IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 6, Issue 2, July 2026
Impact Factor: 8.2

Phycoremediation Potential of Diatoms in Wastewater Management

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Abstract: *Diatoms excel in Phycoremediation through multiple pathways. Their small size and large surface area help diatoms quickly trap heavy metals like cadmium, lead, and chromium on their silica shells. Chemical groups on their surface also bind pollutants, removing over 90% of many contaminants. Diatoms also absorb nitrogen (nitrate or ammonium) and phosphorus very effectively up to 100 mg per litre per day, helping prevent eutrophication. Diatom Phycoremediation transforms wastewater into resources, supporting SDG6 and SDG14. This review examines diatoms' effectiveness for wastewater remediation, focusing on their ability to remove nutrients, bind heavy metals, and break down organic pollutants. It also covers cutting-edge diatom bioremediation techniques, stressing their eco-friendly and economic benefits for tackling water contamination in industrial contexts.*

Keywords: Diatoms, Phycoremediation, waste water management, Organic pollutants.

I. INTRODUCTION

Water pollution caused more deaths compared to all other forms of death including war.

There is need to implement measures that guarantee protection of water since only 1% of water is safe for use [1]. By the year 2050, there will be a significant increase in global demand for water, reaching up to one-third of current levels [2]. It becomes important to protect water by adopting measures to control water pollution.

Wastewater pollution is one of the greatest environmental problems today affecting ecological balance, health, and economic sustainability. Wastewater refers to used or polluted water usually discharged untreated by households, businesses, and agricultural operations [3]. These discharges, to the release of various contaminants posing serious effects both to the ecosystem and human health. [4]. In many instances, wastewater includes high concentrations of nutrients, such as nitrogen and phosphorous, resulting in eutrophication [5], which results in increased oxygen depletion making it difficult for aquatic organisms, including fishes, to survive. When the pollutants come from identifiable and concentrated sources, such as a plant or industry, the resultant problem is referred to as point-source pollution. Unlike point-source pollution, non-point source pollution comes from diffuse sources; hence, its detection becomes very difficult. Both types of pollution have a tendency to cause contamination of surface waters through chemical releases [6].

The discharge from industries might have POPs (Persistent Organic Pollutants). This includes some pesticides and industrial chemicals that do not break down easily but accumulate in aquatic life and affect the higher species that feed on them, including humans [7]. The discharge into water also introduces metals, pathogens, medicines, and other chemical compounds which do not degrade easily and lead to the degradation of water quality and pollution making it non-conformable for recreational purposes and human health. Alteration of the physical chemistry of the water and its toxicity can lead to the decrease of populations and biodiversity and destroy their habitats and food chains. Moreover, municipal effluents have been known to introduce micro plastics because of the increasing use of personal-care and consumer products which contain micro beads of plastic materials [8, 9]. Oil spills caused by the drilling of oil at sea [10, 11] or even the discharge of oil from the factories, agricultural runoff, and urban areas make water non-conformable, deplete oxygen levels, and harm the aquatic life and ecology. [12, 13]

Because ecosystems and communities around the world are closely interconnected, the effects of water pollution extend far beyond local boundaries and can have widespread environmental consequences. By adopting sustainable practices and taking proactive steps to reduce water pollution, we can protect ecosystems and preserve public health for future generations. Ensuring access to safe and clean drinking water is essential, as it is a basic requirement for the survival and well-being of all living organisms.

Research suggests that the conventional physico-chemical treatment process fails in many cases when dealing with the removal of pollutant mixtures from water [14]. Various types of treatment technologies such as chemical treatment, activated sludge process, anaerobic digestion, membrane technology, and advanced oxidation processes are some of the commonly used techniques. These conventional processes suffer from several drawbacks including high energy requirements, high aeration costs, and difficulties in handling sludge [15]. Moreover, secondary solid waste production is another drawback of the conventional wastewater treatment technique where about 0.3–0.5 kg of solid waste per 1 kg of COD removal takes place [16]. Sludge treatment incurs a cost of approximately $150-$300, while effluent treatment plants emit about 3% of GHG emissions, according to Climate Central. Taking into account the effect of wastewater on the environment as well as human health, its treatment should be based on sustainable measures that will help achieve the least impact possible and promote ecological sustainability. As its name indicates, sustainable remediation refers to environmental, social, and economic advantages. It results in the reduction of pollution, energy consumption, exploitation of renewable resources, and working in accordance with natural mechanisms.

