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The potential of phycoremediation in controlling eutrophication in tropical lake and reservoir: a review

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ABSTRACT

Phycoremediation has been successfully used in reducing nutrient levels in wastewater treatment. However, studies on the efficiency of phycoremediation to reduce the nutrient levels in eutrophic lakes are limited. This review focuses on the mechanism and factors involved in employing algae to remove nutrients and pollutants from wastewater before discussing the potential of algal-based techniques in remediating lake eutrophication. Techniques used in phycoremediation of wastewater include algal biofilm, algal turf scrubbers, high-rate algal ponds (HRAP) and immobilized algae. Harvesting mechanisms, factors influencing the phycoremediation and strain selection in phycoremediation of eutrophic lakes were also considered. The review concludes with the challenges facing the application of the techniques.

Keywords: Bioremediation; Eutrophication; Lake; Microalgae; Nutrient

1. Introduction

In the last few decades, lakes have been threatened by pollution due to anthropogenic activities. Pollution from domestic, industrial and agricultural activities have led to a deterioration of lake water quality. One of the major problems regarding lake water quality is eutrophication. Lake eutrophication has been identified as a prevalent challenge worldwide that required prompt action for intervention [1,2]. Lake eutrophication induced by excessive nutrient inputs, especially nitrogen (N) and phosphorus (P), not only promotes excessive algal growth but also threatens the ecological quality of lakes by altering the food web, water quality, and aquatic chemistry [3]. Lake eutrophication can lead to massive growth in toxic dinoflagellates or blue-green algae, causing oxygen depletion and fish kills or producing neurotoxins harmful to humans [4]. Phycoremediation, a technique that uses microalgae or macroalgae to remove or reduce pollutants including nutrients [5], was considered as one of the effective ways to deal with water pollution due to its high efficiency and low-cost usage [5,6]. The use of algae for bioremediation has gained acceptance since its introduction in the 1950s by Oswald et al. [7], who used microalgae for the tertiary treatment of municipal wastewater. The remediation of lake pollution and eutrophication by manipulating algal growth is a potential technique with prospects in tropical climate regions because they receive constant solar input, higher temperatures and high rain intensities which favor algal bloom growth conditions [8].

Phycoremediation technology has been employed in wastewater treatment in many industries [9]. For example, in the electroplating industry, the application of *Desmococcus olivaceus* to treat chrome sludge in an open pond [10] resulted in a reduction of ammonia, nitrate, and phosphate. Sivasubramanian et al. [11] showed how *Chlorococcum* sp., *Chlorella conglomerate*, and *Desmococcus* sp. were able to remove nitrate and phosphate very rapidly from effluent produced by the soft drinks industry. *Leptolyngbya* sp. was able

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to remove about 60% of total nitrogen in dairy wastewater [12]. Kshirsagar [13] showed that *Chlorella vulgaris* had a high nitrate removal capacity, while *Scenedesmus quadricauda* showed the best result for phosphate reduction in wastewater. In Hanumantha et al. [14], phycoremediation using *Chlorella vulgaris* in the field gave better results in nutrient removal compared to laboratory conditions. Additionally, *C. vulgaris* showed high phosphorus removal (>98%) in urban [15] and effluent wastewater [16]. *Botryococcus* sp., *Chlorella* sp., *Scenedesmus* sp., *Phormidium* sp. and *Spirulina* sp. are the most widely used algae for the phycoremediation of wastewater [15,17–23]. Despite its wide application in treating wastewater, information on the use and efficiency of phycoremediation to reduce the nutrient level in lakes is still limited. This work attempts to review the general application of phycoremediation in various studies and systems before looking into its potential in remediating lake water. The review also addresses mechanisms and factors influencing phycoremediation.

2. Physiology and nutrients removal mechanisms of algae

Algal productivity is controlled by the physicochemical factors and biological features directly and indirectly affecting photosynthesis, such as light intensity, mixing rate and temperature, absorption of light, and exposure duration [24]. Among the important factors in selecting algal species are their ability to resist various physiological stresses, such as fluctuating nutrients, organic loading, and extreme temperatures [25], and their potential for scavenging numerous types of pollutants [24].

Eutrophic lake is commonly dominated by *Cyanobacteria* such as *Microcystis*, *Planktothrix*, *Limnothrix*, *Anabaena*, or *Aphanizomenon* [26]. Several of their prokaryotic properties such as gas-vesicles, low CO_2, high pH optimum and nitrogen-fixation bear special ecological significance [26]. Blue-green algae can assimilate many nitrogen forms such as nitrate, nitrite, ammonia, and N_2 and can grow with nitrate as the only nitrogen source [27]. The mechanism of N_2 fixation in blue-green algae had many similarities to that found in some free-living bacteria and in nodules of leguminous crops, where the enzymes involved in fixation of molecular nitrogen are located on the lamellae [27]. However, the expression of certain characteristics is dependent on the form and the size of the *Cyanobacteria*.

