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Review Paper

Phycoremediation - A Clean Technology for Water Pollution Abatement

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ABSTRACT

Phycoremediation has been utilised to remediate wastewater and successfully lower nutrient levels. There isn't many research, though, on how well phycoremediation works to lower nitrogen levels in eutrophic lakes. This review concentrates on the process and variables involved in using algae. Before considering the possibility of algal-based approaches in remediating lake eutrophication, to remove nutrients and contaminants from wastewater. Algal biofilm, algal grass scrubbers, high-rate algal ponds (HRAP), and immobilised algae are methods used in phycoremediation of wastewater. A wastewater treatment method based on microalgae lowers BOD, prevents coli forms, eliminates pollutants and nutrients, and removes heavy metals. The sixth sustainable development target of the UNDP cannot be attained without phytoremediation. Microalgae can effectively treat wastewater at a very low cost, and the biomass they produce can be used to produce biofuels. The cost-effective growing of microalgae and contaminants with wastewater can be replaced by the successful coupling of microalgae with wastewater, which can also scale up production of high-value products. This review mainly focused on the potential of algae and their specific mechanisms involved in wastewater treatment and energy recovery systems leading to important industrial precursors. The review is highly beneficial for scientists, wastewater treatment plant operators, freshwater managers, and industrial communities to support the sustainable development of natural resources.

Keywords: Algae, Biodegradation, Pollutant removal, Phycoremediation, Wastewater treatment.

Highlights

- Phycoremediation is based on the ability of algae and cyanobacteria to photosynthetically *convert sunlight, carbon dioxide, and nutrients into biomass. During this process, these* microorganisms absorb and assimilate pollutants, thereby reducing the concentration of contaminants in water bodies.
- To maximize the efficiency and scalability of phycoremediation, ongoing research is needed in the areas of algal genetics, cultivation techniques, and system design.
- Integrating phycoremediation with existing wastewater treatment processes and exploring novel cultivation systems are promising research directions.
- Phycoremediation holds tremendous potential as a clean technology for water remediation. By harnessing the natural capabilities of photosynthetic microorganisms, we can achieve sustainable and eco-friendly solutions to combat water pollution and preserve aquatic ecosystems for future generations.

INTRODUCTION

Water is in greater demand due to population growth; despite the fact that water covers about 70% of the planet, there is clearly a scarcity. The yearly per capita availability was approximately 3300 cubic meters in 1960; this dropped by 60% to approximately 1250 cubic meters, and by 2025, it is expected to drop even further to 650 cubic meters. For this reason, the time has come to utilize every last drop of water on Earth, beginning with wastewater [13]. Economically speaking, treating water is a challenging endeavour, so finding a less expensive method to do so is urgently needed. One such method is phycoremediation, which employs microalgae to assist treat water. For the elimination or biotransformation of the contaminants With the help of photosynthesis, microalgae—microorganisms that take in carbon dioxide and proliferate in the presence of moisture and nutrients—are being studied extensively for wastewater treatment as a potential replacement for more expensive, traditional methods[59].The choice of a wastewater treatment technology, whether conventional, bioremediation, or advanced, is currently one of the research community's most fascinating topics. Utilising microorganisms like microalgae, phycoremediation is a bioremediation method for treating wastewater. It has been common practise for more than 40 years, according to [3], to utilise algae to treat wastewater. Oswald described the initial application of this discovery. The use of microalgae as an alternative to traditional treatment methods has garnered a lot of interest in previous years. The choice of a wastewater treatment technology, whether conventional, bioremediation, or advanced, is currently one of the research community's most fascinating topics. Utilising microorganisms like microalgae, phycoremediation is a bioremediation method for treating wastewater. It has been common practise for more than 40 years, according to [3], to utilise algae to treat wastewater. Oswald described the initial application of this discovery. The use of microalgae as an alternative to traditional treatment methods has garnered a lot of interest in previous years.

