. Previously, numerous physical and chemical methods were proposed and tested; however,

their cost-effectiveness has always been a subject of debate. This is why biological methods are now favoured.

Terrestrial plants can remove a significant amount of CO₂ from the atmosphere. Nevertheless, given the percentage of CO₂ in the atmosphere is relatively small (0.036%), the utilization of terrestrial plants has not proven to be an economically viable option. Moreover, emissions from heavy industries and the extensive use of vehicles contribute to significantly higher CO₂ levels than what is naturally in the atmosphere (ranging from 10% to 20%). Consequently, there is a pressing need to develop feasible strategies based on addressing these emissions mentioned above.

Phycoremediation has emerged as a promising approach for CO₂ fixation. Research indicates that microalgal biomass contains approximately 40–50% carbon, implying that producing 1 kg of biomass requires about 1.5–2.0 kg of CO₂ [20], [63]. Microalgae excel as autotrophs, conducting photosynthesis more efficiently than C₄ plants. They exhibit rapid proliferation rates, greater tolerance to extreme environmental conditions, and are amenable to intensive culturing techniques. These advantages position microalgae as a superior choice for carbon sequestration. Certain microalgal species have been found to thrive in CO₂ concentrations exceeding 15%, such as *Euglena gracilis*, which exhibited enhanced growth within CO₂ concentrations ranging from 5–45% [64]. Some strain like *Chlorella* sp. as reported by Maeda et al. in 1995, can even grow in pure 100% CO₂, although their maximum growth rate occurs at 10% concentration. Laboratory tests with species like *Cyanidium caldarium* have demonstrated their ability to thrive pure CO₂ [65], [66].

As Brown stated in 1996, the supply of CO₂ not only serves as a carbon source for microalgal growth but also helps regulate the pH of the culture, providing an additional advantage. Reports indicate that, on average, the efficiency of capturing flue gas CO₂ in algal biomass reaches 70% [67], [68], [69]. Recently marine microalgal open farming has become another area of research with significant potential for global biological carbon sequestration.

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

Replacement for Fossil Fuels: Global climate change has become a paramount concern worldwide. Researchers have been actively exploring the utilization of renewable, and clean energy sources as substitutes for fossil fuels, with the aim of reducing CO₂ emissions. As noted in reference [70], the ongoing use of fossil as the primary energy source is deemed unsustainable due to resource depletion. While numerous sources of renewable fuels exist, on earth, biofuels have generated significant interest due to their enhanced sustainability, environmentally-friendly characteristics, and potential for cost-effective technology conversion. Biofuels derived from oil crops, and other food crops fall under the category of 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

Before introducing any new technology to the market, it is essential to conduct thorough safety and environmental impact assessments prior to its full-scale implementation. Phycoremediation, or use of microalgae, is a safe technology that employs only photosynthetic oxygenic organisms, which are generally non-pathogenic. Furthermore, many of these microalgae exert antagonistic effects on other biological agents, such as bacteria, and can effectively reduce bacterial loads [28].

In cases where the toxicity level of algal sludge exceeds acceptable limits, it undergoes treatment before disposal. Interestingly, certain algal species exhibit phycovolatilization, a process in which toxic substances are transformed into non-toxic compounds [72].

From an environmental standpoint, phycoremediation offers several positive attributes, including biological carbon sequestration, effective nutrient removal capabilities, and oxygenation through photosynthesis. Therefore, it can be classified as an environmentally safe technology. Additionally, phycoremediated algal sludge serves as a plant growth promoter and a feed for aquatic organisms, as it has no adverse effects [73].

IX. CURRENT GLOBAL/NATIONAL SCENARIO

Phycoremediation is currently a prominent topic due to its rising demand, attributed to its environmentally-friendly nature and potential as a renewable resource. Globally numerous pilot-scale projects and commercial-scale trials are in progress; with many having been successfully tested. Undoubtedly, this green technology has proven effective for treating various types of wastewater, spanning from domestic sewage, and agricultural waste substrates to agro-industrial wastewater, livestock wastewater to food-processing effluents and various other industrial wastes [74], [75], [76], [77].

