https://doi.org/10.48047/AFJBS.4.4.2022.203-233

AFJBS

African Journal of Biological Sciences

Journal homepage: http://www.afjbs.com

Research Paper Open Access

A Critical Review on Removal of Dyes from Aqueous System Using Adsorption

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Volume 4, Issue 4, Dec 2022

Received: 11 Nov 2022

Accepted: 09 Dec 2022

Published: 28 Dec 2022

doi: 10.48047/AFJBS.4.4.2022.203-233

Abstract :Water is one of the most crucial elements of the environment. Discharge of dye wastewater in large amounts from various industries poses a great challenge to all forms of life. It creates toxic and carcinogenic effects on both human beings and aquatic life. A number of researches have been carried out to prepare new alternative materials and techniques for dye adsorption from wastewater. The main aim of this review paper is to provide an overview of recent and progressive developments in the utilization of different adsorbents, their modification, and their adsorption capacities for dye removal. The paper presents the available comprehensive information on the adsorption of dyes using several possible adsorbents in a systematic and well-organized manner. Hence, a long list of different adsorbents has been compiled including natural-based polymeric materials, activated carbon derived from biomass, waste agricultural materials, etc. for the effective removal of dyes. The use of the adsorption process for the effective removal of dyes employing various adsorbents is due to its eco-friendly aspects. The comparison of adsorbing efficiency of various adsorbents towards different dyes has also been explained. From the pieces of literature that were reviewed, a number of inferences and useful ideas have been drawn out for future aspects of research and exploration in this relevant area.

Key words: Adsorption; wastewater; Dyes; activated carbon; toxicity

INTRODUCTION

Dyes play a crucial role in many industries like paper, pulp, leather tanning, food, textile, rubber, printing, and dye production. [1,2] The dye manufacturing industries produce a significant amount of carcinogenic chemicals, many of which are discharged into wastewater, leading to pollution of rivers and ponds.[3] These dyes hinder light penetration and subsequently impact photosynthesis in marine plants.[4-6] Considering the hazardous and toxic properties of dyes and their derivatives, the purification of wastewater contaminated with color dyestuffs holds significant environmental importance.[9-11]Synthetic aromatic dyes are known to be biologically non-degradable, making their treatment through conventional methods impractical.[12,13]

To remove color from water and wastewater, a variety of techniques, such as aerobic and anaerobic degradation using various microbes, membrane separation, chemical oxidation, reverse osmosis, coagulation, and flocculation, can be used. [2,3,9,10,14] The majority of these techniques have certain limitations, including excessive chemical consumption, sludge accumulation, and ineffective color reduction.

One of the best and most effective methods for removing pollutants is adsorption. It is based on how contaminants and pollutants are transferred from the solution to the solid phase.[12,13,15] The superiority of this method over other methods can be given in terms of design, cost, ease to use, harmless byproducts and non-toxicity of adsorbents in comparison to other methods.[16] In the adsorption technique, numerous adsorbents, including commercially available activated carbon, adsorbents made from natural resources, industrial solid waste, agricultural byproducts, and biosorbents have been utilized by researchers. The greater the percentage of lignin and cellulose in the adsorbent better would be its adsorption capacity. Various strategies for physical and chemical modification can be employed to enhance the adsorption capacity.[17]

The physical method involves the heating of the adsorbent in the oven while the chemical method involves addition of acid or alkali for the activation. Researchers have used inorganic acid as well as organic acid for the activation, in a few papers a mixture of inorganic and organic acids have also been used.

The primary objective of this paper is to give information on various low-cost adsorbents, including biomass-based activated carbon, agricultural by-products, industrial solid waste, and agricultural solid waste for the removal of dyes from an aqueous phase. Various classes of dyes, their toxicity, and structure will also be discussed in detail. In addition, we will explore the adsorption capacity and the influential parameters that impact the adsorption process of different dyes on diverse adsorbents.