Population growth, industrialization, and rapid urbanisation have all contributed to various forms of environmental contamination in recent years. Dumping untreated sewage (such as commercial, residential, and industrial effluent) directly into aquatic environments like rivers, reservoirs, and the sea is considered a rapid and affordable dumping technique in locations where the sewage treatment plant (STP) facilities is not fully developed. Water scarcity and depletion are significantly impacted by this[27].One biological treatment that is regarded as environmentally responsible and sustainable for removing contaminants from wastewater is phytoremediation. In addition to bio-transforming wastewater contaminants, microalgae are a great source of hydrocarbons. Since microalgal oil is extracted from a living plant, it is regarded as a sustainable source of hydrocarbon. Nowadays, wastewater discharge into the environment has increased due to the world's expanding population and diverse businesses. One of the strategies with high potential to photosynthetically digest the excessive contaminants in wastewater is microalgal phycoremediation. As a result, one of the goals of this study is to identify innovative technologies to reduce the negative effects on the environment while also evaluating sustainable hydrocarbons. The release of untreated or processed water from towns and villages, emissions from industrial or processing facilities, runoff from agricultural land, and leachates from waste disposal sites are just a few examples of causes of pollution. We have been forced to look into a workable wastewater treatment and resources regeneration due to a lack of water, energy, and food [16] pH, colour, odour, total nitrogen (TN), total phosphorus (TP), chemical and biological oxygen demands (COD and BOD), total suspended solids (TSS), total dissolved solids (TDS), and metal ions concentration are the fundamental wastewater monitoring parameters[29].In comparison to more expensive conventional treatment technologies, using algae has many advantages. Traditional treatment uses a lot of resources and produces a lot of harmful waste. As an environmentally benign method, phytoremediation is utilised to reduce environmental pollutants [17][49]. *Spirulina sp., Chlorella sp., Chlamydomonas sp., Oscillatoria sp., Nostoc sp., and Scenedesmus sp*. are just a few of the non-pathogenic algae used for wastewater treatment [20].

1. A general composition of wastewater

Several separate streams, each with a range in strength and quantity, contaminate waterways. According to [1], the nature of wastewater serves as a metaphor for the societal habits and technology that are currently prevalent. It is a complex mixture of natural materials, both organic and inorganic, as well as manufactured compounds. The main pollutants in wastewater include amino acids, fats, carbohydrates, and sugars. According to several studies [3][18], wastewater contains significant amounts of sodium, calcium, potassium, magnesium, arsenic, sulphur, phosphorus, bicarbonate, ammonium salts, and heavy metals. According to Deka and Lahkar, persistent organic pollutants (POPs) are chlorinated and aromatic pollutants such polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and organochlorinated insecticides. The combustion of non-renewable fuels including coal, petroleum, burning of biomass, emissions from processing industries, greenhouse gas emissions, home heating, landfills, wildfires, and other sources results in the ubiquitous derivatives known as PAHs.

According to Haddaoui, PAHs are one of the main categories of organic pollutants that are largely present in environments that have been polluted by petroleum products. Due of PAHs' widespread distribution and hazardous effects on living things, interest in how they affect the environment is expanding. Pyrene is the most prevalent PAH contaminant found in wastewater, particularly that produced by the petroleum sectors [35] [37]. Among the many sources of contamination are releases of untreated or damaged.

Table 1 is a summary of the principal contaminants found in the wastewater.

Type of pollutant	Name of the contaminants
PAHs	Acenaphthene, anthracene, benzo[a]anthracene, benzo [a]pyrene, benzo[e] pyrene, benzo[b]fluoranthene, benzo[g,h,i]perylene, benzo[k]fluoranthene, benzo[j] fluoranthene, chrysene, fluoranthene, fluorine, dibenzo [a,h]anthracene, indeno[1,2,3-c,d]pyrene, phenanthrene, pyrene [37]
POPs	Pesticides: cyclodienes, DDT, mirex, PCBs, perchlorobenzene. Chlorine-containing materials: dioxins and furans. Phenols, chlorinated phenols-p-chlorophenol, 2,4- dichloro phenol [42]
Perfluorinated compounds	Perfluorooctane sulfonate, perfluorooctanoic acid
Chlorinated disinfection byproducts	Halomethanes, aldehydes, ketones, hydroxyl- and carboxylic- acids, derivatives of carboxylic acids, oxoacids, and even nitrosamines
Antibiotics	Trimethoprim, ciprofloxacin, sulfamethoxazole [7]
Metal ions	Cadmium (Cd), chromium (Cr), arsenic (As), lead (Pb), mercury (Hg) [43].

