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Phycoremediation of Dyes: A Mini-Review on Mechanisms and Affecting Factors

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ABSTRACT

Pollution is a significant threat to water, the vital resource, caused by high levels of organic and inorganic pollutants, including pesticides, heavy metals, pathogens, drugs, and dyes. One promising solution is phycoremediation, which utilizes algae's naturally abundant biomass. Algae, categorized as either macroalgae or microalgae, have proven effective in pollution mitigation. Their efficiency is further enhanced after undergoing pyrolysis and conversion into biochar, as demonstrated by various studies. Methods such as adsorption, coagulation, and bioconversion have been explored for dye removal using algae. Algae have a high surface area which enables them to adsorb dye molecules and they can produce extracellular polymers that can coagulate the dye particles. Certain types of algae can break dyes down into less harmful substances. The effectiveness of algal bioremediation is influenced by factors such as pH, initial dye concentration, and the amount of algae used. The main goal of this review is to evaluate the mechanisms that the algae implement in removing the dyestuffs from wastewater, with mainly the biological, chemical, and environmental factors in mind. Thereby, this review aims at a holistic view of the algal-based strategies useful in water treatment.

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INTRODUCTION

The Industrial Revolution initiated a significant transformation globally, and its impact persists today as industries expand to meet the growing demands of an increasing population. However, this progress comes at a cost: factory waste has exacerbated the pollution crisis, affecting essential elements of nature, particularly water bodies such as rivers and wells (Umama et al., 2021). Water is vital for the survival of all living beings, and contaminated water poses serious risks to human and environmental health (Babuji et al., 2023).

Various methods, such as sedimentation, flocculation, coagulation, precipitation, oxidation, ion exchange, membrane filtration, and electrocoagulation, have been shown to effectively treat polluted water (Narayanan et al., 2021). However, physicochemical treatments are often impractical due to high operational costs, maintenance expenses, energy consumption, and the risk of secondary pollution (C.-C. Tang et al., 2018; Zhang et al., 2023).

In contrast, phycoremediation presents a cost-effective, environmentally friendly, and

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energy-efficient alternative (Srimongkol et al., 2022; Oberholster et al., 2024; Parida et al., 2025). This method, first pioneered by Oswald in the 1950s (Gani et al., 2016), uses algae to treat water contaminated with chemicals. The process not only effectively removes pollutants but also ensures that harmful compounds are not transferred to the treatment sites through the adsorption mechanisms of algae (Prasad, 2021).

Algae have unique qualities that make them efficient at absorbing hazardous pollutants, including aromatic hydrocarbons (Satpati et al., 2023), phenols (Radziff et al., 2021), heavy metals (Hazaimeh, 2023; Nyika & Dinka, 2023), and organochlorines (C. Tang et al., 2023). These qualities make phycoremediation a viable and sustainable alternative to conventional physicochemical techniques for cleaning up contaminated environments (Al-Jabri et al., 2020; Kumar et al., 2024).

ALGAE CHARACTERISTICS

Algae have been widely applied in wastewater treatment due to their natural ability to remove nutrients, metals, and organic compounds. Algae are a diverse group of photosynthetic organisms, ranging from multicellular species like macroalgea seaweed (which can grow up to 60 meters in length) to unicellular microalgae (which vary in size from 1 mm to several centimeters) (Biris-Dorhoi et al., 2020). Found in a wide range of environments, algae are valued for their high content of bioactive compounds, including complex organic molecules and primary and secondary metabolites (Škrovánková, 2011).

Macroalgae

Unlike microalgae, macroalgae are large and complex. Macroalgae share photosynthetic pigments with higher plants but exhibit higher photosynthetic efficiency. This results in greater oxygen release into water, promoting the aerobic decomposition of organic matter (Majumder et al., 2014). In recent years, interest in macroalgae has surged due to its health-promoting properties, which can reduce the risk of chronic diseases and potentially extend life expectancy.