Nowadays, the industries and researchers all around the world try to turn traditional wastewater treatment into new, improved systems which will be energy-saving, economical, lower carbon emission, and easy to operate. One of the ways to do this is through the combination of the physical, chemical, and biological techniques for more effective treatment process. The current trends in sustainable remediation technologies include anaerobic digestion, membrane bioreactors, microorganism fuel cells, integrated wetlands, and phyco-remediation. All the mentioned sustainable remediation techniques require multi-disciplinary approach involving environmental science, engineering, sociology and other fields of studies to ensure success. Therefore, the increasing problem of environmental contamination calls for more efficient and sustainable wastewater treatment technologies.

Keeping all in the mind, phyco-remediation, using macroalgae for wastewater treatment has been found, an effective and eco-friendly solution [17].

Phycoremediation

It is the type of bioremediation where pollutants like heavy metals, excess nutrients and other toxic chemicals are removed by biological techniques [18]. Phycoremediation is an eco-friendly method where micro and macro bacteria or cyanobacteria are used as pollution extraction tools. These microorganisms show the pollutant extraction mechanism through several ways. Biosorption where pollutants simply stick to the surface of algal cells, or by Bioaccumulation, which shows their capability of metabolizing pollutants through enzymatic activities. Overall it's a cost effective technique for the treatment of toxic chemicals in the water. Post treatment recovered algal mass which is source of carbon sequestration can be used as valuable products like fertilizers, biofuels and as animal feed [19].

Diatoms as Promising Phycoremediation Tool

Diatoms are microscopic photosynthetic organism that have distinctive patterns in their siliceous cell walls called frustules. Frustules are glass like rigid and transparent cell walls made up of hydrated, porous, amorphous silica. Frustules give a definite shape to diatoms. They exist in two symmetric structures i.e. centric (radially symmetric) and pennate (bilaterally symmetric.

Structure of Frustule is two overlapping valves, the upper one is epitheca below this is hypotheca fitted together like Petri dishes. The valves are joined by a girdle. Girdle is a silocon ring or band circling the valves of diatoms The frustule is comprised of a network of micro Nano- pores. It protects the organism from predators and ultraviolet radiations and allows water and gasses to pass through it [20].

ISSN: 2581-9429
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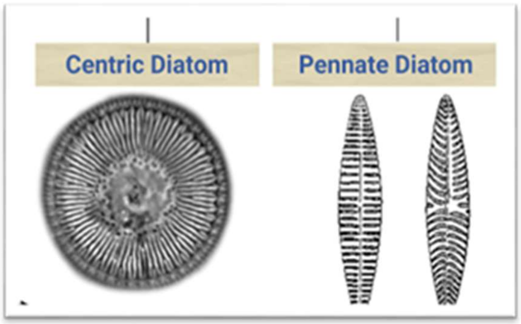
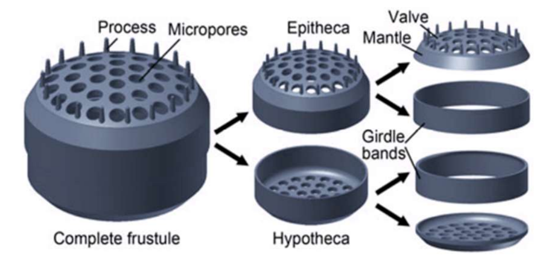
Some benthic species of diatoms are known to have mobility capabilities via a specialized mechanism called the raphe system, while others form biofilms on solid surfaces. Raphe is mainly found in pennate diatoms, help them to glide through surfaces by secreting mucilage.



