



# Biomass-Based Adsorbents for Removal of Dyes From Wastewater: A Review

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### Specialty section:

This article was submitted to  
Water and Wastewater Management,  
a section of the journal  
Frontiers in Environmental Science

**Received:** 26 August 2021

**Accepted:** 04 November 2021

**Published:** 09 December 2021

### Citation:

Aragaw TA and Bogale FM (2021)  
Biomass-Based Adsorbents for  
Removal of Dyes From Wastewater:  
A Review.  
Front. Environ. Sci. 9:764958.  
doi: 10.3389/fenvs.2021.764958

Dyes, especially azo dyes contained in wastewaters released from textile, pigment, and leather industries, are entering into natural waterbodies. This results in environmental deterioration and serious health damages (for example carcinogenicity and mutagenesis) through food chains. Physiochemical, membrane processes, electrochemical technology, advanced oxidation processes, reverse osmosis, ion exchange, electrodialysis, electrolysis, and adsorption techniques are commonly used conventional treatment technologies. However, the limitations of most of these methods include the generation of toxic sludge, high operational and maintenance costs. Thus, technological advancements are in use to remediate dyes from effluents. Adsorption using the nonconventional biomass-based sorbents is the greatest attractive alternatives because of their low cost, sustainability, availability, and eco-friendly. We present and reviewed up-to-date publications on biomass-based sorbents used for dye removal. Conceptualization and synthesizing their state-of-the-art knowledge on their characteristics, experimental conditions used were also discussed. The merits and limitations of various biosorbents were also reflected. The maximum dye adsorption capacities of various biosorbents were reviewed and synthesized in the order of the biomass type (algae, agricultural, fungal, bacterial, activated carbon, yeast, and others). Surface chemistry, pH, initial dye concentration, temperature, contact time, and adsorbent dose as well as the ways of the preparations of materials affect the biosorption process. Based on the average dye adsorption capacity, those sorbents were arranged and prioritized. The best fit of the adsorption isotherms (for example Freundlich and Langmuir models) and basic operating parameters on the removal dyes were retrieved. Which biomass-based adsorbents have greater potential for dye removal based on their uptake nature, cost-effectiveness, bulk availability, and mono to multilayer adsorption behavior was discussed. The basic limitations including the desorption cycles of biomass-based adsorbent preparation and operation for the implementation of this technology were forwarded.

**Keywords:** biomass, bio-adsorbent, conventional treatment techniques, dye removal, optimal conditions, removal efficiency

## HIGHLIGHTS

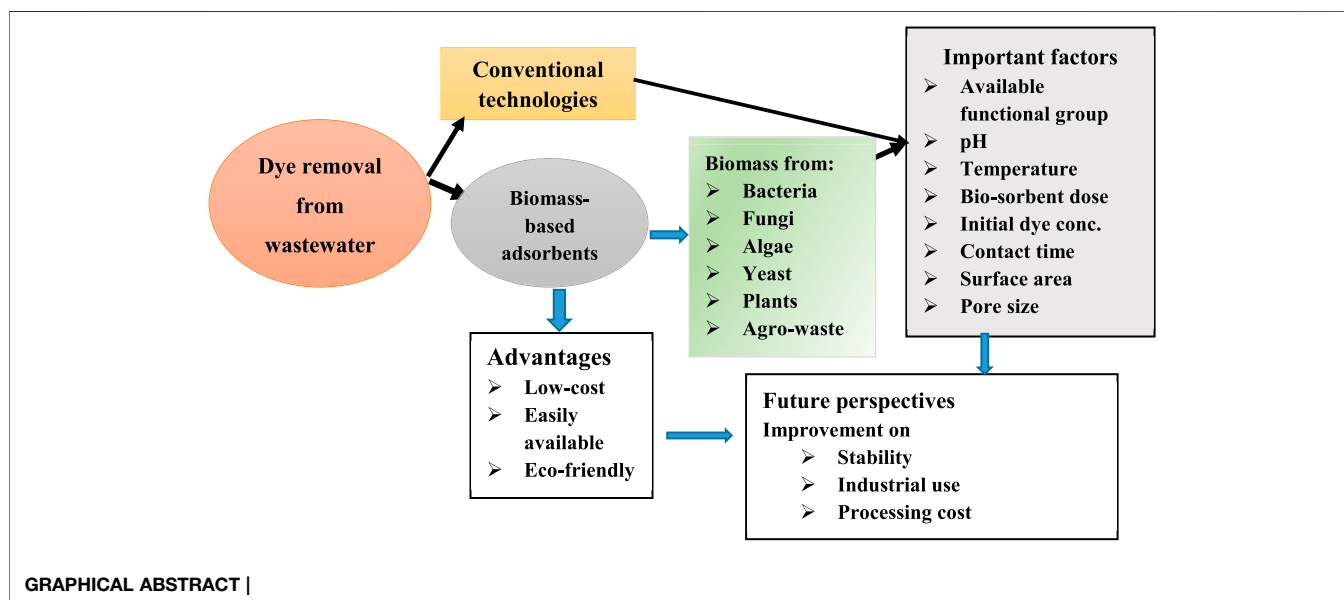
- Dye removal from wastewater using bio-based adsorbents is a promising alternative.
- Algae, yeast, bacterial, fungal, agro-waste, and plant debris are potential bioadsorbent sources.
- Simulated wastewater studies need to switch into pollutants in the actual wastewater.
- Knowing the surface charge nature of the biosorbents is important.
- Suitable modification of biosorbents for enhanced removal is required

## 1 INTRODUCTION

Availability of accepted quality of water is one of the major problems faced in the 21st century (Zhou et al., 2019; Al-Amshawee et al., 2019). The quality of water resources is declining daily due to various anthropogenic activities, unplanned urbanization, and increasing industrialization. Various types of dyes and metal ions are the major pollutants encountered in wastewater effluent, which disturb the aquatic environment (Varghese et al., 2019; Saravanan et al., 2021).

Dyes are organic compounds that are released from several industrial sources including textile, paper, leather, rubber, cosmetic, and printing industries (Piaskowski et al., 2018; Katheresan et al., 2018). To satisfy the modern need, it is assessed that 0.7–1.6 million tons of dyes are delivered yearly and 10–15% of this volume is disposed of as wastewater, making it major water pollutants (Bhatia et al., 2017; Varghese et al., 2019; Syafiuddin and Fulazzaky, 2020). Excessive exposure to dye causes skin irritation, respiratory problems and some dyes even increase the risk of cancer in humans (Amirza et al., 2017). Consequently, it is of most extreme significance to eliminate colors from wastewater viably to guarantee the protected release of treated effluent into streams.

Many technologies have been emerging for treating and handling pollutant-laden wastewater. Some commonly used treatment technologies consist of biological treatments, membrane process, chemical, and electrochemical technology, reverse osmosis, ion exchange, electrodialysis, electrolysis, and adsorption techniques (Varghese et al., 2019; Guo et al., 2019; Ahmad et al., 2015). However, the limitations of most of these methods include the generation of toxic sludge, high operational and maintenance costs, and the intricate technique involved in the treatment (Yahiaoui et al., 2021). Comparatively, the adsorption method is considered a better treatment process in wastewater treatment technologies due to ease of operation, convenience, and simplicity of design (Aragaw and Angerasa, 2020; Aragaw, 2020), but it has a limitation of sludge generation (spent adsorbents after use) as other removal processes (Patel, 2021; Vakili et al., 2019). Activated carbon is undoubtedly considered a universal adsorbent for effluent treatment and is commonly used for the removal of several pollutants (Rahimian and Zarinabadi, 2020). However, its extensive use in wastewater treatment is sometimes limited due to its higher cost. Different varieties of nonconventional sorbents have been investigated for their capacity to remove various types of contaminants from the wastewater (Sivaranjane and Kumar, 2021), but a report of various low-cost adsorbents shows limited sorption potential than commercial activated carbon in the removal of various pollutants (Ahmad et al., 2011a; Varghese et al., 2019). In contrast to these investigations, Hassan and Carr (2021) reviewed studies that revealed the dye-adsorption capacity of some carbonaceous adsorbents derived from biomasses and their composites is noticeably higher than the commercial activated carbon adsorbents (Hassan and Carr, 2021). Therefore, the search for the development of low-cost materials as adsorbents along with the precursor for the preparation of activated carbon is ongoing. Bio adsorbents are the recent materials employed in various sectors to remove dyes and other pollutants. Charcoal, peat, chitin, microbial biomass (fungi, bacteria, yeast, etc.), wood



bark, and other agricultural and industrial wastes are frequently used bio-adsorbents (Kumar et al., 2021).

Owing to eco-friendly, low cost, and good surface characteristics, biomass-based adsorbents are attracting attention and are widely studied. The publication trends (Figure 1) confirmed that recently the number of publications increased. The publication trends with a search query “biosorbents for the removal of dyes” were conducted from PubMed (<https://pubmed.ncbi.nlm.nih.gov/>). The journal article publications were filtered and found a total of 209 papers with a publication date accustomed from 2002 to 2020. Furthermore, the specific search query of the biobased adsorbents for the dyes was retrieved. As it can be observed, publication counts from 2017 to 2020 are highly consistently increased suggested that the nonconventional adsorbents from biomass are recently attracting attention for dye removal. In addition to PubMed, the journal article publications were retrieved from Google Scholar (<https://scholar.google.com/>) because it is not a comprehensive database. The reviewing, filtration, and prioritization criteria on the retrieved publications were employed based on the contents contained in the articles and fitted to the scope of the present review. The retrieved publications were found as adsorbents prepared from different biomasses activated and/or modified with various chemicals or techniques. For example, the bioadsorbents may be activated with acid/base (such as HCl, NaOH) and thermal activation, and also some are composited with inorganic and/or organic nanomaterials. The number of publications from 2017 to 2020 was found as a consistent increase (Figure 1) suggested that wastewater treatments using bioadsorbent are recent and attracting scholars.