Macroalgae can also be utilized for wastewater treatment and as natural fertilizers, improving crop quality while reducing reliance on chemical alternatives. Additionally, their potential as a renewable energy source is promising. Macroalgae are currently being explored for their role in reducing carbon dioxide emissions and for producing biofuels as part of "third-generation" clean technologies (El Boukhari et al., 2020).

Microalgae

Microalgae are unicellular, eukaryotic organisms that also perform photosynthesis and primarily live in aquatic environments. These organisms are particularly advantageous in pollutant remediation due to their extensive biodiversity, advancements in genetic and metabolic engineering, and improvements in screening techniques (Venkata Mohan et al., 2016).

Microalgae can be found as individual cells or small colonies and are known to remove a variety of contaminants from water (Chen et al., 2022). They absorb both organic and inorganic substances and adhere to suspended particles, forming flocs that facilitate contaminant removal (Esmaeili Nasrabadi et al., 2023). Microalgae require nutrients such as nitrogen, phosphorus, and trace elements—common components of polluted wastewater—for growth. Many microalgae species also photosynthesize, reducing the need for organic matter, though some strains can utilize organic material in the absence of light (Yu et al., 2022).

Thus, microalgal bioremediation can be integrated with existing wastewater treatment techniques or used as a stand-alone biological approach. Due to their efficiency, environmental friendliness, and cost-effectiveness, bioremediation methods often compete with or outperform traditional physicochemical treatments (Ahammed et al., 2023).

Biochar: Algae-based biochar and synergetic role in phycoremediation

Biochar, a porous material primarily composed of carbon, demonstrates potential in diverse applications such as water treatment, soil enhancement, energy storage, and carbon sequestration (Anto et al., 2021). Its extensive surface area, porous structure, abundant surface functional groups, and mineral components contribute to its versatility (Zubair & Mujtaba, 2009). The cost effectiveness of biochar due to its production from waste materials push researchers to include it in different pollution treatment processes (Han et al., 2024). The biochar enhances phycoremediation by improving algal growth and by its synergetic effect in adsorption. Biochar was found to be efficient as substrate for algae and cyanobacteria cultivation, namely (Kholssi et al., 2018; Huang et al., 2020; Sinyoung et al., 2025). Since both algae and biochar store carbon in stable forms, combining them can improve carbon sequestration (Sinyoung et al., 2025). To treat algal blooms and encourage the growth of beneficial algae for more cleanup, biochar was used to absorb excess nutrients (such as phosphates) from water bodies (Vasseghian et al., 2024).

Mechanism of dye removal by algae

Algae possess the ability to remove pollutants through mechanisms such as biosorption, coagulation and flocculation, biofiltration, and biodegradation. These algae-based methods are gaining popularity due to their sustainability, affordability, and high pollutant removal efficiency (Mohamed et al., 2023). Dyes, known for their potential to cause genetic mutations, respiratory issues, chromosomal abnormalities, and cancer, pose significant environmental concerns (Al-Tohamy et al., 2022). A variety of techniques, including physical, chemical, and biological approaches, have been employed to remove these contaminants. These methods encompass reverse osmosis, coagulation, electrochemical processes, membrane separation, dilution, flotation, filtration, and softening (Foroughi-Dahr et al., 2015).

Biosorption

Adsorption is often preferred over other methods due to its affordability, simplicity, and ease of maintenance. It generally requires less sediment and is easier to manage compared to alternative approaches (Doğan et al., 2006a). Biosorption, a physico-chemical process, involves the removal of pollutants from wastewater using the adsorption capabilities of biological materials (Nguyen et al., 2021). The diverse range of components and functional groups present in biomass, such as phosphate, thiol, carboxyl, hydroxyl, and amino groups, contributes to the complex structures and variety of biomaterials. These functional groups are influenced by various physico-chemical processes (Fomina & Gadd, 2014). Algal cells bioadsorb pollutants by attaching them to the cell wall components or to extracellular polymeric substances (EPS) released into the water (Feng et al., 2022).

