Review Article

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Sustainable Dye Wastewater Treatment: A Review of Effective Strategies and Future Directions

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The environment and living things are negatively impacted by dye effluents from various industries. Dye effluents must be treated using a sustainable, efficient process. To lessen its negative impacts, dye wastewater must be treated before being released. Through an analysis of prior studies on biological, chemical, and physical procedures, this study assesses the effectiveness of various dye removal strategies. Common physicochemical techniques that efficiently decrease pollutants include sorption, ion exchange, and coagulation. While coagulation depends on settling time, pH, and coagulant dosage, sorption is primarily influenced by contact time, pH, adsorbent dose, and temperature. This study highlights that the most efficient techniques at the moment are enzyme degradation, ion exchange, and sorption dye removal. Moreover, this investigation promotes the application of composite materials including Bentonites and their derivatives for possibly increased dye removal effectiveness. Sorption is recognized as a simple and sustainable approach for wastewater treatment. Recent developments in biological, chemical, and physical therapeutic technologies are compiled in this article. It provides a thorough vision of wastewater treatment's future in lowering environmental pollution and enhancing the sustainability of water resources, and it additionally addresses the integration of eco-friendly technologies.

Keywords: Sorption, Wastewater treatment techniques, Dye, Physico-chemical treatment

INTRODUCTION

The most valuable resource for human survival, water, is experiencing previously unheard-of difficulties. Despite being a vital resource for maintaining life, water is frequently disregarded and squandered in our day-to-day operations [1]. Today, one of the most important worldwide problems is water contamination. Nevertheless, a lot of wastewater is generated and dumped into the aquatic environment annually, thus this problem is still becoming worse. The wastewater produced during dyeing is one kind that needs special consideration [2-10]. A significant number of dyes have been discharged into the environment during the past century due to the ongoing industrialization of printing and dyeing. In numerous industries, dyes are used to color things like textiles, leather, paper, rubber, printing, plastics, etc. Dyes are simple, everyday chemical molecules [11]. Synthetic dyes are vital to many significant businesses, like leather, textile, and paper sectors, since they supply color. A total of 700,000 tons of various coloring compounds are

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produced yearly using 100,000 dyes that are available for purchase. Most dyes are carelessly dumped into environmental water bodies after they have fulfilled their intended purpose [12,13].

The textile sector is responsible for over half of dye effluents present in the global environment, with a majority share of 54%. A substantial amount of dye effluents is generated by various processes in sectors such as paper and pulp (10%), dye manufacture (7%), tannery and paint (8%), and dyeing (21%) [14]. Even though the precise amount of dye effluents discharged into the environment by each industry is uncertain, it may be inferred that the quantity is significant enough to provide a substantial environmental hazard. An outcome of this rapid increase is an environmental disruption accompanied by a substantial pollution problem. According to the United Nations World Water Development Report, the demand for water in the domestic is 70%, agricultural is 22%, and in the industrial sectors 8% has significantly increased, accounting for the total fresh water available. This information is mentioned in the statement "Water for People, Water for Life." As a result, there has been an increase in the generation of substantial quantities of wastewater that include a variety of contaminants [15]. Dyes are a notable type of pollutants that pose challenges in water treatment because of their complex molecular structure and synthetic basis. These qualities add to their resilience to environmental deterioration and stability [16]. The auxochrome, which may be added to the chromophore to boost its affinity for connecting to the fibers and making it water soluble, is one of the two primary components of dye molecules. Chromophores are what give dyes their color. Dyes are categorized in a number of ways and show significant structural variety [17-20].

These may be classed depending on the type of fiber they are applied to as well as their chemical makeup. Another method to classify dyes is according to how soluble or insoluble they are: soluble dyes are those that are acidic, sulfuric, vat, direct, metal complex, reactive, and basic; insoluble dyes are those that are azoic, sulfuric, and disperse. In addition, dyes are chemically defined by an anthraquinonoid unit or a strong azo bond. It is vital to recall that azo dyes make up 65-70% of all dyes generated and are the most commonly employed variety. Despite the existence of a limited number of chemical groups (approximately twelve), the structure-based dye classification system is suitable and offers numerous benefits. It simplifies the identification of dyes within a group and allows for the recognition of their characteristic properties. For instance, azo dyes exhibit strong and versatile properties, while also being cost-effective. On the other hand, anthraquinonoid dyes are weaker and more expensive. The dye technologist and synthetic dye chemist usually utilize this cataloging as distinct from one another.

Here is a brief discussion of certain dye qualities that are categorized based on their usage [21]. Acid dyes are predominantly utilized in the coloration of nylon, modified acrylic materials, wool, and silk. They are also applied, albeit to a lesser degree, in the dyeing processes of paper, leather, food products, cosmetics, and inkjet printing. These dyes typically undergo solubilization in aqueous solutions. The basic chemical classifications of dyes encompass azine, xanthene, triphenylmethane, azo (including premetallized variants), nitroso, and nitro compounds. Cationic (basic) dyes are employed across a variety of substrates, including paper, modified nylons, polyacrylonitrile, modified polyesters, cation-dyeable polyethylene terephthalate, and to a minor extent, in medicinal applications. Historically, their application extended to cotton treated with tannin as a mordant, in addition to wool and silk fibers. The aforementioned water-soluble dyes are designated as cationic dyes due to their propensity to produce colored cations upon dissolution in a solvent. The predominant chemical categories in this classification are diazahelicene, cyanine, triarylmethane, thiazine, hemi cyanine, acridine, and oxazine. Disperse dyes are primarily employed in the coloration of polyester fibers and to some extent, on acrylic, nylon fibers, cellulose, and cellulose acetate. These nonionic dyes, which are predominantly insoluble in water, are utilized to impart color to hydrophobic fibers within aqueous solutions. Frequently, they contain azole, anthraquinone, benzodifuranone styryl, and nitro structural moieties. Direct dyes are utilized for the coloration of cotton, paper, rayon, leather, and to a limited amount, nylon materials. Diluted from an aqueous solution in the presence of electrolytes, these anionic dyes show water solubility and a significant affinity for cellulosic fibers. Within this class of dyes, polyazo compounds are prevalent, although there exist some stilbenes, oxazines, and phthalocyanines.

Solvent dyes are employed in the formulation of petroleum products, oils, waxes, polymers, and lubricants. Because these dyes don't contain polar solubilizing groups like quaternary ammonium, carboxylic acid, or sulfonic acid, they are primarily nonpolar or very weakly polar. Furthermore, they exhibit water insolubility while being soluble in various solvents. While triarylmethane and phthalocyanine variants are also utilized, the primary chemical groups encompass anthraquinone and azo compounds. Common applications of sulfur dyes include the coloration of cotton and rayon; however, the dyeing of silk, leather, paper, wood, and polyamide fibers with sulfur is relatively infrequent. Despite being a niche category, this class of dyes is commercially significant due to its exceptional wash fastness, economical nature, and intermediate structural characteristics. Vat dyes are chiefly employed in the treatment of cellulosic fibers as soluble leucon salts in rayon, wool, and cotton substrates. These dyes are characterized by their water insolubility and are classified into indigoids and anthraquinones, which encompass polycyclic quinones.

Other types include azoic, which is used in cotton and other cellulosic materials, and mordant, which is used in wool, leather, and natural fibers after they have been anodized and processed with metals. Conversely, fluorescent brighteners are utilized in paints, plastics, fibers, oils, soaps, and detergents, and they also include anthraquinone and azo. Presently, more than 100,000 commercial dyes are accessible, producing around 7×10^5-1×10^6 tons annually [22]. The primary pollutants present in wastewater are coloring agents, acids and bases, and organic and inorganic solid materials. The coloring compounds that give the cloth its color are lignin and tannin [23]. However, synthetic dyes pose serious hazards to human health when they combine with other substances to create nondegradable byproducts. Chromium compounds, vat dyes, naphthol, nitrates, soaps, acetic acid, Sulphur, enzymes, and heavy metals including arsenic, copper, lead, mercury, cadmium, cobalt, nickel, as well as several auxiliary chemicals, have all been linked to harmful impacts, according to research [24]. Carcinogenic compounds include hydrocarbon-based softeners, stain removers employing chlorination, formaldehyde-based color fixing agents, and nonbiodegradable dyeing chemicals. In addition to being hazardous, the effluent from textile dyeing factories contains compounds that are mutagenic, teratogenic, and carcinogenic [25].

Raj *et al*.'s animal model experimental research [26] showed a direct link between the primary class of textile dyes, azo dyes and splenetic sarcomas, bladder cancer, and hepatocarcinoma, which are the prime cause of chromosome abnormality in mammalian cells. According to Sudova *et al*. [27], malachite green, a significant carcinogen, has been demonstrated to have detrimental effects on the immune system and the human reproductive system. It has been documented that dispersed blue 291 dye can lead to base pair additions or deletions as well as nucleotide substitutions in DNA, which can result in genetic code mistakes [28]. If dyes are not handled, their high light and thermal stability might cause them to linger in an aqueous environment for a long period of time. As an illustration, contaminated waters may contain hydrolyzed reactive Blue-19, which has a half-life of roughly 46 years at pH 7.0 and 25 °C [29]. Logrono *et al.* [30] have looked into advanced physio-chemical techniques that combine with biological techniques to remove heavy metals like zinc (98%) and chromium (54-80%) and minimize chemical oxygen consumption by up to 98%. For the purpose of eliminating dyes, colored effluents must be treated, since, in addition to producing micro toxicity to fish and other species, they also affect with light transmission and disturb biological metabolic processes, which kill aquatic populations existing in ecosystems. Various strategies have been provided and even examined in order to establish acceptable procedures for the removal of dye; some of these are detailed in the following paragraphs.