For instance, the formation of colonies or aggregates is important for the physiology and behavior of *Cyanobacteria*. The colonies formed may help the *Cyanobacteria* to thrive in mixed conditions, due to their ability to fix nitrogen. Moreover, it can stratify as solitary filaments. Some *Cyanobacteria*, such as *Microcystis* and *Planktothrix* bear gas-vesicle and are able to use water column stability as a resource [28]. They can rise to the water surface where light and carbon dioxide are available or accumulate at some intermediate depth where conditions favor them. Other *Cyanobacteria*, such as *Limnothrix* or *Aphanizomenon*, are more dependent on higher turbulence [26]. Most *Cyanobacteria* have high resistance to zooplankton grazing that limits herbivory impact on them besides having a high tolerance to a wide range of ecological conditions including achieving optimum growth at high temperatures and eutrophic waters [29]. In contrast to *Cyanobacteria*, different green algae species vary in their ecological preferences including the degree of water movement, nutrient levels, pH, hardness and salinity [29].

Spirulina is one of the *Cyanobacteria* species that demonstrate better resistance to physiological stresses, and its use in nutrient removal has been extensively studied by Olguin et al. [17,30–32]. *Spirulina* has the ability to auto-flocculate, making them easier and cheaper to harvest, as well as displaying high tolerance to ammonia-nitrogen. A successful *Spirulina* culture under tropical conditions, with temperatures in the range of 29°C–34°C and sunlight intensity ranging from 476–1,784 μmol photon m^{-2} s^{-1}, was reported by Olguin et al. [30].

Microalgae are also capable of tolerating harsh or heavily polluted environments as they have the ability to eliminate other contaminants, such as heavy metals and organic pollutants [33] through biosorption and bioconcentration [34]. Heavy metal adsorption by microalgae is associated with the presence of high-affinity metal bindings on the algal surfaces, while accumulation is associated with metal uptake by the live cells [34]. Removal of heavy metal by biosorption found to be higher among dead cells compared to live cells [34], which was attributed to the larger surface, volume ratio and higher metal binding attraction. Chojnacka et al. [35] showed that blue-green algae *Spirulina* has the maximum biosorption capacity of Cr, Cd, and Cu. The authors also showed that microalgae biosorption capacity improved with high light intensity.

In addition, microalgae offer great potential for the bioremediation of organic pollutants such as pesticides, phenolics, tributyltin, naphthalene, bisphenol and hydrocarbon [34]. Photosynthesis by microalgae plays a major role in pollutant degradation. The growth and ability of microalgae to degrade organic pollutants in wastewater treatment could be enhanced by the addition of glucose nutrients [36], while biosorption and biodegradation are the mechanisms used to remove compounds [37]. Microalgae used in organic pollutant removal include *Monoraphidium braunii*, *Selenastrum capricornutum*, *Agmenellum quadruplicatum*, *Pediastrum tetras*, *Ankistrodesmus fusiformis* and *Amphora coffeaeformis* [35]. Annex 1 shows the removal of pollutants by selected microalgae.

3. Phycoremediation techniques

Phycoremediation can be categorized based on the attached system or suspension culture system [38]. The attached system, which uses algae attached to media, includes microalgal biofilms and algal turf scrubbers (ATSs), while the suspension culture system includes high-rate algal ponds (HRAPs) or naturally suspended sedimentation ponds. Fig. 1 illustrates the available techniques with a schematic figure, while Table 1 summarizes the advantages and disadvantages of these systems.

3.1. Algal biofilms

Algal biofilms are layers of films containing phototrophic microorganisms, which colonize and grow on wetted surfaces or surfaces submerged in water in the presence of light [39,40], moisture and nutrients [41]. Algal biofilms are based on the symbiotic interactions between microalgae