To ensure the effectiveness of the adsorption process, it is crucial to select an adsorbent that is highly selective, has a high capacity, is durable, and is readily available in large quantities at an affordable price (Doğan et al., 2006a). Algae, with their abundant availability and significant biosorption capacity, have emerged as promising candidates for biosorbents. Consequently, there is growing interest in utilizing algae as potential adsorption agents for wastewater treatment (Youssef et al., 2023).

Coagulation

Many dyes are synthetic compounds with complex, branched aromatic structures, making them difficult to degrade during wastewater treatment (Bayramoğlu & Yakup Arıca, 2007). Physicochemical treatment, particularly coagulation and flocculation, is a commonly used approach (Daud et al., 2022). Chemical coagulants, such as alum, lime, and ferric salts, can neutralize the negatively charged dye molecules, forming insoluble complexes. However, the

Table 1. Some studies showing the removing of dyes via biosorption mechanism

Algae	Dyes studied	Type	Class	References
Caulerpa lentillifera	Astrazon blue	Cationic (Basic)	Azo or Anthraquinone	(Marungrueng & Pavasant, 2007), (Marungrueng & Pavasant, 2006)
	Astrazon red	Cationic (Basic)	Azo	
	Methylene blue	Cationic (Basic)	Thiazine	
Caulerpa scalpelliformis	Remazol black B	Reactive	Azo	(Gokulan et al., 2019),(Aravindhan et al., 2007)
	Remazol brilliant blue R	Reactive	Anthraquinone	
	orange 3 R	Acid or Reactive	Azo	
	violet 5 R	Acid or Reactive	Azo/triphenylmethane	
	Sandocryl blue	Cationic (Basic)	Azo/Anthraquinone	
Spirogyra sp.	Acid Orange 7	Acid	Azo	(Khataee et al., 2013),(M. A. Khalaf, 2008)
	Basic Blue 3	Cationic (Basic)	Azo/Anthraquinone	
	Basic Red 46	Cationic (Basic)	Azo	
	Synazol Red HF6BN	Reactive	Azo	
	Yellow HF2GR	Reactive	Azo	
Chlorella vulg aris	Methylene blue	Cationic (Basic)	Thiazine	(Chin et al., 2020), (Hernández-Zamora et al., 2015), (Arteaga et al., 2018)
	Acid orange 7	Acid	Azo	
	Congo red	Direct	Azo	
	aniline blue	Acid	Triphenylmethane	
Sargassum muticum	Methylene blue	Cationic (Basic)	Thiazine	(Hannachi & Hafidh, 2020)
Scenedesmus obliquus	Methylene blue, ,	Cationic (Basic)	Thiazine	(Abdel Ghafar et al., 2017), (Hamouda et al., 2022), (Cengiz Sahin & Aksu, 2017)
	Disperse orange 2RL	Disperse	Azo	
	Astrazon red	Cationic (Basic)	Azo	
Spirulina platensis	Malachite green	Cationic (Basic)	Triphenylmethane	(Bonyadi et al., 2022)

resulting sludge often contains harmful chemical residues, such as iron and aluminum salts (Hoong & Ismail, 2018).

Natural coagulants, being environmentally friendly, non-toxic, and safer, offer several advantages over chemical coagulants. In 1974, the Indian Journal of Environmental Health reported the use of *Hibiscus sabdariffa* seeds as a natural coagulant for treating turbid water (Hoong & Ismail, 2018). Natural polysaccharides and proteins in these seeds can replace synthetic polyelectrolytes. Natural polymers often have higher molecular weights, leading to more binding sites for coagulation and partial adsorption. The coagulation proteins in *Hibiscus sabdariffa* seeds primarily consist of positively charged peptides like glutamic acid, aspartic acid, and leucine (Yin, 2010). The algal alginate, a biopolymeric compound isolated from brown algae *Sargassum* sp. (Figure 1) was an efficient coagulant for various type of dyes(Subhan et al., 2021).

Beside congo red(Sivalingam & Gopal, 2023; Vijayaraghavan & Shanthakumar, 2016), reactive magenta(Vijayaraghavan & Shanthakumar, 2018), and sulphur black(Vijayaraghavan & Shanthakumar, 2015), crystal violet dye was eliminated by coagulation using alginate (Figure 1)(Vijayaraghavan & Shanthakumar, 2020).