However, biomass-based adsorbents need to be researched and a sufficient number of comprehensive review papers are required because of their being ecofriendly, cost-effective, and widely available. The present review evaluates the adsorption of dyes using bioadsorbents prepared from various biomasses, detailed adsorptive applications, and removal capacities of the

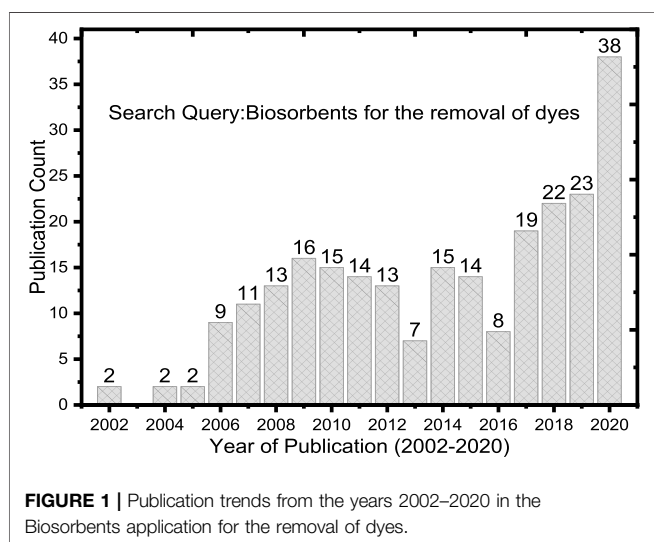
prepared adsorbents for different types of dyes. Also, different wastewater treatment techniques for dye removal are highlighted. Moreover, the limitation of bioadsorbents for the adsorptive removal of contaminants is discussed. At the end, the cost analysis, regeneration capacity, and prospects of the bioadsorbents to the area are pointed out. Thus, this review mainly aimed at assessing the potential of several biomass-based adsorbents utilized so far for the removal of various dyes. Several up-to-date biomass-based adsorbents including fungal, bacterial, algal, yeast, and agricultural and forest biomasses used for a variety of dyes removal are discussed. Furthermore, this review could discourse a literature review in one referenced paper that can draw up the separated publications to the area resulting in suggestion of new/modified research tips by synthesizing at-hand studies.

## 2 WASTEWATER TREATMENT TECHNIQUES FOR DYES REMOVAL

Dyes are colored compounds, used for coloring textiles, wools, and fiber from various industries such as textile, food processing, ink, cosmetics, pharmaceuticals, printer inks, leather, and plastics production (Piaskowski et al., 2018; Rodríguez Couto, 2009), which need to be removed after usage not to pollute the marine environment and ecosystem, and not to pose health effect to humans. It also blocks sunlight penetration thereby inhibiting photosynthesis (Bello et al., 2015; Dey et al., 2017). Dyes are usually classified based on their chemical structure, such as anionic, cationic, and nonionic; reactive dyes are stable and anionic, and display resistance toward light (Heidari et al., 2019; Dai et al., 2018). As shown in Figure 2, several types of dye removal technologies are accessible with varying degrees of success, such as chemical precipitation, reduction, oxidation, coagulation, ion-exchange, reverse osmosis, solvent extraction, flocculation, membrane separation, filtration, evaporation, electrolysis, and adsorption, which have been used to remove and recover toxic contaminants from industrial effluent (Afroze and Sen, 2018; Ahmad et al., 2011b). All the aforementioned methods have their own merits and demerits (Table 1), which need vast considerations to use and investigate during dye removal processes.

### 2.1 Chemical Precipitation

This wastewater treatment method involves chemicals such as hydroxides, carbonates, and sulfides to react with impurities present in the solution to form precipitates that can settle easily. Chemicals introduced in the coagulation tank interact with molecules of dye to form easily removable precipitates (Mohan et al., 2004). The common procedures comprise: 1) the addition of appropriate chemicals into targeted pollutant-containing solutions, 2) precipitate will be formed after interaction of molecule of dye, 3) allow the suspension to settle (i.e. insoluble particles), and 4) separation of the sludge. The most common chemical precipitation method for dye removal is hydroxide precipitation (Ahmad et al., 2015). Vimonses et al. (2010) studied the mechanisms involved in the



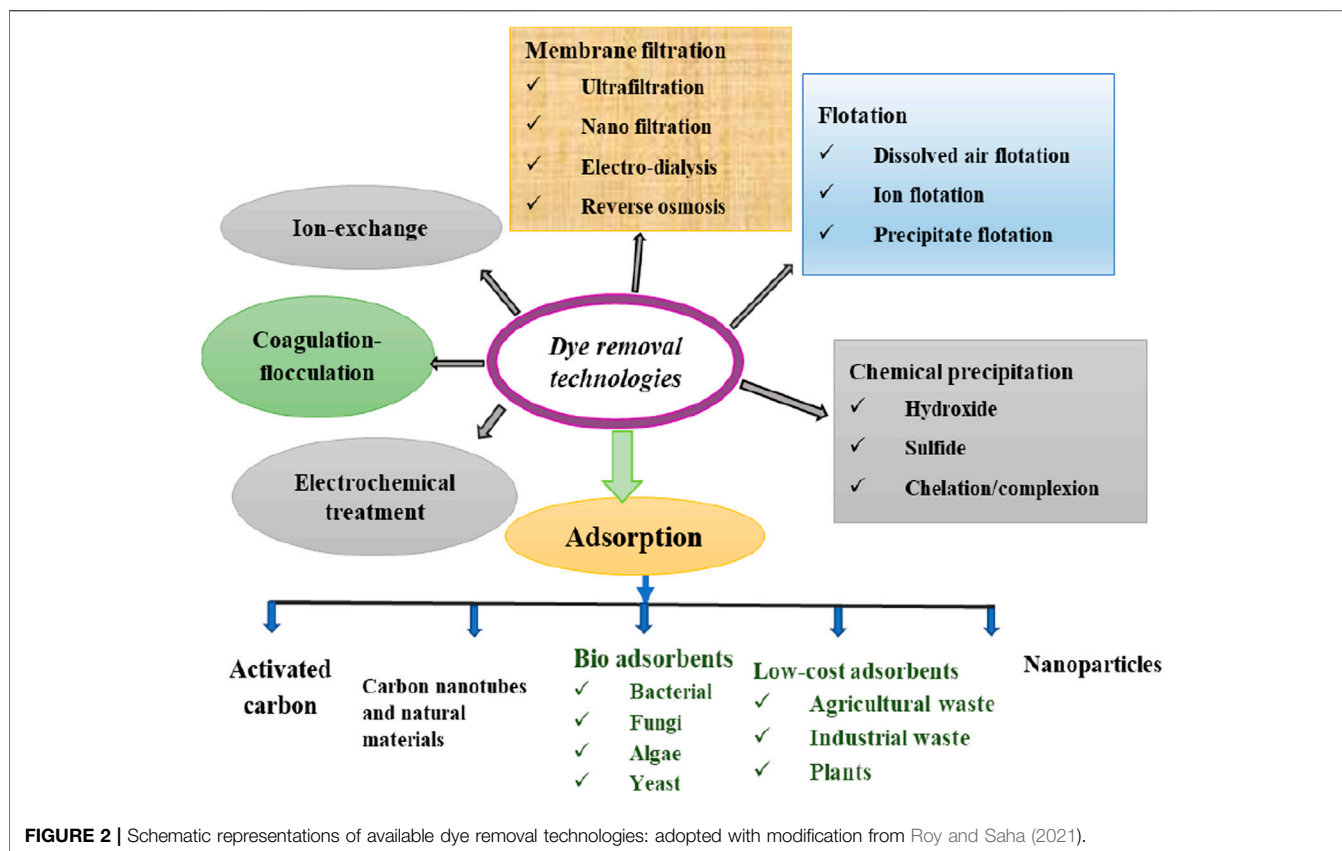


FIGURE 2 | Schematic representations of available dye removal technologies: adopted with modification from Roy and Saha (2021).

TABLE 1 | Advantage and disadvantages of the dye removal process technologies.

Treatment technology	Materials used	Max removal efficiency (%)	Advantages	Disadvantages	Reference
Chemical precipitation	Lime, surfactants, etc. (e.g. sulfides, hydroxides, and carbonates)	70–99.2	Low capital cost, process simplicity	Sludge generation, the extra operational cost for sludge disposal, high-maintenance cost	Afroze and Sen (2018), Shen et al. (2019)
Ion exchange	Ion-exchange resin (ammonium phosphomolybdate (APM) particles), anion, and cation	94.6–96.8	No loss of sorbents during regeneration	Not effective for disperse dyes	Dawood and Sen, (2014), Joseph et al. (2020), Marin et al. (2019)
Membrane technologies	Membranes	90–100	Removal of all dye types, appreciable resistance to temperature, and chemical environment	A limited lifetime before membrane fouling occurs, concentrated sludge production, costlier, suitable for low volume of treatment	Simi and Azeeza, (2010), Collivignarelli et al. (2019), Mondal et al. (2018), Moosavi et al. (2020)
Flotation techniques	Surfactants or collectors (e.g. Polyvinyl Alcohol, Chitosan), gas bubbles		Low cost, shorter hydraulic retention time	Subsequent treatments are required to improve the removal efficiency	El-Hosiny et al. (2017), Al-Zoubi et al. (2015)
Electrochemical techniques	Electrode material (iron plates or aluminum), pH controller	94	The system is very robust, efficient, and easily controllable	The sacrificial anode requires to be replaced periodically, needs continuous monitoring and maintenance, cost of electricity	Mondal et al. (2018), Hendaoui et al. (2021), Simi and Azeeza (2010)
Coagulation-flocculation	Coagulants (ferrous sulfate, ferric chloride, alum, etc.)	99	Complete removal of dye, simplicity, and low capital cost	Produce highly toxic sludge, handling and disposal problem	Collivignarelli et al. (2019), Roy et al. (2018)
Adsorption by commercial AC	Commercial activated carbon (AC)	99.7	The high adsorption capacity for all dyes	Cost of regeneration, high cost of adsorbents, generation of sludge (spent adsorbents)	Collivignarelli et al. (2019), Yeow et al. (2021), Patel (2021)

decolorization of Congo red dye. The removal was governed by combined physiochemical reactions of adsorption, ion-exchange, and precipitation. The precipitation contributed over 70% of total dye removal, followed by adsorption and ion-exchange (Vimonses et al., 2010). Sludge generation, the extra operational cost for sludge disposal, and high maintenance costs are major challenges in applying this process.

## 2.2 Complexion

Complex formation in the treatment process has been considered as a highly effective method for utilization to improve economical adsorbents for wastewater treatment. The hydrophobic dye can be removed from the aqueous solution through inclusion complex formation (Saifi et al., 2021). The potential of  $\beta$ -cyclodextrin ( $\beta$ -CD) was studied to remove highly toxic oil orange SS (OOS) dye by complexation. This process needs the synthesis of complexes that can interact with the particular contaminant. The complexation mechanism may occur simultaneously with the ion-exchange mechanism (Kubra et al., 2021). Hisada et al. (2019) reported the occurrence of simultaneous mechanisms in the removal of Basic Orange 2 (BO2) by poly- $\gamma$ -glutamic acid (PGA) in different pH ranges. Adsorption and complexation/precipitation have occurred in the pH range of 4-5 and hydrogen-bonded organic ammonium carboxylate salt complexes were formed (Hisada et al., 2019). When the pH was greater than 6, complexation/precipitation was significantly suppressed due to the neutral nature of the dye and van der Waals adsorption and hydrophobic interaction's domination. Moreover, 99.5% removal was reported at pH = 5.