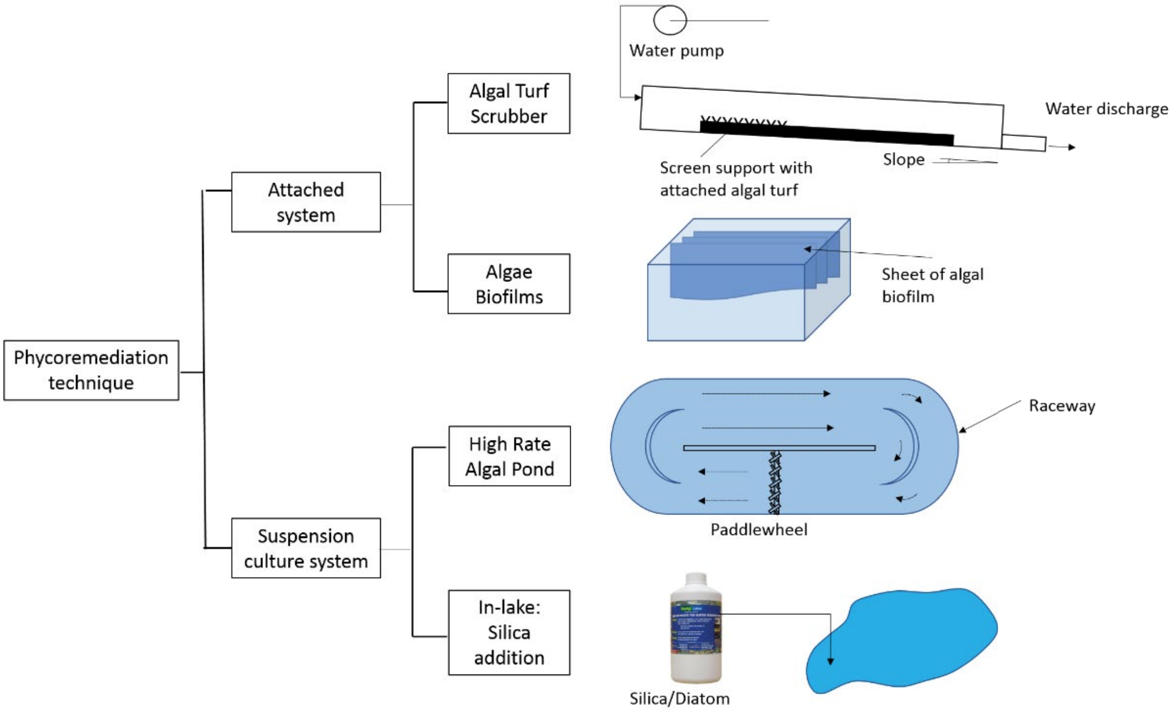


Fig. 1. Phycoremediation techniques.

Table 1
Advantages and disadvantages of phycoremediation techniques

Method	Control parameter	Advantages	Disadvantages
HRAP	Hydraulic retention time, mixing, CO_2 availability, cultivation mode, and grazers control	High nutrient removal, simple and economical	Difficult and expensive to harvest algal biomass, poor and inconsistent effluent quality, limited nutrient and pathogen removal
Sedimentation ponds	Hydraulic retention time, light	Low cost	Poor and inconsistent effluent quality
Microalgal biofilms	Temperature, thickness of biofilms, light intensity, flow	High versatility and adaptability, that is, can combine nutrient removal and fish feeds production, easier and cheaper to harvest algal biomass	Limited for large scale operation
Algal turf scrubbers	Hydraulic retention time, light levels, temperature, and wave surge action, raceway slope	Low cost, easier and cheaper to harvest algal biomass	Limited for large scale operation

and bacteria. The oxygen produced by microalgae during photosynthesis is used by bacteria in the biofilm to oxidize the organic matter and nutrients present in the wastewater, while the CO_2 produced during oxidation benefits the microalgae for photosynthesis [42]. Furthermore, the physical and chemical properties in algal biofilm communities are determined by extracellular polymeric substances (EPS), composed of polysaccharides, proteins, nucleic acids, lipids, and humic acids [41]. EPS plays an important role in assisting cell movement, preventing cell desiccation, protecting cells against toxic substances, and providing stability as an adhesive material [41]. The EPS production is influenced by biofilm age, nutrient availability, species composition, response to stress and also indirectly linked to temperature and light via algal photosynthesis and growth [41].

Microalgal biofilm formation usually starts with the colonization of a submerged surface by the first colonizer or pioneer species, such as diatoms, followed by domination by *Cyanobacteria* and green microalgae [38]. In Sekar et al. [43], the succession pattern of attached algae on Perspex sheets in open-water reservoir experiments was by *Chlorophyceae*, then by diatoms (*Bacillariophyceae*) and lastly by *Cyanobacteria*. Surface media, which have been used for algal biofilms, include plastic sheets or templates, such as polyvinyl chloride [39,44], polystyrene foam [45] and concrete panels [46]. A comparative study on the capability of different media, namely polystyrene foam, cardboard, polyethylene fabric, and loofah sponge, reported the better attachment of *Chlorella* sp. to polystyrene foam [45]. In another work, the attached growth of microalgal on nylon and stainless-steel mesh was found to be much higher than that of polycarbonate and polyethylene plate [47].

The algal biofilm growth and nutrient removal pattern are parallel, where the nutrient uptake capacity was low during the early growth phase, then increased as growth peaked and reduced at the death phase [41]. Schnurr and Allen [48] in their review illustrated the markedly complicated growth of algae in biofilms. Species proportions and successions that shape productivities are influenced by various biotic and abiotic factors [48]. Biofilm thickness, light intensity, flow velocity, and temperature were some of the factors influencing mature biofilm formation and their retainment and removal of nutrients [39,43]. In a study carried out by Jarvie et al. [39], algal biofilm production in the stream was amplified with declining flow velocity and increasing light intensity [13]. The low cost of harvesting through scraping and spooling gives an advantage to the algal biofilm compared to the suspension-based harvesting which uses expensive harvesting procedures such as flocculation and centrifugation [25,30–31].

