Removing Dye Pollutants: A Review of Water Treatment Methods and Economical Adsorbents

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ABSTRACT

Water contamination has developed as a serious environmental concern and attracted global attention as a result of the fast expansion of industry and growing population rates throughout the world. Water scarcity, water quality, and worldwide water shortages are all issues that must be addressed, making efficient wastewater treatment technologies a pressing necessity.In this review, we provide an introduction to water contamination and the various pollutants responsible for it. Additionally, we present a brief overview of the classification of dyes based on their source and provide examples of their applications. Due to concerns regarding environmental and health implications, different water treatment methods have been implemented for the removal of dyes from aqueous solutions. However, these methods often have high handling and maintenance costs and generate toxic sludge. Therefore, this review highlights the benefits and limitations of various water treatment methods, with a particular focus on the promising technique of adsorption. Moreover, given the growing interest in low-cost adsorbents as an alternative to conventional methods for wastewater treatment, we discuss economical adsorbents for dye removal and present a table summarizing the maximum dye adsorption capacities of various adsorbents. It is suggested that, in the evaluation of wastewater treatment technologies, it is vital to consider the cost of preparation and consumption associated with adsorbents. To enhance the practicality and relevance of published research, there is a need for more investigations into the cost analysis of adsorbents, particularly in routine adsorption studies.

Keywords: Pollutant types; dyes; water treatment methods; economical adsorbents

1. INTRODUCTION

Earth is the only planet to have an environment where two basic things air and water are available to sustain life. Therefore,saving water to save the earth and make the future of our upcoming generation safe is what we need today. The rapid growth is not only leading us to environmental disorder but also to a big pollution problem. Many water supplies are now dangerous to both humans and the environment as a result of rapid urbanization, rapid industrial development, heavy energy usage, and a never-ending flow of trash from both home and industrial sources. This is the case in the vast majority of nations, including India. The textile processing stagesfrom dying to finishingconsume a tremendous amount of water on a regular basis. Considering how much water is used, it's only natural that effluent be released into the natural world. This industrial effluent is extremely colourful because it contains the dissolved remains of colours. Water pollution from textile waste is on the rise, and as a result, stricter regulations are being placed on the hazardous organic contents of industrial effluents. Therefore, it is essential that these organic pollutants be removed via appropriate treatment methods before being released into the water course. It's possible that discharging coloured effluents without first bleaching them could have disastrous effects on receiving environments.

Water contamination by visible colored pollutants has become a major concern for the environment due to extensive usage of dye and dyestuff [1].In addition to textiles, dyes are widely employed in numerous other industries, including rubber, paper, plastic, cosmetics, etc. There are more than 10,000 commercially available dyes, and more than 7×10^5 tons of dyestuff are produced annually [2]. As a result of producers and users of dyes focusing solely on the stability and fastness of dyes, dyestuffs that are more difficult to breakdown after use are produced. 10-15% of the dye is lost and discharged as effluent during the dyeing process[3].For the reuse of industrial effluent, advanced water treatment procedures are suggested. Dye-containing wastewater represents water pollution that is not only detrimental to humans but also to aquatic life. As a result, it is necessary to treat these polluted waste waters efficiently and effectively.

2. Pollution in the aquatic environment

Water pollution is an unwanted alteration in the quality of water caused by the presence of hazardous substances. Water pollution is any change in the physical, chemical, or biological qualities of water that has a negative impact on living organisms. After air pollution, it is the most serious environmental concern today. All of the world's major water bodies, including lakes, rivers, seas, and groundwater, are impacted by water pollution. In addition to causing water-borne ailments such as diarrhoea, dysentery, and typhoid, polluted water disrupts the entire environment.Factory waste products, dumping of household waste, and harmful chemical effluents from industries result in the deterioration of the quality of water. Most of the dyes used in the textile industries are not biologically degradable and are stable to light and thus reduce sunlight penetration, which prevents the activity of photosynthesis of aqueous flora which in turn leads to the disruption of the food chain. Thus, water pollution and increased toxicity in water bodies deplete fresh dissolved oxygen, causing aquatic life forms to suffer.Many fish and bottom dwellers die below 2–5 ppm of dissolved oxygen. This kills many aquatic organisms, disrupting the food chain. The water of the rivers is notably polluted and contains strong colours, a fluctuating pH, a large number of suspended solids, and a high temperature. These effluents run off the river through the canal and pollute all surface water.