## 2.3 Ion-Exchange

The ion-exchange technique of wastewater treatment is categorized under widely used techniques. The process is based on the presence of ion-exchange resins that interact strongly with functional groups and charged dyes so that various dyes can be effectively removed from the aqueous solutions. The ion-exchange resins can be anion exchangers or cation exchangers (Ahmad et al., 2015). In the ion-exchange process, strong bonds are formed between solutes (dye molecules) and resins through an exchange of positive and negative ions. Conceptually, anionic (e.g., acid, mordant, reactive, direct, metal complexes) as well as cationic (basic) dyes, if treated with ion-exchange resins, should form complexes in the form of large flocs, able to be separated by filtration. Among different resins, quarternized cellulose and quarternized sugarcane bagasse were reported as viable ion-exchange resins capable of binding hydrolyzed reactive dyes (Singh and Arora, 2011). Several studies are reported in this area, for example, Acid orange 10 was removed from the environment by an Amberlite IRA 400 anion-exchange resin with up to 96.8% removal efficiency (Marin et al., 2019). Ion exchange dominates the mechanism of Congo red adsorption on the magnetic ion-exchange (MIEX) resin (Jia et al., 2020). In ion-exchange processes, there is no loss of adsorbent on regeneration, reclamation of solvent after use is possible and can remove soluble dyes effectively, but technology and organic solvent are expensive (Gnanadoss, 2013).

## 2.4 Membrane Technologies

Membrane filtration is an alternative physical treatment that can be used to remove the color from wastewater. It has some advantages such as appreciable resistance to temperature, good resistance to adverse chemical environment, and excellent performance of color removal (Roy et al., 2018). Also worthy of note are disadvantages, among which the one linked to the high cost of disposal of the remaining concentrated residue following the separation, the high management costs and the inability to deal with high flow rates, and frequent clogging of membrane pores by the dye molecules (Collivignarelli et al., 2019). Reverse osmosis and nanofiltration membrane systems effectively removed dyes such as acid red, reactive black, and reactive blue dyes as an alternative treatment method of wastewater discharged from Iraqi textile mills (Abid et al., 2012). However, Zhou et al. (2019) pointed out the limitation of using membrane technologies for treating dye-containing wastewater due to the short service life of the membrane and the ease to be pollution (Zhou et al., 2019).

### 2.4.1 Ultrafiltration

Ultrafiltration requires less pressure than nano-filtration and reverse osmosis (Shindhal et al., 2021). The success of ultrafiltration has been studied in the discoloration of reactive dyes with a removal efficiency of up to 90% (Erkanlı et al., 2017). In the other study, 98 and 100% color removal efficiencies have been obtained from real wastewater using ultrafiltration and Nanofiltration respectively (Collivignarelli et al., 2019). Ultrafiltration ceramic membrane was effectively decolorized Reactive Black dye solutions at different dye concentrations (Alventosa deLara et al., 2012).

Micellar-enhanced ultrafiltration employs surfactant micelles to solubilize inorganic and organic pollutants from the effluent stream and is subsequently filtered using an open membrane to restrict the micelle-pollutant complex in the permeate stream. Micelles being large can be removed together with the organic pollutants by a porous membrane. More than 90% removal efficiency, along with high throughput, can be attained by using pollutant-specific surfactant (or mixed surfactant system) and high permeability membrane, depending on the charge and other physical properties of the contaminants (Mondal et al., 2018).

### 2.4.2 Nanofiltration

The less energy consumption in NF (compared to RO) makes its use more frequent for the removal of various industrial effluents. The advantages of NF over other conventional separation processes include being less energy-intensive, can be operable under ambient temperature, having no phase change, and usually causing no damage to the species under processing (Mondal et al., 2018). Considering these advantages, the process can play a major role in replacing many of the conventional separation processes. The NF method was employed for the removal of dyes from solutions containing different dyes. The percentage removal of 93.77%, 95.67%, and 97% was reported for red, black, and blue dyes, respectively. The removal process was directly related to operating pressure, pH, TDS, and initial dye concentration, but not to the feed temperature (Abid et al., 2012).

The removal of different classes of dyes such as reactive, acidic, disperse, and direct dyes was studied by spiral-wound NF membrane in the thin composite film. The result reveals that color removal increased up to 98% as dye concentration increased for acidic and reactive blue dyes. Moreover, COD removal efficiencies were also found to be approximately 100% for reactive blue, disperse blue, direct, and disperse red dyes (Hassani et al., 2008).

### 2.4.3 Reverse Osmosis

Reverse osmosis is equally widely used in the textile industry as NF. This process has the potential to remove the dyes and allow the reuse of auxiliary chemicals for dyeing (Mondal et al., 2018). Dye concentration, solution pH, dissolved salts, temperature, and operating pressure on permeate flux and dye rejection affect the RO process. For example, the performance of RO membrane was reported with dye removal percentage of 97.2%, 99.58%, and 99.9% for acid red, reactive black, and reactive blue dyes, respectively, at an initial dye concentration of 65 mg/L, 39°C dye temperature, and 8 bar pressure (Abid et al., 2012).

### 2.4.4 Electrodialysis

The electrodialysis process is electrically driven, comprising appropriate ion-exchange membranes that are placed between the anode and cathode electrodes. This process provides high recovery of water and does not involve phase change and reaction as well as with no need for pressure and chemicals (Al-Amshawee et al., 2019). The ED technique was studied to remove methylene blue dye from simulated saline solutions. The effect of applied voltage, pH, initial dye concentration, and ionic strength on the removal performance was studied. Electrostatic interaction between ions of dye and the fixed charged groups of the ion-exchange membrane, and affinity toward interactions are the main factors in fouling (Lafi et al., 2019).

This technique can also be used in the treatment of textile or tannery dye to remove salts, COD, and color with the integration of ultrafiltration process (Lafi et al., 2018), electrocoagulation process (Deghles and Kurt, 2016), and photodegradation (Sindelar et al., 2015). Moreover, 97% of Indigo Carmine dye was removed by the ED process at various current intensities, conductivity, and pH of solutions (Caprarescu et al., 2016). Although the ED process has attractive advantages in contaminant removal, the following problems are reported such as scaling, membrane fouling, permselectivity, and high cost of electrodes (Peng and Guo, 2020; Xue et al., 2015).

## 2.5 Flotation Techniques

Flotation is a solid-liquid separation process, applicable to particles having a lower density than the solution, then the impurities floated on the top are removed by collectors. It involves the introduction of the transport medium (gas bubbles). The flotation technique was originally applicable in the mineral processing practices to extract minerals and particulate solids from water. The application of these techniques mainly comprises the treatment of heavy metals and dyes containing water and wastewater (Deliyanni et al., 2017; Gross et al., 2017). The efficiency of floatation

techniques are dependent on the surface properties of different particles, pH value, temperature, current density, initial dye concentration, ionic strength, and stirring speed (El-Hosiny et al., 2017). This process can achieve effective treatment of dyes when combining with conventional coagulation, flotation, and electrochemistry in wastewater treatment (El-Hosiny et al., 2018; Hu et al., 2020; Tara et al., 2019). The flotation techniques can be divided into three processes: 1) dissolved air flotation (DAF) process, 2) ionic flotation, and 3) precipitate flotation. The generation of a bubble could be applied for techniques (Kyzas and Matis, 2018). The dissolved air flotation method has been commonly used in wastewater treatment (Al-Zoubi et al., 2015). Ion flotation removes surface-inactive ions from the solution by adding oppositely charged surfactants or collectors followed by introducing gas bubbles through the solutions (Deliyanni et al., 2017).

## 2.6 Advanced Oxidation Processes

Recently, advanced oxidation processes (AOPs) have been effectively investigated in the removal of a variety of contaminants from water and wastewater. Advanced oxidation processes (AOPs) involve the generation of oxidizing species such as hydroxyl radicals and sulfate radicals in sufficient quantity to interact with the organic compounds of the medium (Wang and Wang, 2020; Duan et al., 2020). AOPs comprise all the catalytic and noncatalytic processes that take advantage of the high oxidizing capacity of the hydroxyl radical (OH), and they differ from each other in the way in which this radical is generated (Cuerda-Correa et al., 2020). These processes are mainly based on the *in-situ* generation of the hydroxyl radical that reacts rapidly with most organic compounds. Thus, such a radical is generated in sufficient quantity to interact with organic compounds (Babu et al., 2019; Mokif, 2019).

Photolysis, O<sub>3</sub>-based processes (ozonation and catalytic ozonation), H<sub>2</sub>O<sub>2</sub>-based processes (Fenton, photo-Fenton), sonochemical oxidation, electrochemical oxidation, persulfate-based oxidation, wet air oxidation, and heterogeneous photocatalysis are the major advanced oxidation processes (Cuerda-Correa et al., 2020; Sharma and Feng, 2019; Miklos et al., 2018).

Several studies used advanced oxidation processes (AOPs) to treat different dyes in the wastewater stream. Zero-valent aluminum (ZVAL)-based AOPs were utilized to treat textile wastewater treatment. A color removal efficiency of 94.4% was achieved after the oxidation process (Khatri et al., 2018). Some of the other studies include: Fenton and photo-Fenton processes for the degradation of methylene blue with an efficiency of 65 and 83% respectively at pH of 3 and 30 min contact time (Gowtham and Pauline, 2021), combined sono-photo-electro-Fenton (SPEF) process for the removal of Acid Black 172 and Disperse Blue 56 with a removal efficiency of 97.4 and 95.5% respectively (Mahmoudi et al., 2021a), dark-Fenton process conditions for the removal of methylene blue and acid blue 29 with the removal efficiency of 82 and 95% respectively (Nasuha et al., 2021), electro-Fenton (EF) process and Ozone oxidation for the removal of Basic Blue 9 (BB9) dye with more than 97% removal efficiency (Bustos-Terrones et al., 2021), and electro-

Fenton processes for the complete degradation of reactive red 195 (Elbatea et al., 2021) and more than 94% of neutral red (NR) dye (Ebratkhahan et al., 2021). Temperature, pH, the concentration of the oxidant, the initial concentration of dyes, current density, irradiation time, and reaction time affect the catalytic decomposition of dyes (Javaid and Qazi, 2019; Titchou et al., 2021; Mahmoudi et al., 2021b). Sludge production in the case of Fenton reagent, formation of toxic byproduct in the case of photocatalyst, and high cost due to the use of expensive reagents (for example,  $H_2O_2$ ) and energy consumption (generation of  $O_3$  or UV radiation) are the major drawback of AOPs for dye removal (Cuerda-Correa et al., 2020; Moosavi et al., 2020).

## 2.7 Electrochemical Techniques

This treatment process is a comparatively novel technique, and usually does not require the consumption of chemicals (Roy and Saha, 2021). The anode continuously disintegrates as a result of electrical current flowing through it and produces *in-situ* cations, which acts as electro coagulants that attract the contaminants in the solution. The dyes attached to the electro coagulant either precipitate or flocculate, and thereby are separated. The principle of EC is based on three parameters: 1) the ionic charge, 2) particulate size, and 3) droplet (or vapor) spatial density. The generation of the charged agglomeration involves three stages: 1) coagulant formation by electrolytic disintegration of the anode, 2) destabilization of the suspension, and 3) aggregation to form the floating material (flocs). The EC process is successful in the removal of organic dyes, fine suspended particles, heavy metals, and oil and grease (or other heavier hydrocarbons) from diverse industrial effluents (Mondal et al., 2018). A report revealed that up to 94% of indigo dye could be decolorized at a pH of 7.5 using a continuous electrocoagulation process (Hendaoui et al., 2021). The limitation of this process includes the necessity of electrolytic apparatus, high-cost electricity, and less color removal for some dyes due to the higher flow rate.