TOXIC EFFECT OF DYES:

Dyes show toxic effect for not only terrestrial creatures but also for the marine creatures. Due to highly intensified color they decrease the penetration of sunlight to marine plants and affect photosynthesis [18,19], presence of aromatics and metals also make them toxic for the marine animals. [20,21] Presence of chromium in the complex dyes make them carcinogenic. [22] Additionally, it can seriously harm people, resulting in renal, reproductive, liver, central nervous system disorders, brain and liver.[23] Some dyes such as azo dyes are highly toxic as the effluent contains hazardous amines. [24]

On the central nervous system, methylene blue can have neurotoxic effects. [25] Chromosome fractures, cancer, mutagenesis, and respiratory problems have all been linked to malachite green. Histopathological results also demonstrate multi-organ tissue damage. [26] Azo Dyes like E133 Brilliant Blue, Amaranth, E129 Allura Red, Ponceau 4R (Cochineal Red A) and Azorubine (Carmoisine). Numerous azo dyes have carcinogenic and mutagenic effects, and they can also trigger allergic reactions. With the increase in number of benzene rings, the toxicity of azo dye rises means the more the benzene rings it has, the more poisonous and dangerous the dye is. [27] Due to their combined aromatic structures, anthraquinone reactive dyes are very weakly biodegradable.[28]

VARIOUS TREATMENT METHODS FOR DYE REMOVAL [29,30]

As the toxic effect of dyes have generated concern regarding to its usage, hence its removal from different kind of waste water stream is very important. Several technologies can be used for removing colours from waste water. These technologies involve precipitation method, flocculation-coagulation, electro- flocculation, electrochemical coagulation, biological degradation, chemical oxidation, reverse osmosis, adsorption etc.

a. Precipitation Method

Precipitation is a method for separating a mixture according to how easily its constituent parts may be dissolved. The solubility of a compound is influenced by several parameters, including the ionic strength, pH and temperature of the solution. A chemical may form an insoluble solid and leave solution if certain parameters are changed. It may be used to successfully remove a variety of chemicals that can be difficult to remove using other methods. But the main disadvantage is reagent is sometimes quite costly and is typically required in huge quantities.

b. Flocculation-Coagulation

The coagulation process is utilized to balance charges and create a gelatinous mass that can bridge (or capture) particles and become large enough to get settled in the filter. Flocculation is the mild agitation or stirring that helps the newly created particles clump together into big enough so that they can be filtered out of the solution. It Removes various types of particles from the water and boosts the filtering process. However, it is relatively long procedure. Transferring hazardous substances into the solid state and the subsequent production of sludge.

c. Electro-flotation

Gas bubbles are introduced into the electro-floatation process as the transport medium. Due to hydrophobicity or having been trained to be so, suspended particle matter subsequently binds to the bubbles and moves against gravity, towards the surface of the aqueous solution. It is a quiet process with low energy requirements and highly effective suspended solids removal. Limitation of this method is that the bubble size significantly influences separation effectiveness.

d. Electrochemical Coagulation

For the process of electrocoagulation, Anodes and cathodes, two pairs of metal sheets are placed in groups of two. At anode reduction of water (gain of electrons) takes place while oxidation occurs at cathode (loss of electrons) according to the principles of electrochemistry to enhance the treatment of the wastewater. It is an efficient approach for recycling and recovering priceless metals. The disadvantage includes sludge accumulation on the electrodes and electrode passivation can interrupt the electrolytic process from continuing.

e. Biological Degradation

The substance is altered by the microorganisms through metabolic or enzymatic reactions. Metabolic and growth processes serve as its foundation. The exclusive carbon and energy source for growth is provided by an organic contaminant. The process has limitation as it require to create an environment that is as favourable as possible.

f. Chemical Oxidation (Ozonation, Hydrogen Peroxide)

The process of chemical oxidation involves transferring of electrons from an oxidizing agent to the chemical species being oxidized. In the field of wastewater and water engineering chemical oxidation is utilised to transform putrescible substances into harmless or stable products. It helps in effective cyanide and sulfide elimination treatment. In this method pretreatment is crucial.

g. Adsorption

Adsorption is the process of different molecules being drawn to and held onto the solid or liquid surface, resulting in a larger concentration on the surface. It is the process of a substance known as sorbate or adsorbate accumulating on the surface of a solid known as sorbent or adsorbent.[31] Adsorption can be classified as either chemical or physical. Chemical adsorption or chemisorption involves the formation of strong chemical bonds by exchanging electrons, between molecules of the adsorbate and the adsorbent surface.[32] However, Physisorption or physical adsorption occurs when the adsorbate and adsorbent form a weak Van der Waals intraparticle association. Vander Waals forces, polarity, dipole-dipole interactions, hydrogen bonding and others are the primary physical factors that regulate adsorption. Adsorption is an attractive option for treating contaminated and polluted water. It has been determined that adsorption is a superb alternative approach in terms of design flexibility, beginning cost, sensitivity to harmful contaminants, and easy to operate. Additionally, adsorption does not end up resulting in dangerous chemicals.

