

The role of algae in removing nutrients, heavy metals, and dyes from wastewater

Olfat M A Salem*, Abeer A Mohsen, Zeinab J Abdel Daim, Samira A Awad

Department of Biology, University College of Al-Darb, Jazan University, Jazan, Saudi Arabia

Corresponding Author: Olfat M A Salem

Abstract

The rapid pace of industrialization and urbanization resulting from global population growth, coupled with efforts to expand agricultural land to accommodate this population increase and the development of various transportation methods, have all exacerbated the risk of environmental pollution, making it one of the most serious global challenges. Traditional methods of treating polluted water are often costly and can produce secondary pollutants. In the ongoing search for environmentally friendly solutions, scientists have focused their attention on algae as a sustainable and eco-friendly option. Algae were chosen as a key organism in this field due to their high capacity for removing nutrients, heavy metals, and carbon dioxide (a major greenhouse gas) as well as their ability to decompose organic nutrients through biological processes such as biosorption, bioaccumulation, and biodegradation. This paper reviews the current role of algae in removing nutrients, heavy metals, and dyes from wastewater focusing on the methods and different species used in treatment over the last twenty years.

Keywords: Wastewater, phycoremediation, heavy metals, water treatment, dyes removal

Introduction

Recent decades have witnessed a significant increase in environmental pollution resulting from industrial and agricultural activities, urban sprawl, and all types of human activity. Traditional treatments for this pollution, such as chemical precipitation and filtration, although it is effective, it can cause other problems such as producing harmful waste and costly. For these reasons, biological methods for pollution treatment have emerged. Phycoremediation is a biological wastewater treatment process that uses algae to

remove contaminants through mechanisms such as biosorption, bioaccumulation, and biodegradation, algae used for pollution remediation due to their rapid growth and ability to absorb pollutants. Mechanisms of pollutant removal by algae, including biosorption, bioaccumulation, and biodegradation were illustrated in Fig1.

Generally, biological treatments are used as a secondary treatment process to mainly eliminate substances remaining after primary treatment (Al-Tohamy *et al* 2022) [4]

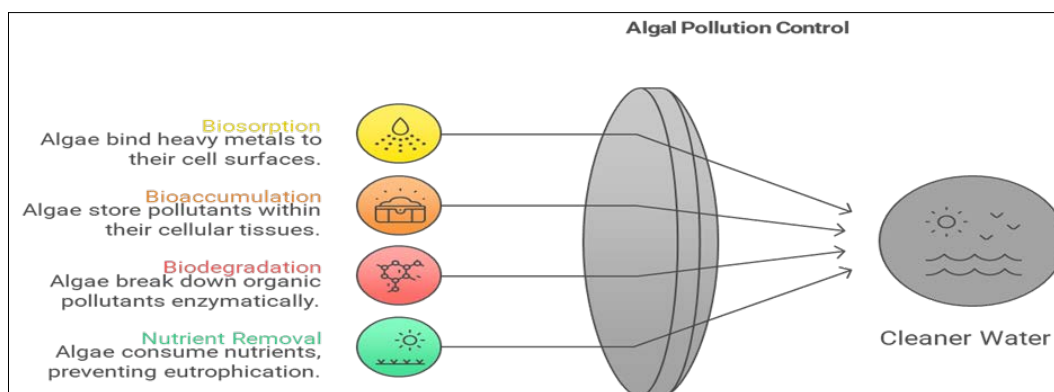


Fig 1: Mechanisms of Pollution Removal by Algae

Types of algae used in water pollution treatment.

Algae used in wastewater treatment are generally classified into microalgae, macroalgae (seaweeds) and also blue green algae, algae-based wastewater treatment studies focus on microalgae, while macroalgae accounts for a much smaller share.

Studies using microalgae and blue green algae, such as *Chlorella*, *Phormidium*, *Nostoc*, *Scenedesmus*, and *Spirulina*, have been extensive in wastewater treatment due to their rapid growth and high nutrient uptake capacity (Chan *et al.*, 2014, Hoballa and Salem 2015, Kottangodan *et al.*, 2019) [13, 19, 22]. One of the systems that has proven most effective is the use of more than one type of microalgae, as

this system is more stable than monoculture systems that rely on only one type. This also allows for adaptation to various environmental changes that may occur (Salem *et al.*, 2021^[38], Wanqing *et al.*, 2024)

Studies used macroalgae focus on the removal of heavy metals, dyes, and phenols. *Sargassum*, *Ulva*, *Turbinaria*, *Gracilaria*, *Cystoseira*, *Padina* and *Cladophora* are effective in removing heavy metals through biosorption processes (Qari and Hassan 2017, Jayakumar *et al.*, 2022, Kumaraguru *et al.*, 2023) [20, 23, 35]. Seaweeds have high metal-binding capacity due to functional groups derived from sulfated polysaccharides, tannins, Alkaloids, sterols, saponins and carotenoids, proteins, and lipids (Mohamed *et*

al 2012, Salem *et al* 2025) [28, 37]. These groups can bind metal ions through adsorption and ion exchange processes.