In order to efficiently treat textile wastewater, researchers are now attempting to develop and use novel treatment techniques, like hybrid technology, which integrates biological and physical processes. Thus, a review of the literature on the decolorization and degradation of hazardous dyes in wastewater has been done in this review research, with an emphasis on effective and inexpensive procedures.

DIFFERENT TECHNIQUES FOR HANDLING DYE EFFLUENTS

A few decades ago, environmental consequences were not given any consideration when choosing, applying, and using colors. It was thought that 50% of the colors utilized by the organization had an unknown chemical composition. Consumers started to become more aware of dye wastes in the 1980s as a result of growing health concerns-mostly cosmetic ones. However, as more knowledge about the consequences of dye consumption on the environment has become known, dye producers, consumers, and the government have all taken major steps to purify wastewater containing dye.

These days, safeguarding aquatic life in water bodies by discovering economical and effective solutions to remediate wastewater discharged from industrial companies is the key focus. Thus, the procedures might be biochemical, physio-chemical, or a mix of the two, which can give efficient strategies for reducing pollutants from wastewater originating from diverse industries such as the textile industry. Physical and chemical techniques can be more affordable, but they cannot assure that all toxins are entirely eliminated, according to Williams [31].

Physico-Chemical Method

Even if physico-chemical wastewater treatment procedures are straightforward to deploy, they might not necessarily be cheap or ecologically advantageous [32]. Due to the generation of many byproducts and sludge that cannot be recycled, a high electricity consumption with a low yield is essential [33]. These strategies use a multistage treatment strategy with a lengthy retention time rather than a single phase. Generally speaking, coagulation and flocculation procedures are utilized in chemical treatments to eliminate organic contaminants [34]. When compared to the water-soluble coloring substance, Kim *et al*.'s study [35] demonstrated the effectiveness of coagulation therapy to combat the insoluble dye material. The chemicals required to adjust pH are quite expensive for the precipitation and coagulation procedures. The main obstacles that prevent the employment of chemical procedures include dewatering, pH alteration, high residual levels in the sludge formation, precipitation costs, disposal and supernatant.

Role of coagulation in wastewater treatment. The coagulation process is essential to the elimination of contaminants from wastewater, claim Ang and Mohammad [36]. The main physicochemical treatment method utilized in industrial wastewater treatment to reduce suspended particles and colloidal turbidity is the coagulation-flocculation process [37]. Previous research indicates that the coagulation process may remove 40% of nitrogen and organic compounds from wastewater [38]. According to Syam Babu *et al*., coagulation is the process by which suspended and polluting particles collide with one another to produce agglomerates that eventually form an insoluble agglomeration complex [39]. Coagulant dosage, settling duration, and pH are the primary elements that determine the amount of contamination removed from wastewater in various types of studies [40]. Table 1 displays the coagulation-affecting factors.
Table 1 Alt Text: Application of coagulation, characteristics of pure water and effective qualities such as coagulant quantity, settling time, particle type, and turbulence are the following factors that affect the coagulation process.

Mechanisms of coagulation. The coagulation/ flocculation mechanism generally consists of four steps such as charge neutralization, sweep coagulation, bridging, and patch flocculation [41]. Figure 1 illustrates the coagulation/flocculation mechanism. Repulsion happens because some of the colloidal particles in the coagulation process have a negative charge. In order to stabilize the colloid particles and eliminate any repulsive force, a

Table 1. Factors Affecting Coagulation [39]

Application of coagulation	Characteristics of pure water	Effective qualities
Charge of particles	a) Alkalinity	a) Coagulant adds quantity
Extraction of coagulants	b) Suspended solids	b) Settling time
Coagulants dose	c) Dissolved oxygen	c) Particle type
Basicity of a coagulant	d) Turbidity	d) Turbulence
Solubility of coagulants	e) Total dissolved solids	Slow mixing
	f) Availability of bacteria	Rapid mixing
	g) pH	
	h) The element contains (Mn, Si, Fl, Na, NH_3, Cl, and Fe)	
	I) Temperature	

coagulant is added. The colloid's zeta potential approaches zero points when a poly-electrolyte is introduced as a coagulant. As a result, according to Amran *et al*., this procedure is known as the charge neutralization mechanism. Moreover, amorphous metal hydroxides precipitate when a large concentration of metal salts is added to water; this process, called sweep coagulation, results in the progressive formation of massive lumps [42]. Because high molecular weight linear-chain chemicals, which are frequently based on polyacrylamide, adsorb onto the surface during the bridging flocculation process, a very big floc may result. Several particles go through this process simultaneously [43]. In the meantime, a local charge reversal takes place as a result of the polymer adhering to the particles, causing the patch flocculation process. An attraction force forms between each particle as a result of this process [44].

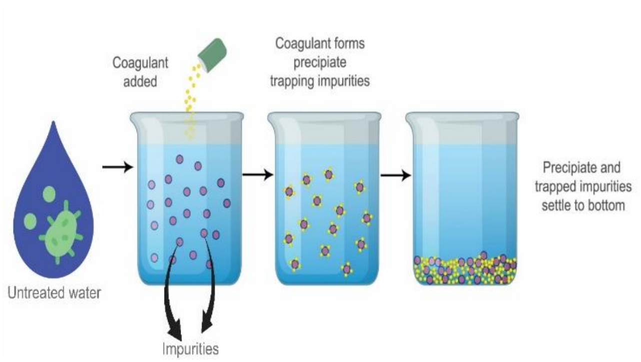

Fig. 1. Coagulation Mechanism for wastewater treatment [45].

Figure 1 Alt Text: The act of adding coagulants to water causes particles to aggregate into bigger clumps known as flocs, as seen in this diagram that depicts the coagulation mechanism in wastewater treatment. To enhance the quality of the water, these flocs can subsequently be eliminated by filtering or sedimentation.

There are two types of coagulants that can be distinguished: natural and chemical. Both coagulants target to eliminate contaminants in their physical (suspended particles & turbidity) or chemical (BOD & COD) forms, according to Kumar et al. Chemical coagulants include pre-hydrolyzing metallic salts like polyacrylamide (PAC), poly ferrous sulfate (PFS), polyferric chloride (PFC), and polyaluminum ferric chloride, as well as synthetic cationic polymers like polyalkylene, polyamine, polyethylenimine, and aminomethyl polyacrylamide [46]. One type of chemical coagulant is hydrolyzed metallic salts such as ferric chloride, magnesium chloride, ferric sulfate, and alum. Natural coagulants include plant-based components like starch and fruit waste, seed and plant extracts, and animal-based compounds like isinglass and chitosan. They also include microorganisms including bacteria, microalgae, and fungus [47].

Coagulants are often manufactured organic substances with a large molecular weight called polymers or polyelectrolytes, which increase the strength, size, and ease of settling of flocs. In solution, effective coagulants may create multicharged polynuclear complexes with improved sorption properties [48]. Numerous chemical-based coagulants have been researched to remove contaminants from wastewater. The pre-treatment of municipal wastewater with polyaluminum chloride, potash alum, and alum was examined by Dhanjal *et al.* [49]. Table 2 lists the benefits and drawbacks of many physio-chemical techniques for treating textile dyes and shows that these techniques are not economical.

Table 2 Alt Text: This table shows the limitations, uses, and advantages of several dye treatment techniques.

Physical Method

Several physical techniques, including ion exchange, oxidation, radiation, and sorption, are routinely applied for wastewater treatment and have had favorable outcomes [62]. Since chitin contains amino nitrogen, it demonstrated a significant ability to absorb the acid dye. Recycled materials are a great source of adsorbents that can remove the dye and colored organic material that can add color to media at a fair price, claim Daassi *et al*. [63]. The potential of activated carbon to cure both basic and acid dyes due to its sorption capability was recognized by Nassar and Geundi [64]. Finding a different desorption technique and understanding why the sorption approach cannot handle materials with undissolved dyes was revealed by Abu-Saied *et al*. [65]. The irradiation procedure required a high concentration of dissolved oxygen, although it has the potential to cure moderate amounts of colored water. On the other hand, when diverse additives are present in the same wastewater, the ion exchange systems respond insufficiently and exhibit more degrading effects when treating different colors.