REMOVAL OF DYES FROM AQUEOUS PHASE USING VARIOUS ADSORBENTS

Clay minerals, siliceous materials, activated carbon, agricultural waste derived activated carbon, metal oxide, and many different forms of adsorbents are utilised in various research to remove dye colours. Figure 1 illustrates various adsorbents that can be employed for the purpose of eliminating colors from wastewater. In this work, the low-cost adsorbents have been classified into five distinct categories :

(i) Household and agricultural waste
(ii) Biomass solid waste
(iii) Activated Carbon obtained from commercial byproducts
(iv) Different inorganic substances for example clay, zeolites, siliceous materials, metal oxide, etc.
(v) Biopolymers and Microbial Biomass

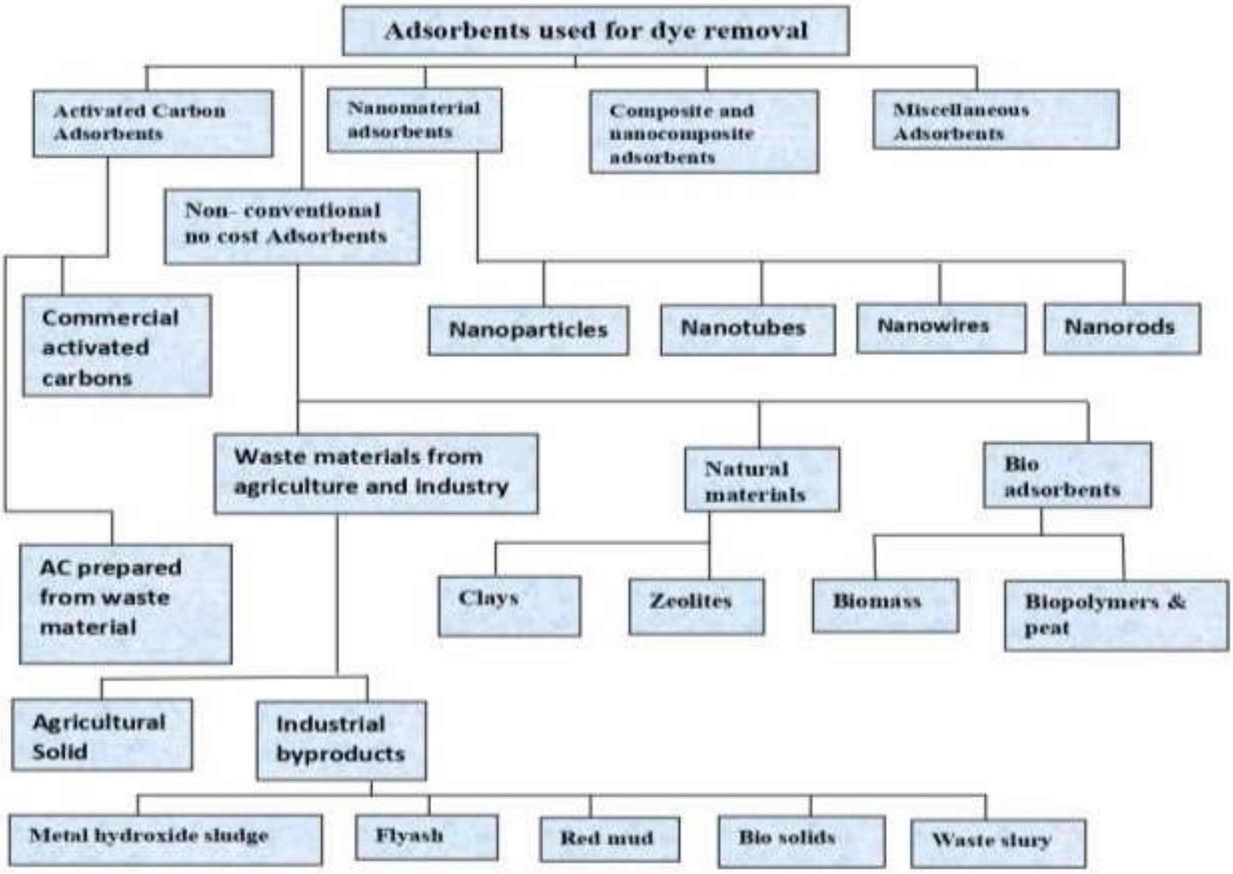

Figure 1. Different Types of Adsorbents used for Dye Removal

Different categories of low-cost adsorbents and their adsorption capacity for a particular dye can be explained as follows:

Agricultural and household waste:

Wastes are readily available in vast numbers all around the world, including domestic garbage and agricultural byproducts. The physicochemical properties of these materials suggest that they may act as potential sorbents. Table 1 below illustrates various agricultural solid waste and their capacity to bind various dyes. Based on current research findings it has been observed that a variety of agricultural solid wastes possess the potential to serve as effective adsorbents for the removal of inorganic and organic pollutants, including dyes.

Table 1. Various Agricultural Solid Waste And Their Capacity To Bind Various Dyes

S.No.	Dye	Materials	Optimum adsorption capacity	References

			Q_m (mg/g)	
1.	Methylene Blue	Poplar Leaf	135.35	33
2.	Basic Red 13	Tree Fern	408	34
3.	Acid Yellow 132	Pine Sawdust	398.8	35
4.	Acid Blue 256	Pine Sawdust	280.3	35
5.	Methylene Blue	Pineapple Stem	119.05	36
6.	Methylene Blue	Banana Peel	20.8	37
7.	Reactive Black 5	Coffee Waste	77.52	38
8.	Congo Red	Coffee Waste	34.36	38
9.	Methylene Blue	Peanut Hull	68.06	39
10.	Methylene Blue	Citrus Sinensis Bagasse	96.4	40
11.	Crystal Violet	Coniferous Pinus Bark	32.78	41
12.	Crystal Violet	Japonica	82.83	42
13.	Crystal Violet	Wheat Bran	80.37	42
14.	Crystal Violet	Grapefruit Peel	254.16	43
15.	Methylene Blue	Swede Rape Straw	264.4	44
16.	Basic Blue 3G	Coffee Residues	179	45
17.	Basic Blue 69	Egyptian Bagasse Pith	168	46
18.	Methylene Blue	Neem Leaf Powder	3.67	47
19.	Methylene Blue	Coconut Coir	15.59	48
20.	Methylene Blue	Cherry Sawdust	39.84	49
21.	Methylene Blue	Rice Husk	40.59	50
22.	Methylene Blue	Yellow Passion Fruit Waste	44.7	51
23.	Methylene Blue	Walnut Sawdust	59.17	52
24.	Methylene Blue	Ground Hazelnut Shells	76.9	52
25.	Methylene Blue	Fallen Phoenix Tree's Leaves	80.9	53
26.	Methylene Blue	Rubber Seed Shell	82.64	54
27.	Methylene Blue	Coffee Husk	90.1	55
28.	Methylene Blue	Coconut Bunch Waste	70.92	56
29.	Methylene Blue	Garlic Peel	82.64	57
30.	Methylene Blue	Orange Peel	18.6	58
31.	Methylene Blue	Mango Seed Kernel	142.86	59
32.	Crystal Violet	Rice Husk	44.87	60
33.	Crystal Violet	Sawdust	37.83	61
34.	Crystal Violet	Pineapple Leaf Powder	78.22	62
35.	Basic Red 46	Pine Tree Leaves	71.94	63
36.	Basic Red 46	Pine Cone	73.53	64
37.	Basic Red 46	Canola Hull	49	65

38.	Basic Red 46	Princess Tree Leaf	43.1	66
39.	Direct Red 23	Rice Husk	4.35	67
40.	Direct Red 23	Rhizophoraapiculata Bark	21.55	68
41.	Reactive Black 5	Peanut Hull	55.55	69
42.	Methylene Blue	Modified Sawdust	111.46	70
43.	Methylene Blue	Modified Pine Cone	142.24	71
44.	Methylene Blue	Pine Cone	109.89	72
45.	Methylene Blue	Spent Rice Biomass	8.3	73
46.	Methylene Blue	Turmeric Powder	157.33	74
47.	Acid Blue 25	Peat	14.4	75
48.	Methylene Blue	Sawdust Carbon	12.49-51.4	76
49.	Methylene Blue	Olive Stones AC	4.8-12.4	77
50.	Methylene Blue	Ficus Carica Bast AC (FCBAC)	30-45	78
51.	Malachite Green	Activated Carbon Prepared From Lignite	200	79
52.	Malachite Green	Orange Peel	483.63	80
53.	Malachite Green	Eggshells	243.20	81
54.	Malachite Green	Functionalized Sawdust	196.08	82
55.	Malachite Green	Treated Ginger Waste	188.60	83
56.	Malachite Green	Breadnut Peel	180	84
57.	Malachite Green	Pomelo Peels	178.43	85
58.	Malachite Green	Treated Jack Fruit Peel	166.37	86
59.	Malachite Green	Neem Leaf Powder	133.6	87
60.	Malachite Green	Native Rice Straw	94.34	88
61.	Malachite Green	Conch Shell Powder	92.25	89
62.	Malachite Green	Walnut Shell	90.80	90
63.	Malachite Green	White Rice Husk Ash	85.56	91
64.	Malachite Green	Crude Sawdust	85.47	92
65.	Malachite Green	Maize Cob	80.64	93