3.2. Algal turf scrubbers

The ATS system is a bioengineering-based technology that cultivates and harvests an attached algal community in the form of a “turf” [38,49]. The attached algal turf is grown on screens on a shallow slopping raceway through which water from streams or a waterbody is pumped onto the raceway, allowing the algal turf to photosynthesize and uptake nutrient or inorganic compounds for their growth [38]. The water that contains a much lower nutrient content will usually be separated by gravity and released back into the waterway at the end of the raceway. Common algal assemblages on turfs are filamentous green algae, such as *Spirogyra* sp., *Microspora* sp., *Ulothrix* sp., *Rhizoclonium* sp. and *Oedogonium* sp. [38]. These dominant species are accompanied by the *Cyanobacteria Phormidium* sp. and *Oscillatoria* sp., along with benthic diatoms [38]. Screens or attached media for turf, which has been used in wastewater treatment include polystyrene mesh [50], nylon net [51,52] and high-density polyethylene plastic mesh [53].

This technology has been utilized for controlling nonpoint source pollution from agriculture areas and animal wastes [51,52,54], aquaculture facilities [55] and tributaries [29]. The controlling factors for successful nutrient removal using an ATS are hydraulic retention time (HRT), light levels, temperature and wave surge action [38,51]. A raceway slope also influences algal productivity; higher production values for filamentous algae have been observed using a 2% slope compared to a 1% slope [51], which was likely due to a better light environment and drainage flow, and the avoidance of pools of water stuck on the raceway. Besides that, the seasonal variation of nutrient loading resulting from the seasonal changes in water use, such as a dairy wastewater system also affects algal productivity [51]. Low algal growth has been found during the summer months, primarily due to the elevated water temperatures and grazing by snails [51].

3.3. High-rate algal ponds

HRAPs, also known as aerobic ponds, are open systems used for cultivating microalgae to treat wastewater [29]. They combine oxidation ponds and algal growth systems and usually form part of an advanced integrated wastewater system. Since lakes are stagnant water bodies, with sizes larger than ponds, the mechanisms and factors influencing phycoremediation in lakes are similar to the mechanism shaping HRAPs. The major difference is the presence of an artificial impeller to oxidize the system and waterbody size. This technique has been widely utilized in treating agricultural, municipal and industrial wastewater. Successful utilization of HRAP includes the treatment of anaerobic effluents from pig waste under tropical conditions [15], agricultural wastewater [56] and sewage effluents [57], using a naturally developed algal community, but with the operating parameters optimized to achieve optimal light conditions [58].

Generally, an HRAP is a shallow pond (0.2–0.5 m) with a typical raceway design and water mixed by paddle wheels [38,59]. The mixing promotes algal growth and prevents biomass settling. The assemblages of algae are developed naturally in the HRAP with no special algal species selected for inoculating it. Green algae, such as *Ankistrodesmus* sp., *Chlorella* sp., *Chlamydomonas* sp., *Euglena* sp., *Micractinium* sp., *Scenedesmus* sp. and the *Cyanobacteria* genus *Oscillatoria*, are the most frequently recorded species used in HRAPs [38]. Since the 1990s, efforts have been made, with regard to certain species of algae, such as the *Cyanobacterium Phormidium bohneri*, to remove nutrients from HRAPs.

Organic matter removal from an HRAP involved a mutualistic relationship between bacteria and algae [60]. The algal photosynthesis process provides dissolved oxygen required for decomposing organic matter by aerobic bacteria, while the algae benefit from carbon, nitrogen, and phosphorus produced by bacteria during the decomposition process. Among the factors influencing nutrient and pollutant removal in the symbiotic algae bacteria applications in wastewater is HRT [7]. HRT is the amount of time in hours for wastewater to pass through a tank, such as an aeration tank [61], determined by dividing the volume of the aeration tank into million gallons by the flow rate through the aeration tank. The flow rate through the aeration tank must be expressed as gallons per hour (gph). The equation is as follow:

$$\text{HRT} = \frac{\text{Volume of aeration tank}}{\text{flowrate}} \tag{1}$$

Under short HRTs and high loading, algae are in their logarithmic growth phase [62]. However, studies showed longer HRT is better for nitrogen removal compared to short HRT, as algae reach their steady growth phase under longer

HRTs and this may facilitate the incorporation of more cells into the symbiotic biomass net [63,64]. Furthermore, lower HRT was shown to increase the amount of free-swimming algae as well as their concentration in the biomass. Cromar and Fallowfield [65] reported that an increase in retention time from four to 7 d elevates phosphorus removal from 69% to 93%.