On the home front, the initial strides towards commercializing this approach have commenced with the operation of world's first full-scale phycoremediation plant at SNAP Alginate Pvt. Ltd., India, [77]. Subsequently, the India based Phycospectrum Environment Research Centre has successfully installed full-scale plants in several industries both within the country and abroad. Notably, renowned industries such as Brintons Carpets in the UK; Pacific Rubiales oil-drilling site in Colombia; KH Exports in India and Ranitec CETP in India have all adopted this technology with success.

X. PROSPECTS

When considering its foremost advantages such as environmental sustainability, carbon credits benefits and the potential for generating wealth from waste, phycoremediation technology is poised to surpass conventional methods in near future. Additionally, the alarming increase in fossil fuel prices, and their limited availability have created an urgent demand for development of sustainable biomass generation at an affordable cost. This has raised the prospect of numerous biofuel industries adopting an integrated approach that combines waste remediation and biomass generation. Such an approach can effectively address biomass constraints, thereby yielding greater commercial benefits.

Furthermore, government-initiated policy amendments aimed at enhancing environmental and industrial waste management will undoubtedly facilitate the seamless implementation of these green technologies in the future.

REFERENCES

- [1] Z. Arbib, J. Ruiz, Álvarez-Díaz, P., C. Garrido-Pérez, J.A Perales, “Capability of different microalgae species for phytoremediation processes: Wastewater tertiary treatment, CO₂ bio-fixation and low-cost biofuels production,” *Water Res*, 2014, vol 49, pp465–474.
- [2] G.T. Ding, N.H. Mohd Yasin, M.S. Takriff, K.F. Kamarudin, J. Salihon, Z. Yaakob, N.I.N Mohd Hakimi, “Phycoremediation of palm oil mill effluent (POME) and CO₂ fixation by locally isolated microalgae: *Chlorella sorokiniana* UKM2, *Coelastrella* sp. UKM4 and *Chlorella pyrenoidosa* UKM7,” *J. Water Process Eng*, vol 35, 2020.
- [3] S. Abinandan, S. Shanthakumar, “Challenges and opportunities in application of microalgae (Chlorophyta) for wastewater treatment: a review. *Renew.*,” *Sustain. Energy Rev*, 2015, vol 52, pp123–132.
- [4] F. Hussain, S.Z. Shah, H. Ahmad, S.A. Abubshait, H.A. Abubshait, A. Laref, M. Iqbal, “Microalgae an ecofriendly and sustainable wastewater treatment option: Biomass application in biofuel and bio-fertilizer production: A review,” *Renew. Sustain. Energy Rev*. 137, 110603, 2021.
- [5] A.K. Poonia, S.Kajla, B. Koul, J.S. Panwar, “Algae: The high potential resource for biofuel production. In: *An Integration of Phycoremediation Processes in Wastewater Treatment*,” Elsevier, 2022, pp. 155–176.
- [6] J. Radjenović, M. Petrović, D. Barceló, “Fate and distribution of pharmaceuticals in wastewater and sewage sludge of the conventional activated sludge (CAS) and advanced membrane bioreactor (MBR) treatment,” *Water Res*. 2009, 43 (3), pp831–841.
- [7] I. Rawat, R. Ranjith Kumar, T. Mutanda, F. Bux, “Dual role of microalgae: Phycoremediation of domestic wastewater and biomass production for sustainable biofuels production,” *Appl. Energy* 2011, 88 vol 10, pp 3411–3424.
- [8] K.B. Chekroun, M. Baghour, “The role of algae in phytoremediation of heavy metals: a review. *J. Mater. Environ. Sci.*,” 2013. 4 vol 6, pp873–880.
- [9] B. Rath, “Microalgal bioremediation: current practices and perspectives,” *J. Biochem. Technol.* 2012, 3 vol 3, pp299–304.
- [10] Y.K. Leong, J.S. Chang, “Bioremediation of heavy metals using microalgae: Recent advances and mechanisms” *Bioresour. Technol.* 2020, 303, 122886.
- [11] G.A. Lutz, A. Ciurli, C. Chiellini, F. Di Caprio, A. Concas, N.T. Dunford, “Latest developments in wastewater treatment and biopolymer production by microalgae,” *J. Environ. Chem. Eng.* 2020, 104926.
- [12] X. Zeng, M.K. Danquah, X.D. Chen, Y. Lu, “Microalgae bioengineering: From CO₂ fixation to biofuel production,” *Renew. Sustain. Energy Rev.* 2011, 15 vol 6, pp3252–3260.
- [13] C.Liu, S. Subashchandrabose, H. Ming, B. Xiao, R. Naidu, M. Megharaj, “Phycoremediation of dairy and winery wastewater using *Diplosphaera* sp. MM1,” *J. Appl. Phycol.* 2016, 28 vol 6, pp3331–3341.
- [14] A.A Adedibu, “Spatial pattern of solid waste generation in Ilorin,”. Paper presented at the annual conference of Nigerian Geographical Association, Ibadan, Nigeria, 1982.
- [15] Nigerian Institute of Safety Professionals Contractor employee HSE training manual, level 3. ECNEL Ltd, Port Harcourt. 2003.