66.	Malachite Green	Rice Bran	68.97	94
67.	Malachite Green	Wheat Bran	66.57	94
68.	Malachite Green	Eucalyptus Bark	59.88	95
69.	Malachite Green	Tamarind Seed	54.95	96
70.	Malachite Green	Lemon Peel	51.73	97
71.	Malachite Green	Sea Shell Powder	42.33	98
72.	Malachite Green	Potato Leaves Powder	33.3	99
73.	Rhodamine B	Banana Bark	40.161	100
74.	Red Brown C4R	Tapioca Peel	121.47	101
75.	Acid Violet 17	Bagasse	38.32	102
76.	Acid Red 119	Pea Shell	44.48	103
77.	Acid Blue15	Used Tea Leaves	126.53	103
78.	Reactive Blue 19	Orange Peel	45.5	104
79.	Indigo Carmine	Coffee Residue	30	105
80.	Indigo Carmine	Rice Bran	9.7	106
81.	Indigo Carmine	Activated Carbon	87.8	107
82.	Reactive Blue 19	Orange Peel	45.5	108
83.	Reactive Blue 19	Modified With NaOH Orange Peel	25	108
84.	Reactive Blue 19	Modified With CTAB Orange Peel	100	108
85.	Reactive Blue 19	NaOH-Orange Peel Modified With CTAB	166	108
86.	Methylene Blue	Orange Peels Calcinated At 300 °C	14.31	109
87.	Methylene Blue	Orange Peels Calcinated At 400 °C	14.85	109
88.	Methylene Blue	Orange Peels Calcinated At 550 °C	7.30	109
89.	Reactive Red 3b	Orange Peel Modified With HCl	33.33	110
90.	Direct Red 79	Orange Peel	151.50	111
91.	Direct Yellow 27	Orange Peel	153.85	111

92.	Remazol Golden Yellow	Orange Peel	5.63	112
93.	Reactive Gray Bf-2r	Orange Peel	11.4	112
94.	Violet B	Orange Peel	49.20	113
95.	Violet 5R	Orange Peel	87.26	113
96.	Remazol Brilliant Blue	Orange Peel	11.62	114
97.	Reactive Blue	Orange Peel	38.72	115
98.	Deazol Black B	Orange Peel	1.74	116
99.	Reactive Navy Blue	Orange Peel With Pulp	9.22	117
100.	Reactive Red 141	Orange Peel	5.40	118
101.	Malachite Green	HCHO Treated Potato Peel	125	119
102.	Malachite Green	H_2SO_4 Treated Potato Peel	111	119
103.	Methylene Blue	HCHO Treated Potato Peel	47.62	120
104.	Methylene Blue	H_2SO_4 Treated Potato Peel	41.60	120
105.	Methylene Blue	Potato Peel	33.55	121
106.	Reactive Red 198	Potato Peel	93	122
107.	Reactive Blue 5	HCl Treated Potato Peel	3.61	122
108.	Acid Red 37	Potato Husk	23.53	123
109.	Methylene Blue	Banana Peel	111.11	124
110.	Coloured Effluent From Palm Oil Mill	Natural Banana Peel	49.75	125
111.	Coloured Effluent From Palm Oil Mill	Methylated Banana Peel	87.72	125
112.	Colored Effluent From Palm Oil Mill	Banana Peel Activated Carbon	135.14	125
113.	Reactive Blue 114	Pomelo Peel	16.3	126
114.	Congo Red	Nano-Porous Pomelo Fruit Peel	1.08	127
115.	Methylene Blue	Banana Peel	385.12	128
116.	Remazol Brilliant Blue	Rambutan Peel	112.69	129
117.	Methylene Blue	NaOH-Treated Rambutan Peel	231.34	130