Table 2. Benefits and Limitations of Various Physicochemical Approaches Used for the Treatment of Dyes

Methods	Limitations	Applications	Benefits	Ref.
Zeolites are used as adsorbent	Reduced active surface through immobilization of nanosilver particles	Disinfection processes	Controlled release of nano silver, bactericidal	[50]
Electrochemical destruction	High cost of electricity	Environmentally friendly since the electron, which serves as its primary reagent, is a clean reagent.	Breakdown compounds are nonhazardous	[51]
Ion exchange	Not effective for all kinds of dyes	Charged ions created as a result of dye degradation are collected by an ion-exchange resin.	Regeneration: no adsorbent loss	[52]
Nanoparticles (Ag, ZnO, TiO_2, coated ceramic filters) as adsorbent	Leaching problem	Large surface area, quick sorption equilibrium, low diffusion resistance, and high sorption capacity	Provides an affordable and efficient means of protecting the environment through bioremediation.	[53]
Sodium hypochlorite	Release of aromatic amines	The strong oxidizing potential of sodium hypochlorite towards the decolorization /degradation of dyes	Starts the azo bond's cleavage and speeds it up.	[54]
Photochemical methods Photo-catalytic degradation by Irradiation	Requires a lot of dissolved O_2	It produces radical species that quickly react with textile dyes, destroying their chemical structure.	Effective oxidation at the lab scale	[55]
Membranes and membrane processes	Relative high energy demand, Concentrated sludge production	Every aspect of wastewater treatment and water fields	Reliable, largely automated process	[56]
Wood chips as adsorbent	Requires long retention times	Wood chips have a beneficial impact on the breakdown of wastewater dyes because they offer a natural habitat for microorganisms.	Good sorption capacity for acid dyes	[57]
Cucurbituril as adsorbent	High cost	A cyclic polymer with a hydrophobic cavity and low solubility in aqueous solutions used for decolorization of dyes	Good sorption capacity for various dyes	[58]
Magnetic nanoparticles	*In vitro* cytotoxicity	Wastewater Treatment	Gives stability, oxidation protection, and a surface to which ligands specific to certain contaminants can be applied.	[59]
Oxidative processes ozonation	Short half-life approx. 20 min	Elimination of color from textile effluents	Simple and easy to utilize It is possible to apply ozone in its gaseous form. Not producing any sludge	[60]
Photochemical oxidation with H_2O_2	Formation of byproducts	The production of hydroxyl radicals, which can break down a variety of organic contaminants and are extremely reactive and nonselective.	No sludge production	[61]
Nano-adsorbents	High production costs	Point-of-use, elimination of organics, bacteria heavy metals	High specific surface, higher sorption rates, small footprint	[56]

Role of adsorption in waste water treatment. Dabrowski defined sorption as the difference in a material's concentration at the interface between two of its neighboring phases [66]. The following systems can experience sorption: liquid-liquid, solid-liquid, solid-liquid, and liquid-gas. Sorption is currently one of the most used techniques for treating industrial wastewater. For example, even at low quantities, heavy metals can be collected and removed from wastewater *via* sorption [2,3,5-8,17-20,67-73]. In light of this, sorption is a straightforward and practical technique for treating wastewater when compared to alternative methods. The efficiency of sorption tactics varies depending on several factors, such as pH, adsorbent dosage, temperature, and length of contact.

Knowing the starting pH state is essential to maximize the effectiveness of pollutant removal because the sorption procedure is pH-dependent. The capacity of hydrogen ions in functional groups such as hydroxyl (OH), amine (NH), carboxyl (COOH), and metal ions to adhere to the adsorbent surface is influenced by the pH of the solution [74]. Because of the influence of adsorbent capacity on the original concentration of adsorbate, the adsorbent dose is one of the most critical elements in the sorption process and plays a critical role in choosing the optimal course of action [75]. The removal capacity may rise in response to an increase in adsorbent dosage due to active sorption sites and enlarged surface area [76].

One of the elements that influences the adsorption process and physicochemical reactions is temperature. A rise in temperature would result in a decrease in the response rate for exothermic processes and an increase in the reaction rate for endothermic reactions, according to Xu *et al*. [77]. One could use contact time to describe the sorption capacity. This is the reason why the sorption process takes a while to achieve equilibrium, or the point at which sorption stops [78]. The use of contact duration varies throughout time based on the adsorbate and adsorbent material in order to achieve maximum process. Adsorption of organic contaminants from wastewater is one of the most widely used and significant methods. These days, a variety of techniques, including silicate, clay, and solid wastes, may be used to absorb waste from various industries and agriculture [79].

Mechanism of Adsorption

Wastewater is often treated using the sorption method due to its efficiency and effectiveness. Aims have been made to clarify several aspects of water treatment by sorption using nano adsorbents due to the vital importance of water quality and the rapidly expanding applications of nanotechnology [80]. The method of sorption entails the adhesion of pollutants onto a solid surface. Fundamentally, this phenomenon is characterized as a surface interaction in which sorption occurs primarily through physical forces; however, at times, weak chemical bonding may also play a role in the sorption mechanism. A molecule (pollutant) that is bound to the solid surface is designated as an adsorbate, while the solid surface itself is referred to as an adsorbent. The dynamics of sorption are influenced by a multitude of parameters, including temperature, the intrinsic properties of both the adsorbate and adsorbent, as well as the presence of additional pollutants, alongside experimental conditions (such as pH, pollutant concentration, contact duration, particle size, stirring rate, and temperature). An equilibrium state is attained when the concentrations of the adsorbed pollutant and that present in the aqueous phase stabilize.

The correlation between the quantity of pollutant adsorbed and its concentration in water at this equilibrium state is termed an adsorption isotherm. Sorption represents a significant industrial separation technique for the purification of effluent streams. It is increasingly acknowledged as a viable and cost-effective approach for the treatment of wastewater. Among the various methodologies available, the utilization of adsorbents for pollutant removal has proven to be straightforward (in terms of operational feasibility), economically advantageous, and effective in eliminating both organic and inorganic contaminants from polluted water sources [81,82]. This separation methodology is extensively employed in the extraction of dyes from aqueous solutions. Specifically, adsorption is utilized in sectors such as textiles, leather, dyeing, cosmetics, plastics, food production, and the paper industry, where the recovery of water is critically important. To achieve and maintain optimal recovery of the desired water quality, meticulous selection of the adsorbent is of utmost significance. Many adsorbent kinds have been used to remove colors from wastewater over the last few decades. N-vinylpyrrolidone (NVP) and acrylamide (AM) were added to carboxymethylcellulose (CMC) to create a copolymer. On the copolymer, the MB dye removal effectiveness was 99.4% [83].

Notably, activated carbon (AC) has been extensively leveraged for dye removal. However, due to its status as a finite natural resource, sluggish sorption kinetics, limited sorption capacity for large adsorbates attributable to its microporous structure, challenges associated with disposal, as well as the elevated costs and difficulties related to regeneration, it has been imperative to explore inexpensive and effective adsorbents, such as bentonite clay and its composite. Consequently, in light of the aforementioned limitations associated with AC, clay minerals have been rigorously investigated due to their pronounced sorption and complexation capabilities.

Physical and chemical adsorption, electrostatic interactions, H_2 bonds, π-π reactions, and precipitation are the most likely adsorption processes of dye molecules to biosorbents [84].

Adsorption is a procedure that involves several steps that must be followed.

Four steps comprise the sorption mechanism [85]:

1. The contaminated molecules are transported by the solution to the adsorbent's border layer.
2. Diffusion happens between the adsorbent's border surface and the inner layer.
3. Go from the interior layer to the active sites inside the pore.
4. The process of sorbate sorption into the solid phase.

Composite and Biosorbent Use for Dye Removal

Blending two materials with dissimilar chemical and physical characteristics yields a composite material. When they are combined, a material that is particularly made to accomplish a certain goal-like being stronger, lighter, or even stiffer and stronger is produced. Their large surface area, mechanical and thermal resilience, and numerous network functionalities made them more appealing for use in dye removal applications. Because it is less expensive and more environmentally friendly than other materials, composite and its modified forms are often used for dye removal. Compared to conventional adsorbents, composite materials provide better regeneration, selectivity, and sorption capacity because of their low price, wide surface area, and high porosity [72, 86-100]. Because biological sources are environmentally safe, they are utilized for many purposes (dye sorption, catalysis, biofuel synthesis, *etc*.) [101-103]. The bulk of biosorbents come from biological sources and bio-organisms, including plants, animals' shells, algae, fungi, bacteria, and yeast [104-106]. The diverse organic pollutants that biosorbents are particularly adapted to adsorb are addressed in full below. We will talk about chitin, peat, alginate compounds, agricultural wastes, and biomass as biosorbents for the sorption of various pigments to provide a hygienic and pleasant environment for living creatures [105]. Peat works well as a biosorbent for a variety of pollutants due to its affordability, accessibility, and abundance. Uncooked peat is made up of humic acid, cellulose fulvic, and lignin. It is a composite soil mixture that is exceptionally porous and contains a substantial quantity of organic matter (humic components) at different stages of decomposition. Dyestuff molecules can interact chemically with lignin and humic acid. Additionally, they include many functional groups, including alcohols, ether, phenolic hydroxides, carboxylic acids, ketones, and aldehydes. Depending on the source materials, peat is classified into four groups: herbaceous, woody, sedimentary, and moss [104]. Agricultural wastes are the most popular bio-adsorbents among low-cost adsorbents for eliminating dyes and heavy metals. Utilizing these compounds has several benefits, including low cost, high adsorption capacity, low energy consumption, good efficiency, and ease of maintenance [107].