2.1.Pollutants

A pollutant is a chemical released into the environment that has unintended consequences or reduces the utility of a resource. In addition to slowing or speeding up the growth of many plant and animal species, pollutants can also disrupt human conveniences, comforts, and health.Agricultural practices, industrial emissions, and humans all have a significant impact on the issue of contaminants in wastewater. All of these practices have produced various contaminants and disrupted the water cycle, raising widespread concern about the long-term impact on wildlife and human health.

2.2 Types of Pollutants

The various types of water pollutants on the basis of their chemical nature can be classified into the following major categories:Organic pollutants, Inorganic pollutants, Biological Pollutants,and Miscellaneous pollutants(Thermal and radioactive pollutants)

2.2.1 Organic Pollutants

Organic pollutants are contaminants containing organic chemicals that are discharged into the water supply and serve as a substrate for microbes.During the process of decomposition, the dissolved oxygen in the receiving water may be used up at a pace that is larger than the rate at which it can be replaced. This results in oxygen depletion, which has serious repercussions for the organisms that live in streams. Large amounts of suspended particles in organic effluents restrict light that may reach photosynthetic organisms and are thus responsible for altering the characteristics of river bed, making it an undesirable environment. The residual dyes from different sources (such as textile industries, paper and pulp industries, dye and dye intermediates industries, pharmaceutical industries, tannery and bleaching industries, etc.) are considered a wide variety of organic pollutants introduced into the natural water resources or wastewater treatment systems [3]. This group of pollutants includes dyes, detergents, pesticides, aromatic hydrocarbons, phenols, polychlorinated biphenyls (PCBs), and other organic chemicals.

2.2.2 Inorganic Pollutants

Apart from the organic matter discharge in the water body through sewage and industrial wastes, high concentrations of heavy metals and other inorganic pollutants contaminate the water. These substances cannot be broken down by natural processes and so remain in the environment. Mineral acids, inorganic salts, trace elements, metals, metal compounds, complexes of metals with organic compounds, cyanides, sulphates, and other chemical compounds are included in this category of pollutants. The accumulation of these compounds has an adverse effect on aquatic flora and fauna.

2.2.3. Biological Pollutants

Biological substances come from living organisms and can affect human health. They include things such as pollen from trees, dead mass, microorganism, insects or insect parts, certain fungi, bacteria, and viruses. The main source of these pollutants is urban garbage, agriculture waste, human and animal excrement, and urine. Organic pollutants (biological hazard) occurs through faecal contamination. Faecal contamination of water can introduce a variety of pathogens into waterways, including bacteria, viruses, protozoa, and other parasitic worms[4].

2.2.4. Miscellaneous (Thermal and radioactive pollutants)

Some other factors like heat, radioactive substances, etc. may also target water and make it unfit for human beings' use and were included under miscellaneous pollutants.Thermal pollutants are the result due to the discharge of hot water from thermal power plants, nuclear power plants, and industries where water is used as a coolant. As a result of hot water discharge, the temperature of the water body increases and adversely affects aquatic life. A rise in temperature also results in a fall in the solubility of oxygen. Any reduction in dissolved oxygen (DO) in water, particularly when organic pollutants are also present, may result in the loss of sensitive species. For example, in summer fish may have high metabolic rates because their body temperatures are elevated in the warm water. In addition, they are confronted with a relatively low oxygen supply, as warm water contains less dissolved oxygen than cold water. The interaction between these variables may be decisive.Radioactive pollutants originate mainly from the mining and processing of ores, research laboratories, hospitals, discharge from nuclear power plants and nuclear reactors, and also while testing nuclear weapons. These are toxic to life forms; they accumulate in the bones, teeth and can cause serious disorders.