- [16] S.I. Omofonwan, J.O.Eseigbe, "Effects of solid waste on the quality of underground water in Benin Metropolis, Nigeria," *J Hum Ecol* 2009, 26 vol 2 pp99–105.
- [17] A. Demirbas, "Waste management, waste resource facilities and waste conversion processes," 2011, *Energy Convers Manag* 52 vol 2 pp1280–1287.
- [18] P.H. Rao, V. Sivasubramanian, "Phycoremediation – present and the future," *J Algal Biomass Utln*, 2016, 7 vol 3 pp68–69.
- [19] T.J. Lundquist, I.C.Woertz, N.W.T. Quinn, J.R. Benemann, "A realistic technology and engineering assessment," A report submitted to Energy Biosciences Institute, University of California, Berkeley, California, 2010.
- [20] P.H. Rao, R.R.Kumar, N.Mohan, "Phycoremediation: Role of Algae in Waste Management," *Research Gate*, 2019, DOI: 10.1007/978-981-13-7904-8_3.
- [21] W.J. Oswald, "My sixty years in applied algology," *J Appl Phycol*, 2003, 15 pp99–106.
- [22] O. Pulz, "Photobioreactors: production systems for phototrophic microorganisms," *Appl Microbiol Biotechnol*, 2001, 57 vol 3 pp287–293.
- [23] C. Posten, "Design principles of photo-bioreactors for cultivation of microalgae," *Eng Life Sci* 2009, 9 vol 3 pp165–177.
- [24] F.G. Acién, E. Molina, A. Reis, "Photobioreactors for the production of microalgae. In: *Microalgae-based biofuels and bioproducts*," Woodhead Publishing series. Elsevier, 2018, pp 1–44.
- [25] W.J. Oswald, H.B. Gotaas, CG. Golueke, W.R. Kellen, E.F. Gloyna, E.R. Hermann, "Algae in waste treatment," *Sewage Ind Wastes* 1957, 29 Vol 4 pp437–457.
- [26] W.J. Oswald, "Micro-algae and waste-water treatment. In: Borowitzka MBL (ed) *Micro-algal biotechnology*. Cambridge University Press, Cambridge, UK, 1988, pp 305–328.
- [27] J.C. Dodd, "Elements of pond design and construction. In: Richmond A (ed) *Handbook of microalgal mass culture*," CRC Press, Boca Raton, 1986, pp 265–283.
- [28] J. Garcia, R. Mujeriego, M. Hernandez-Marine, "High rate algal pond operating strategies for urban wastewater nitrogen removal," *J Appl Phycol* 2000, 12 pp331–339.
- [29] P. Chevalier, De la Noue, "Efficiency of immobilized hyperconcentrated algae for ammonium and orthophosphate removal from wastewaters," *Biotechnol Lett* 1985, 7 pp395–400.
- [30] De la Noue, P. Chevalier D. Proulx, *Effluent treatment with immobilized microalgae and cyanobacteria: A critical assessment. In Wastewater treatment by immobilized cells*, Boca Raton: CRC Press Inc, 1990, pp 143–152.
- [31] M.B. Johnson, Z. Wen, "Development of an attached microalgal growth system for biofuel production," *Appl Microbiol Biotechnol* 2010, 85 pp525–534.
- [32] T. Liu, J. Wang, Q. Hu, "Attached cultivation technology of microalgae for efficient biomass feedstock production" *Bioresour Technol* 2013, 127 pp216–222.
- [33] F. Gao, Z. Yang, C. Li, G. Zeng, D. Ma, L. Zhou, "A novel algal biofilm membrane photobioreactor for attached microalgae growth and nutrients removal from secondary effluent," *Bioresour Technol* 2015, 179 pp8–12.
- [34] I. Setlik, S. Veladimir, I. Malek, "Dual purpose open circulation units for large scale culture of algae in temperate zones. I. Basic design considerations and scheme for pilot plant," *Algological Studies (Trebon)* 1970, 1 pp111–164.
- [35] E.W. Becker, In: Sir J (ed) *Microalgae – biotechnology and microbiology*. Cambridge University Press, Baddiley, 1994.
- [36] W.H. Adey, U.S. Patent No. 4,333,263. Washington, DC: U.S. Patent and Trademark Office, 1982.
- [37] A. Nithiya, P.H. Rao, T.S. Kumar, "Bioremediation of aquaculture wastewater using nitrifying bacteria-microalga consortium with special reference to ammoniacal nitrogen," *Int J Curr Res Acad Rev* 2016, 4 vol 12 pp164–177.
- [38] N. Renuka, A. Sood, R. Prasanna, A.S. Ahluwalia, "Phycoremediation of wastewaters: a synergistic approach using microalgae for bioremediation and biomass generation," *Int. J. Environ. Sci. Technol*, 2015, 12 vol 4, pp1443–1460.
- [39] K. Stauch-White, V.N. Srinivasan, W.C. Kuo-Dahab, C. Park, C.S. Butler, "The role of inorganic nitrogen in successful formation of granular biofilms for wastewater treatment that support cyanobacteria and bacteria," *Amb Express*, 2017, 7 vol 1, pp1–10.
- [40] B.K. Yadav, M.A. Siebel, J.J.A. van Bruggen, "Rhizofiltration of a heavy metal (lead) containing wastewater using the wetland plant," *Carex pendula. Clean (Weinh)*, 2011, 39 vol 5, pp467–474.
- [41] B. Koul, K. Sharma, M. P. Shah, "Phycoremediation: A sustainable alternative in wastewater treatment (WWT) regime," *Environmental Technology & Innovation*, 2022, DOI: 10.1016/j.eti.2021.102040.