## 2.8 Coagulation-Flocculation

Coagulation-flocculation is among the most widespread physiochemical processes for the removal and distraction of coloring substances in wastewater. The removal of color by coagulation is strongly dependent on the structure of dye molecules (chromophores and auxochromes), so structural considerations of dyes are very important when choosing the most appropriate coagulant for dye removal (Mcyotto et al., 2021). The method can be separated into coagulation (destabilization of the colloidal suspensions by charge neutralization), flocculation, and sedimentation (physical processes that allow the smaller particles to be grouped so that they can be easily separated by sedimentation). The removal efficiency of color up to 99% has been reported for treating simulated water containing Brilliant green and Congo red (Collivignarelli et al., 2019). Moreover, many reports are accessible on dye removal by coagulation and flocculation from simulated and real wastewater. Magnesium chloride, lime, alum have been widely used coagulants in the process (Roy et al., 2018).

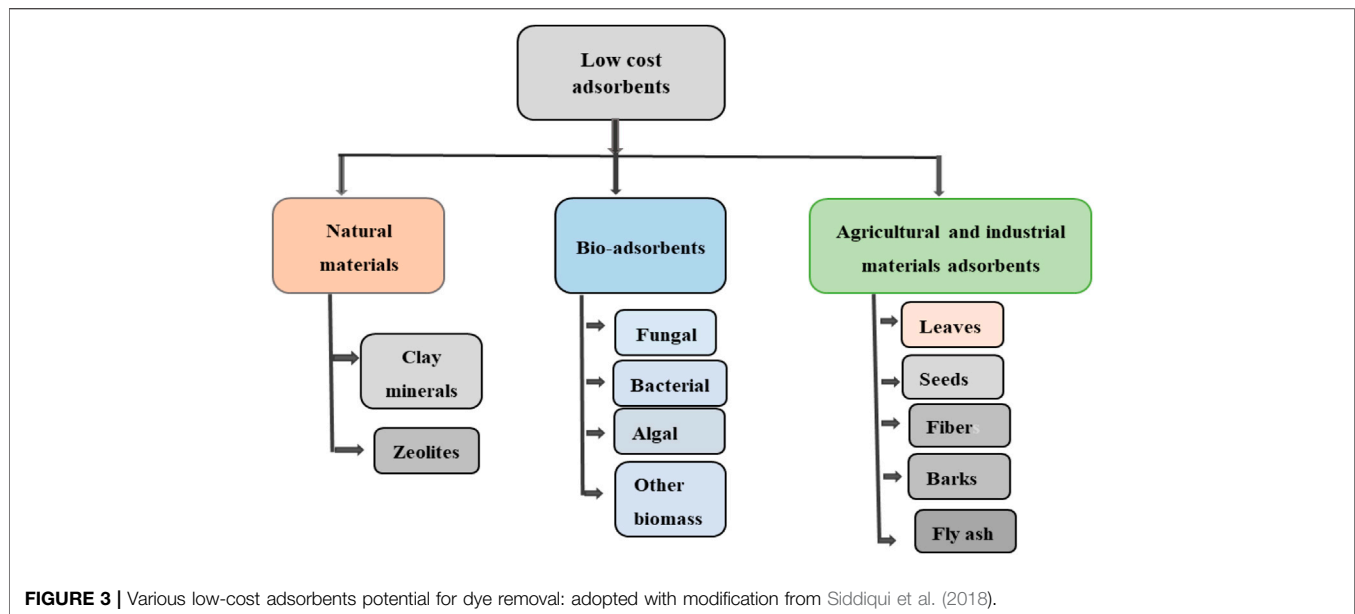
## 2.9 Adsorption

Adsorption is found to be a very effective, cheap, and commonly used method among all available dye removal techniques (Kandisa and Saibaba KV, 2016). Adsorption technique in wastewater treatment comprises removals of contaminants using commercial activated carbon and various available potentially low-cost adsorbents including biomass-based adsorbents. Several potential low-cost adsorbents have been studied in the application of wastewater treatment containing dyes (Figure 3) and widespread studies on dyes, their classification, and harmfulness in conjunction with various dye-containing wastewater treatment approaches, and adsorption characteristics of various nonconventional and cost-effective sustainable adsorbents were reported (Dawood and Sen, 2014; Mondal et al., 2018). The application of waste organic materials (e.g., compounds extracted from peels, leaves, barks) and microbial biomasses (fungus bio-sorbent, bacterial, and green algal biomasses) is gaining an increasing interest being effective, low-cost, and ecologically friendly sorbents. Moreover, newly discovered carbon nanomaterials (carbon nanotubes, graphene, and their derivatives) have been used for dye removal processes (Piaskowski et al., 2018).

Activated carbon (AC) is a commonly used adsorbent that refers to a group of carbon materials with high oscillation and high internal surface which are unique because of their remarkable interior area, pore structure, high adsorption capacity, surface reactivity, and low cost compared to inorganic adsorbents such as zeolite (Hasanzadeh et al., 2020). Special processes for the production of activated carbons in powdered, granular, and spherical forms have so far been developed. Activated carbon can be commercially produced from pyrolysis of carbon or carbon-containing plant materials, such as coal, bamboo wood, charcoal, kernels, or fruit shells, such as coconut shells, and is subsequently activated (Heidarinejad et al., 2020; Yeow et al., 2021; Hassan and Carr, 2021).

There are three main processes for the activation of carbon which are steam activation, activation with carbon dioxide, chemical activation. Among the above three methods, steam activation is the best environmentally and economically viable option, while chemical activation results in the highest surface area and porosity (Rahimian and Zarinabadi, 2020). In the chemical activation process, the chemically active agents (such as phosphoric acid, KOH,  $H_2SO_4$ ) are utilized initially to prepare the precursor followed by heat treatment up to 450–700°C. The charcoal is then washed with water to remove the acid from the carbon and dry.

The adsorption method is attractive and preferable, and carbonaceous adsorbents fit that purpose due to their high dye-binding capacity (Hassan and Carr, 2021). The performance of some commercial activated carbons (CAC) was evaluated for the removal of the Reactive Black dye from synthetic wastewaters (Table 2) (Giannakoudakis et al., 2016). The activated carbon samples were Norit Darco 12 × 20 (DARCO), Norit R008 (R008), and Norit PK 1–3 (PK13) with the maximum theoretical adsorption capacities 348, 527, 394 mg/g respectively at 25°C for all carbon samples. Moreover, Shu et al. (2017) modified the commercial activated carbon by loading copper metal and used it in the removal of dyes containing



Rhodamine B, MB, Amaranth, Congo red, and Eosin-Y from the wastewater; they found that the adsorption capacity is better in MB than in Rhodamine B (Shu et al., 2017). Although the removal of dye using CAC is efficient, its cost is high for industrial applications. And some studies reported that the adsorption capacities of some biomass-based activated carbons prepared in the laboratory scale showed superior adsorption capacity than CAC; however, limited information is available on the application of biomass-based activated carbon at the industrial level. Coal-derived activated carbon was supposed to be the most efficient type of activated carbon in adsorption. The efficiency of treatment is 99.8%, and it can treat various types of dyes (Yeow et al., 2021). The capacity of removal of Reactive Red 120 was compared using *Spirulina platensis* (microalgae) and CAC. The batch adsorption system revealed that the maximum adsorption capacities of microalgae and CAC to dye were 482.2 and 267.2 mg/g respectively at pH of 2 and 25°C (Cardoso et al., 2012). The percentage removal of the dye using AC was 93.6–97.7%, while it was 94.4–99.0% using microalgae. In another study, the adsorption capacity for Remazol Red on CAC has higher than activated carbon prepared from olive stone (Uğurlu et al., 2008). The substitution of CAC by emerging alternatives needs a detailed study like a method of activation and other desirable properties of adsorbents.

Several factors that affect dye adsorption capacity include initial dye concentration, pH, temperature, the dosage of adsorbents and their type, contact time, etc. For certain dye adsorption, the optimum parameters of each sorbent vary significantly (Yadav et al., 2021), the optimization of each factor is helpful to large-scale industrial applications and the understanding of the adsorption mechanism. For an efficient treatment process, adsorbent should have enough mechanical strength and can tolerate various conditions of wastewater, high adsorption amount, and rapid adsorption

rate, effective to a variety of dyes or have selectivity for a certain pollutant, and easy to be regenerated and reused (Zhou et al., 2019).

Dyes from the industrial wastewater effluents are effectively removed by using activated carbon; however, it has some constraints such as capital cost, energy consumption, and loss of its ability after sorption-desorption cycles. To have effective removal of dyes, several economically available nonconventional adsorbents are required (Kandisa and Saibaba KV, 2016). Therefore, bioadsorbents obtained from fungal, bacterial, algal, and agricultural, or forest biomass are promising environmentally friendly adsorbents utilized for dye and heavy metal removal.

### 3 BIOADSORBENTS

Different technologies can be used for the treatment of wastewater containing dyes. Among them, biological methods are the most promising due to environmentally safe treatment capability (Przystaś et al., 2018; Batool and Valiyaveetil, 2021). A biological treatment especially biosorption using nonliving biomass is a relatively inexpensive way to remove dyes from the wastewater. The effective removal of dyes from the effluent depends on the unique surface chemistry with the presence of different functional groups in the cell wall of microorganisms (Karthik et al., 2016) such as alcohol, aldehydes, ketones, carboxylic, ether, phenolic, which make the bio-sorbents having a high affinity toward dye and attractive material for dye removal (Siddiqui et al., 2018). Biological materials including chitin, peat, chitosan, yeast, and fungi biomass are frequently used in the sorption of dye from the solution through the mechanism of chelation and complexation (Almeida and Corso, 2019).



TABLE 2 | Some of the applications of commercial activated carbon for removal of dye.

