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Phycoremediation: A Green Technology for Wastewater Treatment: A Review

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Abstract

Industrialization and the population growth leads to the scarcity of fresh water, the waste is released from industries drain into the water body also impacts the water quality. Particularly, the release of waste water from industries causes the environment degradation by releasing toxic materials such as heavy-metals and harmful chemicals. Several algal species have been studied and utilized for the treatment of wastewater. Phycoremediation is effective green approach to reduce the amount of pollutant from various types of polluted sites and thus providing the valuable compounds. While on the other hand the use of conventional wastewater treatment method is inefficient to remove the pollutant from environment fully, and moreover it is an expensive treatment and energy demanding method. Thus, phycoremediation is comes out as a cost effective and eco-friendly method. In phycoremediation, algae consortia are used to eradicate the pollutants from wastewater bodies.

Keywords: phycoremediation, industrialization, environment degradation, toxic metals, algae consortia.

Introduction

Every year, large quantity of waste (solid and liquid) are produced worldwide. By 2050, annual global waste production shall increase from 2.01 to 3.40 billion tones (Kaza et al., 2018). Only very small portion is recycled and remaining left untreated, that will lead to many types of pollution such as air, thermal, water, land pollution etc. (Koul et al., 2022). Wastewater is a mixture of organic and inorganic substances and the contaminants and its components, includes ammonium, phosphate, carbohydrates, and magnesium that supports the microalgal growth (Natesan et al., 2024). Wastewater not only hinders the environment sustainability but it also impacts the humans by dissolving as trace in various fresh water bodies, even crops also assimilate the harmful elements via improper or from unhygienic source of irrigation pathways. Wastewater treatment is pivotal process to do it's releasing into the environment. So, phycoremediation is a method in which, by using micro and macroalgae can reduces the pollutants from the wastewater before it released into the other destinations.

Phycoremediation

Phycoremediation is a technique to remove pollutants from the wastewater that has been released from industries into the water bodies, it shows tendency to eradicate the heavy-metals, toxins, chemicals from wastewater (Walters et al., 2025). Phycoremediation is a microalgal based process in which it converts the pollutants and impurities of wastewater into the biomass through photosynthesis and many other metabolic processes.

Species of algae used in Phycoremediation

Primarily used microalgae to remove the contaminants from wastewater are *Chlorella vulgaris*, *Spirulina platensis*. Microalgae and bacteria can survive in contaminated water by heavy metals such as Cadmium, Lead, Zinc, Chromium, Copper and Mercury. So instead of using a single species of alga to treat the wastewater it is better to use multiple species of microalgae this is termed as

microbial consortia (Barra & Greco, 2023). Microalgae like *Chlorella*, *Spirulina*, *Chaetoceros*, and *Porphyridium* has capacity to remove heavy metals up to 90%, like Pb (90%), Cd (62%), Cu (83%), after 14 days of cultivation (Barra & Greco, 2023). *Chlorella vulgaris* and *Arthrospira platensis* both shows efficiency in removing of these heavy metals such as Ni(II), Cu(II), Zn(II), Cd(II) (Barra & Greco, 2023). These microbial consortia shows generally of 14 days of incubation time, temperature ranging from 20-35°C, some requires Day and Night cycles, some requires light intensity, optimum pH from 5 to 6 range.

Chlorella sp.: It requires an incubation time-period of 14 days, and effectively removed heavy metals such as Pb, Cd, Cu (Soeprbowati & Hariyati, 2012).

Chaetoceros sp.: Incubation time period of 14 days, requires temperature of 20°C, and effectively removes Pd to 81% (Soeprbowati & Hariyati, 2012).

Porphyridium sp.: Incubation time-period of 14 days, effectively removes cadmium (Cd) to 73% and copper (Cu) to 96% (Soeprbowati & Hariyati, 2012).

Spirulina sp.: Incubation time-period of 14 days, and removes cadmium (Cd) to 70% (Soeprbowati & Hariyati, 2012).

Chlorella vulgaris and *Arthrospira platensis*: Requires pH of 5.5, and temperature of 20°C, removes the heavy metals like Ni (II), Zinc (II), Cadmium (II), Copper (Cu) (Piccini et al., 2019).

Pseudochlorococcum typicum: Requires temperature of 20°C, Day and Night cycle of 16hr and 8hr, removes Hg (II) to 97%, Pd (II) to 70%, Cd (II) to 86% (Shanab et al., 2012).

Chlorella vulgaris: Requires pH of 2, temperature at 25°C, incubation time-period of 10 days, removes chromium Cr (VI) to 43%, chromium Cr (III) to 98.3%, arsenic As 32.4% (Saavedra et al., 2018)

Chlamydomonas reinhardtii: Require pH of 9.5, incubation time-period of 180hrs, removes arsenic (As) to 38.6% (Saavedra et al., 2018)

Galdieria sulphuraria: Requires temperature of 42°C, Day and Night cycle for 24hrs, light intensity of 4000 Lux, removes Nitrogen to 99% (Rahman et al., 2021)

Now question come, how does it cope with wastewater pollutants? How do they work?