Using Bentonite and Its Composites to Remove Dye

The most prevalent and esteemed variety of clay utilized in the process of water purification is bentonite, which operates as an adsorbent and is predominantly comprised of montmorillonite, although certain instances may include rarer clay minerals, such as beidellite, saponite, hectorite, and nontronite. The sorption behavior of organophilic bentonites when interacting with aqueous solutions containing organic compounds was examined by Stockmeyer [108]. The studied organoclays exhibit variations in their total cation exchange capacity (CEC) influenced by the exchange of organic counter ions [108]. Bentonite clay presents a compelling and cost-effective alternative for the elimination of dyes. The sorption characteristics pertaining to various dye types have been scrutinized in this section. Espantaleona *et al*., 2003 documented the sorption capacities of Acid Yellow 194, which were found to be 24.9 and 71.1 mg/g on natural and acid-activated bentonites, respectively, while the capacities for Acid Red 423 were reported as 29.1 and 85.2 mg/g, respectively [109]. Furthermore, the k value associated with HCl-activated clay is significantly (2-3 times) lower than that observed for pristine clay.

Lin *et al*. investigated the sorption of Amido Black 10B onto both pristine and acid-activated montmorillonite (activated with 6 M HCl) from aqueous solutions [110]. Özcan *et al*. evaluated the sorption of Acid Red (AR57) and Acid Blue (AB294) dyes from aqueous solutions onto acid-activated bentonite [111]. The acid-activated bentonite exhibited remarkably high sorption capacities for AR57 (416.3 mg/g) and AB294 (119.1 mg/g). Teng *et al*., 2006 investigated the sorption of methyl orange onto acid-activated MMT clay and reported an enhancement of approximately eight times in comparison to the natural clay [112]. Li, 2007 introduced a novel adsorbent, EPI-DMA cationic polyelectrolyte/bentonite (EPI-DMA/bentonite), for the removal of Reactive Blue K-GL (RBK-GL) dye from aqueous solutions through sorption methods. The sorption capacity (mg/g) was determined to be 68.60 at 23 °C [113]. The Freundlich and D-R isotherm models better explained the equilibrium sorption data. In order to remove Alizarin Yellow R dye from aqueous solutions, Chun-li *et al*. produced and used TiO_2-pillared bentonite and TiO_2-pillared bentonite doped with yttrium, manufactured by the sol-gel process [114].

The XRD analysis confirmed that the interlayer distance increased to 1.9 µm or more, sustaining a value of 1.8 nm or more after calcination at 500 °C. The findings indicate that TiO_2 pillared bentonites exhibited significantly faster and higher sorption performance than all other varieties of bentonite. The sorption isotherms adhered to the equations of Freundlich and Langmuir. The sorption process was characterized as endothermic. The mechanisms of sorption were identified as physical surface sorption and ion-exchange type. Xiu Qiong investigated the elimination of Reactive Red X-3B dye from wastewater utilizing modified clay [114]. The results showed that, in comparison to activated carbon, it had a higher effectiveness in removal. In 2013, Díaz-Gómez-Treviño and colleagues documented the elimination of Remazol Yellow from aqueous solutions on both iron-modified montmorillonite KSF and montmorillonite KSF [115]. Based on the experimental findings, it is evident that the MMT KSF exhibited an approximate removal of 10% greater Remazol yellow dye compared to iron-modified MMT KSF; however, the standard deviations associated with the unmodified material were significantly elevated. The kinetic analyses indicated adherence to the pseudo-first-order model (Lagergren), which is predicated upon a surface reaction mechanism. The experimental results were more effectively fitted to the Freundlich and Langmuir-Freundlich sorption models. Using a batch sorption technique, Rehman (2013) recorded the sorption properties of Brilliant Green (BG) dye onto naturally existing red clay (RC) [116].

According to Mahdavinia, cationic crystal violet dye was successfully removed from aqueous solutions using nanocomposite super absorbents made by solution polymerizing sodium acrylate with sodium montmorillonite nanoclay and carrageenan biopolymer [117]. The solution polymerization process of partially neutralized acrylic acid was conducted in the presence of sodium montmorillonite nanoclay and carrageenan biopolymer. Ammonium persulfate (APS) and N,N'-methylenebisacrylamide (MBA) served as the initiator and crosslinking agent, respectively. The persulfate initiator undergoes thermal decomposition to yield sulfate anion radicals, which subsequently abstract hydrogen from H_2O molecules, resulting in the formation of hydroxyl radicals. These hydroxyl radicals have the ability to start the polymerization of sodium acrylate. In the context of a cross-linking agent, namely MBA, cross-linking reactions may occur, ultimately yielding a three-dimensional polymeric network. The carrageenan biopolymer along with dispersed Na-MMt sheets becomes integrated into the crosslinked poly (sodium acrylate). It was shown that adding nanoclay to a superabsorbent based on carrageenan increased both rates of dye sorption and elimination efficiency by 11%. This suggests that the Freundlich isotherm ($R^2 > 0.96$) provides a superior fit for the experimental data compared to the Langmuir model. The sorption capacity (Q_{max}) was determined to be 55.8 mg/g.

Mahdavinia *et al*. also revealed in the same year that cationic crystal violet dye could be adsorbed onto nanocomposite hydrogels made of kappa-carrageenan by solution polymerizing acrylic acid monomer with Laponite RD and Na-MMt nanoclays present [118]. Kun-hong *et al.* elucidated the sorption properties of methyl orange utilizing a nano-MoS2/bentonite composite, which was synthesized through the calcination of MoS3 that had been deposited on bentonite in a hydrogen environment [119]. The findings indicate that the nano-MoS2 particles are uniformly distributed on the bentonite surface and engender layered structures characterized by a layer distance of approximately 0.64 nm. The removal efficiency reached a commendable level (around 88%) within a duration of 70 min when the dosage of the composite was increased to 0.1 g in a 150 ml solution of 20 mg l^{-1} methyl orange. Moreover, the efficacy of methyl orange removal is notably influenced by variations in temperature and pH levels. The composite exhibits enhanced removal efficiency for methyl orange at relatively lower temperatures, specifically at 20 °C. The elimination efficiency is considerably elevated in acidic environments (pH 2) but is significantly diminished under alkaline conditions. The sorption behavior of methyl orange conforms to the pseudo-second-order kinetic model. Sebastian *et al*. investigated the removal of two dyes, Acid Green 25 and Acid Green 27, using layered anionic clay (MgAl) - sodium alginate (Alg) composites with varying alginate concentrations (3 wt%, 5.9 wt%, 11 wt%, and 20 wt%) which were prepared via in-situ co-precipitation techniques (120). The scanning electron microscopy (SEM) imagery of pristine MgAl crystals revealed a flake-like morphology with sharp edges, arranged in layered formations, while sodium alginate exhibited a smooth surface texture. At lower alginate concentrations, diminutive alginate particles were observed dispersed across the clay surface and interspersed within the layers of the clay. Conversely, at elevated alginate concentrations, alginate began to form a smooth, continuous, or semi-continuous layer over the clay substrate. The clay-alginate composite containing 5.9% alginate demonstrated the highest sorption capacity for both dyes under study. The maximum sorption capacity of the composite was augmented by 51% for Acid Green 25 and 160% for Acid Green 27, relative to the pristine layered clay sample. The isotherm data were effectively described using the Freundlich isotherm model. The kinetics of sorption were scrutinized employing both normal first-order and Lagergren first-order kinetic models. Yang *et al.* (2015) reported on the sorption of methylene blue (MB) dye utilizing TiO_2-WO_3-bentonite composites synthesized through a hydrothermal method, with and without ultrasonic pretreatment [121]. The maximum sorption capacity for MB was elevated to 70.9 mg g^{-1}. The influence of pH on the sorption capacity of MB on U/TiW-NB was assessed at 35 °C. It was discerned that the sorption capacity of U/TiW–NB for MB increased with rising pH from 3 to 5, remained approximately constant within the pH range of 5-9, and exhibited further enhancement at pH = 11. Liu et al. elucidated the sorption phenomena of anionic azo dye (Amido Black 10B) utilizing a cross-linked chitosan/bentonite composite [122]. The cross-linked chitosan (CCS)/bentonite (BT) composite was synthesized through the intercalation of chitosan within bentonite, coupled with the cross-linking reaction mediated by glutaraldehyde. The sorption efficiency of Amido Black 10B onto the CCS/BT composite was determined to be maximized at pH 2, with an adsorbent dosage of 0.05 g at 293 K; the optimal contact time was established at 60 min, and the dye concentrations examined were 200 and 250 mg l^{-1}. The sorption isotherm data were effectively modeled by the Langmuir isotherm, with the maximum sorption capacity reaching 323.6 mg/g at 293K and pH 2. The kinetics of Amido Black 10B sorption conformed to a pseudo-second-order kinetic model. The negative values of ΔG° indicate the spontaneity of the sorption process of AB10B onto the CCS/BT composite within the temperature range of 293-313 K. The positive values of ΔH° (kJ mol^{-1}) recorded at 15.78, substantiated by the increased sorption of AB10B at elevated temperatures, confirmed that the sorption process is endothermic in nature.