By combining photocatalytic activity and adsorption, alginate beads containing zinc oxide (ZnO) nanoparticles were demonstrated as an alternative to remediate water contaminated with sedge dye (Pholnak et al., 2022). Mcyotto et al. work indicate that the removal efficiency is related to the dye structure (Mcyotto et al., 2021).

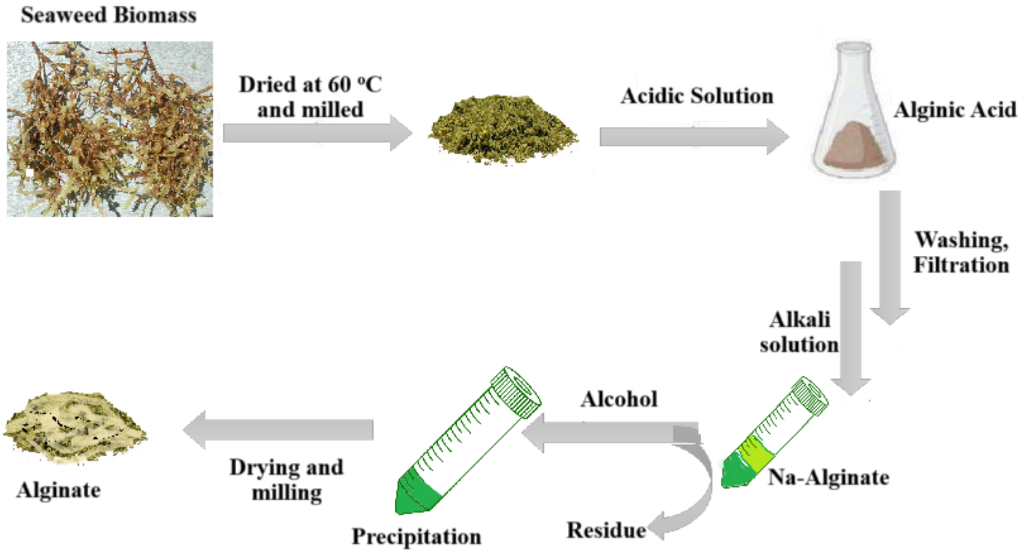


Fig. 1. Classical alginate extraction procedure from macroalgae

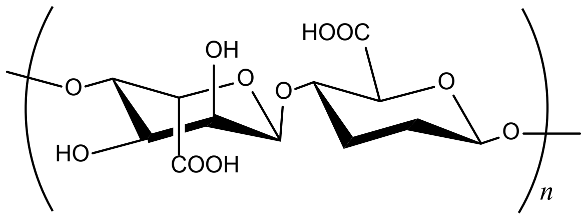


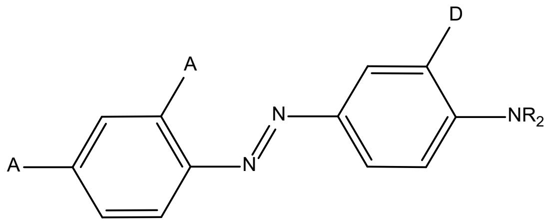
Fig. 2. Chemical structure of alginate

Biodegradation

Biodegradation refers to the alteration of materials by biological activity, either chemically or physically. In complete biodegradation, living organisms utilize organic polymers as energy and nutrient sources, leading to the production of microbial biomass (Pooja et al., 2023). Algae are capable of degradation of azo dyes by adsorption, enzymatic degradation or using both (Majumdar et al., 2022). Certain enzymes produced by the microalgae cause deterioration and dyes removing, by conversion to simple, nontoxic compounds, such as NH_2 and CO. One peroxidase enzyme was primarily involved in this activity, but the microalgae also produced catalase, malate dehydrogenase, bromo, and chloroperoxidase(Sigamani et al., 2024). A wide variety of *Chlorella* sp. could break down azo dyes (Figure 3) into simple organic compounds or CO_2 by metabolizing aromatic amines and breaking down the azo link(Touliabah et al., 2022).