118.	Malachite Green	Activated Carbon From Rambutan Peel	329.49	131
119.	Acid Yellow 17	Activated Carbon From Rambutan Peel	215.05	132
120.	Methylene Blue	Cucumber Peel	111.11	133
121.	Brilliant Green	Binary Oxidized Cactus Fruit Peel	166.66	134
122.	Direct Red 12B	Garlic Peel	37.96	135
123.	Remazol Brilliant Blue	Activated Carbon From Pomegranate Peel	370.86	136
124.	Crystal Violet	Peels Of Grapes	249.68	137
125.	Ultramarine Blue	Yam Peels	0.94	138

Biomass Solid Waste-Derived Activated Carbon

Agricultural waste is used to derive an activated carbon. The quantity of agricultural byproducts makes them a useful supply of affordable raw materials for activated carbon. The following Table 2 lists several biomass-based activated carbons along with their highest capacity for adsorbing dyes.

Table 2. Biomass solid waste generated activated carbon and their maximum capacity towards adsorption of different dyes

S.No.	Dyes	AC From Biomass Solid Waste	Optimum Adsorption Capacity Q_m (mg/g)	References
1.	Congo Red	Coal-Based Mesoporous	189	139
2.	Acid Blue 264	Pinewood	1176	140
3.	Basic Blue 69	Pinewood	1119	140
4.	Basic Blue 9	Pinewood	556	140
5.	Basic Green 4	Rice Husk	511	141
6.	Malachite Green	Bagasse Fly Ash	42.18	142
7.	Acid Blue 80	Bagasse	391	143
8.	Acid Blue	Rice Husk	50	144
9.	Methylene Blue	Plant Leaf Powder	61.22	145
10.	Yellow X-GL	Attapulgite/Rice Hull	213	146
11.	Malachite Green	Coconut Shell	214.63	147
12.	Methylene Blue	Hazelnut Husks	204	148

13.	Methylene Blue	Pine Fruit Shell-Carbon	529	149
14.	Methylene Blue	Walnut Shell-Carbon	315	150
15.	Methylene Blue	Oil Palm Shell-Carbon	243.9	151
16.	Methylene Blue	Wood Apple Rind-Carbon	40	152
17.	Malachite Green	Fly Ash	40.65	153
18.	Malachite Green	Hydrilla Verticillata Biomass	91.97	154
19.	Malachite Green	Daucus Carota Plant	52.60	155
20.	Malachite Green	Mango Seed Husks	47.90	156
21.	Malachite Green	Almond Shell	29	157
22.	Methylene Blue	Orange Albedo	77.79	158

Activated carbon derived from industrial and commercial by-products

Waste slurry, red mud, fly ash, biosolids, and metal hydroxide sludge are examples of common industrial by-products that may also be used as low-cost adsorbents.[159] Insoluble metal hydroxides are commonly found in metal hydroxide sludge, which is used to remove azo colours.[160] During burning activities fly ash is produced in significant volumes. It could also include several dangerous substances, as heavy metals.[161] However, the sugar industry commonly discharge bagasse fly ash, which has been extensively employed for the purpose of adsorbing colours. It is important to note that this ash does not possess substantial quantities of toxic metals. [162] In 2010, it was estimated that 67.5 million tonnes of fly ash were produced worldwide.163 Red mud waste is produced when bauxite processing waste is discharged during the manufacturing process of alumina.[164]Typically, simple dyes like methylene blue are adsorbed using red mud.[165] The following Table 3 lists numerous industrial byproducts and their highest potential for adsorption towards dye removal

Table 3. Industrial byproducts and their maximum capacity towards adsorption of dyes

S.No.	Dyes	AC from Industrial By-Products	Optimum Adsorption Capacity Q_m (mg/g)	References
1.	Remazol Brilliant Blue	Metal Hydroxide Sludge	91	166
2.	Congo Red	Metal Hydroxide Sludge	271	167