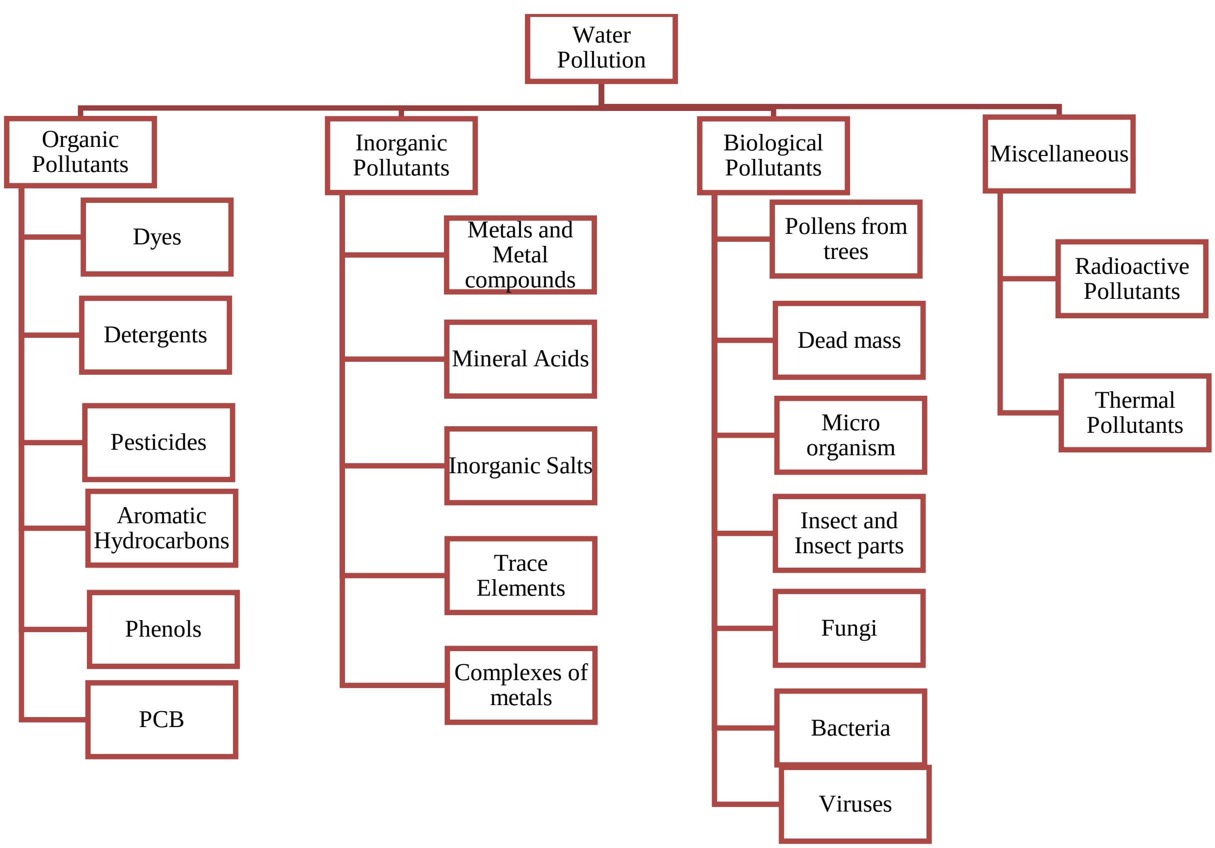

Fig 1: Classification of waterpollutants on the basis of their chemical nature

3. Dyes

Dyes or dyestuffs may be defined as colored substances that show affinity towards the substrate and are capable of imparting their characteristic colours. Dyes have complex molecular structures and are of synthetic origin. Every year, thousands of tonnes of harmful dye effluents are released into waterways due to the widespread use of dyes in a wide variety of industrial applications. The presence of these dye effluents is extremely harmful to the ecosystem. Dyes are water-soluble and intensely coloured substances and are mainly used in textiles, plastics, pharmaceuticals, paint, paper and electroplating industries[5]. Dyes are considered to be the obnoxious type of pollutants as they cause the highest aquatic environment contamination among all industrial sectors[6]. Dyes are known to be mutagenic, toxic,and carcinogenic and they are generally resistant to light, water, oxidizing agents and difficult to degrade [7].

3.1 Classification of dyes

Dyes exhibit structural diversity and can be classified in several ways. Broadly dyes can be classified on the basis of their source. Dyes can be produced from natural and synthetic sources.

3.1.1. Natural Dyes

Organic substances like natural dyes are utilized to impart colour to a wide range of manufactured goods. In prior to the year 1856, natural dyes are extracted from plants, animals, insects, and minerals sources. Natural dyes are as Turmeric, Onion, Henna, Jackfruit, and Eucalyptus are used in the textile industry [8]. Due to the increase in the population and industrial activities, natural dyes do not meet industrial demands and also their applications have been limited.