Moreover, algae can colonize man-made surfaces, such as polythene in sewage water, and are generally harmless (Chia et al., 2020). The adhesion of algae to surfaces initiates the biodegradation process, facilitated by the production of ligninolytic and exopolysaccharide enzymes. In liquid environments, these enzymes interact with plastic surface molecules, triggering biodegradation (Chinaglia et al., 2018). Algae can utilize polymers as a carbon source, as evidenced by increased cellular contents (protein and carbohydrates) and higher specific growth rates in species found on polyethylene surfaces (Ahmed et al., 2018).

Previous research has identified five primary biodegradation processes: fouling, corrosion, hydrolysis, penetration, degradation of leaching components, and pigment coloration through diffusion into the polymers (Kumar et al., 2017). The biodegradation of the triphenylmethane



A, Acceptor = NO_2, CN
D, Donor= OH, NHR, NR_2

Fig. 3. Basic structure of azo dyes

dye known as malachite green, by *Cosmarium* sp. revealed the ability in removing the dye(Daneshvar et al., 2005). *Spirogyra* sp. and *Oscillatoria* sp. showed a good efficiency for removing blue and red dyes by biodegradation (Brahmbhatt & Jasrai, 2013). *Chlorella vulgaris* treated by Disp. Orange 2RL (Azo dye) induce the activiation azoreductase enzyme leading to the biodegradation of the dye (55.22%) (El-Sheekh et al., 2018). The degradation of reactive blue 19 and remazol brilliant blue R dye in different aquatic medium, by *Scenedesmus quadricauda* was investigated (Ergene et al., 2009). Beside many other algae, *Chlorella kessleri* (Omar, 2008), *spirulina* (Saloglu & Sahin, 2021) were efficient in the decomposition both mono- and di-azo tartrazine (Touliabah et al., 2022).

Factors Affecting Phycoremediation

Phycoremediation, the use of algae to purify water from various pollutants, is influenced by several factors, including pH, temperature, contact time, algal biomass concentration, and dye concentration (Waqas et al., 2015; Agoun & Avci, 2025). To optimize this technique, a careful consideration of these factors is essential.

Influence of pH

The pH of the environment where algae are cultivated significantly impacts phycoremediation. The functional groups on the algal surface, which play a crucial role in pollutant capture, are affected by pH (Sun et al., 2019). At lower pH, the biosorbent surface acquires a positive charge, facilitating the binding of anionic dyes. Conversely, at higher pH, the surface becomes negatively charged, attracting cationic dyes (Ali, 2010). In a study where *Lychaete pellucida* is used for the bioremoval of four common azo dyes, the pH effect study shows that anionic groups of the reactive dyes and the algal positive surface electrostatically interacted to increase reactive dye adsorption at basic pH (H. A. Khalaf et al., 2023). Studies (Anbia & Ghaffari, 2011; Namasivayam et al., 2024) showed that reactive dye adsorption is inhibited by a negative surface charge (in basic media) because of electrostatic repulsion.

Influence of Contact Time

The duration of contact between algae and contaminants is another important factor. In the initial stages, rapid adsorption occurs due to available pores. However, as equilibrium is reached, the adsorption rate stabilizes. Pratiwi et al. found that the optimal contact time for efficient adsorption is around 110 minutes (Pratiwi et al., 2019).

Influence of Initial Dye Concentration

The initial dye concentration directly affects phycoremediation efficiency (Maleki et al., 2010). Higher dye concentrations can lead to increased adsorption due to greater contact between dye molecules and the biosorbent. Al Hamadi et al. observed that *S. platensis* exhibited higher adsorption rates at higher dye concentrations (Ayele et al., 2021).

