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# Algal-Based Remediation of Synthetic Dyes: A Mini Review

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**ABSTRACT**
A wide variety of algal species have been employed in the breakdown and removal of synthetic dyes from the environment. This paper reviews the various algal species having the potential to remediate synthetic dyes based on published literature. Algae mostly employ the following processes, bioaccumulation, biodegradation, biosorption and photodegradation for dye removal. The notable species of algae that have been employed in the remediation of dyes are *Ulva lactuca*, *Gracilaria*, *Sargassum*, *Laminaria*, *Fucus vesiculosus* (macroalgae), *Chlorella vulgaris* and *Spirogyra* (microalgae). These species aid in the regulation of contamination in the environment through accumulating and metabolizing the dyes into less harmful substances.

**KEYWORDS**
Algae, dyes, bioaccumulation, biodegradation, biosorption, photodegradation

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## INTRODUCTION

Synthetic dyes are compounds with complex xenobiotic characteristics and chemical structures that are highly resistant to degradation. They exist in different forms and are employed in industrial sectors like textile, tannery, cosmetics and food among others[1]. Dyes enter the environment due to several anthropogenic human activities, which is leading to serious irreversible ecological damage, thus, affecting human health and other biological systems[2], Concerning the aforementioned reasons, the neutralization of these dyes tends to be of great concern, as it will aid in a significant decrease in environmental contamination[3,4]. The employment of biological methods to neutralize dyes such as the use of living cells like in algae is very vital[5,6].

Algae-based remediation (phycoremediation) has emerged as an eco-friendly, cost-effective and sustainable alternative for dye degradation and adsorption. Algae possess unique abilities to uptake, degrade, or transform toxic dyes using their metabolic pathways[7]. Additionally, they contribute to oxygen production and nutrient cycling, making them a promising tool for integrated wastewater treatment. Exploring the potential of algal species in dye remediation can help develop efficient bioremediation strategies and contribute to sustainable wastewater management[7,8]. Some of the important gaps that have not yet been documented are the detailed metabolic pathways involved in dye breakdown by the algal species, application on large-scale industrial wastewater treatment, strain-specific efficiency and as well, the impact of dye mixtures[9,10].

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Phycoremediation involves the complete elimination or biotransformation of environmental pollutants by algal species[11-15]. According to Rao *et al.*[16] phycoremediation is the involvement of certain algal species in the removal or isolation and storage of toxic and non-toxic substances from different forms of waste, which is achieved through metabolic uptake, accumulation, or biotransformation[5]. It is nature-friendly, relatively cheap, generate limited odour and as well consumes less energy[17]. García *et al.*[18] referred to phycoremediation as a safe technology that employs non-pathogenic, photosynthetic organisms (algae) that possess antagonistic effects that enable them to eliminate excessive bacterial loads in the environment. It is mostly associated with the reclamation of wastewater as most algae dwell in aquatic environments. The quality of wastewater undergoing algal treatment determines the algal sludge toxicity which is usually treated before disposal[2,5]. The by-product of algal remediation can be transformed into useful components like aquatic feed or growth promoters in plants[19]. Moreover, certain algal species exhibit specialized abilities to convert toxic substances to unstable less harmful variants[20]. Algal mineralization of synthetic compounds is mainly achieved via the trapping and conversion of solar radiation to energy[16]. However, there are some limitations associated with the use of algae for remediation, for example, the high toxicity of some dyes may inhibit algal growth, deterring their remediation efficiency. Fluctuations in factors such as pH, illumination, temperature, nutrients, salinity, dye concentration, quantity of Biosorbent and agitation may interfere with algal remediation. Also, the process of algal remediation relatively takes longer periods to attain significant dye removal[5,17].

Algae are photosynthetic organisms with a simple cellular organization that can withstand extreme environmental factors like heavy metals contamination, increased salt levels, imbalance of nutrients and intense temperatures[21]. Algae are highly effective at removing various contaminants owing to their fast growth, extended cellular surfaces and ability to absorb and metabolize pollutants[22,23]. Algal species (both micro and macroalgae) have been reported to metabolize dyes either via biosorption onto their surface or enzymatic degradation[14,24,25]. The ability of some algal species to adapt to diverse feeding mechanisms (autotrophic, heterotrophic and mixotrophic) enables them to effectively remediate pollutants such as dyes[16]. The rate and extent of dye degradation are influenced by the chemical structure of dyes and algal species involved[26].