Wastewater treatment

Wastewater is a by-product of domestic, industrial, agricultural, and commercial waste, the chemical and biological components of wastewater were illustrated in Fig 2.

Process of wastewater treatment requires the removal of chemical and biological pollutants, when this is done using traditional methods, it results in high energy consumption and secondary pollution from the use of disinfectants. Therefore, living organisms including, plants, fungi, bacteria, and Protozoa are used for this treatment, and algae are considered among the most suitable types of organisms for this purpose.

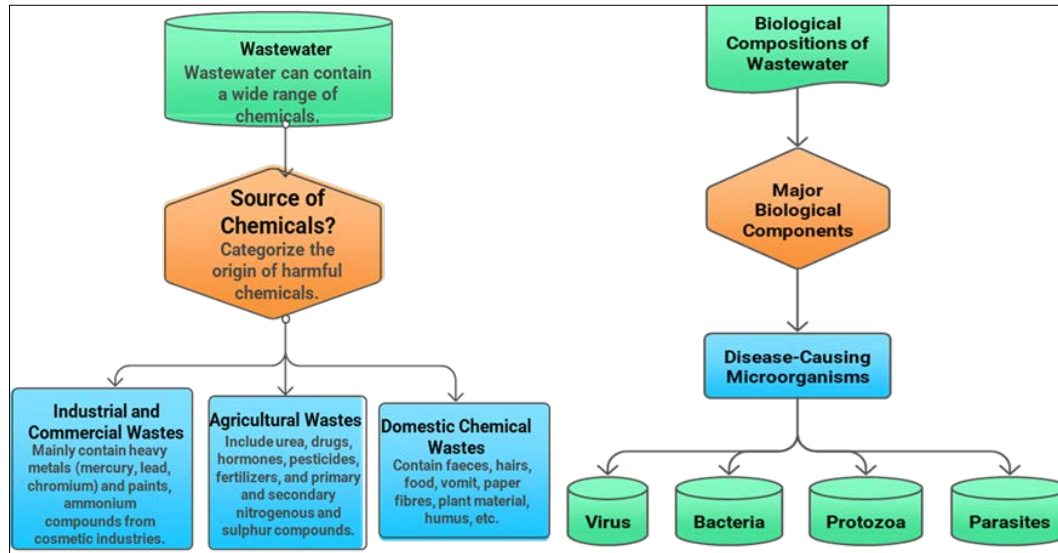


Fig 2: Overview of the major chemical and biological components present in wastewater.

Algal bioremediation (algal therapy) is considered a smarter and more sustainable approach than other methods. In this process, algae utilize compounds such as nitrogen, phosphorus, sulfur, and minerals as nutrients to boost their growth, thus reducing water pollution by these elements. Microalgae are the primary species used in this treatment, and their efficiency depends on biotic and abiotic factors, as well as the selection of appropriate strains. They offer a sustainable solution for tertiary and quaternary treatments due to their ability to digest complex pollutants (Kaloda *et al.* 2021, Srimongkul *et al.*, 2022) [46]. Compared to conventional systems, photosynthetic microalgae require less energy input because they utilize sunlight as their energy source, while simultaneously reducing the overall carbon footprint of the reclamation process. The technology of using cyanobacteria, is flexible, as it utilizes a wide range of chemicals as energy sources and produces biomass and biofuels through both organic and inorganic photosynthesis (Bag *et al.*, 2019) [11].

Hybrid wastewater treatment systems, which combine two or more technologies, are a way to address the shortcomings of individual technologies while improving process efficiency. Using microalgae and cyanobacteria to remove dissolved organic matter from wastewater, and subsequently using it as a soil amendment, is a very promising approach (Shahid *et al.*, 2021) [40].