Mechanism of Phycoremediation

To understand the mechanism of phycoremediation, first we have to understand the properties of heavy-metals, their sources, signs of toxicity, then cellular functioning of algae with regard to heavy-metals or toxic metals. From all the elements present, only 53 are considered as the heavy metal (HM), because they show the properties of the transition elements, the elements from the P-block like actinides and lanthanides. Phycoremediation is a mitigation process for pollutants in wastewater, depending on the type of pollutants present in wastewater there are different types of mechanisms for phycoremediation (Danouche et al., 2021). Phycoremediation can be of speciation, according to the relation between heavy-metal and algae to reduce the number count of heavy-metal build up by gradual mechanism, over centuries and importantly their evolution over the time.

There are following two types of mechanisms for phycoremediation

- (a) Extracellular Mechanism
- (b) Intracellular Mechanism

Extracellular mechanism

Is the process in which heavy metal removal is done by use of living algae, this process often termed as biosorption. The algal cell wall will act as the primary meeting site between the heavy-metals and algae. As the cell wall constitutes of macromolecules like carbohydrates, lipids and

proteins which exert different negative groups on their surface such as amino, hydroxyl, carboxyl, phosphate, phenol, etc., by the opposite charges on both cell wall and heavy-metals causing binding of them, by which it is considered as the first step. The negative groups on the cell wall accepted the charge from positive metal ions thus binding them together, to form complex, this phenomenon often known as chelation or phytochelation. The process of phytochelation is mainly catalyzed by enzyme phytochelatase (PCS), which induces binding with heavy metals like cadmium, arsenic and lead. It is a kind of passive binding. It is also associated with the microalgal strains too, mostly it is done by the algae from the Chlorophyta like *Chlorella* and *Scenedesmus*. For example, the growth pattern of *C. sorokiniana* and *S. obliquus* in contaminated media with Pb (II), Cd (II), Cu (II) and Cr (VI) was significantly different (Danouche et al., 2020). This is dependent to the physiology of the strain, growth stage and the cell walls composition and structure (Spain et al., 2021).

2. Physiochemical interaction between the cell surface and the heavy metal: In this, mainly chelation and complexation involved. Here ions such as Mg, Na, K, Ca get incorporated into the cell wall via ion exchange. Here primarily electrostatic and Vander Waal forces are responsible. Simultaneously, micro precipitation also occurs (Danouche et al., 2021).

3. Extracellular polymeric substance (EPS) interaction between heavy metals: extracellular polymeric substances are high molecular weight biopolymers which are secreted by microalgae and bacteria. They form a hydrated matrix surrounding the cells and plays an important role in immobilization and detoxification of heavy metals. EPS is a complex mixture of polysaccharides, lipids, proteins, inorganic components, nucleic acids, etc. Carboxyl (-COOH), Hydroxyl (-OH), Amino (-NH₂), Phosphate (-PO₄³⁻), Sulphate as the major functional groups into the EPS as they responsible for metal binding (Garcia-Garcia et al., 2016). EPS can be of three types, (a) Soluble EPS: In which it is not directly attached to cell surface and found dissolved in the surrounding growth media, leads to the metal complexation in the bulk solution, soluble EPS bind the heavy metal in the surrounding environment reducing their bioavailability and toxicity before they reach the cell surface. For instance, *Chlamydomonas reinhardtii*, on the stress level of Cadmium (Cd²⁺) increases, the release of polysaccharides into the environment which causes immobilization and detoxification of metal Cadmium (Danouche et al., 2021). (b) Loosely bound EPS: It acts as a first protective barrier, adsorption of heavy metals and preventing the direct contact with the cell wall, easily removed by mild centrifuge or washing, they mainly contribute to the extracellular biosorption. This is shown by *Chlamydomonas reinhardtii* (Danouche et al., 2021). (c) Tightly bound EPS: It provides structural stability and serves as the major binding site for the heavy metals. Strongly attached to the cell wall forms a compact gel like matrix, even they reduce the intracellular uptake and enhance the tolerance under the stress conditions. This is seen in *Chlorella pyrenoidosa* with arsenic (As) (Xiao et al., 2023).

The extracellular mechanism or biosorption process can be further categorized into primary active transport and secondary active transport. Primary active transport uses ATP-binding cassette (ABC) transporters, an energy-dependent membrane proteins and direct expenditure of energy to drive the uptake of metal against the concentration gradient (Barra & Greco, 2023). Conversely, secondary active transport relies on the preexisting electrochemical gradients of ions which created by primary membrane. It consists of symporters and antiporters. Symporters transport the metal ions into the direction of cell membrane i.e. sodium dependent phosphate symporter.

Antiporter facilitates the exchange of ions in opposite direction of the cell membrane, i.e. proton coupled divalent metal transporter, it uses proton gradient.

Intracellular Mechanism

It is bioaccumulation process or intracellular accumulation of heavy metals using cell membrane of living microalgae. It refers to the intracellular accumulation of heavy metal via the cell membrane of living microalgae predicated on active and passive transport pathways. It is divided in two phases, first is rapid, passive and non-specific absorption into the cell wall, followed by the active or passive transport across the cell membrane and plasma membrane to the cytoplasm (Danouche et al., 2021, Garcia-Garcia et al., 2016).