Pond depth, which restricts light penetration for algal growth, also affects nutrient removal efficiency. Pond depth is also important for determining the biomass concentration as the available light within the pond has been shown to affect microalgal productivity [29]. A shallow pond is recommended as they provide the maximum amount of light to the microalgae and biomass concentration [66]. However, microalgae biomass was unstable in shallow pond (depth < 300 mm) as they react actively to changes in light [67]. Therefore, the balance between light and thermal stability is important for improving microalgal photosynthesis. Besides that, Sutherland et al. [67] showed that deeper ponds offer greater areal productivity and nutrient removal, as areal productivity almost doubled in 400 mm deep HRAP compared to 200 mm deep HRAP. Furthermore, a deeper pond is less vulnerable to culture wash-out during heavy rain events than the shallow pond [68]. This suggests that growth in the shallowest HRAP was more constrained than the deepest HRAP even with adequate light and mixing regime.

Organic loading rate and horizontal mixing velocity are also important in shaping nutrient removal in HRAPs; a higher frequency of mixing increases microalgal productivity and improves nutrient uptake and treatment [69]. Nutrient removal in HRAP is also dependent on the mechanisms involved in the productivity of algae, harvesting of biomass, ammonia-nitrogen volatilization and orthophosphate precipitation [30]. The produced algae biomass in the HRAPs can be harvested using a gravity settling method with harvested productivity ranging between 7.5 to 11.5 g m^{-2} d^{-1}.

3.3.1. Harvesting of produced biomass in HRAP

An effective harvesting system is crucial for successful phycoremediation in HRAPs in reducing the nutrient load because the dead cells will return the nutrients to the system [34], the harvested biomass can be used as aquaculture and livestock feed, extracted for compounds such as pigments, lipids, and fatty acids, which are biodiesel precursors [34] and hydrocarbon as a value-added chemical for the bio-based plastic industry [70]. However, harvesting produced biomass remains one of the major limitations of phycoremediation in HRAPs. In contrast to the attached system, where algae removal can easily be undertaken by scrubbing the media, harvesting methods need to be introduced in HRAPs.

One of the methods suggested in several studies to resolve the harvesting problem is the immobilization of microalgae [71,72]. By keeping the living cells within a gel matrix [73], immobilized algae become an efficient system in nutrient removal from wastewater, besides suspension cultures. Rai and Mallick [73] showed that immobilized *Chlorella* and *Anabaena* have a higher uptake rate for both N and P, probably due to increased cell wall permeability, an increase in the cell retention time within bioreactors, and higher metabolic activity [72]. Furthermore, numerous factors influence nutrient removal efficiency by immobilized algae, including a selection of the most appropriate species [74]. Species isolated from wastewater should show higher efficiency than commercially available ones, due to their significant adaptability to temperature and chemical changes in the medium. In addition, many studies have shown that green algae and *Cyanobacteria* can be successfully immobilized for nutrient removal [71,75,76].

Some major advantages of the immobilization method are its capacity to concentrate high biomass for use as by-products, avoid the filtration of treated wastewater, be highly resistant to toxic compounds within treated wastewater, and immobilize more than one microorganism [73]. Immobilization saves the entrapped microalgae from grazing by aggressive zooplankton and reduces the competition for nutrients with other microbial species. A small number of studies have also shown that nutrient removal using immobilized algae is much more efficient than the suspended algae method [75,77].

Besides the immobilization method, which is commonly used in wastewater treatment, Carmichael et al. [77] studied the harvesting method of *Aphanizomenon flos-aquae* (*Cyanobacteria*) from Klamath Lake for human dietary use, which could also be applied to phycoremediation in lakes. The initial process is to use a large harvester to move the *A. flos-aquae* from the lake to the irrigation canal. From the canal, a large series of screens are used to remove the biomass using the self-powered barge technique.

Another method for harvesting microalgae is flocculation. Vandamme et al., [78] reviewed three different technologies used in flocculation (1) chemical flocculation; (2) biological flocculation; and (3) physical flocculation. The disadvantage of chemical flocculation is biomass contamination; however, this problem could be minimized by using natural polymers. Meanwhile, biological flocculation by bacteria or fungi may result in the microbiological contamination of the biomass, which may also interfere with food or feed applications of the microalgal biomass. On the other hand, physical flocculation methods may avoid contamination of the biomass with chemicals and microorganisms, as they use magnetic nanoparticles for harvesting.