3.1.2 Synthetic Dyes

The first synthetic dye was discovered by William Henry Perkin in 1856. Synthetic dyes are broadly classified into anionic, cationic, and non-ionic dyes. Anionic dyes include various dyes groups such as acid dyes, direct dyes and reactive dyes,while cationic dyes are the basic dyes and the non-ionic dyes are vat dyes and disperse dyes. [9-10] The dyes classifications and their applications are presented in Table 1. All these dyes are water-soluble except disperse dyes and vat dyes. These dyes-based effluents can cause serious hazards to the water stream and environment due to their synthetic origin and complex molecular structures which decrease their ability to biodegrade.

Table 1: Classification of synthetic dyes

Dyes	Example of dyes	Application of dyes
Acid dyes (Anionic dyes)	Congo red Methyl (orange and red) Orange (I, II) Acid (blue, black, violet, yellow)	Applied in the form of their sodium salts on Wool Silk Nylon (Polyamide) Polyurethane fibres
Direct dyes (Anionic dyes)	Martius yellow Direct black Direct orange Direct blue Direct violet Direct red	Cotton Wool Flax Silk Leather in (alkaline or neutral bath)
Reactive dyes (Anionic dyes)	Reactive red Reactive blue Reactive yellow Reactive black Remazol (blue, yellow, red, etc)	Cellulosic Fibres Wool Polyamide
Dispersedyes (Non-ionic dyes and Water-insoluble dyes)	Disperse blue Disperse red Disperse orange Disperse yellow Disperse brown	Polyamide Fibres Polyesters Nylon polyacrylonitriles
Vat dyes (Non-ionic dyes and Water-insoluble dyes)	Indigo Banzanthrone Vat blue Vat green	Wool Flax Rayon Fibres
Basic dyes (Cationic dyes)	Methylene blue Basic red Basic brown Basic Blue Crystal violet Aniline yellow Brilliant green	Polyester Wool Silk Mod-acrylic Nylon

4. Water treatment methods for the removal of dyes

Due to environmental and health concerns associated with wastewater effluents, different water treatment methods have been used for the removal of dyes from aqueous solutions. The treatment methods can be divided into physiochemical, chemical, and biological methods [11]. Each method has its own benefits and limitations in terms of design, dye separation efficiency, and total cost as listed in Table 2.

Table 2: The benefits and limitations of various water treatment methods for the removal of dyes

Water treatment method	Benefits	Limitations	References
Physiochemical Methods			
Ion Exchange	No loss of sorbents during regeneration	Not effective for dispersing dyes	[12]
Membrane technologies (such as filtration, Reverse osmosis, and nanofiltration membrane systems)	Effective for all dyes with high-quality effluents, chemical and temperature resistance	Suitable for treating low volume, production of sludge, and frequent clogging of membrane pores by the dye molecules,only effective until membrane fouling starts, more expensive.	[13] [14]
Electrochemical methods like Electro kinetic coagulation	Easily controllable, efficient, and economically feasible	Continuous monitoring and maintenance are required, in addition to the expense of electricity, need further treatments by flocculation and filtration, and the production of sludge	[14]
Adsorption (Using commercial activated carbon and various low-cost adsorbents including biomass-based adsorbents)	High adsorption capacity for all dyes, Effective, cheap, commonly used method as easy handling	High cost of adsorbents (If commercial activated carbon is used) Need to dispose of adsorbents Low surface area of some adsorbents	[13]
Chemical Methods			
Fenton reagent	Effective process and cheap reagent	Sludge production and disposal problems	[15]
Ozonation	No production of sludge	Half-life is very short (20 min) and high operational cost	[16]
Photocatalyst	Economically feasible and low operational cost	Degrade of some photocatalysts into toxic by-products	[17]

Chemical precipitation	Easy method and small funding requirements	High maintenance costs and additional costs for sludge disposal	[18]
Coagulation and flocculation	Minimal initial investment and thorough dye removal	Generate hazardous sludge, handling, and disposal issues	[13]
Biological Methods			
Aerobic degradation	Efficient in the removal of azo dyes and low operational cost	Very slow process and provide a suitable environment for the growth of microorganisms	[19]
Anaerobic degradation	By-products can be used as energy sources	Need further treatment under aerobic conditions and yield of methane and hydrogen sulfide	[20]