1. Metal transporters in microalgae cell membrane: metal transporters located in the plasma membrane play a crucial role in heavy-metal uptake, homeostasis and detoxification of microalgae. These, transporter protein regulates the efflux and influx of essential metals (Fe, Zn, Cu, Mn) and non-essential metals (Cd, Pb, Hg). For the uptake of divalent cation metal ions from the extracellular environment, it requires ZIP Transporters (Trt/Irt-like Proteins), ZIP proteins are typically up regulated under metal-deficient conditions to enhance metal acquisition. However, toxic metals such as Cd^{2+} can enter cells by mimicking Zn^{2+} due to similar ionic properties. In the model green microalga *Chlamydomonas*, several ZIP homologs have been identified and characterized as regulators of zinc and iron homeostasis. CDF Family (Cation Diffusion Facilitators), CDF transporters, also known as Metal Tolerance Proteins (MTPs), mediate metal efflux from the cytosol either to the extracellular space or into intracellular compartments such as vacuoles. Common substrates: Zn^{2+} , Co^{2+} , Cd^{2+} these transporters are essential for detoxification and long-term intracellular metal sequestration (Barra & Greco, 2023).

2. Chelation by Metallothionein: Metallothionein are low-molecular-weight, cysteine-rich proteins characterized by a high density of thiol (-SH) groups. These thiol groups have strong affinity for heavy-metal ions, and rapid binding of free metal ions (Cd^{2+} , Hg^{2+} , Cu^+ , Zn^{2+}). Metallothionein expression is induced under metal stress and oxidative conditions. In green microalgae such as *Chlamydomonas*, MT genes are transcriptionally activated in response to cadmium and copper exposure. It shows functional significance such as immediate detoxification, regulation of essential homeostasis and protection against oxidative change (Barra & Greco, 2023).

3. Chelation by Phytochelatins (PCs): Phytochelatins are enzymatically synthesized peptides derived from glutathione through the action of phytochelatin synthase. It done by these steps, (a) Metal ions activate phytochelatin synthase, (b) PCs bind metals via cysteine thiol groups. (c) Metal-PC complexes are transported into vacuoles via ATP-dependent transporters. Phytochelatins are particularly important for detoxifying Cd^{2+} , Pb^{2+} , and As^{3+} . In species such as *Chlorella*, phytochelatin synthesis is strongly correlated with cadmium tolerance. It shows functional significance, major intracellular detoxification pathway, facilitates long-term sequestration, maintains cytoplasmic metal equilibrium (Balzano et al., 2020).

4. Heavy-Metals compartmentalization in the vacuole, chloroplast and mitochondria: Vacuole is the main detoxification site of heavy metals in plants, they work as metal enter the cytoplasm, then they bind to the chelating molecules forming metal-chelator complex which then transported into vacuole via tonoplast transporters. It is important because it keeps toxic metal away from sensitive cellular machinery, reduces oxidative stress, and allows plant to tolerate high metal concentrations. For example, cadmium is mainly stored in vacuoles (Danouche et al., 2021). Mitochondria are highly sensitive to heavy metals because they generate ATP, are the major

sources of reactive oxygen species. In this metal can bind to mitochondrial proteins then disrupts the electron transport chain which increases the oxidative stress causing mitochondrial DNA damage. It gives only minor storage for some metals. Chloroplasts are also sensitive because, they contain photosynthetic machinery. Heavy-metal can inhibit the chlorophyll synthesis, damage thylakoid membrane, disrupts the photosystem II and reduces carbon fixation, so among the vacuole, mitochondria and chloroplast, vacuole provides maximum storage to heavy metals while rest are in sensitive to metal binding. Intracellular heavy-metal removal in microalgae involves a sophisticated network of chelation and compartmentalization pathways. Metallothionein, phytochelatins, and polyphosphates bind toxic metals in the cytosol, while vacuoles serve as major storage compartments. Chloroplasts and mitochondria participate in regulated metal distribution, ensuring cellular homeostasis. Together, these pathways underpin the efficiency of microalgae in phycoremediation applications.

Recent Advancement in Phycoremediation Process

Currently for wastewater treatment two technologies are emphasized i.e. the activated sludge process and (more recently) the membrane bioreactors or membrane photobioreactor (Dey et al., 2024).

Conclusion

Rapid industrialization and population explosion is the main reason for freshwater scarcity and degradation of environmental resources. As highlighted by (Walters et al., 2025), the discharge of untreated industrial effluents containing heavy-metals and toxic chemicals into water bodies has severely compromised water quality. Phycoremediation utilizes microalgal species such as *Chlorella vulgaris* and *Spirulina platensis*, either individually or as microbial consortia, to remove heavy metals and nutrients efficiently. Studies demonstrate remarkable removal efficiencies, with certain species eliminating up to 90% of lead or 97% of mercury under optimized conditions.

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