Algal species from *Chlorella* and *Scenedesmus* have been reported with the capability to remediate wastewater from different industrial sources as they often flourish in sewage, have increased growth rates and as well high potential in pollutant removal[16]. A study conducted by Yan and Pan[26] revealed the potentiality of *Chlorella pyrenoidosa*, *Chlorella vulgaris* and *Oscillatoria tenuis* in the biodegradation and bio decolorization of over 30 azo dyes to basic aromatic amines. Another research by Obaid[7] reported effective dye removal by the algal species *Chroococcous*, *Chlorococcum*, *Desmococcus* and *Cosmarium*. This review aims at disclosing how algae remove synthetic dyes using certain mechanisms, which subsequently, provides an alternative for mitigating environmental pollution caused by these dyes.

## ALGAL MECHANISMS FOR DYE REMOVAL

**Biosorption:** Biosorption is a passive mechanism that is associated with the binding of dye molecules (chromophores) to functional groups (like hydroxyl, amino, carboxyl and phosphate groups) on the algal cell walls which is triggered by electrostatic attraction and complexation[17]. Nair *et al.*[8] reported that algal biosorption may be accomplished via either van der Waals force or electrostatic forces exerted between the dyes and biomass (physisorption) or through the establishment of covalent bonds between biomass and dyes (chemisorption). The kind and characteristics of the functional groups exhibited by algae vary by the species. Algae are recognized for having an extensive cellular surface and high binding affinity that aid them in adsorbing dyes and other pollutants[27]. The algal cell wall is made up of cellulose along with diverse polysaccharides and proteins, serving as binding sites for different pollutants. Both live and decayed algal biomass have been reported in the effective adsorption of various synthetic dyes[8,28]. The live algae utilize these dyes as nutrient sources for growth by transforming them into simpler carbon compounds[5]. The effectiveness of algal biosorption of dyes depends on the optimization of certain parameters which include temperature, pH, light, pollutant levels, competing ions and the biosorbent quantity[28,29].

Several kinds of research have reported various algal species as natural bio-adsorbents for removing synthetic dyes from industrial wastewater, some of which include *Chlorella vulgaris*, *Codium decorticatum, Chlamydomonas variabilis, Enteromorpha flexuosa, E. intestinalis Spirulina platensis*, *Spirulina* (*Arthrospira*) species, *Ulva lactuca*, *Spirogyra* species, *Nannochloropsis oculata, Phormidium* species, *Pithophora* species, *Sargassum swartzii* and *Scenedesmus* quadricauda[8,24,27-35].

**Bioaccumulation:** Bioaccumulation is an active pollutant detoxification process that activates many metabolic activities within algal cells. It is also referred to as the ability of algae to take up pollutants like dyes into their cells for metabolism or storage[5,36]. The capability of algae to accumulate contaminants is dependent upon the species, contaminant levels and other environmental factors[37]. Algae accumulate dyes either by active transport through various transporters or by the process of endocytosis that requires energy. The dyes accumulate as nutrients within the algal cytoplasm with the aid of different transport proteins on the cell surface[28]. The oxidative stress induced by the accumulated dyes is usually regulated by antioxidant enzymes secreted by the algae[5]. Furthermore, algae can also reduce the toxic impact of dyes by storing them in vacuoles or binding them to various kinds of proteins[38]. Bioaccumulation of dyes is achieved by certain algal species like *Chlorella vulgaris*, Cyanobacteria and *Sargassum* species[39].