AC Adsorbents	Activated/ modified with	Type of dye used	Removal capacity (mg/g)	Fitted adsorption model	Fitted kinetic model	Used dye concentration (mg/L)	Mixing time (min)	Optimum sorbent dosage (g/L)	Optimum solution pH	Percentage removal (%)	Reference
Nano-activated carbon (NAC)	NaOH	Methylene blue (MB)	28.09	Langmuir	-	50	60	1.0	7	98.7	Shokry et al. (2019)
Commercial activated carbon (CAC), supplied by Merck 325–400 mesh size		Reactive violet 5 (RV-5)	517.1	Liu	General order	400	150		2	96.2	Ribas et al. (2014)
Copper-loaded activated carbon (Cu-AC)	HCl	MB	373	Langmuir	Pseudo-2nd order	400	240	2	7–8	99.5	Shu et al. (2017)
Norit Darco 12 × 20 (DARCO)	Chopping to get fine powder	Reactive Black 5	348	Langmuir-Freundlich	Pseudo-2nd order	0–700	800	1	10	-	Giannakoudakis et al. (2016)
Norit R008 (R008)			527								
Norit PK 1–3 (PK13)			394								
Pinus trees based AC (commercial)		Turquoise blue	-	Redlich-Peterson and Racke-Prausnitz	Pseudo-2nd order				2	-	Schimmel et al. (2010)

A good adsorbent used in the removal of dye must have several desirable properties including large surface area, high adsorption capacity, large porosity, easy availability, stability, feasibility, compatibility, eco-friendly, ease of regeneration, and highly selective to remove a different variety of dyes (Nasar and Mashkour, 2019). The pore volume of the bioadsorbents and functional groups of dyes are the deciding factors in achieving high dye adsorption. The presence of a large pore volume allows the binding of the highest number of dye molecules to the adsorbent (Hassan and Carr, 2021; Moosavi et al., 2020). Higher surface area, higher porosity, and low ash content lead to high adsorption capacity. Functional groups (hydroxyl, carboxyl, etc.) on the surface of biomass-based adsorbents are important properties determining the hydrophobicity or hydrophilicity of biochar as well as their adsorptive mechanism (Law et al., 2021).

The diversity of microbes consisting of different species of bacteria, fungi, yeast, and algae has been studied to remove dye molecules (Karthik et al., 2016). Besides the high sorption capacity toward dye, the dye removal performance can be improved by combining the biosorption process with the biodegradation processes by living cells (Singh and Singh, 2017; Roy et al., 2018). Many factors affect the biomass biosorption capacities including pH, bio-sorbent dose, initial dye concentration, temperature, contact time (Pearce et al., 2003). Recently, the potential of bio-sorbents prepared from bacterial, fungal, algal, yeasts, forest biomasses, and agricultural and industrial wastes has been studied for treating both dye-containing simulated and field wastewater.

### 3.1 Adsorbents From Fungal Biomass

Fungal biomasses are composed of sugars, proteins, and lipids, and different functional groups (alcohols, carboxyl, and alkanes) which provide it certain properties and applications as a biosorption in treatments of wastewater (Isaza-Pérez et al., 2020; Ahmed and Ebrahim, 2020). Biotreatment of dye-containing wastewater effluent by fungal cell was provided a cost-effective, easily applicable, eco-friendly (Salem et al., 2019; Argumedo-Delira et al., 2021), and absence of nutrient needs (Ghany et al., 2019). Different species of fungus have been used as an effective candidate for the removal of a variety of dyes from effluents such as *Trichoderma* sp. (Argumedo-Delira et al., 2021), *Sarocladium* sp. (Nouri et al., 2021), growing *Rhizopus arrhizus* (Gül, 2013), different varieties of white-rot fungi (Gnanadoss, 2013; Dai et al., 2018; Forgacs et al., 2004), *Aspergillus niger* (Salem et al., 2019; Asses et al., 2018), *Aspergillus flavus* (Mahmooda Takey, 2014), *Lentinus concinnus* (Bayramoglu and Yilmaz, 2018), *Penicillium simplicissimum* (Chen et al., 2020), *Pycnoporus cinnabarinus*, *Pleurotus ostreatus* and *Trametes hirsute* (Pecková et al., 2020), macro fungi spent mushroom waste (SMW) (*Agaricus bisporus*) (Ahmed and Ebrahim, 2020), *Trichoderma harzianum* (Karthik et al., 2020), and many others.

Bayramoglu and Yilmaz (2018) studied the removal of azo dye (Reactive Yellow 86 dye (RY-86)) using free (*Lentinus concinnus*) and immobilized fungal biomasses with polyvinyl alcohol/polyethylene oxide hydrogels (PVA/PEO) along with

isotherms, kinetics, and thermodynamic studies (Bayramoglu and Yilmaz, 2018). They reported, maximum RY-86 dye adsorption for the free fungal and composite fungal biomasses was 190.2 and 87.6, respectively, using 200 mg/L initial dye concentration at pH 5.0 with 2.0 h contact time (Table 3). Moreover, the equilibrium data were well described with the Freundlich and Temkin isotherm models. The adsorption of RY-86 dye was fitted best by the pseudo-second-order kinetic model. The adsorption performance of fungal biomass is dependent on the chemical structure and surface charge of several dyes associated with the electrostatic interaction. From FTIR studies, it was observed that the carboxylate, hydroxyl, and amine groups were involved in the adsorption of the RY-86 dye. Similarly, Bayramoglu and Arica (2018) reported that the amine, carboxyl, and hydroxyl groups are involved in the adsorption of the Congo Red by iminodiacetic acid and triethylenetetramine modified fungal biomasses of *Funalia trogii* (Bayramoglu and Arica, 2018).

Fungal biomass (*Trichoderma harzianum*) was used to remove Reactive Red-3 (RR3) from an aqueous solution (Table 3). The biosorption mechanism revealed that the fitted kinetics (pseudo-second-order) suggested the adsorption mode of chemisorption in which the adsorbate (RR3 dye) is monopolized over the external layer of the biomass by electrostatic interaction (Karthik et al., 2020). After all the vacant spots are monopolized, the RR3 dye starts propagating into the adsorbent opening for further interactions.

Table 3 summarizes the application of fungal immobilization to dye removal. Most species of fungi potentially achieved more than 90% of a specific type of dye except *Pleurotus ostreatus*, *Aspergillus flavus*, and *Diaporthe schini* which had a removal efficiency of 53%, 53.62, and 87%, respectively. This variation might be due to the poor monitoring of experimental conditions, the processing of bioadsorbents, and the availability of functional groups that have a limited binding capacity with the dye molecule.

It has been observed that (Table 3) in low pH solutions, the removal rate of anionic dyes is increased while the removal rate of cationic dyes is lower. Conversely, a high pH solution increases the removal of the cationic dyes and causes a low removal percentage for anionic dyes (Ahmed and Ebrahim, 2020). The point of zero charges ( $pH_{pzc}$ ) is an essential parameter for understanding the mechanism and the favorability of the adsorption process. The  $pH_{pzc}$  value indicates the type of active sites and the adsorption ability of adsorbents. When pH is greater than  $pH_{pzc}$  it is favorable for cationic dye adsorption due to the existence of functional groups ( $OH^-$ ,  $COO^-$ ), whereas anionic dye adsorption is favorable at pH less than  $pH_{pzc}$  because the surfaces of adsorbents become positively charged (Zhou et al., 2019). In general, the use of fungal biomass is a promising substitute to the current technologies for dye decoloration and adsorption. In addition to optimizing the environmental parameters, considering the genotype and the preparation of the biomass are important for effective dye adsorption performance.

### 3.2 Adsorbents From Algae Biomass

Algae are considered one of the sources of the most favorable types of bio-sorbents because they have high biosorption capacity

and are easily available in large amounts (Singh and Singh, 2017; Azam et al., 2020). The biosorption depends on the composition and structure of the algal cell wall, which is made up of several polysaccharides: xylan, mannan, alginic acid, chitin. These components, along with the proteins present, can provide acid-binding sites such as amino, amine, hydroxyl, imidazole, phosphate, and sulfate groups (Singh et al., 2018). Encapsulation and surface modification can be used as pretreatment methods to improve the adsorption capacity of algae. Citric acid-functionalized brown algae were reported to improve the adsorption capacity for textile dye (crystal violet) removal in aqueous solutions (Table 4). An optimum monolayer uptake capacity of 279.14 mg/g was reported for the modified algal adsorbent (Essekri et al., 2021). Moreover, electrostatic attractions and  $\pi$ - $\pi$  interactions were responsible for the dye adsorption toward the algal biomass surface. Magnetically responsive brown algae (*Sargassum horneri*) was utilized for the adsorption of five water-soluble dyes. The magnetic modification leads to rapid and selective separation through an external magnetic field by using microwave-synthesized iron oxide nano and microparticles (Angelova et al., 2016). The sorbent had maximum sorption capacity for acridine orange (193.8 mg/g) but lower for malachite green (110.4 mg/g) at 2 h contact time.

Table 4 revealed that *Spirulina* and *Chlorella* species are common types of microalgae studied and achieved up to 99% removal efficiency. Similarly, *Sargassum* species of macro algae are commonly studied and can remove more than 90% of dyes. MB is among the common dyes removed by various dye species. The type of dye to be removed significantly depends on the pH of the solution. Anionic dyes are removed in acidic conditions and cationic dyes (e.g. MB) in alkaline conditions. This is due to the involvement of  $H^+$  ions in the biomass-pollutant interaction process. If the surface of the adsorbent possesses a positive charge, the hydrogen ions ( $H^+$ ) may compete productively with the cations present in the dye solution, resulting in a decrease in the amount of adsorbed dye. The carboxyl groups have a negative charge at a higher pH, which results in electrostatic binding of the cationic dyes. Moreover, the biosorption performance is strongly influenced by other parameters including the processing of biomass into adsorbent, initial contaminant concentration, biomass dosage, temperature, and contact time.

### 3.3 Adsorbents From Bacterial Biomass

The role of bacteria in bioremediation applications can be based on the adsorption of contaminants from aqueous media (Sarvajith et al., 2018) through different mechanisms using dead biomasses (Roy et al., 2018). Their small size, ubiquity, and capability to grow under varying environmental conditions make them good adsorbents (Singh et al., 2018). Bacterial species have been proved to be highly effective to treat wastewater containing reactive dyes by adsorption under optimized environmental conditions (San Keskin et al., 2015; Mishra and Maiti, 2018; Zabłocka-Godlewska et al., 2018). The bacterial dye decolorization rates vary with the type of bacteria, the reactivity of dye, and operational parameters such as temperature, pH, co-substrate, electron donor, and dissolved oxygen concentration. As