A typical shape of Centric and Pennate Diatoms

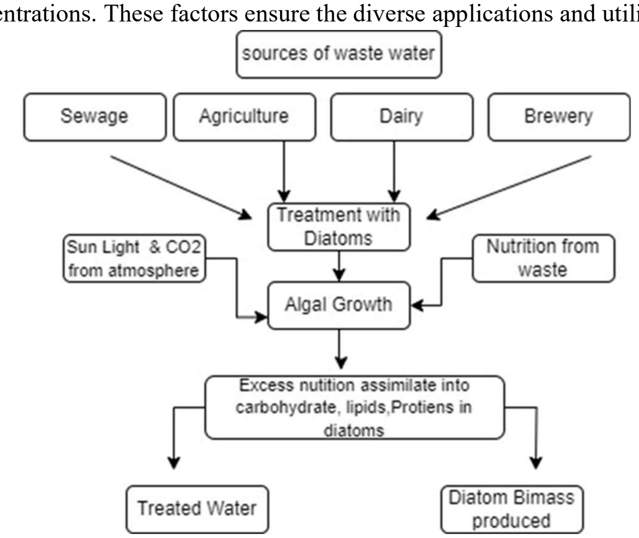


A detailed Anatomy of Centric Diatom

Diatoms are present in moist ecosystems and are aquatic organisms, some floating freely in the water, while others are attached to certain substrates. The importance of diatoms in nature lies in their contribution to primary productivity and nutrient cycling. However, apart from their role in nature, diatoms are also valued by industries for several reasons. This includes their distinctive porosity and strong silicon-based frustules as well as hardiness against adverse conditions, which makes them effective candidates in manufacturing different materials.

Recently, the use of diatoms has been explored further in the process of phyco-remediation. The latter refers to eco-friendly treatment of water pollution through diatoms, which can use their silica frustules as pollutant absorbers while simultaneously utilizing photosynthesis to capture energy and convert carbon dioxide into organic products.

Diatoms may thrive on the surplus industrial waste released into the aquatic ecosystem as a source of nutrients. The biomass that has been formed, during Phycoremediation may be utilized for other industrial goods, such as biofuel. It is undoubtable to believe that small-scale businesses may be established in partnership with establishments like as breweries, restaurants, and textile industries, among others, in order to treat wastewater and use biomass to produce useful goods like fertilizers [21]. Diatoms can be cultivated in various aquatic environments, because they easily adapt different pollutant types and concentrations. These factors ensure the diverse applications and utility of Diatoms.



An outline of the process of Phycoremediation performed through Diatoms

DOI: 10.48175/IJARSCT-37726

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II. APPLICATION OF PHYCOREMEDIATION IN WASTE WATER TREATMENT

Nutrient Removal

Water runoff from industries, residential areas, agricultural fields are loaded of chemicals like Nitrogen, phosphorus and other nutrients. When untreated water directly discharged into rivers, lakes, and streams, it poses serious threats of eutrophication in these water bodies. Removal of these nutrients through conventional methods are difficult, Phycoremediation offers a sustainable way to get rid of the problem. The microalgae used in the process absorb nutrients from the waste and using CO_2 they convert them various organic compounds with the release of O_2. Diatoms are important because they are wide spread in aquatic systems and responsible of overall 20-25% photosynthesis. Diatoms have a major role in nutrient cycling and can be viewed as a cost-effective and ecologically friendly way to stop eutrophication. Diatoms require silicon in order to grow, because silicon serves as a major component of their silica cell walls. The absence of silicon may lead to decrease the population of diatoms and thus a change in the composition of the phytoplankton community, making eutrophication worse. Due to their rapid growth rate, non-toxicity, and ability to compete for nutrients, particularly when silicon is present, diatoms are very beneficial. Shen et. al has experimented and found the feasibility of cultivation of the marine diatom C. muelleri in mariculture wastewater through controlled nutrient regulation, irradiated by UV-C (wavelength ranging in100 to 280 nano-meters). At optimized levels of key nutrients, specifically silicate, phosphate, and ammonium, maximize diatom biomass production was recorded [22].