4. Application of phycoremediation in lakes and reservoirs

Applying phycoremediation in lakes will require knowledge of the factors controlling primary productivity. Temperature, light availability, macro, and micronutrient availability are the basic factors controlling phytoplankton production in lakes [79,80]. Nutrients (e.g. N, P, Si) in relatively fixed proportions are required for algal cell reproduction. Reduction in the silica content of eutrophic lakes could lead to a change in dominance from the silicifying diatom blooms to the *Cyanobacteria* blooms [81]. *Chroococcus*, *Planktothrix*, *Nostoc*, *Oscillatoria*, *Phormidium*, *Anabaena*, *Gloeocapsa* and *Microcystis* are among the most commonly reported *Cyanobacteria* in lakes receiving pollutants from different sources [82]. Studies have shown that *Cyanobacteria* are efficient in removing nutrients from wastewater as they require a higher amount of nutrients (N, P) for their growth [26]. Toxin production by toxigenic strains of *Cyanobacteria* will affect natural grazers and another aquatic biota, and these need to be harvested. Species of the genera *Oscillatoria* and *Anabaena* are among the most distributed toxin producers in eutrophicated freshwaters [26]. Harvesting algae in lakes can be expensive, which means it is not feasible for large-scale applications.

Cyanobacterial dominance depends not only on nutrient enrichment but also on the specific *Cyanobacterial* species involved. Understanding the mechanisms influencing *Cyanobacteria* dominance in lakes such as nutrient ratio, light requirements, and CO_2 competition is important to alter them to control their dominance [83]. In contrast to laboratory or pilot conditions, most environmental factors in natural water bodies are not controlled, which may influence algal dominance. In tropical environments, such as Malaysia, controlling temperature to sustain high algal biomass, such as on raceways, may not be crucial due to a uniform warm temperature and a moderate diurnal variation in solar radiation throughout the year [84]. Carbon limitations and pH rises associated with the photosynthetic uptake of CO_2 during periods of peak photosynthesis or algal bloom can be a challenge in lake environments.

Reducing nutrient loading, especially involving phosphorus, from the catchment is a vital prerequisite to reduce or prevent eutrophication and *Cyanobacteria* dominance. This can be undertaken through the strict control of influent waterbodies and their pollutant levels, such as rivers that enter a lake, based on an understanding of the total maximum daily load and lake carrying capacity. Additionally, phycoremediation could be considered as one of the measures to reduce nutrient levels in a waterbody. Fig. 2 illustrates some ways of applying phycoremediation in lakes. One possible method of nutrient removal by algae in lakes is by channeling nutrient-rich water from a lake to a raceway constructed on land, then discharging the nutrient-reduced water back into the lake. Alternatively, HRAPs or ATSs can be created at the inlet of water bodies such as the one studied in the Chesapeake Bay tributaries (USA) to reduce nutrient content in water flowing into the lake [51]. Raceways can also be deployed in littoral zones and sheltered areas of lakes where wind effects are at their lowest and the chances for algal bloom occurrence are at their highest. Understanding hydrodynamic patterns of the lake, such as through modeling, will enable the selection of the best sites for raceway construction.

Excessive algal bloom, especially *Cyanobacteria*, is shaped by a combination of factors, such as light environment, temperature, water turbulence, and water N:P ratio. Different algal bloom species, filamentous or colony-forming, are often difficult to predict due to several interacting factors undermining the lake environment [26]. The success in employing in-lake measures to remove nutrients or harvesting algae depends on the lake's trophic conditions [85]. Hypereutrophic lakes or ponds, especially those located near agricultural areas, which have experienced frequent excessive algal bloom, have greater potential in terms of employing phycoremediation techniques to skim or harvest the algae. Manual harvesting of *Spirulina* or *Arthrospira* has been carried out in the soda lake of Lake Chad by the local population as their food source [86]. Similar manual harvesting of algal biomass has been observed in some urban lakes in Malaysia. During harvesting, toxic *Cyanobacteria* should be skimmed using an algal skimmer machine to avoid exposing the population to toxins produced by the algae. Future research should be carried out to develop and apply low-cost and affordable technology to in-lake algal harvesting.

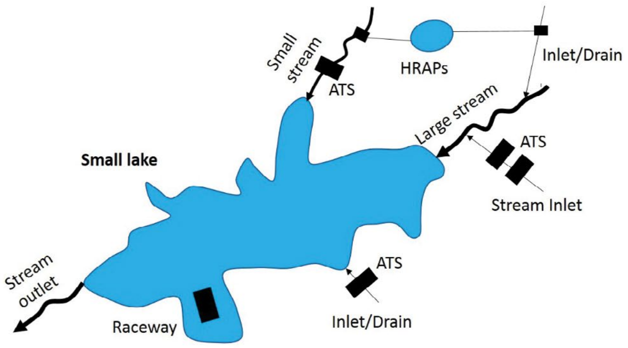
Another potential phycoremediation method is to alter species dominance from *Cyanobacteria* to diatoms by introducing silica. The in-lake application by Kiran et al. [4,87] showed that dosing a lake with a nano silica-based micronutrient mixture shifted the *Cyanobacteria* blooms to diatom blooms, reducing 56% and 21.4% of nitrate and phosphate, respectively. Diatom blooms reduce the excess nutrients (N, P) and carbon in the lake, as they can consume N and P faster than other algae, in addition to being the best sequesters of CO_2. Besides, they are an excellent food source for zooplankton and fish, as they are not toxic [87]. Furthermore, their transparent silica shells require less light, thus promoting diatom growth, even on cloudy and rainy days. The combination of these abilities makes diatom species effective for nutrient removal in lakes