**TABLE 3** | Application of some species from fungal biomass for dye removal.

Adsorbent source/species	Modified with	Type of dye	Adsorption capacity	Fitted adsorption model	Fitted kinetics model	Mixing time (hr)	Optimal sorbent dosage (g/L)	Dye concentration (mg/L)	Optimal pH	Percentage removal (%)	Reference
Dead- <i>Trichoderma harzianum</i>		RR3	172.63	Freundlich	Pseudo-2nd order	12.5	0.5	100	4	95	Karthik et al. (2020)
Dead- <i>Aspergillus flavus</i>		Methyl orange	-	-	-	0.67 (40 min)	2.0	1.0	5.5	53.62	Mahmooda Takey, (2014)
Dead- <i>Pleurotus ostreatus</i>	Heat	Allura Red AC (AR)	118.3 ± 9.9	Langmuir		1		250	5	53	Pecková et al. (2020)
<i>Lentinus concinnus</i>		RY-86	190.2	Freundlich and Temkin	Pseudo-2nd order	2	1.0	200	5	97.6	Bayramoglu and Yilmaz, (2018)
<i>Funalia trogii</i>	Triethylenetetraamine (TETA)	Congo Red	193.7	Langmuir	Pseudo-2nd order	0.5	1.0	200	5	96.6	Bayramoglu and Arica, (2018)
<i>Neonectria radicicola</i>	-	Acid Orange 51, Reactive Red 75, Direct Blue 86 (DB)	120.6, 75.37 and 200.5	Redlich-Peterson	Pseudo-1st order	1	1.0	50	2	94.9, 97.3, 99.6 respectively	Ghariani et al. (2019)
inactive <i>Phoma sp.</i>	-	Acid Red 18 (AR)	63.58	Langmuir	Pseudo-2nd order	3	1.25	200	2	90	Drumm et al. (2019)
Inactive- <i>Diaporthe schini</i>		Crystal violet (CV)	642.3	Sips	Elovich	3.5	0.4	100	7.5	87	Grassi et al. (2019)
<i>Aspergillus niger</i> strain		Red azo dye		Freundlich		2	3.5	500	9	99.4	Mahmoud et al. (2017)
<i>Trametes sp.</i> SC-10	heat-treated	Acid Blue 161	221.6	Langmuir	Avrami fractional-order	6		600		89.47	Puchana-Rosero et al. (2017)
Dead- <i>Aspergillus fumigatus</i>		MB		Langmuir and Freundlich		2	2.0	12	7	93.43	Kabbout and Taha, (2014)

**TABLE 4 |** Application of some of the species from algal biomass for dye removal.

Alga Adsorbent source/species	Algal types	Modified with	Type of dyes	Adsorption capacity (mg/g)	Fitted adsorption model	Fitted kinetics model	Mixing time (hr)	Optimal sorbent dosage (g/L)	Dye concentration (mg/L)	Optimal pH	Removal efficiency (%)	Reference
<i>Spirulina platensis</i>	Microalgae	Ultrasonic-assisted	Naphthol green-B	137.9	Freundlich	Pseudo-1st order	1	3	100	3		Gunasundari et al. (2020)
<i>Spirulina platensis</i>	Microalgae		Reactive Red 120	482.2	Liu					2	94.4–99.0	Cardoso et al. (2012)
-	Green microalgae	Calcination	Malachite green		Langmuir	Pseudo-2nd order	0.25		20ppm	9	93.9	Amreen et al. (2020)
<i>Spirulina sp.</i>	Microalgae	Silica coated with magnetite particles	MB	90.90	Freundlich		1		100	6	>97	Kausar et al. (2020)
<i>Chlorella pyrenoidosa</i>	Microalgae		Rhodamine B	63.14	Sips	Pseudo-2nd order	2		100	8		da Rosa et al. (2018)
<i>Chlorella vulgaris</i>	Microalgae		MB		Freundlich		72		100		83.04 ± 2.94	Chin et al. (2020)
<i>Chlorella sp.</i>	Microalgae	Wet torrefaction process	MB Congo red	113.00 164.35	Langmuir		120 4	1 2	210 ppm 450 ppm	7	-	Yu et al. (2021)
Brown algae (BA)	Brown algae	Citric acid-functionalized	CV	279.14	Langmuir	Pseudo-2nd -order	1	1	20	6.5	90	Essekri et al. (2021)
<i>Sargassum muticum</i>	Brown algae		MB	92	Langmuir	Pseudo-2nd -order	0.5	0.3g	39	5		Hannachi and Hafidh, (2020)
<i>Sargassum horneri</i>	Brown algae	Iron oxide nanoparticles	Acridine orange	193.8	Langmuir	Pseudo-2nd order	1.5	30 mg	250		>90	Angelova et al. (2016)
embedding of <i>Ulva fasciata</i> and <i>Sargassum dentifolium</i>	Macro-algae	Cellulose acetate (CA)	MB		Langmuir	Pseudo-2nd order	0.5	20	100	7	98	Moghazy et al. (2020)
<i>Phormidium animale</i>	Blue-green algae	-	Remazol Black B	41.667	Langmuir	Pseudo-2nd order	24	4	93.16	2	99.66	Bayazit et al. (2019)
<i>Enteromorpha flexuosa</i>	Green macroalga	Microwave-assisted	Crystal violet	119.02	Langmuir	Pseudo-2nd order	0.02 (1 min)	1.5	20		90.3	Elgarahy et al. (2019)
			MB	126.79	Langmuir	Pseudo-2nd order		1.5	20		93.4	
Dried- <i>Phormidium animale</i>	Blue-green algae	-	Acid Red P-2BX (ARP-2BX)	100	Langmuir	Pseudo-2nd order	24	4	91.71	2	99.7	Gül et al. (2019)
<i>D. antarctica</i> (dried)	Brown algae		MB	702.9	Toth	Pseudo-2nd order	9			10		Guarín et al. (2018)
<i>Chlorella vulgaris</i>	Microalgae		MB	275	Freundlich		72		100		83.04	Chin et al. (2020)

TABLE 5 | Some of the species from bacterial biomass studied for the application of dye removal.

Bacterial adsorbent source/species types	Modified with	Type of dyes	Adsorption capacity (mg/g)	Fitted adsorption model	Fitted kinetics model	Mixing time (min)	Dye concentration (mg/L)	Optimal sorbent dosage (g/L)	Optimal pH	Removal efficiency (%)	Reference
<i>Aureispira</i> sp. (CCB-QB1)	Formaldehyde (0.5%)	Congo red	1.48	Langmuir	Pseudo-2nd order	60	0.2%	0.5	7.6	88.1	Hasyimah et al. (2020)
<i>Gluconacetobacter hansenii</i>		Remazol Black B	17.513	Langmuir	Pseudo-2nd order	80		0.5	3.5	92	Leal et al. (2021)
<i>Bacillus</i> sp.	Sodium alginate	reactive Brilliant Red	588.235	Langmuir I		1440		8	3		Horciu et al. (2020)
<i>Penaeus indicus</i> shell biomass		Acid Blue 25 (AB25)	415.33			40	116.45	0.27	2	95.64	Kousha et al. (2015)
<i>Rhodopseudomonas palustris</i>		Fast black K salt		Freundlich			100	1	8	72	Öztürk et al. (2020)
Polysulfone <i>Escherichia coli</i> composite	poly(acrylic acid) (PAA)	MB	225.2	Langmuir		300	200		7		Kang et al. (2020)
<i>Acidithiobacillus thiooxidans</i>		Sulfur blue 15 (SB15)	769.2	Langmuir	Pseudo-2nd order	20	2000	1.0	8.3	87.5	Nguyen et al. (2016)
<i>Rhodococcus erythropolis</i> AW3		CV	289.8	Langmuir	Pseudo-2nd order	90	50	0.5	9	93	Canizo et al. (2019)
<i>Bacillus catenulatus</i>	HCl	Basic blue 3	139.74	Langmuir	Pseudo-2nd order	10	2000		9		Kim et al. (2015)

shown in **Table 5** the literature revealed that *Pseudomonas* spp. are relatively more successful to treat reactive dyes-containing wastewater (Mishra and Maiti, 2018; Eslami et al., 2016). Treatment of textile dyes using extremophiles can effectively be achieved. For example, 87% of Reactive Black and 85% of Reactive Red dyes were removed by haloalkaliphilic bacteria grown from textile wastewater (Seyedi et al., 2020).

Kim et al. (2015) isolated the bacterial strains (*Bacillus catenulatus* JB-022) from polluted ponds and soils for the biosorption of cationic dye. The isolate achieved 58% of cationic basic blue dye removal at the initial concentration of 2000 mg/L. The maximum sorption capacity for basic blue dye was found to be 139.74 mg/g from the Langmuir adsorption isotherm. The presence of carboxyl and phosphonate groups at the adsorbent surfaces can act as a potential surface functional groups capable of binding to cationic pollutants (Kim et al., 2015). Several functional groups on the *Penaeus indicus* biomass surface were likely involved in Acid Blue 25 dye binding, but the amino groups, alpha-chitin were by far the most important ones (Kousha et al., 2015). *Bacillus subtilis* had been immobilized in calcium alginate bead and utilized in batch and continuous reactor for the removal of MB. The kinetic study in the batch and continuous contactor gave greater than 90% removal (Uppendar et al., 2016).

Different biocomposites have been reported for improved performance of dye removal (Chen et al., 2019; Hu et al., 2019). A bacterial strain (*Clavibacter michiganensis*) was studied for the removal of a reactive dye by joining with electrospun polycaprolactone and polylactic acid nanofibrous polymeric webs (Sarioglu et al., 2017b). The biocomposite was a promising material for the treatment of textile dyes with reusable and improvable properties. Moreover, electrospun nanofibrous-encapsulated bacterial cells were utilized for MB dye treatment (Sarioglu et al., 2017a). In another study, a design of a paper-like multifunctional purifier that has a biomass-based structure by embedding polyethyleneimine derived from ammonium compounds onto the substrate of bacterial cellulose was reported with higher adsorption capacities toward anionic dyes (including methyl orange, congo red, and methyl red) (Hu et al., 2019). Kang et al. (2020) used polysulfone and *Escherichia coli* biomass to prepare polysulfone *Escherichia coli* biomass composite fiber (PSBF) and they combined poly(acrylic acid) (PAA) at the surface of the composite. The adsorption performance of the prepared material on MB was studied by considering several parameters; they found an adsorption capacity of 225.2 mg/g at a pH of 7 fitted by Langmuir isotherm (Kang et al., 2020). Moreover, the regeneration ability of the composite was tested by desorption using an HCl-acidified solution at a pH of 2 as an eluent and the material can be reused at least 3 times.

**Table 4** revealed that Langmuir isotherm was fitted by most biosorption studies, indicating that the monolayer coverage adsorption was the dominant process. Similarly, the pseudo-2<sup>nd</sup>-order kinetic model showed the best model fit. The adsorption involves valency forces through the sharing or exchange of electrons between the adsorbent and dye molecules by covalent forces and ion exchange (Mohd Nasir et al., 2021). At acidic pH maximum biosorption has been

occurred in the case of metallic cations due to the involvement of the carboxyl functional group present in the bacterial cell walls, which is responsible for binding metal ions via different mechanisms. The fidelity of biosorption depends not only on the kind of ions but also on the type of bacterial species due to variation in their cell wall compositions (Roy et al., 2018). The presence of different anionic functional groups, gram-negative bacteria containing phospholipids, peptidoglycan, and lipopolysaccharides, and in the gram-positive bacteria including peptidoglycan, teichoic acids were responsible for the metal-binding capacity of the bacterial cell wall. Extracellular polysaccharides have also the ability to bind ions.

### 3.4 Adsorbents From Yeasts

Yeast is a single-celled organism, a member of the kingdom of fungi that have many favorable applications in the treatment of dye-containing solutions due to their high capacity to adsorb and accumulate pollutants, fast growth, faster decolorization than filamentous fungi, and the ability to survive unfavorable environments (Sen et al., 2016). The yeast surface consists of several functional groups including carboxyl hydroxide, polymer, amino, and phosphate, etc. that affect the desired pH of the solution to be analyzed (Singh et al., 2020).