4.1.Adsorption

Adsorption is defined as the build-up of material at the interface of two phases (liquid-solid interface or gas-solid interface). The substance that accumulates at the interface is called adsorbate and the solid on which the adsorption takes place is called adsorbent [21]. Adsorption can be classified into two types: Chemical adsorption or chemisorption and physical adsorption or physisorption. Chemisorption is illustrated by the formation of strong chemical associations between molecules or ions adsorbate to the adsorbent surface, which is generally due to the exchange of electrons [22] and thus it is generally an irreversible process. Physiosorption is characterized by weak van der Waals intraparticle bonds between adsorbate and adsorbent and thus is reversible in most cases [23]. Despite the presence of several conventional methods, the adsorption technique appeared to be the most promising method for dye removal because of the flexibility and simplicity of design, minimal disposal of the volume of sludge, simple regeneration, less investment in terms of initial cost, and high efficiency [24].The past years have seen a developing interest in the preparation of low-cost adsorbents including biomass-based adsorbents as alternatives for wastewater treatments [24].

4.2. Adsorbents

One of the most important characteristics of an adsorbent is the quantity of adsorbate it accumulates. The adsorbents are generally effective in removing dyes that are resistant to biological degradation.According to Linsen, a good adsorbent should generally possess a porous structure (resulting in high surface area) and the time taken for adsorption equilibrium to be established should be as small as possible so that it can be used to remove dye wastes in lesser time [25]. Other desirable properties that an adsorbent should possess include easy availability, feasibility, stability, compatibility, eco-friendly, ease of regeneration, and highly selective to remove a variety of dyes [26]. Figure 2 depicts various adsorbent materials used for the removal of dyes from wastewater, whereas Table 4 presents the adsorption capacity of various adsorbents for the removal of different dyes.