Macronutrients like C, N, P, Si and micronutrients like Fe, Mg, Ca, K, Mn, Cu, and Co are required for the growth of the algae. Generally, in sewage, concentration of Nitrogen exists in between 20 to 85 mg/L whereas phosphorous present in between 4 to15 mg /L leads to growth of 0.3–1.4 mg /L algal biomass. Concentration of micronutrients are not significant because they are needed in a low quantity. This makes the sewage waste suitable to treat using diatoms. [23]. A study was conducted at lab scale in which the colony of diatom was developed in the municipal waste water and analysed its impact on water quality. About 95% N, 88.9% P, 91% COD and 51% BOD reduction in water sample was observed [24]. An analysis was carried out to find out the potential of two marine species of diatoms, Chaetoceros curvisetus and Chaetoceros simplex for nutrient removal from waste water. Through a controlled experiment, diatoms were grown on different sources of nitrogen, i.e. nitrate, ammonia and urea. Fast growth and higher protein production were observed in diatoms, with urea or nitrate compared to ammonium, out of which the urea turned out as a better source. While both diatoms effectively converted absorbed nitrogen into cellular proteins, C. simplex showed the highest cell density. When the urea was used as nitrogen source, C. simplex removed nitrogen and phosphorous, 97.86% and 98.5% respectively. In the same conditions, C. curvisetus removed 91.62% of nitrate and 100% of phosphate. The study concluded that C. simplex is better eco-friendly and sustainable tool for the nutrient removal [25].

Hildebrand et al. discovered absorption of silica in the form of silicic acid in pennate diatoms [26]. Diatoms play a key role in silicate cycle globally, due to a strict dependency on silicic acid for the construction of their cell walls [27]. A huge deposits of dead cell walls, sometimes known as Diatomaceous earth (DE) or diatomite, are found on the sea floor. Usually It is composed of 80% to 90% silica, 2% to 4% alumina minerals, and 0.5% to 2% iron oxide, however the precise composition of every deposit is different [28].

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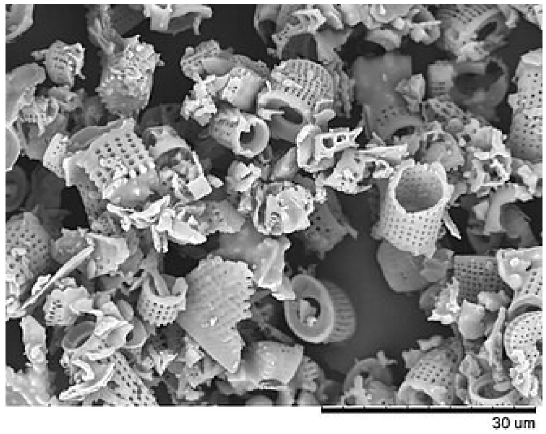

Diatomaceous earth: fossilized cell walls of Diatoms

Commercially DE is used in different forms, which are granulated, milled or calcined.

Since long the diatomaceous earth is used in chemical laboratories for many operations and studies for the filtration of extremely small particles. Its uses are significant in drinking water filtration procedures [29]. DE-containing medium have been used as filters in Beer, wine, fish tanks, sugar, syrups, honey, and pool waters [30]. It is an ingredient of several compounds that are used both pesticides [31] and non-pesticide products, such as toothpastes, water filters, snacks, drinks, medications, and personal care items, contain diatomaceous earth. A Panel for Cosmetic Ingredient Safety, researched and found that Diatomaceous Earth is safe in cosmetics [32].

III. HEAVY METAL UPTAKE BY DIATOMS

Metallic elements have been present on Earth since its formation, and recycled between the different environmental segments through biotic and abiotic processes. These metallic elements have always been present in soil water and living organisms [33]. Any specific metallic element is considered as a contaminant when its concentration exceeds the limits of tolerance of the organisms who are the part of the ecosystem [34].

Heavy Metal (HM) is the terminology used for those metallic elements which are toxic to the biological process of the environment. Even in a small concentration they cause a considerable degree of toxicity towards all living things varying from microorganisms to human beings [35]

Bioaccumulation of heavy metals discharged through human activities are seriously effecting the aquatic food chain. Heavy metals persist long in the aquatic system and significantly harm the living things [36]. Various advanced methods are available for the uptake of heavy metals from waste water. Some of them are activated carbon adsorbent, membrane filter techniques, chemical precipitation and ion exchange process. However, they are energy extensive, costlier and less sustainable. Phycoremediation is now a days emerging as an effective, sustainable method to condition the water. Being a predominant micro algal species in aquatic system it is the first exposed to the pollution. They considerably remove the harmful metals from the contaminated environment.