Chinoune *et al.* investigated the effectiveness of magnesium hydroxide-coated bentonite, designated as the B–$Mg(OH)_2$ composite, in the removal of anionic reactive dyes, specifically Procion Blue HP (PB) and Remazol Brilliant Blue R (RB) from aqueous solutions [123]. The optimized experimental conditions included a dye concentration of 100 mg l^{-1}, an adsorbent dosage of 2 g l^{-1}, a pH of 2, a temperature of 298 ± 1 K, and a contact time of 3 h. Under acidic conditions at pH 2, the maximum dye sorption efficiencies were recorded at 98.2% for RB and 87.8% for PB. Kinetic analysis indicated that the sorption process adhered to a pseudo-second-order model, with the rate constants being quantitatively assessed. The Langmuir monolayer sorption capacities for PB and RB in aqueous media were estimated at 298 K to be 40.22 mg/g and 66.90 mg/g, respectively. The evaluation of thermodynamic parameters for the sorption of PB and RB onto the B–Mg $(OH)_2$ composites yielded ΔH° (kJ/mol) and ΔS° (J mol^{-1} K^{-1}) values of 27 and 101.28 for PB and 19.46 and

51.55 for RB, respectively. An increase in temperature from 278 K to 313 K resulted in enhanced sorption for both dyes, affirming that the sorption process is characterized as physisorption, endothermic, and spontaneous in nature. Table 3 shows the ability of different biosorbent and composite materials used for dye removal from wastewater.

Table 3 Alt Text: Here, the maximum sorption capacity of various composites and biosorbents for extracting dye from wastewater is discussed, along with its operating temperature.

Hybrid Adsorbent Use for Dye Removal

An eco-friendly substitute for conventional adsorbents is metal-organic framework (MOF) composites. The ability of these MOF composites to effectively remove dangerous organic contaminants from aqueous solutions is impressive. As photocatalysts for the breakdown of different contaminants, semiconductors have demonstrated a great deal of promise. Researchers have investigated a number of strategies, including doping, surface modification, and hybridization with other materials, such as MOFs, to further improve the efficacy of semiconductor photocatalysts. TiO_2, ZnO, CdS, MoS_2, Fe_2O_3, ZrO_2, V_2O_5, Cu_2O, and CuO are among the metal oxides that have been used to degrade a variety of contaminants, turning them into CO_2 and H_2O as byproducts [136]. ZnO and TiO_2 are two metal oxides that have become extraordinary photocatalysts because of their exceptional qualities and lack of toxicity [137]. When semiconductors and MOFs are combined, positive outcomes have been observed in terms of improving the semiconductors' light absorption, charge separation, and catalytic activity, which will result in more effective and efficient wastewater treatment procedures [138].

Table 3. Capability of Different Composite and Biosorbents for Removal of Dye from Wastewater

Composite/Adsorbent	Maximum sorption capacity (mg/g)	Operating temperature (°C)	Ref.
Rice Husk biochar and burnt clay composite	0.975	20	[124]
Chicken Egg shell and Anthill clay composite	23.87	30	[125]
Acrylic polymer/bentonite composite	36.60	30-70	[126]
Alkali-treated orange tree sawdust	78.74	20	[127]
Wheat shells	16.56	30	[128]
Magnetized Tectona grandis sawdust	172.41	30	[129]
Eggshell	0.80	25	[130]
Orange peel	18.60	30	[131]
Raw orange tree sawdust	39.68	29	[127]
Eggshell membrane	0.24	25	[130]
Bentonite-Alginate Composite	601.9339	70	[132]
Montmorillonite clay Raw-Bentonite used for removal of Methylene Blue	289	35	[133]
Magnesium hydroxide coated bentonite (B-M(OH)$_2$) composite	66.90	25	[123]
Activated carbon bentonite alginate beads (ABA) for removal of methylene blue	756.97	30	[134]
Crosslinked chitosan/bentonite composite for the elimination of Amido black 10B	323.6	20	[122]
TiO_2-WO_3-bentonite composite for Methylene dye elimination	70.9	35	[121]
Magnetic Fe_3O_4/bentonite nanocomposite for elimination of methylene blue	1666.7	25	[135]

It has also been shown that adding metal oxides to MOFs increases their contact with adsorbates, which normally have poor interactions with the MOF's pore surfaces [139]. To enhance the sorption performance in photocatalytic processes, researchers added MOFs to the surface of other photocatalysts. When ZnO, an n-type semiconductor, is combined with MOFs, researchers are interested. Through a hydrothermal process, Xiao et al. created MIL-125/ZnO catalysts, which were then used to photodegrade the methyl orange (MO) dye. After 60 min of UV radiation exposure, the MIL-125/ZnO composite showed a MO removal rate of 96.89%. It also had a lot of oxygen defects, which made it easier to create oxidative holes and reduced the bandgap of MIL-125/ZnO [140]. Furthermore, Zn-MOF/ZnO was synthesized by Gupta et al. to remove H_2S [141].

Regeneration and Safe Disposal of Adsorbent

Adsorbent regeneration and disposal pose serious difficulties that affect their usefulness in environmental cleanup. Reducing environmental hazards and improving sustainability need efficient management of depleted adsorbents. Up to 99% desorption efficiency may be attained by thermal regeneration, but it requires a significant amount of energy, endangers structural integrity, and results in a 10-20% mass loss [142]. Depending on the teregeneration type, chemical regeneration exhibits varying levels of efficiency, with multi-component solutions surpassing others. The molecular makeup of contaminants and the existence of co-contaminants affect the regenerant selection. Scaling up from laboratory to industrial applications presents difficulties for many regeneration techniques, including advanced oxidation and electrochemical processes [143]. Safer disposal techniques must be developed since traditional disposal techniques, such as burning, have the potential to release hazardous materials back into the environment [142]. Solid waste problems are made worse by discarding used adsorbents, underscoring the necessity of efficient reuse and regeneration techniques [144].

An adsorbent's reusability is a key practical consideration that makes it a green and commercially appealing technique. The solid treatment issue is made worse by the disposal of adsorbents employed after contaminants have been adsorbed. Reuse and regeneration of wasted solid adsorbents should be taken into consideration in order to run an economical and environmentally sustainable sorption process. Chemical desorption is frequently employed to extract metal ions, such as zinc from powdered mango leaves, where HCl produced an elution efficiency of 94.7% [145]. This technique, which uses biological agents like chlorella to regenerate anion exchange resins, is economical and reduces secondary pollution [146]. To increase regeneration efficiency and safety, the Vacuum Regeneration technique uses a vacuum system to gasify organic waste from adsorbents [147]. With an efficiency of over 90%, advanced oxidation techniques such as electrochemistry can both decompose contaminants and replenish magnetic adsorbents [148]. To eliminate organic contaminants while maintaining sorption capacity, roasting entails heating saturated adsorbents, such as opal [149]. Although these approaches offer efficient regeneration options, there are still issues with scaling them up for broad use and making sure that disposing of wasted adsorbents doesn't endanger the environment.

Ion exchange method. Ion exchange occurs when ions move from one electrolyte to another or from an electrolyte solution to a complex. It is a technique for cleaning, sorting, and decontaminating solutions that contain ions or are watery. Soil humus, clay, zeolites, and ion exchange resins are typical examples of ion exchange materials. These substances mostly serve as cation exchangers, which swap out positively charged ions for negatively charged ones, or anion exchangers, which swap out positively charged ions for negative ones. Ion exchange is another kind of sorption process, in addition to sorption and absorption. Typically, ion exchange systems feature ion exchange resins that operate in a cyclical manner. Water is circulated through the resin until it becomes saturated, at which point the effluent contains a higher concentration of ions than desired and must be treated. Regeneration of the resin involves backwashing to eliminate accumulated solids and flushing out removed ions using a concentrated replacement resin solution. The necessity of backwashing restricts the application of ion exchange in wastewater treatment.

Mechanism of ion Exchange

The operation of the entire process can be elucidated through a straightforward illustration in Fig. 2. Within a demineralizer, the incoming water flowing through cation exchange resin will rid itself of all cations. These metallic cations are transformed into acids, with the loss of ions being compensated by an equivalent number of Hydrogen ions. Subsequently, these produced acids are eliminated through a regenerated anion exchange resin that exhibits an alkaline nature. However, in this instance, the anions are substituted with a proportional quantity of hydroxides in the wastewater. The capacity of the bed is restricted to a specific predetermined level, causing the resin to become depleted and necessitating the regeneration procedure. The anion resin is rejuvenated using sodium hydroxide while the cation exchange resin is revitalized utilizing either sulphuric or hydrochloric acid.

Strong acid cation resins utilize H^+ ions as the exchange material for swapping ions with the cations existing as total dissolved solids (TDS) in raw water. During regeneration, a weak acid solution is flushed through the depleted resin bed, causing cations to trade places with the H^+ ions found in the acid. Strong base anion resins employ OH^- ions for ion exchange with the anions present as TDS in untreated water. In the regeneration process, a dilute solution of NaOH is circulated through the exhausted resins, facilitating the exchange of anions with the OH^- ions housed in the base [150].