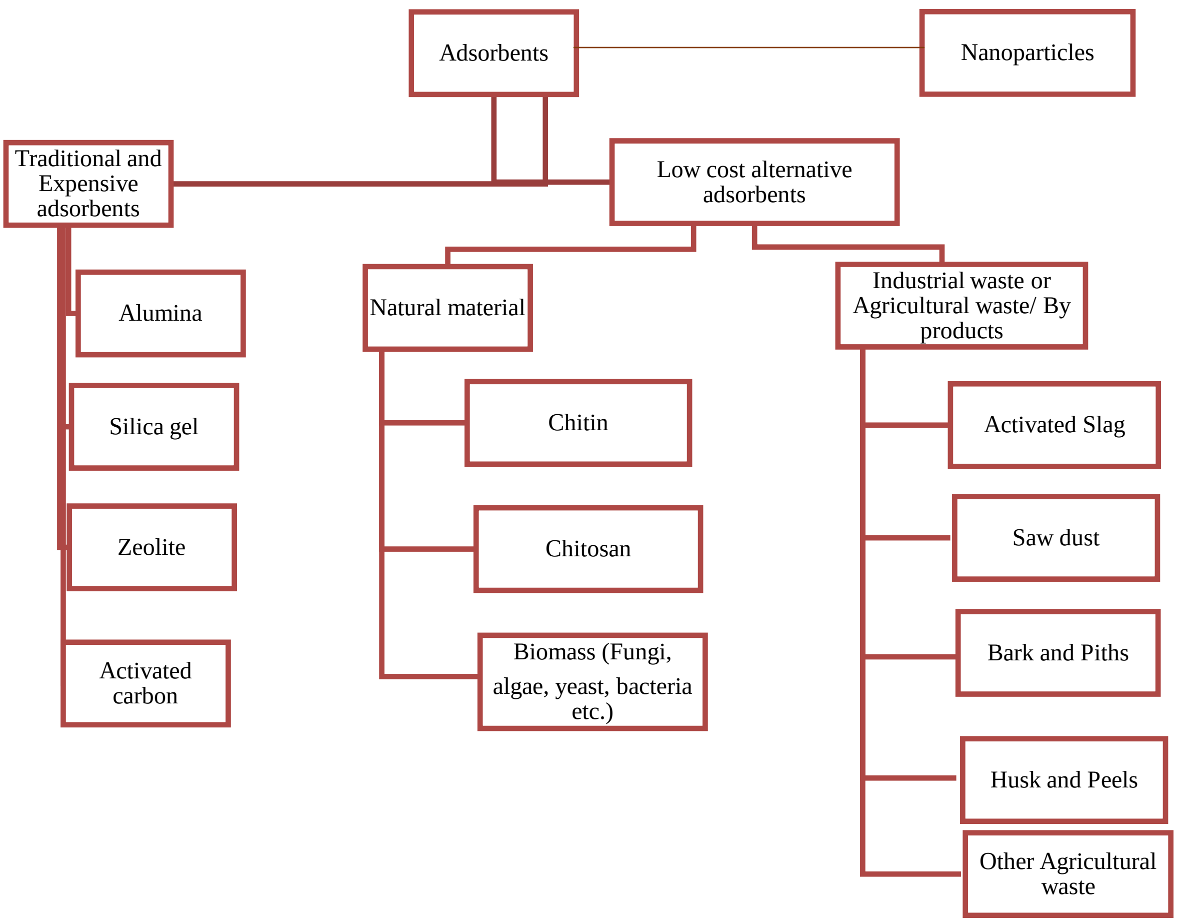

Figure 2: Various adsorbent materials used for the removal of dyes from wastewater

4.2.1. Traditional and Expensive Adsorbents

Though activated carbon, alumina, silica gel, zeolites, charcoal, clays and minerals, polymers, and nanoparticles, have all been used effectively to remove harmful contaminants from wastewater due to their high adsorption uptake ability. This is due to their origin, regeneration potential, environmental friendliness, and availability but are expensive materials. So, there is a pressing need, however, to find ways to lower the expense of employing these adsorbents in wastewater treatment without sacrificing efficacy or using other low-cost alternative adsorbents.

4.2.1.1. Alumina

Alumina is a synthetic porous crystalline gel, which is available in the form of granules of different sizes having surface areas ranging from 200 to 300 m^2g^{-1}. Adak et al. studied the removal of crystal violet dye from wastewater using surfactant-modifiedalumina and obtained a good adsorption capacity of 116 mg/g [27].

4.1.1.2. Silica Gel

Silica gel is prepared by the coagulation of colloid salicylic acid resulting in the formation of porous and non-crystalline granules of different sizes. Various researchers like Vora et al and Farukh et al investigated the adsorption of basic dyes onto silica gel [28-29]. Although the adsorption capacities were high the drawback was that silica is an expensive adsorbent.

4.1.1.3. Zeolites

Zeolites are important microporous adsorbents, which are found naturally and are prepared synthetically too. They are also considered selective adsorbents and show ion exchange properties as well as molecular adsorption [30,31]. Ozdemir et al used zeolite-like amine-modifiedsepiolite as an adsorbent for the removal of everzol yellow, everzol black, and everzol reddyeswith good adsorption capacities as shown in Table 4[32].

4.1.1.4. Activated carbon

It is the oldest adsorbent known and is usually prepared from cork, coal and biomass based activated carbons (from coconut shells, rubber seeds, lignite, wood, etc.), using one of the two basic activation methods: physical and chemical [33-35].However, some commercial activated carbon is still pricey despite its widespread application in wastewater treatment.

4.2.2. Low-cost alternative adsorbents (LCAs)

4.2.2.1. Natural materials

Natural materials used as LCAs are the ones existing in nature and are used as such, or after some minor treatment. Chitin and Chitosan are versatile materials and have been used successfully for the removal of dyes [36]. Yoshida et al. used cross-linked fibres for dye adsorption [37]. Biomass which is available in large quantities and at low prices has got an increasing interest in dye wastewater treatment. A number of studies have been carried out to investigate the efficiencies and mechanisms of the removal of dyes by various types of biomass. This includes microorganisms such as algae, yeasts, bacteria, and fungi that are capable of decolorizing a wide range of toxins with high efficiency[38-44].The mechanism involved during the sorption of dye from the solution is chelation and complexion [45]. Fungal biomass can be produced cheaply using relatively simple fermentation techniques and inexpensive growth media [40, 41]. Fungal biomasses are constituted of sugars, proteins, and lipids, as well as various functional groups (alcohols, carboxyl, and alkanes), which provide it specific qualities and uses them as a biosorbent in wastewater treatment[42].Several fungus species have been employed as successful candidates for the removal of a variety of dyes from effluents, including*Aspergillus niger*used for the removal of Congo Red dye from aqueous solutions [40].