Moreover, studies have also shown that green algae (*Chlorella* and *Scenedesmus*) display higher tolerance to many contaminants and nutrients and are commonly used in wastewater phycoremediation [24]. Wang et al. [88] revealed that the removal rate of NH_4–N and phosphorus by *Chlorella* sp. ranges from 74.7% to 82.4% and 83.2% to 90.6%, respectively. However, Ganf and Oliver [89] showed that green algae (*Dictyosphaerium pulchellum*) was replaced by blue-green algae (*Microcystis aeruginosa*) in a stratified lake, due to the vertical separation of light and available nutrients. The presence of gas vesicles permits the vertical movement of *Cyanobacteria* without the circulation of water. Based on the abovementioned criteria, diatom species are probably the most ideal microalgae to be used in the phycoremediation of eutrophic lakes, given their special attributes, such as silica shells, compared to green algae.

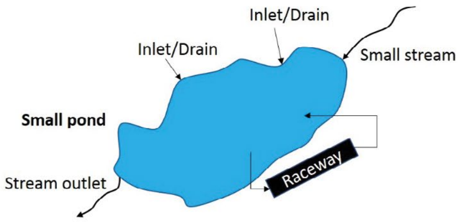
5. Technical limitations and adverse environmental effects of phycoremediation in lakes

One of the biggest challenges in employing phycoremediation in lakes (including man-made lakes such as reservoirs) is to control environmental factors that may influence algal dominance. The monitoring of algal communities has not been carried out continuously in many waterbodies to understand the existing ecosystem state. Seasonal factors, such as wet and dry seasons for waterbodies in the tropics, strongly influence algae physio-ecology in the system. Different algal species dominance was observed in different seasons due to different lake physical and chemical conditions. Waterbodies are strongly shaped by local climates such as rain, wind and air temperature that cannot be controlled. Wind, for example, has a strong influence in causing upwelling and downwelling that transport and circulate nutrients within the water column to promote biological productivity in the water bodies. Waterbodies are also exposed not only to dust, and other debris but also to the infestation of predators that feed on algae, viruses and heterotrophic bacteria [85]. All these factors can provide technical constraints in implementing phycoremediation in lakes.

a) Lake with streams and drain inlets



b) Pond with small stream



c) Pond with drain inlets and outlet

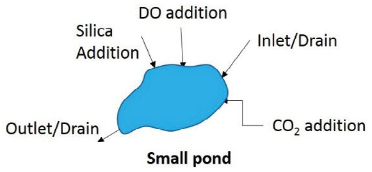


Fig. 2. Phycoremediation application in waterbodies.

Factors such as carbon limitations and pH increase during periods of peak photosynthesis or algal bloom can limit the application of phycoremediation in waterbodies. A pH rises during periods of algal bloom, commonly observed in hypereutrophic or eutrophic lakes [85] and on raceways [68,90], could affect productivity CO_2 addition has been considered for raceways and HRAPs to enhance algae productivity and reduce predator grazing by zooplankton [91]. The injection of CO_2 in large quantities into ponds is expensive due to additional costs associated with CO_2 purification, storage, and distribution [92]. Injection of bicarbonate has been suggested as an alternative measure to conventional CO_2 supply, with a potential cultivation cost reduction of 55% and energy savings of 80%–90% [93].

Channeling nutrient-rich water from a lake to a raceway constructed on land for phytoremediation, then discharging the nutrient-reduced water back into the lake can also be challenging. The application of such channeling may be restricted by land availability nearby and the large costs involved in system construction and raceway maintenance. The effectiveness of such phycoremediation technique is also limited to small water bodies. Channeling is probably cheaper than other physical measures, such as desilting or dredging, but the energy requirement for operations, as well as maintenance costs, would most likely limit its large-scale application.

Introducing different species of algae or dosing with silica to alter species dominance is probably limited to small waterbodies. Additionally, the overall implication of introducing silica into lakes, especially natural ones, is not widely known from the environmental perspectives. Application probably should be made in small urban ponds on an experimental or pilot scale prior to any application in natural water bodies. More research is also needed to assess the economic feasibility of such an application.