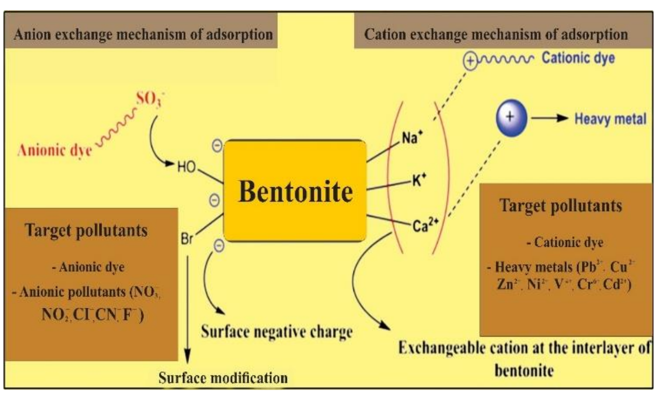

Fig. 2. Ion Exchange mechanism of dye and heavy metal sorption [151].

Figure 2 Alt Text: In this process, the ions in a solution are swapped out for ions from a solid surface or material. The surface of heavy metals and dyes attracts positively charged metal ions or dye molecules, which are then exchanged for counter-ions like calcium or sodium. By getting rid of harmful contaminants, this method helps to clean water.

Classification of Ion Exchange Adsorbent

Ion-exchange adsorbents get their name from the fact that they can absorb contaminants that have opposite charges to them. Because of reactive dyes (anionic), this review only considers anion-exchanging adsorbents. The effectiveness of several adsorbent types, such as ion exchange, lignocellulosic biomasses, resins, protein biomasses, clay, and microbial biomasses, in removing color from wastewater containing reactive dyes has been carefully examined [54].

a) Ion exchange resins

Polymeric granules or beads having a variety of functional groups that can bind ions with opposing charges are known as ion-exchange resins. These resins fall into one of two categories: anion exchange or cation exchange.

- **Bio-based ions exchange resins**

The efficiency and environmental advantages of sustainable ion exchange materials, especially bio-based resins, have drawn a lot of interest in wastewater treatment. Recent research demonstrates the efficiency of biological ion exchange (BIEX) systems, which combine ion exchange and biodegradation to remove pharmaceuticals and dissolved organic carbon at high removal rates. BIEX systems remove more than 90% of drugs by using resins like Purolite A860 and MAEX. By increasing biological activity, these systems lower brine waste and increase treatment effectiveness [152].

- **Commercial resins for anion exchange**

These are the initial batch of adsorbents created to address the widespread problem of color pollution in wastewater from the textile sector. Commercially available anion-exchange resins include Macrosorb (Crossfield) based on zeolite and S6328 (Bayer), MP62 (Bayer), and Amberlite IRC-71 (Dow) based on synthetic organic polymers.

Among them, S6328 and MP62 [153], as well as Amberlite IRC-71 [154], have been studied for their effectiveness in removing reactive dyes.

- **Non-commercial resins for anion exchange**

The removal of reactive colors from dyehouse effluent has prompted research into a variety of ion-exchange resins as potential adsorbents. These include poly(acrylic acid-N-isopropylacrylamide-trimethylolpropanetriacrylate) cross-linked with sodium alginate [155], partial diethylaminoethylated cotton dust waste [156], and other materials. Notable ion-exchange resins include several cellulose-based composites and ethylenediamine functionalized and potassium fluoride-activated paper sludge [157].

- **Advantages and disadvantages**

The commercial forms of ion-exchange resins are expensive despite being recyclable and easy to use. This has led to research into more cost-effective alternatives, such as modified and unmodified cellulosic biomasses. Despite their popularity, the non-biodegradability of synthetic ion-exchange resins poses a challenge for their disposal.

b) Dye binding capabilities of absorbents derived from biomass

Biomasses are organic polymeric materials that are renewable in nature, originating from sources such as plants, wood, plant-based materials, deceased microorganisms, agricultural residues, and animal-derived substances. These biomasses can be categorized primarily into two groups, specifically lignocellulosic and proteinous. While protein biomasses may stem from plants, animals, or microorganisms, lignocellulosic biomasses typically have a plant origin. Research has been conducted on various types of biomasses, including lignocellulosic and microbial varieties, for their potential as adsorbents in the elimination of reactive dyes.

c) Chitosan and its derivative

Reactive dye removal has been thoroughly investigated using chitosan, a byproduct of the seafood industry. This substance has been examined in different forms, such as fine powder [158], porous particles [159], flakes [160], and films [161], to assess its efficacy in dye removal. Additionally, squid pens rich in chitin have also been explored for their dye-removal capabilities. However, studies have presented conflicting outcomes regarding the dye-binding capacity of chitosan, which is influenced by factors like the source and molecular weight of the substance. One chitosan powder that was made from commercial shrimp was not very good at removing dyes, while a different chitosan powder made from Indian shrimp performed quite well at doing so. Various derivatives of chitosan, including cross-linked nanoparticles [162] and beads [163], have also been scrutinized for their sorption properties.

d) Dye Removal by using microbial biomass

The ability of microbial biomasses-living or dead-to remove reactive dyes from wastewater has been the focus of a great deal of research. These biomasses could be made up of microalgae, fungus, or bacteria that can either absorb dye molecules or use enzymes to break down the colors' chromophores, leading to their decolorization. Bacteria like *E. coli* [164], *Nostoc linckia* [165], *Lemna gibba* [166], *Corynebacterium glutamicum*, *Alcaligenes faecalis, Commomonas acidovorans* [167], *Paenibacillus azoreducens sp* [168]. *Pseudomonas luteola* [169], *Lysinibacillus sp*. [170], *Desulfovibrio desulfuricans*, and others have been investigated for their dye-removal capabilities. Additionally, modified bacteria and bacteria attached to electrospun polysulfone mats [171] have also been explored as potential adsorbents.

A variety of fungi, such as *Trametes versicolor* [172], *Rhizopus arrhizus* [173], *Aspergillus parasiticus* [174], *Thamnidium elegans* [175], *VITAF-1 fungal strain* [176], *Rhizopus nigricans*, *Penicillium ochrochloron* [177], *Termitomyces clypeatus* [178], *Aspergillus versicolor* [179], *Aspergillus niger*, and *Symphoricarpus albus*, among others, have been examined as potential adsorbents for eliminating reactive dyes. Moreover, mixed cultures like *Aspergillus versicolor* and *Rhizopus arrhizus* with dodecyl trimethylammonium bromide [180], *Phanerochaete chrysosporium* [181], Aspergillus fumigatus, and other mixed cultures originating from textile effluent, as well as Aspergillus fumigatus isolated from textile effluent, have been subject to investigation. Additionally, various algae species, including Spirulina platensis [182], *Enteromorpha prolifera* [183], and *Chlorella vulgaris* [184], have been explored for their potential in dye removal processes.

- **Advantages and disadvantages of Biomass use as an Adsorbent**

The primary benefits associated with biomass-derived adsorbents may encompass their convenient disposal due to their high biodegradability and cost-effectiveness. Nonetheless, the limited capacity of various cellulosic biomasses to bind dyes suggests their inability to rival commercial ion-exchange resins. Cellulose, hemicellulose, lignin, and polyphenols are the primary components of cellulosic biomass, all of which exhibit weak anionic characteristics. Owing to their weak anionic properties, cellulosic adsorbents are not efficient for eliminating anionic reactive dyes. Conversely, chitosan possesses a cationic nature, allowing it to bond with reactive dyes through ionic interactions. The potential of quaternized and cross-linked chitosan derivatives as adsorbents that can take the place of industrial ion-exchange resins in the elimination of dye from wastewater can be inferred. However, the cost of chitosan has increased due to its increased demand as a nutritional supplement. The main obstacles in dye removal through biosorption include challenges in sourcing and transporting large quantities of biomasses, as well as issues related to poor hydrodynamics, limited recyclability, and the extraction of biomasses from treated wastewater.

Advanced oxidation processes (AOPs). Potential substitute methods for removing dye from textile effluents include advanced oxidation processes (AOPs), namely Fenton oxidation, ozonation, electrochemical oxidation, and photocatalysis. AOPs are a viable alternative for wastewater treatment because of their natural capacity to fully mineralize pollutants, particularly those that are resistant to biodegradation, and to interact seamlessly with traditional methods. Target compounds undergo advanced oxidation, which produces a variety of radicals and reactive species. Advanced oxidation processes (AOPs) are new approaches that work by reacting active radicals which may be produced in a variety of ways with organic pollutants. Utilizing hydrogen peroxide (H_2O_2), ozone (O_3), and ultraviolet light separately or in combination are examples of advanced oxidation processes.