- [42] P. Gani, N.M. Sunar, H.M. Matias-Peralta, A.A. Abdul Latiff, I.T.K. Joo, U.K. Parjo, Q. Emparan, C.M. Er, Phycoremediation of dairy wastewater by using green microalgae: *Botryococcus* sp,” *Appl. Mech. Mater.*, 2016, pp773–774.
- [43] M. Baghour, D.A. Moreno, J. Hernandez, N. Castilla, L. Romero, “Influence of thermal regime of soil on the sulfur (S) and selenium (Se) concentration in potato plants,” *J. Environ. Sci. Health A* 2002, 37 vol. 6, pp1075–1085.
- [44] J.N. Kumar, C. Oommen, “Removal of heavy metals by biosorption using freshwater alga *Spirogyra* hyaline,” *J. Environ. Biol.*, 2012, 33 vol 1, 27.
- [45] Y.C. Lee, S.P. Chang, “The biosorption of heavy metals from aqueous solution by *Spirogyra* and *Cladophora* filamentous macroalgae,” *Bioresour. Technol.*, 2011, 102 vol 9, pp5297–5304.
- [46] E. Romera, F. González, A. Ballester, M.L. Blázquez, J.A. Munoz, “Comparative study of biosorption of heavy metals using different types of algae,” *Bioresour. Technol* 2007, 98 vol 17, pp3344–3353.
- [47] A.K. Upadhyay, R. Singh, D.P. Singh, “Phycotechnological approaches toward wastewater management,” In: *Emerging and Eco-Friendly Approaches for Waste Management*, 2018 pp. 423–435.
- [48] A. Malik, “Metal bioremediation through growing cell,” *Environ. Int.*, 2004, 30 vol 2, pp261–278.
- [49] S.K. Mehta, J.P. Gaur, “Use of algae for removing heavy metal ions from wastewater: Progress and prospects,” *Crit. Rev. Biotechnol.*, 2005, 25 vol 3, pp113–152.
- [50] L.E. De Bashan, Y. Bashan, “Recent advances in removing phosphorus from wastewater and its future use as fertilizer,” *Water Res.*, 2004, 38, pp4222–4246.
- [51] Y.K. Leong, J.S. Chang, “Bioremediation of heavy metals using microalgae: Recent advances and mechanisms,” *Bioresour. Technol.*, 2020, 303, 122886.
- [52] N. Dewangan, “Wastewater treatment using inverse fluidization unit by algae. B. Tech Thesis, Department of Chemical Engineering, National Institute of Technology (NIT), Rourkela, Odisha, 2016
- [53] L.H.B. Lee, I. Lustigman C. Yu, S. Hsu, “Effects of lead and cobalt on the growth of *Anacystis nidulans*. *Environ Contam Toxicol.*, 1992, 48 pp230–236.
- [54] R.P. Gupta, S. Ahuja, P.K. Khan, H. Saxena, Mohapatra, “Microbial biosorbents: meeting challenges of heavy metals pollution in aqueous solutions,” *Curr Sci.*, 2000, 78 vol 8, pp767–973.