2. Remediating wastewater using microalgae

Biologists have been researching the possible application of microalgae in wastewater treatment in nations such as the United States, Taiwan, Thailand, Australia, and Mexico. Microalgae biotreatment is primarily appealing due to its remarkable ability to transform solar energy into valuable biomasses. The algal systems are being developed to successfully remove harmful minerals like lead, cadmium, mercury, scandium, tin, arsenic, and bromine. They are also known to be effective in cleaning human sewage, livestock wastes, industrial, agricultural, and waste from food processing facilities. As a possible tertiary and secondary therapeutic method, algal systems are suggested. The removal of organic ions occurs in the tertiary process through biological and chemical means, which raises the treatment cost. Hard implementation, secondary pollution, and wastewater treatment are all expensive endeavours; the cost of treatment typically doubles with each additional step in the water treatment process [60].

3. Innovations in technology for wastewater reuse and disposal

Chemical treatment, the activated sludge process, anaerobic digestion, membrane filtration, advanced oxidation, and the electro-Fenton process are examples of traditional wastewater treatment techniques [30]. It is crucial to develop appropriate wastewater treatment processes that are easy to apply, efficient, and environmentally friendly in order to minimise water contamination due to the increasing complexity of effluent compositions as anthropogenic activities grow.

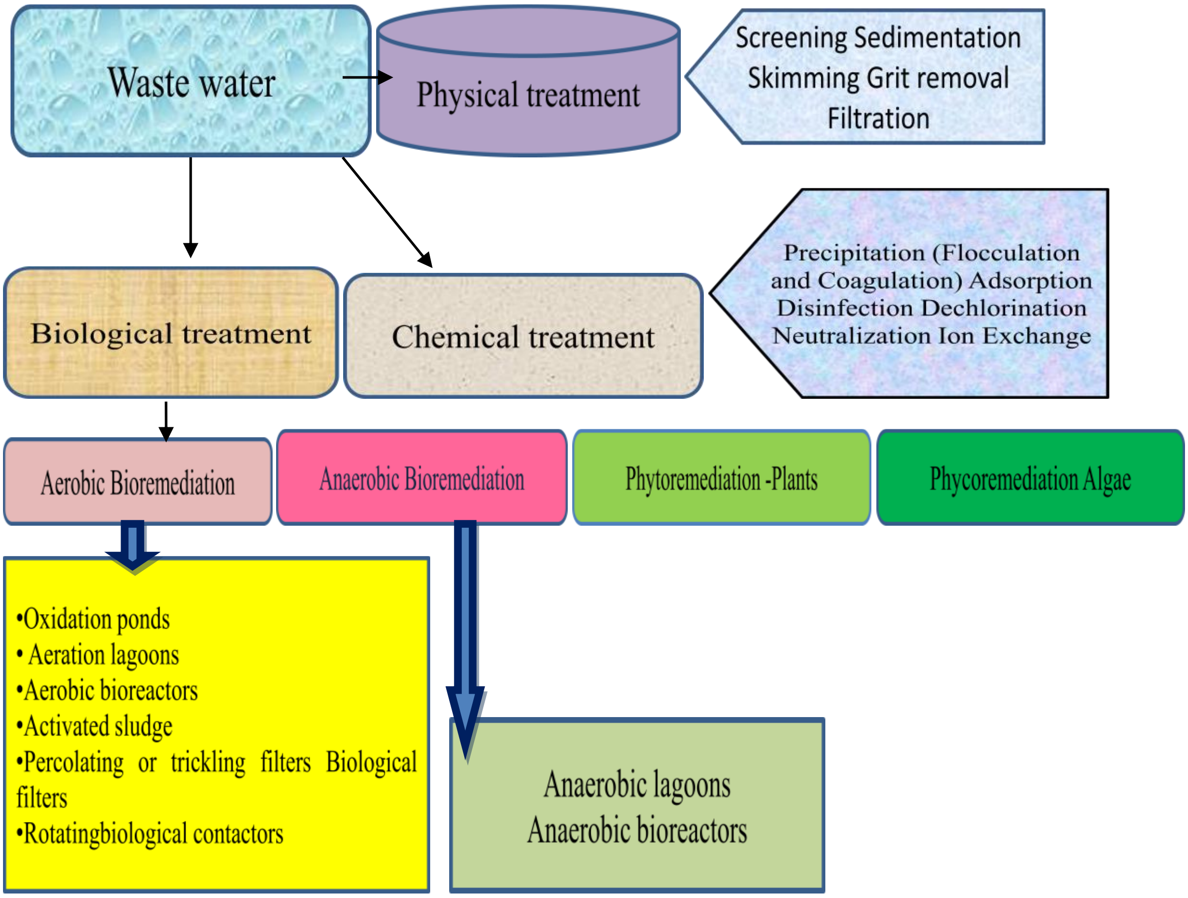

Fig. 1 shows a generalised diagram of the different wastewater treatment facilities that are available.

Treatment of effluents with complex compositions has been demonstrated to be inefficient using purely physical-chemical approaches. There are numerous issues with conventional wastewater treatment. Methods, such as high energy costs, aeration-related expenses, and sludge control. It has been demonstrated that treating effluents with complicated compositions using only physical-chemical approaches is inefficient. Traditional wastewater treatment methods have a number of shortcomings, including high energy consumption, aeration-related expenses, and sludge control. The typical technique of treating wastewater produces secondary solid waste in the range of 0.3-0.5 kg biomass (dry) for the removal of 1 kg of COD, while the sludge treatment costs between $150 and $300. The activated sludge process produces 0.78 kg of carbon dioxide equivalents per cubic metre of air. Around 3% of greenhouse gas emissions to the environment, according to Climate Central, come from effluent treatment plants. A well-known and commonly used wastewater treatment method is the anaerobic process, in which the resulting sludge is digested to produce steam (methane). The energy required for the anaerobic sludge process is two times