Advanced oxidation processes (AOPs) represent a classification of technological methodologies that enable the synthesis of hydroxyl radicals (**.**OH) and alternative reactive species, including the sulfate radical (SO_4^-). The hydroxyl radical is recognized as the second most powerful oxidizing agent, surpassed solely by fluorine, exhibiting a redox potential (E_o) of 2.8 V, which is superior to that of numerous other oxidizing agents, such as sulfate anion radicals (SO_4^-), ozone (O_3), and hydrogen peroxide (H_2O_2), among others. Glaze *et al.* (185) were trailblazers in the production of hydroxyl radicals (·OH) in quantities sufficient to substantially augment water purification methodologies, thereby coining the term "Advanced Oxidation Processes". Since the 1990s, the advancement of AOPs has significantly proliferated, incorporating a diverse array of strategies aimed at the production of hydroxyl radicals and other reactive oxidant species, including superoxide anion radicals (O_2•−) and singlet oxygen ($O_2(^1\Delta_g)$). Hydroxyl radicals are produced through the employment of one or multiple primary oxidants (*e.g*., ozone, hydrogen peroxide, oxygen) and energy modalities (*e.g*., ultraviolet light), frequently in tandem with catalysts (*e.g*., titanium dioxide). According to Harvey and Rutledge (186), the chemical dynamics associated with AOPs can be broadly delineated into three distinct stages:

- Generation of ·OH;
- Initial interactions between ·OH and target molecules, resulting in their fragmentation;
- Subsequent interactions by ·OH until complete mineralization is attained.

The mechanism that governs the production of ·OH (Stage 1) is profoundly affected by the particular AOP technique employed. Advanced oxidation methods combine great environmental efficacy with different degrees of economic viability to provide a workable alternative for wastewater dye removal. Some AOPs, such as solar photo-Fenton and UV/TiO_2 photocatalysis, provide more affordable and energy-efficient options, while others, like ozonation, may be more expensive. Their cost-effectiveness and sustainability are further increased when AOPs are combined with biological treatments, which makes them a viable choice for treating industrial wastewater.

Biological Method

Removing dye from textile effluent at the lowest practical cost and in the shortest amount of time is ecologically acceptable when done utilizing biological techniques like bioremediation, which uses biological phenomena to break down colors [187]. Ali demonstrated the use of biological material in applications, including bacteria, fungi, yeasts, and algae that can both dissolve and absorb various synthetic hues [188]. Using biologically based methods to break down wastewater from the textile sector has proven to be successful. Biological degradation, or bioremediation, produces less sludge and is more economically and environmentally sound than alternative methods. It eventually helps with color removal by stimulating degradation of synthetic dyes to less hazardous inorganic products due to the breakage of the link (*i.e*., chromophoric group) [189]. The observation that biological activities are effective at decreasing COD and turbidity but unsuccessful at eradicating color derives from Lewinsky [190] and Lin and Lo [191]. In order to create biological approaches for decolorization in the future, Muda *et al.* [192] described the success and advantage of a two-phase process wherein anaerobic processes are used in the first phase and aerobic processes are used in the second.

Role of enzymes in the removal of dyes from waste water. The best biomolecules for assisting the slow breakdown and elimination of complex substances are enzymes. Numerous bacterial taxa have been found to include non-specific cytoplasmic enzymes with azoreductase-like functions [193]. The enzymes responsible for the degradation of textile dyes are enumerated in Table 4. These enzymes encompass laccases, which target amaranth dye, direct blue 14, methyl orange, and Novacron red; horseradish peroxidase, which acts on acid blue 25; and azoreductase, which is employed for acid red and reactive BL, respectively. Mendes *et al.* identified azoreductases as a distinct class of enzymes [194]. Through the catalysis of a reduction reaction, these enzymes facilitate the cleavage of the azo bond (-N=N-) to yield colorless water, resulting in the formation of an aromatic amine. A plethora of scholars have elucidated methodologies for the application of bacterial cytoplasmic azoreductases within the domain of environmental biotechnology [195]. Azoreductase constitutes a rare enzyme that can be classified based on its primary amino acid composition [196].

Microbial enzymes are capable of highly effective bioremediation. Few strains of microbes have been studied at the enzymatic level, despite the fact that many have been reported to be used in the bioremediation of pollutants. Numerous chemical compounds have undergone biodegradation using a variety of enzymes. The fact that these enzymes are biodegradable, nontoxic, highly selective to their substrates, and active at low doses makes them beneficial. Additionally, they function in mild pH and temperature environments and are resistant to inhibitors. Various methods of action, including oxidation, reduction, elimination, and ring-opening, distinguish laccases, peroxidases, oxygenases, dehalogenases, azoreductases, and hydrolases from one another [197]. Laccases, peroxidases, and azoreductases are essential enzymes for the breakdown of dyes [198]. They make it easier for complicated dye molecules to break down into less dangerous forms. Under ideal circumstances, crude lignin peroxidase from bacteria such as Escherichia coli and Pseudomonas aeruginosa has demonstrated remarkable efficacy in breaking down a variety of dyes, indicating the possibility of industrial uses [199].

Enzyme engineering has become a key tactic for improving color degradation, especially when it comes to treating wastewater from textiles. In order to facilitate the bioremediation of hazardous dye-laden effluents, this method focuses on altering enzymes to increase their stability, efficiency, and substrate specificity. Important developments in this area are outlined in the sections that follow.

Site-saturation mutagenesis states that by altering certain amino acid residues, this approach has been used to increase the catalytic efficiency of dye-decolorizing peroxidases (DyPs) and produce versions with enhanced activity towards substrates such as ABTS [200]. Genetic Engineering states that sophisticated genetic approaches enable the optimization of enzymes, increasing their efficacy against complex textile effluents that natural enzymes frequently find difficult to break down [201]. Lignin peroxidase engineering states that, lignin peroxidase mutagenesis has produced variations with a much higher affinity and catalytic activity for a variety of azo dyes, indicating that designed enzymes may perform better than their wild-type equivalents [202]. In the nanozymes technique, Cu-chelated polydopamine nanozymes have demonstrated promise in simulating laccase activity, offering a more stable and effective substitute for conventional enzymes in dye degradation [203]. Enzyme engineering offers a potential approach to dye degradation, but there are still issues with the biocatalysts' scalability and viability from an economic standpoint in commercial settings. To overcome these restrictions and maximize the application of modified enzymes in practical settings, more study is required.

Table 4 Alt Text: The different enzymes that degrade synthetic dyes in textiles are included in this table, including ligninases, laccases, and peroxidases. Additionally, it emphasizes the fungi, bacteria, and plants that manufacture these enzymes, providing information on natural remedies for environmental cleanup and color degradation.

Table 4. Textile Dye-degrading Enzymes

Enzyme's name	Dyes	Biological source	Ref.
Azoreductase	Acid red	Acinetobacter radioresistens (Bacteria)	[204]
DyP-type peroxidases	Reactive blue19	Thermobi fidafusca (Bacteria)	[205]
Luffa actangula peroxidase lignin peroxidase	Navy blue HE2R	Lignin peroxidase Ipomoea hederifolia, Cladosporium cladosporioides (Plant-Fungus consortium)	[206]
Veratryl Alcohol Oxidase	Reactive orange13	Alcaligenes faecalisPMS-1 (Bacteria)	[207]
Azoreductase	Reactive red BL	Alcaligenessp.AA09 (Bacteria)	[208]
Tyrosinase Laccase Riboflavin Reductase Manganese peroxidase	Reactive red195A	Ganoderma lucidum IBL-05 (Fungus)	[209]
Soyabean peroxidase	Methyl orange	Bio wastes of soyabean hulls (Plant)	[210]
Lignin peroxidase; Laccases; Tyrosinase; NADH–DCIP reductase; Riboflavin reductase	Amaranth dye	Acinetobacter calcoaceticus NCIM 2890 (Bacteria)	[211]
Laccase; Manganese peroxidase	Novacron red	Leptosphaerulina sp. (Fungus)	[212]
Horse reddish peroxidase	Acidblue-25 (AB25)	Horse radish roots (Plant)	[213]

Limitations of Biological Method

Although useful in many contexts, biological approaches have serious drawbacks that may reduce their efficacy. These drawbacks can make its practical application more difficult, such as longer reaction times and the requirement for regulated environmental conditions. Comprehending these difficulties is essential to a fair evaluation of biological approaches. Changes in temperature, pH, and nutrient availability can have an impact on microbial activity and treatment effectiveness since biological processes are extremely sensitive to these variations [214]. Biological treatments frequently have slower response rates than chemical procedures, which results in lengthier wastewater processing durations [214]. The existence of particular microbial communities is necessary for biological techniques to work, but maintaining and optimizing these populations can be challenging. Health concerns may arise from the discharge of germs due to incomplete treatment [214].

When opposed to chemical approaches, biological processes frequently happen more slowly, which can cause delays in findings and make real-time applications more difficult. Kinetic analyses of biological interactions, for example, show that conventional techniques such as stopped-flow analysis could not offer the quick insights required in dynamic contexts. Because biological tests depend on particular parameters (such as pH and temperature) to guarantee accuracy, they are less adaptable in a variety of contexts. As demonstrated in quality control settings where environmental variability might impact test outputs, the use of biological approaches in field investigations may be limited by their dependence on controlled conditions.

Scalability and Practical Feasibility of Wastewater Treatment Techniques

The affordability and scalability of sorption, biological, and physico-chemical methods for environmental remediation are critical factors for experts in the area. Each strategy has unique advantages and challenges that influence how it is applied in real-world scenarios.