- [55] E.P.Y. Tang, W.F. Vincent, D. Proulx, P. Lessard, J. De la Noue J, “Polar cyanobacteria versus green algae for tertiary wastewater treatment in cool climates,” *J. Appl Phycol* 1997, 9, pp371–381.
- [56] E.P. Lincoln, A.C. Wilkie, B. French, “Cyanobacteria process for renovating dairy wastewater,” *Biomass Bioenergy.*, 1996, 10, pp63–68.
- [57] E.J. Olguin, “Phycoremediation: key issues for cost-effective nutrient removal process,” *Biotechnol Adv.*, 2003, 22 pp81–91.
- [58] R. Blier, G. Laliberte, J. De la Noue, “Production of the cyanobacterium *Phormidium bohneri* in parallel with epuration of a dairy anaerobic effluent,” *Process Biochem.*, 1996, 31 pp587–593.
- [59] R. Sharma, S. Chandra, A. Singh, K. Singh, “Degradation of pulp and paper mill effluents,” *IIOAB J.*, 2014, 5 pp6–12.
- [60] E.G.Lee, J.C. Mueller, C.C. Walden, “Decolorization of bleached kraft mill effluents by algae,” *TAPPI.*, 1978, 61vol 7, pp59–62.
- [61] M.G. Tesmer, T.W. Joyce, “Algal assay bottle test response to pulp and paper mill effluents,” *TAPPI.*, 1980, 63 vol 9, pp105–108.
- [62] R. Munoz, B. Guieysee, “Algal-bacterial processes for the treatment of hazardous contaminants: a review,” *Water Res.*, 2000, 40 pp2799–2815.
- [63] T.M. Sobczuk, F.G. Camacho, F.C. Rubio, F.G.A. Fernandez, E.M. Grima, “Carbon dioxide uptake efficiency by outdoor microalgal cultures in tubular airlift photobioreactors,” *Biotechnol Bioeng.*, 2000, 67 pp465–475.
- [64] Y. Nakano, K. Miyatake, H. Okuno, K. Hamazaki, S. Takenaka, N. Honami, M. Kiyota, I. Aiga, J. Kondo, “Growth of photosynthetic algae euglena in high CO₂ conditions and its photosynthetic characteristics,” *Acta Hort.*, 1996, 9, pp49–54.
- [65] J. Seckbach, H. Gross, M.B. Nathan, “Growth and photosynthesis of *Cyanidium Caldarium* cultured under pure CO₂,” *Israel J Bot.*, 1971, 20 pp84–90.
- [66] L.E. Graham, W.L. Wilcox, “Algae. Prentice-Hall, Upper Saddle River,” 2000.
- [67] J.R. Benemann, R.P. Goebel, J.C. Weissman, D.C. Augenstein, “Microalgae as a source of liquid fuels,” Final technical report USDOE-OER, 1982.
- [68] J.C. Weissman, R.P. Goebel, “Design and analysis of microalgal open pond systems for the purpose of producing fuels,” A subcontract report, U.S. Dept. of Energy, 1987.