6. Conclusion

Most studies on phycoremediation are focused on wastewater and effluent treatment. Literature findings show that microalgae have a significant effect in terms of reducing nutrient levels and pollutants (including organics and heavy metals) from different wastewater and sewage thus having potential in lake remediation. Knowledge about the limitation, effectiveness, and application of phycoremediation in lakes, however, is still limited. Physiology and nutrient removal mechanisms of algae including their ecology were discussed. Potential application of phycoremediation techniques in lakes includes using the attached system such as ATS or suspension culture system using HRAP. Technical limitations of applying phycoremediation in lakes and reservoirs include addressing carbon limitation during phycoremediation processes and controlling seasonal changes in natural conditions. Additionally, introducing new algae species in lakes can cause potential environmental ramifications. More phycoremediation studies should be carried out in the natural environment, such as in lakes and ponds, to understand and prove phycoremediation suitability for controlling eutrophication in lakes.

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Supplementary information

Annex 1
Removal of pollutants by selected microalgae

Species	Reduction of pollutant	Water/wastewater used	References
Botryococcus sp.	COD: 88%, BOD: 82%, TIC: 76%, TC: 58%, TN: 52%, TOC: 39%, phosphate: 37.5%, pH: 7%	Grey water	[22]
Botryococcus sp.	Nitrate: 78.8%, BOD: 69.03%, total organic carbon: 67.93%	Food processing wastewater	[69]
Chlorella vulgaris	Free ammonia: 80%, nitrite: 89%, nitrates: 29%, TKN: 73%, Phosphate: 94%, BOD: 22%, COD: 38%	Industrial effluent (laboratory)	[14]
	Phosphate: 100%, TKN: 12%, ammonia: 29%, nitrites: 88%, nitrates: 84%, BOD and COD: 83%	Leather-processing, chemical plant, effluent	
Chlorella vulgaris	Total nitrogen: 87.9%, total phosphorus: 98.4%	Urban wastewater	[15]
Chlorella vulgaris	Nitrate: 28.69%, total phosphorus: 28.8%	Slaughterhouse effluent wastewater	[23]
Chlorella vulgaris	COD: 98.3%, BOD: 98.7%, TKN: 93.1%, total phosphorus: 98.0% nitrate: 98.3%, Phosphate: 98.6%, chloride: 94.2%, total coliforms: 99.0%, faecal coliforms: 99.0%, TDS: 98.2%	Wastewater	[16]
Chlorella sp.	Ammonia: 93.9%, total nitrogen: 89.1%, total phosphorus: 80.9%, COD: 90.8%	Municipal wastewater	[57]
Diatom (*Nitzschia* sp, *Navicula* sp., *Cocconeis* sp., *Gymphonema* sp., *Gyrosigma* sp.) – Nualgi	Nitrate: 82%, phosphate: 80%, TKN: 83%, COD: 94%, BOD: 89%	Eutrophic lake	[4]
Diatom (*Nitzschia* sp, *Navicula* sp., *Cocconeis* sp., *Gymphonema* sp., *Gyrosigma* sp.) – Nualgi	Nitrogen: 95.1%, phosphorus: 88.9%, COD: 91%, BOD: 51%	Urban wastewater	[91]
Scenedesmus obliquus, Chlorella vulgaris, Chlorella kessleri	Nitrogen: >90%, phosphorus: >98%	Wastewater	[20]
Oscillatoria sp., *Phormidium corium, Spirulina laxissima, Scenedesmus quadricauda, Euglena viridis, Navicula viridula* (mix culture)	Phosphate: 100%, NO_3–N: 100%, NO_2–N: 100%, NH_3–N: 98.9%, organic nitrogen: 91.7%	Sewage water	[19]
Chlorella vulgaris, Scenedesmus quadricauda	Nitrate: 78.1%, phosphate: 62.7%, COD: 80.6%, BOD: 70.9%, Phosphate: 81.3%, nitrate: 70.3%, COD: 70.97%, BOD: 89.2%	Domestic wastewater	[13]
Oscillatoria limosa, Nostoc commune	Nitrate: 84%–98%, Phosphate: 84%–98%	Wastewater	[21]
Scenedesmus obliquus	Ammonium: 90%–97%, phosphorus: 85%	Wastewater	[18]
Spirulina maxima	Total phosphates: 99%, ammonia-N: 100%	Seawater supplemented with anaerobically treated pig slurry	[31]
*Leptolyngby*a sp.	Total nitrogen: 60%, total phosphorus: 52.3%, nitrite nitrogen: 61.28%	Dairy wastewater	[12]

COD = Chemical oxygen demand; BOD = Biochemical oxygen demand; TIC = Total inorganic carbon; TC = Total carbon; TN = Total nitrogen; TOC = Total organic carbon; TKN = Total Kjeldahl nitrogen; TDS = Total dissolved solids