Nutrients removal

A study by Andriana *et al.* (2013) [6] demonstrated that the total phosphorus removal in artificial wastewater was 53%, 25%, and 11% for the algal species *Neochloris vigensis*, *Chlorococcum spec.*, and *Scenedesmus rubescens*, respectively. Another study (Zhou *et al.*, 2014) [45] investigated the potential for simultaneously removing

multiple organic and inorganic pollutants, including total nitrogen, total phosphorus, and minerals, using *Chlamydomonas reinhardtii*, *Scenedesmus obliquus*, *Chlorella pyrenoidosa*, and *Chlorella vulgaris*. The ability to remove nitrates with high efficiency occurred by *C. vulgaris*, *Neochloris oleoabundans*, and *Dunaliella tertiolecta* (Taziki *et al.*, 2015) [42]. *Chlorella* algae in wastewater enabled it to remove more than 99% of the phosphorus concentration. Furthermore, the chemical oxygen demand (COD) decreased by 71%, the resulting biomass can be used to produce biofuel (Salghero *et al.*, 2016) [39].

Studies have shown that algal systems efficiently remove nitrogen, phosphorus, and many pollutants from wastewater (Plöhn *et al.* 2021) [32]. In this study, mixed algal cultures, both free and fixed in alginate, were used. The highest biological oxygen demand (BOD) removal rates were 86.4% and 71.2% after 32 and 48 hours, respectively, for free and fixed cells. Furthermore, the highest chemical oxygen demand (COD) removal rates were 83.74% and 59.71% after 32 and 48 hours for free and fixed cells, respectively. (Salem *et al.*, 2019) [36]. The removal of organic matter from wastewater is more efficient using certain types of bacteria, which take significantly less time compared to algae, which also require significant amounts of carbon dioxide. Therefore, it is preferable to use algae in conjunction with bacteria that help remove certain nutrients (Nguyen *et al.*, 2022) [29].

Lelis *et al* 2024[24], showed that *Ulva lactuca* (Chlorophyta) can be used for bioremediation of ammonium in elastomer industry wastewater. Using marine algal biomass for pollutant removal reduced energy consumption and use of chemicals, in the same time production of valuable biomass.

Dyes removal

The efficiency of algae to biosorbe dyes depends on operating conditions such as pH, temperature.

Dosage of dyes also affect therefore, efficiency can be improved by operating under optimal conditions (Paul *et al.*, 2011) [31].

The decolorization process of dyes by algae had been done by different mechanisms; one of them was enzymatic degradation as *Nostoc sp. C. vulgaris* and *Scenedesmus sp.* have a high ability to decolorize the two dyes (crystal violet and malachite green) , *Chlorella vulgaris* and the Cyanobacterium *Aphanocapsa elachista* for biodegradation of four dyes; Disp orange 2RL, Reactive yellow 3RN, Reactive Black NN and Tracid Red BS, the maximum decolorization was observed in Disp. Orange 2RL (Azo dye) by *Chlorella vulgaris* (55.22%) after 7 days of incubation, while, *Aphanocapsa elachista* decolorized reactive yellow 3 RN (Azo dye) by 49.16%, azo reductase enzyme in the used alga is responsible for degradation of azo dyes into an aromatic amine by cleaving the azo linkage. (Hoballah and Salem 2015, El-Sheekh *et al.*, 2018) [16, 19].

One of the most important parts of the algal cell that is mainly relied upon to determine the ability of algae to bio absorb nutrients is the cell wall, which contains many functional groups, such as amine, carboxyl, hydroxyl, and phosphate groups, that attract pigment molecules to the cell wall, thanks to the presence of polysaccharide compounds and heterolipids.(Charumathi and Das 2012, Ayele *et al.*, 2021) [8, 14].

The level of carbohydrates and amino acids concentrations in *Nostoc sp.* and *C. vulgaris* tissues are strongly affected by bioremediation of MG dye compared with CV dye. In conclusion, Crystal Violet (CV) and Malachite Green (MG) dyes are considered as stress factors and *Nostoc sp. C. vulgaris* species exert their bioremediation activity without the dyes being absorbed into the cells (Salem *et al.*, 2021) [38]

The Marine macroalgae can removing dyes in a short time, for example, *Ulva lactuca* could decolorize 91% of Methylene Blue in just 110 minutes and *Corallina officinalis* biomass can biosorbe the textile dye by removal efficiency reached up to 99.9% in 2 h (Pratiwi *et al.*, 2019, Youssef *et al.*, 2023) [33, 44].

Sargassum crassifolium removal percentage of malachite green ranged between 95.6% and 98.3% in 150 min, the brown algae outnumbered the green *Ulva lactuca* and red *Gracilaria corticata* alga used, this may be due to its high binding site affinity, the negative free energy of adsorption, and the great pores on its surface (Omar *et al.*, 2018) [30].