- [69] J.R. Benemann, W.J. Oswald, "Systems and economic analysis of microalgae ponds for conversion of CO₂ to biomass". Final report, US DOE, 1996.
- [70] S.A. Khan, M.Z. Rashmi Hussain, S. Prasad, U.C, Banerjee, "Prospects of biodiesel production from microalgae in India," *Renew Sust Energy Rev*, 2009, 13 pp2361–2372.
- [71] S. Chinnasamy, P.H. Rao, S. Bhaskar, R. Rengasamy, M. Singh, "Algae: a novel biomass feedstock for biofuels," In: *Microbial biotechnology: energy and environment*, 2012, pp 224–239.
- [72] P.H. Rao, R.R. Kumar, B.G. Raghavan, V.V. Subramanian, V. Sivasubramanian, "Is phycovolatilization of heavy metals a probable (or possible) physiological phenomenon? An in-situ pilot-scale study at a leatherprocessing chemical industry," *Water Env Res*, 2011b 83 vol 4 pp291–297.
- [73] P.H. Rao, R.R. Kumar, V.V. Subramanian, V. Sivasubramanian V, "Environmental impact assessment of *Chlorella vulgaris* employed in phycoremediation of effluent from a leather-processing chemical industry," *J Algal Biomass Utln*, 2010, 1vol 2 pp42–50.
- [74] T. Cai, S.Y. Park, Y. Li, "Nutrient recovery from wastewater streams by microalgae: status and prospects," *Renew Sust Energ Rev*, 2013, 19, pp360–369.
- [75] S.K. Gupta, F.A. Ansari, A. Shriwastav, N.K. Sahoo, I. Rawat, F. Bux, "Dual role of *Chlorella sorokiniana* and *Scenedesmus obliquus* for comprehensive wastewater treatment and biomass production for bio-fuels," *J Clean Prod*, 2016, 115 pp255–264.
- [76] F.A. Ansari, B. Ravindran, S.K. Gupta, M. Nasr, I. Rawat, F. Bux, "Techno-economic estimation of wastewater phycoremediation and environmental benefits using *Scenedesmus obliquus* microalgae," *J Environ Manag*, 2019, 240 pp293–302.
- [77] V. Sivasubramanian, V.V. Subramanian, B.G. Raghavan, R.R. Kumar, "Large scale phycoremediation of acidic effluent from an alginate industry," *ScienceAsia*, 2009, 35 pp220–226.