Algae are considered one of the most favorable sources of adsorbents due to their high adsorption capacity and extensive availability. There are reports indicating that alga has a relatively high adsorption capacity for the removal of dyes [38,39].Adsorption of dyes for their removal from aqueous solutions is dependent on the composition and structure of the algal cell wall, which consists of several polysaccharides: alginic acid, chitin, xylan, and mannan, In conjunction with the existing proteins, these components can provide acid-binding sites such as hydroxyl (found in carbohydrates and alcohols), phosphate (found in RNA and DNA), ester (found in lipids), carboxyl (found in organic acids and fatty acids) sulfhydryl (found in amino acids such as cysteine), amino, amine, and imidazole groups (found in proteins and amino acids) [38,39].Encapsulation and surface modification can be used as pretreatments to improve the adsorption capacity of algae [46].

4.2.2.2. Industrial /Agricultural/domestic wastes or by-products

A number of industrial/agricultural wastes/by-products are investigated as adsorbent materials for the removal of dyes by a number of workers. Yasipourtehrani et al used activated slag, a by-product of the iron ore processing industry for the removal of methylene blue and methyl orange dye[47]. Saw dust prepared from Eucalyptus wood was utilized for the removal of Congo Red dye from wastewater with good adsorption capacity [48]. Compost from pine bark was used as an effective low–cost biosorbent for the removal of Basic Violet 10 and Direct Blue 151 dyes from single and bi-solute mixtures in batch and fixed-bed column experiments [49].

Ahmed et al studied the removal of Methylene blue (MB) dye using the rice husk biochar, cow dung biochar, and domestic sludge biochar synthesized through slow pyrolysis at 500 °C and obtained adsorption capacity of 17.972, 17.506, and 19.219 mg/g respectively[50]. Other agricultural solid wastes from cheap and readily available resources such as Orange peel, locust bean pods, dead leaves of oak trees, Sea plants that is, *Posidonia oceanica* L. leaves, Grass wastes, and corncobs have also been successfully employed for the removal of dyes from aqueous solutions [51-55].A critical review of low-cost adsorbents including agricultural wastes for dye wastewater treatment was presented extensively by Gupta and Suhas[56].

4.2.3. Nanomaterials

The application of nanoparticles for the removal of contaminants has recently been an intriguing topic of research due to their unique qualities, which are creating new potential and cost-efficient techniques, hence numerous nanoparticles have been explored for this purpose [57-59]. Alumina is a well-known adsorbent, and the form of γ -alumina has been reported to be more adsorptive than α -alumina [27].

Table 4: Various types of adsorbents and their adsorption capacity for different dyes

S.No.	Adsorbent	Dye	Adsorption capacity (mg/g)	Reference
Traditional / Expensive adsorbents				
1.	Surface modified alumina	Crystal violet	116	[27]
2.	Chromatographic grade silica	Cationic dye Basic Red	66	[28]
3.	Surface functionalized Silica gel	Rhodamine B and Crystal violet	45.4, 149.2	[29]
4.	Zeolite like amine modified Sepiolite	Everzol Yellow, Everzol Black, Everzol Red	169, 120, 108	[32]
5.	Activated carbon from coal	Methylene Blue	29.5	[33]
6.	Coconut shell-activated carbon	Rhodamine B	600	[34]

7.	Powdered activated carbon from rubber seed and rubber seed shell	Methylebe blue Congo red	769.23 458.43	[35]
Low-cost Alternative Adsorbents (Natural materials)				
8.	Chitin	Reactive Black 5	131.56	[36]
9.	Chitosan	Reactive black 5	696.99	[36]
10.	Chara sp. (Algae)	Alizarin dye		[38]
11.	Oscillatoria sp. (Algae)	Methylene Blue		[39]
12.	Aspergillus niger (fungus)	Congo Red	14.72	[40]
13.	Formotopsis carnea (fungus)	Orlamar Red BG Orlamar Blue G Orlamar Red GTL	503.1 545.2 643.9	[41]
14.	Agaricus bisporus (Macrofungi, Mushroom)	Methylene Blue Congo Red	239.8 76.4	[42]
15.	Brewer's Yeast biomass (BYB)	Malachite green, Reactive Red 239, Direct Blue	212.05, 152.9, 139.2	[43]
16.	Aureispira sp. (CCB-QB1) (Bacterium)	Congo Red	1.48	[44]
Low-cost Alternative Adsorbents(Industrial waste or Agricultural waste/ By-products)				
17.	Activated slag	Methylene blue Methyl Orange	6.33, 2.04	[47]
18.	Eucalyptus wood Saw Dust	Congo Red	66.67	[48]
19.	Pine bark compost	Basic Violet 10 Direct Blue 151	127 42	[49]
20.	Rice husk biochar, Cow dung biochar and domestic sludge biochar	Methylene blue dye	17.972, 17.506, and 19.219	[50]
21.	Orange Peel	Direct Red 23, Direct Red 80	10.72, 21.05	[51]
22.	Other agricultural wastes like locust bean pod	Rhodamine B	1111.1	[52]
23.	Dead leaves of oak trees Sea plant (*Posidonia oceanica* L.) leaves	Crystal violet Methylene Blue	31.65 27.78	[53]
24.	Grass wastes	Methylene Blue	241.2	[54]
25.	corncobs	Methylene Blue	523.18	[55]
Nanoparticles				
26.	Alumina nanomaterial	Anionic orange G dye	93.3	[57]
27.	Alumina nanomaterial	CBG Dye	263.16	[58]
28.	Modified Nano alumina	Alizarin yellow	37.7	[59]