Physico-Chemical Methods

- Effectiveness: Methods such as photocatalysis and advanced oxidation processes have demonstrated a high level of efficiency in eliminating pollutants, such as heavy metals and endocrine-disrupting chemicals [215,216].
- Limitations: These techniques can be expensive owing to the use of chemicals and frequently need a large energy input, which may limit their scalability in commercial applications [216].

Biological Methods

- Sustainability: Biological techniques, such as phytoremediation and microbial fuel cells, are more ecologically friendly and sustainable since they rely on natural processes [217].
- Scalability: Although promising, biological treatments may not be scalable due to the time required for effective cleanup and the necessity for certain environmental conditions [216].

Sorption Techniques

- Industrial Applications: Because sorption techniques are effective at eliminating a variety of contaminants, they are frequently employed in industries. This is especially true when employing activated carbon and innovative adsorbents [218].
- Cost-Effectiveness: The development of low-cost adsorbents from agricultural waste enhances the feasibility of these methods for large-scale applications [216].

On the other hand, physico-chemical techniques can be expensive and have an adverse effect on the environment, even if they could provide results quickly. For industrial applications, a well-rounded strategy that incorporates several approaches may produce the most efficient and long-lasting results. The findings imply that further study into sorption methods is essential to solving problems in a range of sectors. To increase the efficacy and efficiency of sorption processes, the researchers recommend more research into novel adsorbents and better techniques.

Interdisciplinary Approaches

Several potential options that incorporate chemical, physical, and biological processes are highlighted by multidisciplinary approaches to wastewater dye removal. Compared to traditional techniques like chemical oxidation, using microorganisms and enzymes to break down synthetic colors offers a more ecologically friendly and sustainable solution [219]. When customized to certain dye structures, this procedure may be both economical and successful. Laccases, peroxidases, and ligninases are examples of enzymes that have demonstrated the ability to degrade complex color compounds into less toxic metabolites. A potential adsorbent for the removal of dyes is biochar, which is made from waste materials such as agricultural wastes. Biochar's sorption capability is increased by functionalizing it, which involves adding different functional groups to its surface [220]. This enables it to trap a variety of dyes, including ones that are challenging to remove using conventional techniques. This method offers a practical and affordable color removal option in addition to encouraging the recycling of waste materials. It has been demonstrated that electrocoagulation using bio-composite adsorbents-materials that have both organic and inorganic components-improves dye removal efficiency. Bio-composite sorption improves electrocoagulation by giving dye molecules more surface area to bind to, whereas electrocoagulation employs an electrical current to create coagulants that destabilize dye particles [221].

This hybrid technology is more environmentally friendly for industrial usage since it uses less energy than conventional techniques. Coagulation and filtration procedures may be optimized by knowing how various colors interact, especially when they are oppositely charged. By increasing the effectiveness of dye aggregation and subsequent filtration, this knowledge aids in the improvement of removal tactics [222]. This can lower operating costs and boost the overall effectiveness of wastewater treatment systems. Although there is a lot of promise in these multidisciplinary techniques, there are still difficulties in optimizing them for the many dye kinds and concentrations that are frequently present in effluent from the textile industry. In order to provide universal solutions, continuous study is necessary due to the complexity of dye structures, changing solubility, and toxicity levels. Widespread acceptance of these techniques will also depend on their economic viability and ability to be scaled up for large-scale industrial applications. In conclusion, multidisciplinary approaches that integrate physical, chemical, and biological processes present viable ways to remediate wastewater polluted with dyes. It is feasible to develop more efficient, eco-friendly, and effective textile industry treatment systems by continuously improving these strategies and tackling the outstanding issues.

CONCLUSION

Wastewater is classified by hazardous substances and non-biodegradable dyes. The textile sector utilizes various chemicals and dyes in production. Pretreatment waste can pollute untreated water bodies. This review evaluates modern techniques for removing dyes from industrial wastewater. Treatment methods are categorized as physical, chemical, bacterial, enzymatic, and composite techniques. This systematic approach has demonstrated significant benefits. Research shows that degradation efficiency is affected by dye properties, concentration, pH, salinity, and byproduct formation. Bioremediation with native bacteria is deemed sustainable socially, environmentally, and economically. Further research is essential for advancing bioremediation technologies from laboratory to commercial use. These techniques hold substantial promise for addressing wastewater challenges in developing nations, particularly India. Various enzymatic methods and combinations have successfully eliminated pollutants from textile wastewater. Ongoing research is crucial for ecological conservation before progressing enzyme-based technologies toward commercial readiness. Numerous impurity removal techniques exist, with coagulation and sorption preferred for their simplicity, cost-effectiveness, and efficiency.

Thus, these methods substantially lower impurities, leading to cleaner wastewater. Nevertheless, advancements in these techniques have prompted the exploration of natural resource-based materials for sorption and coagulation, utilizing agricultural waste. Employing natural coagulants and adsorbents can lessen adverse environmental and public health effects. Previous studies have confirmed the effectiveness of natural coagulants and adsorbents in pollutant removal. Therefore, further research could enhance the stability and efficacy of these materials across various wastewater types. Additionally, ongoing improvements in the recovery and reuse of these resources are vital for promoting environmental sustainability. Ultimately, continual research is necessary to assess the potential of natural coagulants and adsorbents in achieving circular economy goals on an industrial level. Composite materials are economically viable and environmentally friendly, making them suitable for dye removal. Their benefits include high regeneration, sorption capacity, and selectivity due to porosity, low cost, and surface area. Biologically derived materials are applicable in dye sorption and biofuel production. Biosorbents from algae and fungi are effective for treating dye-laden wastewater. Although sorption methods yield favorable results, their future application may be limited by high costs and difficult regeneration processes. Improving bentonite by integrating various polymers and nanoparticles is suggested to enhance its dye sorption efficiency.

The study shows that composite adsorbents have the potential to increase wastewater treatment efficiency. The improved sorption capabilities and targeted pollutant removal provided by the composite materials may result in more economical and environmentally friendly treatment options. Testing these composite adsorbents in pilot-scale wastewater treatment systems is essential to evaluating their practical performance, including long-term cost-effectiveness, durability, and efficiency. To ensure that these adsorbents are appropriate for a wide range of industrial applications, more research should concentrate on streamlining the synthesis procedures to increase scalability and lower manufacturing costs. Perform long-term research on the reusability and stability of composite adsorbents under various operating circumstances to gain a better understanding of their durability and maintenance needs in practical situations. To assess the life cycle of composite adsorbents and make sure that their use does not have unanticipated environmental effects, a comprehensive environmental impact study is advised. The full potential of composite adsorbents in wastewater treatment may be achieved by following these suggestions, offering a long-term solution for cleaner water management.

Challenges and Future Prospect

Sustainable treatment of dye wastewater constitutes a paramount environmental concern due to the presence of deleterious chemicals in effluents originating from the dye manufacturing sector. The predominant focus is directed towards the development of treatment methodologies that exhibit both efficiency and economic feasibility, while also being environmentally responsible. Despite the advancements that have been achieved, a multitude of challenges persists, including the emergence of secondary pollutants, heightened costs, and substantial energy demands. Future advancements are anticipated to encompass the optimization of existing technologies alongside the exploration of novel strategies aimed at enhancing both sustainability and effectiveness. Numerous contemporary treatment methodologies, including advanced oxidation processes (AOPs), are susceptible to the production of secondary pollutants, thereby complicating the treatment process and potentially causing additional environmental harm. Conventional physicochemical methods often incur exorbitant costs and are marked by significant energy consumption, thus rendering them less amenable to widespread application. Although biological approaches such as bioremediation exhibit considerable potential, they frequently face challenges regarding efficiency and scalability, particularly within diverse environmental frameworks.

Microbial degradation is highlighted as a potentially efficacious strategy for resource recovery and sustainability, with prospects for optimization through the manipulation of process parameters and biotransformation pathways. AOPs are considered effective for the elimination of dyes, offering expedited and more economically viable solutions. Future research endeavors may prioritize the mitigation of secondary pollutants while enhancing the environmental sustainability of these methodologies. The innovation of composite adsorbents is anticipated to enhance the efficiency and speed of dye elimination, representing a promising direction for forthcoming research initiatives. While the enhancement of existing technologies continues to be a primary focus, it is critical to consider the integration of multiple treatment methodologies to address the limitations inherent in singular approaches. This comprehensive strategy possesses the potential to yield more holistic and sustainable solutions for dye wastewater management, thereby aligning with overarching global sustainability objectives.

In the near future, scholarly focus must enhance dye sorption through bentonite clay modification and mechanistic modeling frameworks. There is a critical need to evaluate new methods for separating bentonite from water and improving dye removal rates. Detailed investigations of adsorbate-adsorbent interactions are essential for understanding functional group roles in dye sorption. Current desorption regeneration methods are impractical; thus, cost-effective regeneration techniques must be developed for sustainability. Pilot-scale studies should be undertaken to evaluate the industrial applicability of clay-based adsorbents. Researchers must prioritize the removal of trace contaminants in drinking water for public health. The literature lacks comprehensive studies on pathogenic contaminant removal from wastewater, necessitating prioritization in future research. The development of bentonite-based composites represents a promising area for effective adsorbents in the treatment of water and wastewater contaminants.

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