Several studies revealed the bio-adsorption of different dyes using yeast biomass. Different species of yeast that could potentially remove different types of dyes are summarized in **Table 6**. Several factors including pH of the solution, the concentration of pollutants, and mass of yeast, temperature contact time influence the bio-sorption method (Al-Najar et al., 2021). For example, in the optimal condition of pH = 2, biomass dose = 2.0 g, and temperature = 30°C, complete

decolorization of indigo dye was achieved by yeast (*Diutina rugosa*) biomass (Bankole et al., 2017). NADH-DCIP reductase and lignin peroxidase played a major role in the asymmetric cleavage, initial reduction, and deamination of indigo dye. Ramazole blue was also decolorized effectively by Baker's yeast cells, but pH of the solution, bio-sorbent dosage, initial dye concentration, and contact times significantly affect the removal process (Mahmoud, 2016; Dil et al., 2017).

Ruscasso et al. (2021) investigated the biosorption of two reactive dyes (Reactive Blue 19 (RB 19) and Reactive Red 141 (RR 141)) using the Antarctic yeast (*Debaryomyces hansenii* F39A) with considering several factors. They found that 90% of RR 141 and 50% of RB 19 was adsorbed at pH 6.0, initial dye concentration of 100 mg/L, and 2 g/L biomass dose, but when the dosage of biomass was increased to 6 g/L the adsorption of RB 19 increased to 90%. Moreover, the adsorption process followed pseudo-second-order kinetics for each dye system and the Langmuir isotherm was the best fitted model (Ruscasso et al., 2021).

Semião et al. (2020) studied the adsorption performance of residual yeast and diatomaceous earth for the removal of Reactive Blue 160 dye (RB 160). They found that the two biosorbents had a dye removal capacity of 8.66 mg/g and 7.96 mg/g respectively at a pH of 2 (Semião et al., 2020). The positive charge in the biomass functional group is responsible for the chemical interaction with the anionic dye. Biosorption of yeast isotherm data was better fitted by the Freundlich isotherm model, but for diatomaceous earth, Langmuir isotherm was fitted indicating that the active sites of residual yeasts are more heterogeneous. In another research, the brewer's yeast biomass was assessed as a biosorbent for removal of basic dyes (safranin O (SO), MB, and malachite green (MG)) from aqueous solutions within 1 h

**TABLE 6** | Some of the studied yeast species used for dye removal.

source/species of yeast biomass	Type of dye used	Adsorption capacity (mg/g)	Fitted adsorption model	Fitted kinetics model	Contact time (hr.)	Dye concentration (mg/L)	Optimal sorbent dose (g/L)	Optimal pH	Removal efficiency (%)	Reference
<i>Debaryomyces hansenii</i> F39A	RB 19	0.0676–0.169 mmol/g	Langmuir	Pseudo-2nd order		100	2 6	6	90 90	Ruscasso et al. (2021)
	RR 141									
<i>Saccharomyces cerevisiae</i>	Ramazole blue		Freundlich		1	100	0.25 g	2	100	Mahmoud, (2016)
<i>Diutina rugosa</i>	Indigo dye		Temkin		120	10	2.0 g	2	99.97	Bankole et al. (2017)
<i>Yarrowia lipolytica</i>	CV	56.497	Langmuir	Pseudo-2nd order	16	8		7	98.82	Dil et al. (2017)
	Brilliant Green	65.359			16	10		7	99.93	
	Acid Scarlet 3R							5–6	>90	
<i>Scheffersomyces spartinae</i>	Reactive blue 160	8.66	Freundlich	Pseudo-2nd order	4	150	10	2	-	Tan et al. (2016) Semião et al. (2020)
Residual yeast (brewery industry)										
Brewer's yeast biomass (BYB)	MB	212.05		Pseudo-2nd order	1	30	1.7	6		Lin et al. (2019)
	malachite green									
	Reactive Red 239	152.9	Langmuir	Pseudo-2nd order	0.5		0.63	2		de Castro et al. (2017)
	Direct Blue 85	139.2		order	1			2		

(Table 6). The adsorption kinetics of MB and MG followed pseudo-second-order, while SO followed pseudo-first-order. The maximum monolayer adsorption capacities of BYB for MB, MG, and SO were 212.05, 212.05, and 76.77 mg/g, respectively. Hydroxyl group, cyano group, and other functional groups are the major sources of adsorption by yeast (Lin et al., 2019). Table 6 revealed that most studies showed the best fit for Langmuir isotherm and pseudo-second-order kinetic models, suggesting the dominance of monolayer chemisorption except some yeast species in which the Freundlich and Temkin isotherm models showed the best fit model.

### 3.5 Adsorbents From Forest or Agricultural Debris Wastes

The utilization of agricultural wastes and plants for the adsorptions of organic pollutants and inorganic pollutants is treated as an alternative to conventional wastewater treatment methods (Mo et al., 2018). Several studies have been conducted in the use of nonconventional, naturally occurring, low-cost biomass as adsorbents such as seeds, straw, fruit peels, leaves, bark, sawdust, ash, sludge, and others that are easily available. Different studies show that the dye adsorption abilities of those biomasses mainly depend on the types of dyes as well as the techniques of processing (Deniz and Kepekci, 2017); (Kharat, 2015).

Rice husk, sawdust, and bark are commonly used abundant, cheap, and low-value by-products for the preparation of adsorbent materials that are used in the removal of dye (Chuah et al., 2005); (Amirza et al., 2017). Sewu et al. (2017) prepared biochar from Korean cabbage (KC), rice straw, and wood chip and can be used as an alternative to activated carbon to remove Congo red and CV (Sewu et al., 2017), but KC had better adsorption performance than others. Potato peel biochar was considered a promising adsorbent for removing Cibacron Blue dye. The sorption ability of this waste follows the order: calcined > activated > native materials (Bouhadjra et al., 2021).

Activated carbon provided from *Persea Americana* was suggested for basic yellow dye removal from wastewater with 98% removal. This activated carbon can substitute the commercially available adsorbents (Regti et al., 2017). Pathania et al. (2013) synthesized *Ficus carica bast* (FCBAC) AC that showed an encouraging adsorption capacity for MB with a low amount of operating parameters such as an initial dye concentration of 0.5 g/L, sorbent dosage (5 g/L), contact time 1.3 h, and temperature (30°C) at a pH of 7.8 (Pathania et al., 2013). The isotherm models confirmed that the sorption is heterogeneous and occurred through physicochemical interactions.

Watermelon peels were used in the preparation of modified biochar with ozone initially and further modification with ammonium hydroxide and triethylenetetramine for the removal of Acid Yellow 11 (AY11) dye (El Nemr et al., 2020). The sorption study revealed that the capacity of prepared watermelon biochars was ranged between 76.94 and 462.18 mg/g at pH of 1.0, contact time of 3 h, and room temperature, and more than 96% removal of AY11 was achieved. Moreover, the isotherm model fitted Freundlich

and Langmuir isotherm and the kinetics followed the pseudo-second-order model. Electrostatic interaction was responsible for the primary mechanism controlling the adsorption of AY11 dye onto the biochars. In another study, pea (*Pisum sativum*) peels were used to prepare biochar for the removal of Acid Orange 7 (AO7) dye with a similar modification process stated in the utilization of watermelon peels for AY11 removal. The adsorption capacity of the modified biochar was significantly enhanced from 78.18 to 523.12 mg/g at equilibrium. Up to 98% of AO7 was removed by triethylenetetramine-modified biochar, while 96% removal was achieved using unmodified biochar (El-Nemr et al., 2020).

Mandarin (*Citrus reticulata*) peel (MP) was utilized in the removal of SO from aqueous solution with the maximum adsorption capacity of 464 mg/g, 0.4 g/L adsorbent dose, 2 h contact time, and 84.75% removal. Hydrogen bonds,  $\pi$ -interactions, and electrostatic interactions were the possible adsorptive mechanisms of SO removal (Januário et al., 2021). Moreover, the desorption study revealed that the adsorption capacity was maintained more than 50% after four cycles.

Agricultural and forestry wastes are generally rich in cellulose, hemicellulose, and lignin. Its surface comprises several active groups including hydroxyl, carboxyl, amino, carboxyl, methyl, and so on (Zhou et al., 2019). These functional groups can adsorb dyes through mechanisms of complexation, hydrogen bonding, ion exchange, etc (Dai et al., 2018). Various agricultural and forest waste materials are summarized in Table 7 along with the biosorption capacity and the required reagents to activate them. Different acids have been used to activate the bio-sorbents to enhance the binding sites, the chemistry of the aqueous solution, to improve porosity and specific surface area. For example, phosphoric acid stimulates bond cleavage in agricultural waste biomass to increase the carbon yield (Bello et al., 2019). Phosphoric acid promoted dye biosorption by grafting phosphate functions onto the biomass and enhancing the acid functions involved in dye fixation (Benabbas et al., 2021). Moreover, H<sub>2</sub>SO<sub>4</sub>, NaOH, and KOH are the common activating agents during the preparation of agricultural waste-based bioadsorbents (Table 7).

Several environmental conditions including adsorbent dosage, temperature, contact time, pH of the solution, the particle size of the plant-based adsorbent, agitation, and initial dye concentration significantly affect the biosorption process. The pH of the solution affects both the chemistry of the aqueous solution and the binding sites present on the surface of adsorbents (Kumar et al., 2021).

## 4 Cost Analysis of Biomass-Based Adsorbents

Several authors reported that the cost of bioadsorbents prepared from microbes and forest and agricultural waste is low as compared with conventional treatment technologies, although they did not incorporate cost-benefit analysis in their study. The advantages of biosorption are related to the nature of adsorbent material used in the adsorption processes of dyes. To be economical, the availability of a large quantity of adsorbent material and the ease of preparation or processing, and the requirements of activation are significantly important along with the concepts of green chemistry (Bulgariu et al., 2019).