**Biodegradation:** Biodegradation is an active process that deals with the conversion or breakdown of dye molecules into less toxic or non-toxic compounds by certain algae with the help of specialized enzymes or cellular metabolites[28]. This often occurs through enzymatic reactions and involves the activities of novel enzymes like laccases, peroxidases or azoreductases that may sometimes completely neutralize the dye molecules in water and carbon dioxide. In some instances, these enzymes transform the dyes into useful mineral elements through a process called biomineralization[40-42]. Interestingly, several algal species have been reported to be effective in dye remediation due to the possession of the azoreductase enzyme. Some of these species include *Chlorella vulgaris, Lyngbya lagerheimii, Nostoc linckia, Oscillatoria* species, *Oscillatoria limnetica*, *Oscillatoria rubescens, Elakatothrix viridis, Volvox aureus, Haematococcus* species, *Scenedesmus obliquus*, *Spirogyra* species (CRW1), *Cladophora* species (PKS33), which degraded dyes like methyl red, orange II, G-Red (FN-3G), basic cationic, basic fuchsin, malachite green MB, safranin, Congo red, reactive blue, reactive black 71, indigo, disperse red 1, direct blue, direct red 31 and acid orange[8,43-48].

**Photodegradation:** Photodegradation is a process employed by certain algae that is associated with their release of oxygen during photosynthesis which can often speed up the breakdown of dyes in the presence of solar radiation (photocatalytic degradation)[49]. It often involves the initiation of a redox reaction upon the interaction of a photocatalyst (on the algal surface) with the dye molecule when exposed to light which subsequently leads to the creation of oxygen groups (like hydroxyl), superoxide radicals and hydrogen peroxide[49]. This is very vital in the mineralization of synthetic azo dyes from wastewater in the presence of nanoparticles serving as catalysts[50]. During algal photodegradation of dyes, photons are absorbed and intracellularly degraded through the process of photodissociation[51] *Sargassum* sp. induced with nanoparticles displayed an effective photodegradation of malachite green due to exposure to a visible light source[52]. Lebron *et al.*[53] studied the photocatalytic reduction of methylene blue dye with the dried biomass of two microalgal species (*Chlorella pyrenoidosa* and *Spirulina maxima*) and the result revealed an effective color removal.

## ALGAL STRAINS EMPLOYED IN THE REMEDIATION OF SYNTHETIC DYES

A wide range of algal species have been reported to have high potential in neutralizing synthetic dyes. Some of these species will be discussed in this section.

**Cyanobacteria:** Cyanobacteria (blue-green algae) are bacteria characterized by photosynthetic abilities that are important in ecological processes like pollution control. They have been employed in the remediation of various synthetic dyes including species of *Aphanocapsa elachista, Phormidium autumnale* (UTEX1580), *Hydrocoleum oligotrichum, Chroococcus minutus* and *Gloeocapsa pleurocapsales*. Some of the dyes that were mineralized by these species are indigo, disperse orange 2RL, Tracid red B5, reactive yellow 3RN, reactive black NN, methyl red, basic fuchsin, acid orange, amido black 10R and FF sky blue[54-58].

**Microalgal species:** Microalgae are diverse microscopic, unicellular, photosynthetic, aquatic organisms. They are of great importance as they participate in various ecosystem services such as absorption of excess atmospheric carbon dioxide and pollutant uptake[15,20].

*Chlorella* species are green microalgae inhabiting freshwater, marine, or brackish ecosystems. They are the most common microalgae used in dye removal and this is due to their great potential in the tolerance of dye polluted environments[7,34,59]. *Chlorella vulgaris* has been reported to possess high efficiency in dye remediation from industrial effluent or wastewater. They have been used in the breakdown of dyes like ethidium bromide, remazol black B, remazol red RR, remazol brilliant blue R, remazol golden yellow RNL, malachite green, reactive red 195, reactive red 198, reactive yellow 176, reactive yellow 3RN, reactive black NN, reactive orange 122, reactive green 19, reactive violet 1, disperse orange 2RL, Tracid red B5, Tectilon yellow 2G, Congo red, brilliant blue R, napthol green B, Brazil wood, orange G and G-red (FN-3G)[32,57,60-63]. Other species of *Chlorella*, *C. pyrenoids* and *C. marina*, have also shown a promising potential in dye remediation[45,64,65].