greater than the energy generated by the sludge digestion. Depending on the reactor, setup, and operational circumstances, a longer retention period is required, ranging from 16 to 30 days. For the treatment of wastewater, a wide range of non-pathogenic algae are being used, including *Spirulina* spp., *Chlorella* spp., *Chlamydomona*s spp., *Oscillatoria* spp., *Nostoc* spp., and *Scenedesmus* spp. ([13].When grown in swine wastewater, *Chlorella reinhardtii* and *Chlorella vulgaris* reduced the TN and COD by 90% and 46% and 93% and 59%, respectively [49].The antiretroviral drug concentrations of Abacavir, Efavirenz, Telzir, Darunavir, and Lamivudine that are found in domestic wastewater are efficiently decreased by Pseudokirchneriella subcapitata [41].

4. Phycoremediation: the biodegradation of wastewater using algae

A diverse group of primarily eukaryotic species, algae (phyco means "algae" in Greek) varies in size from single cells to highly developed plants. Algae utilise CO2 in the presence of sunlight, fix carbon from CO2, and release oxygen (O2) into the environment. Because they make up the majority of all photosynthetic activity and serve as the foundation of the food chain, algal cells are essential to life on Earth[40]. Algal cells produce O2, which is utilised to degrade organic molecules, and because of their own growth, algae may use the released CO2. Use of algae (including Cyanobacteria, microalgae, and macroalgae) in industrial processes for pollutant removal or to derive products from wastewater, such as algal biomass, is referred to as phytoremediation. Algae are utilised as a food supply, energy source, stabiliser, compost, and wastewater processor. They are also used to process wastewater and cut down on CO2 emissions from power plants. An alga produces a substantial amount of biomass and energy. Some algae species have up to 60% of their total biomass made up of lipids, which permits greater combustion heat and energy values [36]. In order to grow, microalgae use nutrients (NPK and others) and organic carbon from wastewater. The growing of microalgae in wastewater has the potential to considerably reduce the need for freshwater and the use of fertilisers ([29]. Therefore, using industrial effluent to grow microalgae to test the viability of treating contaminated water simultaneously while also reducing the need for fresh water and extra nutrients becomes a viable option. In order to reduce the pollution caused by industrial effluent, microalgae can play a crucial role [5][26][29][44]. Thus, phycoremediation includes the following applications: (i) reducing excess nutrients from municipal sewage and industrial effluent containing organic material, (ii) eliminating nutrients and xenobiotic substances using biosorption by algal-biosorbent, (iii) processing effluents with heavy metal ions, (iv) reducing CO2, and (v) monitoring of potentially toxic substances using algae as biosensors[54].