**TABLE 7** | Applications of agricultural debris wastes for adsorptive removal of dyes.

Sources of waste biomass	Modified with	Type of dye used	Adsorption capacity (mg/g)	Fitted adsorption model	Fitted kinetics model	Mixing time (min)	Dye concentration (mg/L)	Optimal sorbent dose (g/L)	Optimal pH	Removal efficiency (%)	Reference
Locust bean pod	Ortho-phosphoric acid	Rhodamine B (RhB)	1111.1	Langmuir	Pseudo-2nd order	95	1000	0.1	2.87	95	Bello et al. (2019)
pine cone	NaOH solution	Malachite green	111.1	Langmuir	Pseudo-2nd order	60				80	Kavci, (2020)
<i>Persea americana</i> AC (C-PAN)	Phosphoric acid (H <sub>3</sub> PO <sub>4</sub> )	Basic Yellow 28	400	Langmuir	Pseudo-2nd order	30	100	0.2	-	98	Regti et al. (2017)
<i>Ficus carica</i> bast	H <sub>2</sub> SO <sub>4</sub>	MB	55.56	Langmuir and Tempkin	Pseudo-2nd order	80	500	5	7.8	88	Pathania et al. (2013)
Lime-peel	KOH	Malachite green		-	-	60	100	2		94.68	Ahmad et al. (2017)
Dead leaves of oak trees	No modification	CV	31.65	-	-	60	50	0.1	7		Sulyman and Gierak, (2020)
Sea plant ( <i>Posidonia oceanica</i> L.)	before the study	MB	27.78								
Grass waste	H <sub>3</sub> PO <sub>4</sub>	MB	241.2	Langmuir and Temkin				0.8	10		Jawad et al. (2020)
Pine-apple crown leaf	KOH and magnetite (Fe <sub>3</sub> O <sub>4</sub> )	methyl violet				180	20	6	5	>97	Astuti et al. (2019)
Potato peel waste	H <sub>3</sub> PO <sub>4</sub> & calcination	Cibacron Blue P3R	270.3	Langmuir		180			2.2	94	Bouhadjra et al. (2021)
Corncoobs	KOH and heat	MB	523.18	Langmuir	Pseudo-2nd-order		150	0.3	5	99.52	Sun et al. (2021)
<i>Ficus carica</i> bast (FCBAC)	H <sub>2</sub> SO <sub>4</sub>	MB	-	Langmuir and Tempkin	Pseudo-2nd order	0.5	80	5	7.8	85	Pathania et al. (2013)
activated carbon from beverage sludge (ACBS)	HCl solution	Allura Red AC	287.1	Freundlich	Pseudo-2nd order	50	60	0.25	2	90	Streit et al. (2019)
		CV	640.7	Sips	Pseudo-2nd order	50	60	0.25	8	98	



The cost of forest wastes is only associated with the transport cost from the storage place to the site where they will be utilized (Adegoke and Bello, 2015). Some authors argue that the naming of “low-cost adsorbents” actually only indicates their original prices so that their local availability, transportation, treatment process, and both recycle and lifetime issues, and the processes of regeneration and treatment should be critically investigated (Zhou et al., 2019). Unfortunately, most studies on biomass-based adsorption have been conducted on the laboratory scale using simulated wastewater, so that the cost analysis of the biomass-based adsorbents is limited, particularly for microbial biomass.

A comprehensive cost analysis was carried out for the biochars made from agro-waste (Coconut shell, Groundnut Shell, and Rice husk) for their adsorption performance of the Basic Red 09 dye removal from wastewater. It was estimated that the cost of 1 g of adsorbent is ₹4.54, ₹0.91, and ₹0.97 for Coconut shell, Groundnut shell, and Rice husk, respectively, by considering operational costs including manufacturing costs, maintenance costs, feedstock costs, transportation costs, labor costs, and the distribution costs (Praveen et al., 2021). Groundnut shell-based biochar had maximum adsorption capacity (46.3 mg/g) as well as the least cost (₹0.91) per unit gram of Basic Red 09 dye removal. Bello et al. (2019) prepared phosphoric acid-functionalized locust bean pod AC for the removal of RhB dye and studied the preliminary cost analysis of this adsorbent. They concluded that the AC prepared from this plant material was approximately six times cheaper than conventional AC. Phosphoric acid and deionized water contribute most of the cost (Bello et al., 2019).

## 5 Regeneration of Bioadsorbents

After the adsorption process is accomplished, the desorption process is of great importance to regenerate and reuse those used adsorbents and to reduce the generation of waste as well as to keep the process price down (Zhou et al., 2019). The common desorption methods include thermal treatment, acid ( $H_2SO_4$ ,  $HNO_3$ , HCl,  $H_3PO_4$ , NaOH) treatment, organic solvents (methanol and ethanol), biological methods, and vacuum methods (Hassan and Carr, 2021). In the case of the solvent desorption process, the eluent (dye-saturated substrate) is mixed with the appropriate solvent to extract the dye and then separate the adsorbent by filtration. The dye-solvent mixture is dried to evaporate the solvent (Zhou et al., 2019).

The regeneration process should be cost-effective and should have potentially low energy consumption. Some authors stated that the recovery step of powder-activated carbons is very costly, time-consuming, and not very efficient so that they are not suitable for industrial applications (Moosavi et al., 2020), and more particularly reusability is almost impossible for low-cost products (Saha et al., 2020). However, some studies report the regeneration of biomass-based adsorbents (Essekri et al., 2021; Elgarahy et al., 2019; Kang et al., 2020; Pathania et al., 2013; Yang et al., 2021). Saha et al. (2020) studied Congo red loaded java citronella (*Cymbopogon winterianus*) based bio-adsorbent and commercial AC regeneration using ethanol. They found 90.3 and 83.7% desorption for biomass and commercial AC, respectively,

from dye-loaded adsorbents (Saha et al., 2020). Moreover, the adsorbents were effective up to two adsorption-desorption cycles. In another study, the adsorption capacity of biosorbent prepared from mandarin (*Citrus reticulata*) peels was maintained more than 50% after four cycles (from 77.90 to 41.55 mg/g) during the removal of Safranin orange (SO) dye. HCl was the best chemical that had a good performance during desorption (Januário et al., 2021). Dahiru et al. (2018) reported the efficiency of the banana peel-based adsorbent for the removal of Malachite green (MG) and Methylene blue (MB) decreased from 100 to 64% and 76% after 5 consecutive usages respectively (Dahiru et al., 2018).

## 6 Biosorbent Prospects for Dye Adsorption

Various adsorbents can be prepared, modified, and applied to different contaminants in the environment. The preparation process for the activation and modification of adsorbents determines their characteristics. In general, the most critical characteristics of a good adsorbent are surface area, void active sites, and reproducibility in the activation processes (Leng et al., 2021). Among all the adsorbents, the biomass-derived adsorbent is preferred comparatively having the highest surface area, regardless of the activation techniques, depending on source types resulted in increasing the adsorption of the contaminants.

Among the adsorbents, bioadsorbents are the most popular for the adsorption of dyes, contaminants in general, from wastewater due to their versatility, cost-effectiveness. Also, their byproducts are not hazardous, and in addition to easy operation. Moreover, the biomass-derived adsorbents are commonly cellulose-based structures and can produce a good porous carbon that can adsorb various types of contaminants in the natural environment. One of the important features for the use of biomass-derived adsorbent for removal of dyes is that it can be used on a large scale because of its huge availability. Also, biomass-derived adsorbents have high affinity/binding capacity for various types of contaminants, and also have good regeneration capacities. In addition, their good surface chemistry such as pore distribution, specific surface area, and functional groups helps for the removal of dyes in the wastewater (Sherugar et al., 2022).

However, environmental factors such as temperature, pH, ionic strength, nutrient availability, photodegradation through natural light, which can arise in some seasonal and temporal variations, may affect structural characteristics and chemical constituents of the biomass. Thus, this can strongly affect the real adsorption capacity of biomass-based adsorbents. As a result, the biomass-derived adsorbents should be well characterized to understand the adsorption mechanisms for certain contaminants. In addition, studies should be conducted in a multi-pollutant system to meet the requirements of real wastewater treatment containing diversified contaminants that can assure stability resulted in the suitability of biomass for the practical biosorption process (Zhou et al., 2019).

The other most significant constraint for utilizing biomass-derived adsorbents for dye removal is the scaling up and cost analysis. Although there are several available low-cost adsorbents, their processing and improvements (activation, cross-linking, drying, autoclaving, etc.), modification, and transportation cost

should be considered to improve the selectivity of a certain pollutant with the corresponding sorption capacity. In addition, the recovery or regeneration procedure may also need a significant amount of energy and solvents depending on the activation processes used. After the dye-removal from wastewater, the effective utilization, and handling of the adsorbent and the eluent containing the contaminants more concentrate is important. The major solution for this management is the reuse and regeneration of the adsorbent several times using efficient regenerating agents (Patel, 2021). After complete exhaustion of the adsorbents, dumping, storing, or disposing of are options but safe disposal is necessary (Vakili et al., 2019). The potential solutions for safely disposing of the final effluent include stabilization and immobilization, for example, using a cement-based system as a binding agent (Dey et al., 2017). Consequently, difficulties are faced in the comparison among them. This indicates the necessity for more researches that can compare the superiority of an effective dye removal technique over the other.

## 7 CONCLUSION AND RECOMMENDATION

The review gave a general overview on the removal and degradation of dyes from wastewater using conventional removal technologies and biomass-based adsorbents with particular emphasis on the various bio-adsorbents such as biomasses from fungi, bacteria, algae, yeast, forest, and agricultural wastes. The review reveals that the conventional dye treatment methods have some particular limitations related to operation efficiency, total cost, energy, and generation of toxic by-products, although they have good performances to a particular pollutant. The adsorption method is a good water and wastewater treatment process due to its suitability, ease of operation, and simplicity of design. Among different available adsorbents, biomass-based treatments are found to be the recent materials employed at various sectors to remove dyes and other pollutants. Distinctive surface chemistry with the incorporation of several functional groups (alcohol, ketones, aldehydes, carboxylic, ether, phenol) makes those bio-sorbents with a high attraction toward dye and makes the biomass-based adsorbents effective material for dye removal. The bio-sorption process is affected by various environmental parameters such as pH, initial dye concentration, temperature, contact time, and adsorbent dose

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as well as the ways of the preparations of materials. Although most biomasses achieved a good removal efficiency, each study reviewed has considered different parameters for efficiency determination. Thus, making the comparison among them difficult, most parts of each biomass reviewed show a remarkable removal efficiency of up to 99%. More studies are important that can compare and define the superiority of biomass over the other. Basic dyes (particularly MB and CV) are among frequently studied types of dye by most biomass-based adsorbents reviewed, of which 83–99% removal efficiency is reported.

Most of the studies on biomass-based adsorption concentrated on the removal of a single pollutant, however, in real dye-containing wastewater, like textile industries that usually comprise a mixture of many dyes. For practical applications, further studies should be conducted in the mixed and multi-pollutants system to satisfy the requirements of wastewater treatment. The adsorbent's stability and the cost of adsorbents are also essential parameters that can determine the suitability of the adsorbent for practical applications. Most of the reported researches are limited to laboratory assessments of adsorption capacity, while the cost analyses are neglected, all factors are needed to be considered such as the local availability, transportation, treatment process, and both recycle and lifetime issues. Desorption study is also an essential activity to keep the process price down, recover the adsorbed compounds, and minimize the amount of waste.

## AUTHOR CONTRIBUTIONS

TA: Review contents construction, Supervising, Writing—review and editing, Proofreading. FB: Writing—First draft, Formal analysis, Graphics, and synthesis.

## ACKNOWLEDGMENTS

The authors thank their expertise for their constructive comments and proofreads. Also, the authors thank the researchers and/or scientists, and organizations for their contribution in the field, and apologize if any fault on the scientific papers or do not adequately acknowledge the scientific papers.

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