The use of nanotechnology increased the efficiency of algae, seaweed are practical and economical biomaterials for producing various metal nanoparticles with excellent efficiency. Algal biomolecules act as reducing and stabilizing agents, leading to the stabilization of the nanoparticles. Green metal nanoparticles have been studied for diverse applications, including environmental remediation. Phyco-Synthesized Zinc Oxide Nanoparticles Using Marine Macroalgae, *Ulva fasciata* demonstrated high effectiveness in removing color from leather tanning wastewater, achieving $96.1 \pm 1.7\%$. Moreover, zinc oxide nanoparticles demonstrated high efficacy in reducing the hexavalent chromium (Cr (VI)) content in tanning wastewater representing a removal rate of 93.4% (Fouda *et al.*, 2022, Alprol *et al.*, 2023) [3, 18]. Further research is still

needed to discover the optimal conditions for biosynthesis of nanoparticles.

Heavy Metal Removal

Heavy metals, such as lead, cadmium, mercury, and chromium, pose serious environmental and health risks. Industrial and agricultural sites are the primary sources of water pollution with these metals, followed by domestic wastewater. Using algae to treat wastewater contaminated with heavy metals is a sustainable method for removing them and is part of bioremediation. This includes biosorption, either through passive adsorption of pollutants independent of metabolic processes, or active adsorption of pollutants via the metabolic pathway (Ahmed *et al.*, 2019, Znad *et al.*, 2022) [33, 46].

Algae possess a high capacity for binding metals due to the presence of functional groups in their cell walls. These groups can bind to metal ions through adsorption and ion exchange processes. This study aimed to investigate the feasibility of biologically purifying wastewater of heavy metals using the unicellular green flagellate *Dunaliella sp.* (Qari and Hassan 2014) [34]. Adsorption of metal ions using the biomass of dead seaweed (*Halimeda opuntia*, *Turbinaria turbinata*, *Kappaphycus sp.* and *Padina sp.*) offers a relative advantage compared to other natural adsorbents. (Foday and Shu 2021, Madkour and Dar 2021, Mingu *et al.*, 2023) [17, 25, 27]

The ion exchange mechanism was used in a study employing calcium-loaded brown alga *Sargassum muticum* during mercury and cadmium removal processes. It was found that cadmium was removed solely through ion exchange, while mercury removal involved not only ion exchange but also a reduction process (Carro *et al.*, 2015) [12], also the cadmium removal by *Padina* through ion exchange as mentioned by Aloufi *et al.*, 2024[2], and by *Cystoseira sedoide* (Bengourna *et al.*, 2024) [10]

The fixation technique is an environmentally friendly method used to fix algae to a carrier to improve the stability and adsorption performance of the bio-adsorbent. Fixed algae offer environmental benefits, and their reusability reduces the cost of the adsorption process, according to lifecycle assessment and technical and economic analysis. It also naturally produces biofilms, reducing the overall cost of separating the algal biomass from the rest of the medium (Mandotra *et al.*, 2020, Chen *et al.*, 2023) [15, 26].

Adapted *Sargassum* algae exhibit a marked difference from free *Sargassum* with respect to copper ions. The adsorbents also demonstrate a high capacity for metal adsorption, improving the biosorption of nickel ions by 49% and copper ions by 36% (Barquilha *et al.*, 2017) [9]. When using adapted cells, the highest removal rates of the three heavy metals were recorded after 48 hours for a mixture of algal cultures: 97.8% for manganese, 89.0% for lead, and 97.37% for zinc (Salem *et al.*, 2019) [36].

Tetrademus obliquus algae cultured in sodium alginate beads in wastewater was compared with free cells to investigate the potential of stabilization techniques in heavy metal extraction efficiency, offering promising prospects for sustainable wastewater treatment processes (Aguiar *et al.*, 2024) [5].

Although algae have excellent potential for heavy metal accumulation, they suffer from limitations such as low biomass and sensitivity to high heavy metal concentrations. These issues can be addressed through advanced

interventions such as genetic modifications that enhance biomass production (Ankit *et al.*, 2022) ^[7].

Conclusion

Using algae (microalgae and seaweed) in treatment is a promising and sustainable solution for treating polluted water. These algae absorb pollutants from the water as they grow and produce oxygen during photosynthesis, thus improving water quality. The resulting biomass can then be used to produce biofuel or fertilizer. This method has advantages, including its low cost compared to traditional methods, its environmental friendliness, and the fact that it does not produce secondary pollutants. However, further development of treatment and separation technologies for microalgae is still needed to increase its efficiency and enable its widespread use.

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