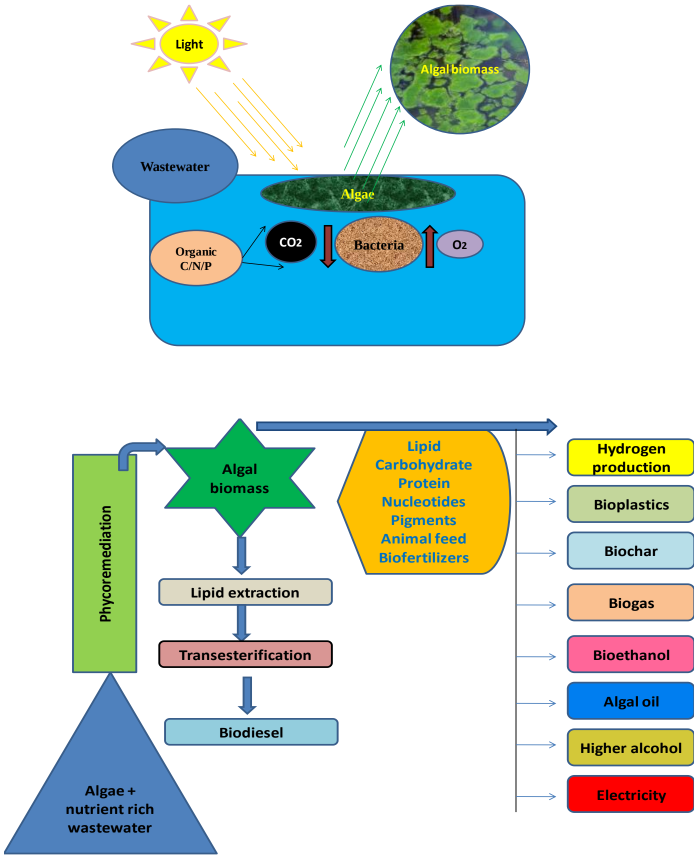

Fig.2 (A) Diagrammatic illustration of the phycoremediation process and,(B) outline of the mechanisms and routes involved in the conversion of algal biomass.

5. Various types of algae used in the treatment of wastewater

A complex category of aquatic plants known as algae lack the conventional roots, branches, and leaves of terrestrial plants. Its cell walls are made of cellulose. There are macro- and microalgal species of algae. Microalgae are single-celled creatures with a maximum size of 0.2-100 m, while macroalgae are multicellular species with a maximum size of several metres (Liu et al., 2020). The unicellular or fundamentally multicellular nature of algae allows them to grow quickly and cling to severe environments. Algae are photosynthetic prokaryotic or eukaryotic creatures. The term "algae" refers to thallophytic creatures that have pigments for photosynthesis. Because of their straightforward cellular structure, microalgae actually utilise CO2, water, and nutrients more effectively than terrestrial plants do [38].By co-digesting different ratios of cow dung, chicken manure, and Chlorella pyrenoidosa grown in digestate water, biogas was produced from algae. The 2:1:2 substrate ratio resulted in the highest methane output of 68%. The exopolysaccharides (EPS) from Chlorella vulgaris were used to co-precipitate iron (III) chloride and iron (II) sulphate, resulting in the magnetic nanocomposite particles (Fe3O4@EPS). According to [25] the Fe3O4@EPS resulted in the greatest decrease of 91% of PO4 3 and 85% of NH4 +.