5. Cost analysis of adsorbents

Several studies suggest that the use of adsorbents made from microorganisms and forest and agricultural waste is cost-effective when compared to traditional treatment methods, despite not including an estimation of the actual costs.The success of adsorption depends on the material used as an adsorbent during dye adsorption procedures. To ensure that adsorption is affordable, it is necessary to have a large supply of the adsorbent material, simple preparation or processing, and green chemistry approaches, along with activation needs [46, 60].While some authors contend that "low-cost adsorbents" merely reflect the initial pricing, it is essential to consider lifetime cost, recycling, regeneration, and treatment in addition to the initial cost [61]. In a review by Ighalo et al on the cost of adsorbent preparation and usage in wastewater treatment, they reported that adsorbent costs could be determined based on raw material prices, discounted cash flow, cost indices, adsorbent price per gram of adsorbate removed, yearly capital expenditure, operational expenditure, and adsorbent application price [62].

6. Reuse studies and safe disposal of used adsorbents

Once the dye has been removed from wastewater, it is crucial to make optimal use of both the adsorbent and the eluent that contains the more concentrated pollutants. It is possible to carry out multiple cycles of adsorption and desorption with minimal or no sludge formation, which enables the recurring regeneration of the algal biomass. The use of desorbing agents, such as acids, alkalis, and EDTA (ethylene diamine tetraacetic acid), can facilitate the removal of adsorbed metal ions from the adsorbent surface. After the adsorbents have been completely used up, they can be dumped, stored, or disposed of; however, proper disposal is essential [46, 63]. One potential approach for the secure disposal of the final effluent is stabilization and immobilization, such as utilizing a cement-based system as a binding agent [46].

7. Conclusionsand recommendations

This article provides a comprehensive review of dye classification based on their chemical nature and origin, which includes dyes obtained from either natural or synthetic sources. It also covers the classification of synthetic dyes with examples and applications. Despite the existence of various traditional dye removal techniques, this review highlights their limitations, such as high cost, sludge formation, and operational inefficiency, although they exhibit strong performance for specific pollutants. Among the different wastewater treatment methods, adsorption stands out as the most promising approach due to its simplicity, low cost, and versatility. Many studies have shown that adsorption using different types of adsorbents is the most efficient and cost-effective approach for extracting dyes from aqueous solutions. This article describes various adsorbent materials, including traditional and expensive ones such as alumina, silica gel, zeolite, and activated carbon, as well as low-cost adsorbents such as natural materials (chitin, chitosan, biomass of algae, fungi, bacteria, etc.) and agricultural and industrial wastes (activated slag, sawdust, husk, and seeds), along with their corresponding adsorption capacities for different dyes.

Despite the numerous studies on low-cost alternative adsorbents, many challenges remain unresolved. Most adsorption research has focused on eliminating a single pollutant, whereas real-world wastewater, such as that generated by the textile industry, typically contains multiple colors. Therefore, additional research is required to investigate mixed and multi-pollutant systems to address the needs of practical wastewater treatment. Critical factors that determine the practical usefulness of adsorbents include their stability and cost. While most studies have only examined adsorption capacity in the lab, a more accurate depiction should also consider factors such as local availability, transportation, treatment procedures, and concerns about recycling and lifespan. Research into desorption, regeneration, and spent adsorbent disposal is also crucial to reduce process costs, recovering adsorbed chemicals, and minimizing waste.

8. Conflict of interest

The author declares no conflict of interest.

9. References

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