Other important microalgal species that have proven to be very effective removal of a wide range of synthetic dye removal are *Spirogyra* species, *Scenedesmus quadricauda, S. bijugatus, S. officinalis, Elakatothrix viridis, Volvox aureus, Valoria bryopsis, Padina pavonica, Coelastrella* species, *Acutodesmus obliquus*, *Microspora* species, *Anabaena oryzae*, *Wollea saccata, Chara vulgaris, Enteromorpha intestinalis, Haematococcus pluvialis, Iridaea cordata, Oscillatoria limnetica*, *Chlamydomonas reinhardtii, Spirulina platensis, S. maxima, Isochrysis galbana, Tetraselmis* species, *Nannochloropsis* species, *Dunaliella salina*, *Desmodesmus* species, *Desmodesmus subspicatus, Oedogonium subplagiostomum, Laminaria digitata, Bifurcaria bifurcata, Turbinaria conoides, Raphidocelis subcapitata, Chaetophora elegans, Chlorococcum* sp., *Ulothrix* species, *Navicula* species, *Nitzschia perminuta, Chroococcus minutus, Gloeocapsa pleurocapsales, Phormidium ceylanicum, Hydrocoleum oligotrichum, Cosmarium* species, *Vaucheria* species and *Phaeodactylum* tricornutum[14,28,39,53,55,66-74].

**Macroalgal species:** A quite number of researches have reported the high effectiveness of macroalgal species in dye remediation[75]. Some representatives of the dye degrading macroalgal species are *Stoechospermum marginatum, Ulva lactuca, U. fasciata, Sargassum crassifolium, S. dentifolium, S. swartzii, S. glaucescens, S. muticum, S. latifolium, Gracilaria corticata, G. parvispora, Caulerpa racemosa, C. scalpelliformis, Fucus vesiculosus, Nizamuddinia zanardinii* and *Gelidium corneum* which were reported to have remediated dyes like acid orange II, acid black 1, malachite green, crystal violet, methyl orange, methylene blue, eriochrome black T, remazol brilliant blue, sandocryl golden yellow and reactive red C2G[8,14,53,75-87].

## ALGAL CONSORTIA EMPLOYED IN DYE REMEDIATION

Algal consortia is a co-culture of algal species or hybrid culture of algal and other microbial species like bacteria and fungi that are used for remediation of dye from wastewater or effluents[88]. This strategy has proven to be very sustainable in the remediation of dye-contaminated environments due to their synergistic effects and enhanced capabilities[89]. In a consortium, each of the strains or species may target specific sites on the dye molecules or may utilize the metabolites produced by another strain or species. Although the use of microbial consortia in dye removal has proven to be very effective, there is limited data on the development of algal consortia for dye remediation[89].

Moghazy *et al.*[81] used a consortium of *Ulva fasciata* and *Sargassum dentifolium* in the complete neutralization of methylene blue dye. Another study, a consortium of *Scenedesmus obliquus* and *Oscillatoria* sp. was employed in the effective remediation of reactive orange 122 and reactive red 194[90]. Effective remediation of malachite green was also observed while using an algal consortium of *Chlorella, Cosmarium* and *Euglena* species with the application of an artificial neural network (ANN)[14,91,92]. Dye wastewater was successfully treated with a consortium of microalgae, *Chlorella sorokiniana* and a fungus, *Aspergillus* species[93]. Some research revealed the effectiveness of mixed cultures of algae and yeast in the degradation of dyes, implying that microbial consortia can also yield beneficial outcomes for decolourization of dyes[8,14]. Ayed *et al.*[94] used an algal-bacterial consortium (*Pseudomonas putida, Chlorella* and *Lactobacillus plantarum*) for the complete degradation of CI RB 40 reactive azo dye under optimized conditions.

## CONCLUSION

Numerous algal species have demonstrated high effectiveness in degrading various synthetic dyes, either individually or in combination. This has significantly contributed to mitigating the environmental impact of these pollutants. Ongoing research continues to explore new algal species capable of dye mineralization, utilizing advanced biotechnological strategies. Consequently, further discoveries in this field are anticipated shortly.

## SIGNIFICANCE STATEMENT

This review presents the mechanisms and techniques governing algal remediation of synthetic dyes, focusing on recent advancements. It consolidates knowledge on algal species, their metabolic pathways and interactions with other organisms, while identifying research gaps in optimizing dye degradation and assessing economic feasibility for large-scale use. It also emphasizes the significance of dye pollution mitigation using algal systems. The employment of new and more advanced biotechnological approaches such as genetically engineered microalgae and hybrid treatment systems may optimize the efficiency of dye removal.

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