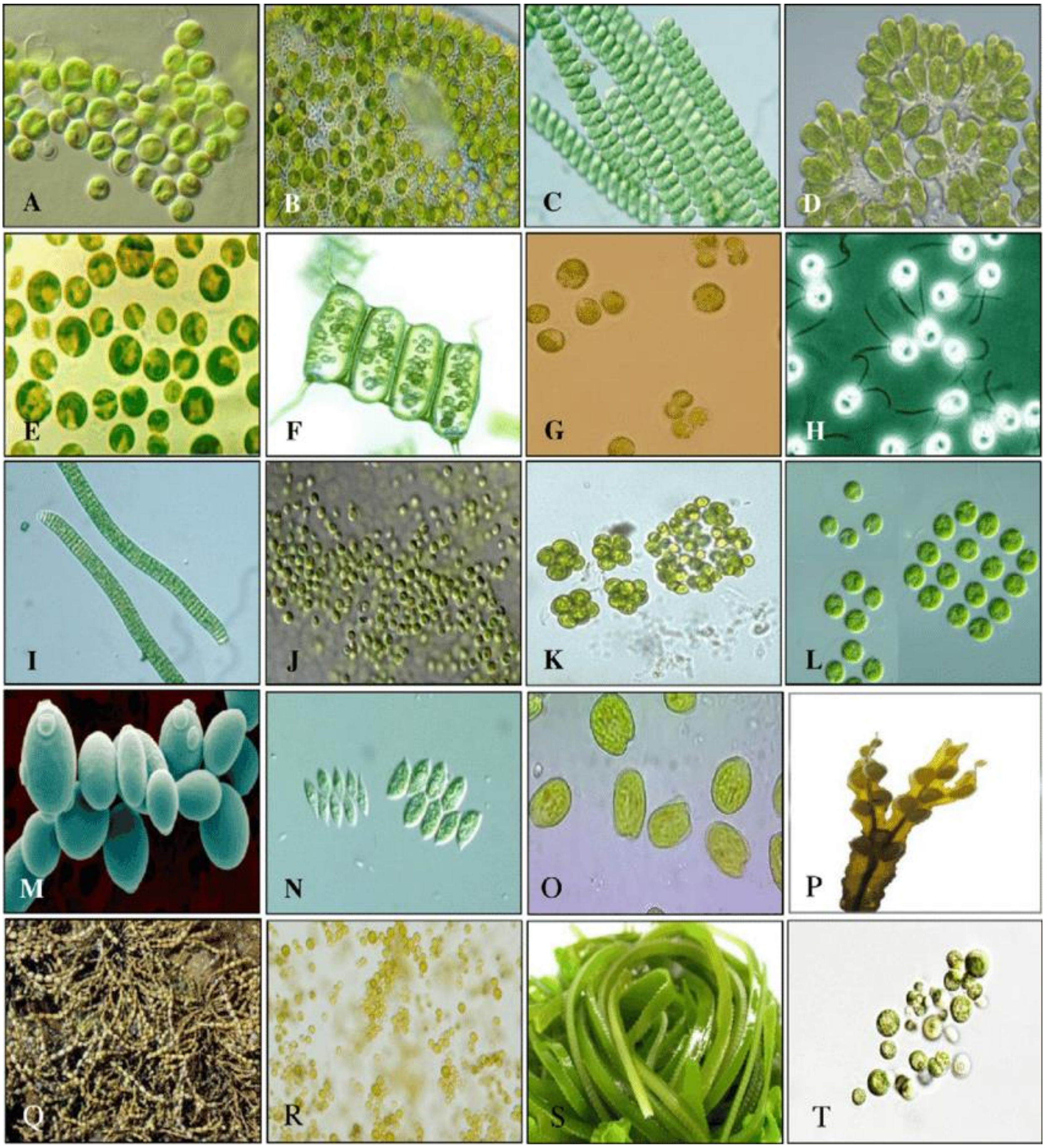

Fig. 3 Algal species deployed in waste water (WW) treatment regime. (A) *Chlorella vulgaris* (B) *Chlorella pyrenoidosa* (C) *Spirulina platensis* (D) *Botryococcus braunii* (E) *Chlorella variabilis* (F) *Scenedesmus obliquus* (G) *Diplosphaera sp*. (H) *C. reinhardtii* (I) *Oscillatoria sp.* (J) *Nannochloropsis sp.* (K) *Scenedesmus rubescens* (L) *Chlamydomonas reinhardtii* (M) *S. cerevisiae* (N) *Scenedesmus acutus* (O) *Tetraselmis chuil (*P) *Fucus vesiculosus* (Q) *Ascophyllum nodosum* (R)*Chlorella zofingiensis* (S) *Laminaria japonica* (T) *Scenedesmus rubescens*.(Source Koul, B., Sharma, K., & Shah, M. P. (2022).