Dichromate using industries often discharge effluent contaminated with Cr (VI)compounds, which is very toxic to all live forms. Two marine micro-algal species, namely Phaeodactylum tricornutum strain CCY0033 and Navicula pelliculosa strain CCMP543, have been found extremely effective in bioremediation of dichromate. In turn the Lipids are produced by this organisms, which act as a biofuel. Both of the algal strains grew well in the media containing up to 1 mg of dichromate per litre, and produced high biomass[37].

Phycoplankton, as the principal producer, is among the first organisms affected and exposed to these pollutants. Diatom algae are the predominant phycoplankton population in the aquatic ecosystem, making a considerable contribution to the removal of heavy metals from the contaminated environment and rendering them harmless in the process of returning the contaminated environment to its pre-polluted state. There has been a long history of production microalgae used to condition waste water [38]. This is a practical and economical method of eliminating heavy metal pollution from the environment [39].

Diatoms remove heavy metal from aquatic system mainly via Biosorption and Bioaccumulation. Cell wall of these microalgae contains lipids, proteins and carbohydrates which have various functional groups like amino, carboxyl, phenol, phosphates and sulphate etc., bearing negative charges [40]. Cell wall of the diatoms which is an interface between inner cellular system and outer environment adsorbs the heavy metals from the surrounding through active functional groups present on them. The phenomenon is called biosorption. Biosorption is a non-metabolic process where no energy is required and uptake of pollutants depends upon the cellular composition of micro algae and the kinetic equilibrium [41]. As it is equilibrium dependent process, the concentration of diatoms, pH and temperature of the environment and the interaction of sorbent with different heavy metal ions play a key role [42].

Biosorption mainly takes place through various physiochemical mechanisms like chelation, complex formation, Ion exchange and addition to it micro-precipitation and physical adsorption also happens. These mechanisms collectively enable the diatom to clean up the waste water by removing heavy metals [43].

Bioaccumulation is a metabolic process where the metal ions first adsorbed on the cell wall and then transferred inside the cell at a faster rate than it can be eliminated. [44]. It proceeds through three successive stages, including biosorption, element transfer inside the cell via protein and absorption and accumulation of metal inside the cell [45]. Iron plays a crucial role in photosynthesis, diatoms have strategies to accumulate and utilise iron. Protein contain in cell wall mediates the uptake and storage of iron inside the cell. [46]. E. Torres. et. al. reported that the marine diatom Phaeodactylum tricornutum is proved to be better biosrobent then any other commercial resin for the uptake of Cd in waste water [47]. A batch study was performed to find out the feasibility of diatom Nitzschia subminuscula as a biosrobent for the uptake of Cd II, Cu II and Zn II. The outcome of the study showed the strong environmental friendly and cost effective potential of the species, which can be effectively used in treatment of wastewater and tannery effluents contaminated with heavy metals. [48]. An investigation is done to determine the scope of bioaccumulation and transformation of Hg in a marine diatom Phaeodactylum tricornutum. Different concentration and varying mercury species were used to explore the Hg detoxification mechanisms and biogeochemical cycling of Hg in oceanic environment. The study confirms the important role of *P. tricornutum* in the self-purification of aquatic ecosystems and biogeochemical cycling of mercury.49

IV. CONCLUSION

Diatoms are proving themselves as a remarkable tool for pollution control and the restoration of aquatic environment. Their extraordinary anatomy made them instrumental in removing the pollution in more sustainable way. Though the Phycoremediation is still in its experimental phases and mostly performed at lab scales, the detailed studies of its mechanism give insights of improved efficiency, with cost effective solutions. Ongoing researches will indeed explore their contributions in eco-friendly technologies to balance anthropogenic activities and natural environment.

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IJARSCT

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International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal

ISSN: 2581-9429

Volume 6, Issue 2, July 2026

Impact Factor: 8.2

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