Table 2. optimal conditions for dye removal

Factor	Optimal conditions
pH	**8–10** for anionic dyes, **4–6** for cationic dyes
Contact Time	~110 minutes
Dye Concentration	Higher concentrations improve adsorption, but saturation must be considered
Biomass Concentration	~0.15 g/50 mL (avoid excessive biomass to prevent reduced efficiency)
Temperature	25–30°C (avoid >30°C to prevent biosorption decline)

Influence of Biomass Concentration

The concentration of algal biomass also influences dye removal capacity. Increasing biomass concentration provides more biosorption sites, leading to improved dye removal (Saravanan et al., 2021). However, excessive biomass can result in a decrease in solute adsorption per unit weight of adsorbent. Aravindhan et al. discovered that the absorption of basic blue dye by *Caulerpa scalpelliformis* decreased from 54.16 to 19.58 mg/g as the seaweed biomass concentration increased from 0.15 to 0.5 g/50 mL (Aravindhan et al., 2007).

Influence of temperature

Higher temperatures often increase adsorption rates by enhancing diffusion but may also affect the structural integrity of biological materials (Doğan et al., 2006b). The effect of temperature on dye biosorption by *Chlorella vulgaris*, showing that temperature can significantly influence biosorption efficiency and capacity, with optimal temperatures enhancing the binding interactions between algae and dyes (Aksu & Tezer, 2005). However, other study shows that the temperature may cause thermal inactivation of the algae enzyme(s) responsible for removing the color of the azo pigments. The removal of azo dyes increases to the optimum temperature, after which there is a marginal decrease in the decolorization activity (Sompark et al., 2021). This may be related to the reduction in high temperatures, the death of cells, or the denaturation of the enzyme azoreductase(Saratale et al., 2011). Cetin et al. (2006) shows that the dye removal activity was significantly increased above 45 °C(Tiwari, 2012).

Furthermore, Khalaf et al. (H. A. Khalaf et al., 2023), illustrates that biosorption capacity decreased as the temperature increased, with a highest percentage at 25 °C. And the biosorption was thermally suppressed at a temperature above 30 °C. This may be the consequence of a weak contact between dye molecules and the biomass's active binding sites at high temperatures, which damages the biomass's active binding sites.

Optimized Conditions for phycoremediation

Based on the research findings, the potential optimized conditions for effective phycoremediation can be recapitulated as following (Table 2).

pH Optimization

For anionic dyes (e.g., reactive dyes, the basic pH (8–10) was optimal due to enhanced electrostatic attraction. While Acidic pH (4-6) enhances adsorption of cationic dyes by providing negatively charged functional groups on the algal surface.

Optimal Contact Time

A contact duration of 110 minutes appears to be the best time for equilibrium adsorption *(Pratiwi et al., 2019; Senturk, 2024)*. Shorter times may lead to incomplete adsorption, while longer times do not significantly improve removal efficiency.

Optimal Initial Dye Concentration

Note that this is determined by the extent of pollution, but we can summarize it as follows. Higher initial dye concentrations enhance adsorption due to a greater interaction between dye molecules and algae. However, an upper limit exists where adsorption sites become saturated. Therefore, batch experiments at different concentrations are necessary to determine the saturation point.

Optimal Biomass Concentration

Moderate biomass concentration (~0.15 g/50 mL) is recommended, because excess biomass can reduce dye adsorption per unit weight due to reduced surface area (binding sites), and possible particle aggregation.

Temperature Optimization

The best temperature ranging from 25 to 30°C. Above 30°C, biosorption efficiency drops due to thermal degradation of algal binding sites and potential enzyme deactivation (e.g., azoreductase). Some studies suggest enhanced activity at 45°C, but this varies with algae type. Thus, maintain temperature around 25°C for maximum biosorption efficiency while avoiding thermal deactivation.

CONCLUSION

Algae, as photosynthetic organisms, play a vital role in aquatic ecosystems. Their ability to manage wastewater through phycoremediation, primarily through adsorption, offers a promising solution for pollution control. Generally speaking, to enhance the effectiveness of phycoremediation, the pH should be adjusted based on the dye charge, the saturation point should be determined by performing batch experiments, temperature maintained around 25°C and the biomass concentration ~0.15 g/50 mL.

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