6. Algal bioremediation of PCBs and PAHs

Due to their toxicity, adaptability, and widespread dispersion in the ecosystem, PAHs and PCBs are the two main families of organic pollutants that are closely regulated and assessed. Typically, PCBs are used in a variety of industrial applications. According to Deka and Lahkar these substances are regarded as the principal and most harmful contaminants that have a negative impact on the ecosystem and the general populace. These contaminants are also thought to cause cancer in both humans and animals. The USEPA took this into consideration and designated these chemicals as one of the main pollutants because of its harmful effects on the environment. contaminants. *Ulva lactuca,* one of the efficient algae species, PCB concentrations can be accumulated in amounts between 7 and 13 g/kg of dry algal biomass [35].Several algae species have been discovered as being efficient at removing PCBs, including *Desmarestia sp., Caepidium antarcticum, Fucus vesiculosus, Cystoseira barbata, Fucus virsoides, Gracilaria gracilis, Skeletonema costatum, Nitzschia sp.,* and *Selenastrum capricornutum.* In order to effectively remove benzo(a) pyrene, two algae species have been identified: *Selenastrum capricornutum and Scenedesmus acutus.* When the algal cells were subjected to benzo(a)pyrene for 15 h and 72 h, respectively, *Selenastrum capricornutum* and *Scenedesmus acutus* showed the maximum clearance rates of 99% and 95% BioMnOx, an algae-based product, effectively reduced Bisphenol A by up to 78%. *Desmodesmus sp. WR1 was the type of alga utilised to make BioMnOx.*

Table 3. Various algae species are utilised to degrade PCBs and PHAs.

Pollutants	**Name of the algae**	**References**
Benzo(a)pyrene	*Selenastrum capricornutum Scenedesmus acutus*	[23]
Bisphenol A	*Desmodesmus sp.*	[50]
Naproxen	*Cymbella sp.* *Scenedesmus quadricauda*	[18]
Chlorobenzenes	*Chlorella pyrenoidosa*	[56]
Diazinon	*Chlorella vulgaris*	[52]
Chlorpyrifos	*Chlorella pyrenoidosa Merismopedia sp.*	[10]

7. Strategies for the sustainable utilization of phycoremediation

The combination of phycoremediation with traditional treatment facilities is more efficient. Some wastewater treatment techniques produce large amounts of dangerous and complex chemicals, making biological remediation incapable of completely eliminating all pollutants. To ensure complete elimination of physicochemical features including COD, colour, pollution, and heavy metal residues, it is imperative to employ technical advancements such physico-chemical procedures. However, if sufficient chemical neutralisation procedures are used, it may be a sustainable process. This may involve additional technological and economic costs (increased electricity use, principal costs, and contaminant discharge), which might not be entirely ecologically sound (chemical pollution, environmental unfriendliness). High levels of pollutants in the wastewater, including polyphenols, can occasionally drastically lower microbial activity. The various separation methods, including flotation, centrifugation, and coagulation/flocculation, account for around 30% of the operation costs associated with algae production. Immobilisation or connected algal cultivation methods could lower this cost [10]. *Chlorella vulgaris* immobilisation with alginate beads was demonstrated to be potentially suitable for the treatment of municipal wastewater reverse osmosis concentrate. On the other hand, the interaction of pH, alkalinity, and salinity may significantly affect, among other things, their stability and effectiveness in removing nutrients[33].

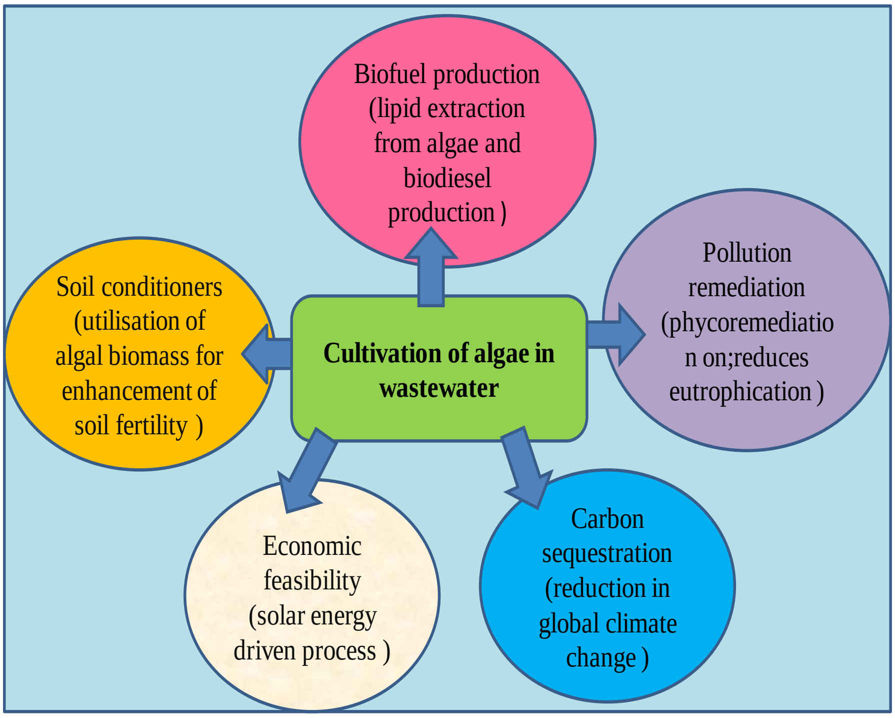

Fig .3 Various Techniques for the Long-Term Use of Phycoremediation

8. Techniques for Phycoremediation long-term effective use Advantages of using algae for wastewater treatment

i) Unlike conventional chemical therapies, algae have the ability to address multiple problems at once. As an illustration, algae might be utilised for bioremediation, and the biomass obtained could be used to alleviate the energy problem and environmentally sustainable generate a range of bioactive substances [13].

(ii) Depending on the situation, there are numerous ways to use algae. According to [55], the algae-based photobioreactor system could be run in batch, semi-continuous, or continuous mode.

(iii) Astaxanthin, beta-carotene, phycocyanin, and eicosahexaenoic acid, among others, could be produced from algal biomass as active secondary metabolites [6].

(iv) Algal technology is a very reliable procedure that may be used alone or in conjunction with other industrial processes like physicochemical purification techniques. The main prerequisites for an algal-based treatment system are adequate fertiliser, water, and land availability [48].

(v) According to [47], phycoremediation is a cost-effective treatment method that doesn't even need a lot of electricity or harmful materials to run.

(vi) Algae capacity to store CO2 offers a very promising option to the threat of global warming. The atmosphere will thereafter be cleaned with the help of the released O2. A possible method for producing alternative fuels is the recent development of biohydrogen utilising algae [32].

(vii) Phycoremediation technology can handle fluctuations in the consistency and volume of the material given to it, such as wastewater with different impurity concentrations.

CONCLUSION

The usage of both microalgae and macroalgae has been the subject of numerous research. Algal systems have several advantages, including the fact that they are based on purification cycles that naturally occur in the ecosystem. Reusable wastewater and beneficial algal biomass can be used in phycoremediation technologies to provide vital byproducts including food, animal feed, compost, biodiesel, and the ability to reduce environmental carbon emissions. By removing significant strains of both microalgae and macroalgae with increased functionality for carbon sequestration as well as waste reduction and the manufacture of valuable byproducts, the distinctive features of algal biomass are critical to encourage the advancement of phycoremediation technologies. The review shows that algae have been shown to be effective for treating various wastewaters (petroleum, coal gasification, pharmaceutical, aquaculture, dye, domestic wastewater, food industry, oil mill, piggery, tannery, leather, textile, and dairy effluents), and they may one day replace traditional treatment methods by having a wide range of applications in treating various pollutants like metal ions, PAHs, PCBs, microplastics, personal care products, and others.

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