3.	Basic Red 18	Activated Sludge	285.71	168
4.	Basic Blue 9	Activated Sludge	256.41	168
5.	Methylene Blue	Sewage Sludge	114.9	169
6.	Vat Red 10	Sewage Sludge	73.1	170
7.	Vat Orange 11	Sewage Sludge	58.7	170
8.	Methylene Blue	Coal Fly Ash	16.6	171
9.	Methylene Blue	Fly Ash	7.99	172
10.	Methylene Blue	Fly Ash	5.57	173
11.	Congo Red	Red Mud	4.05	174
12.	Rhodamine B	Red Mud	92.5	175
13.	Methylene Blue	Red Mud	75	175
14.	Remazol Brilliant Blue	Red Mud	27.8	176
15.	Indigo Carmine	Activated Sewage Sludge	60	177

Inorganic materials

The most popular inorganic materials for color removal include clays, minerals, siliceous materials, zeolites, and metal oxides. The composition of the clays may consist of a combination of finely divided clay minerals and clay-sized crystals of various minerals like quartz and carbonate. The minerals comprising the colloidal components of rocks, soils, sediments, and water are usually referred to as clays. They are used as an effective adsorbent because in nature they are available in plenty, have a layered structure, high capacity for sorption and are affordable.[178] Clays are categorized based on variations in their layered structure. Adsorption capability varies significantly with pH because ion-exchange mechanisms are primarily responsible for dye adsorption on clay minerals.[179] Smectites (montmorillonite, saponite), kaolinite, mica (illite), serpentine, vermiculite, pylophyllite (talc), and sepiolite are a few examples of clays. Alunite, dolomite, perlite, and silica beads are a few examples of siliceous materials. Silica beads have the greatest adsorption properties of any siliceous materials due to their mechanical stability, porous structure, large surface area and hydrophilic surface.[180, 181] A strong and frequently irreversible nonspecific adsorption is also caused by the acidic silanol that is present on the surface of siliceous materials. Silane coupling agents containing amino groups can be utilized to modify the surface of silica to improve its interaction with dyes. Zeolites have a high porosity due to the cavities in their three-dimensional chemical structure.

The presence of negative charge is balanced by specific cations that have the ability to undergo exchange with them in aqueous solutions. Clinoptilolite, a mineral belonging to the heulandite group, is the most prevalent and extensively studied zeolite. Due to strong ion-exchange capability, large specific surface areas, and especially their low price make zeolites, a preferred adsorbent. Fe_2O_3, magnetic Fe_3O_4, TiO_2, and other composites are among the several metal oxide nano adsorbents that researchers have employed to remove dyes.[182,183,184] The following Table 4 lists numerous inorganic materials and their greatest potential for adsorption capacity towards dye removal.

Table 4. Inorganic materials and their optimum capacity towards adsorption of dyes

S.No.	Dyes	Inorganic Materials	Optimum adsorption capacity Q_m (mg/g)	References
1.	Methylene Blue	Magnetized Mesoporous Silica	34.3	185
2.	Basic Blue Dye	Magnetite Nano Composites	7.474	186
3.	Basic Blue Dye	Polyaniline Composites	47.97	186
4.	Basic Blue Dye	Polyaniline-Magnetite (Fe_3O_4) Composites	78.13	186
5.	Crystal Violet	Gracilaria corticata seaweed activated carbon/Zn/alginate polymeric composite beads	2.0015	187
6.	Congo Red	$ZnFe_2O_4/SiO_2$/Tragacanth gum magnetic nanocomposite	128.205	188
7.	Acid Red B	Magnetic CuFe2O4 powder	86.8	189
8.	Malachite Green	Activated Carbon/ $CoFe_2O_4$ Composites	89.29	190
9.	Methylene Blue	Magnetic Fe_3O_4/Activated carbon nanocomposite particles	321	191
10.	Congo Red	Magnetic Cellulose/Fe_3O_4/Activated carbon composite	66.09	192
11.	Methyl Orange	Multi-walled carbon nanotube (MWCNT) decorated with Fe_3O_4 nanoparticles	278.8	193
12.	Methyl Orange	Multi-walled carbon nanotube (MWCNT) decorated with Fe_3O_4 nanoparticles modified using polyaniline	446.25	193
13.	Methylene Blue	Raw Ball clay	34.65	194
14.	Methylene Blue	Modified Ball clay	100	194

15.	Methylene Blue	Modified Montmorillonite	322.6	195
16.	Methylene Blue	Clay	58.2	195
17.	Methyl Orange	Modified Montmorillonite	24	196
18.	Acid Blue	Clay/carbons mixture	64.7	197
19.	Basic Red 46	Gypsum	39.17	198
20.	Congo Red	Kaolin	1.98	199
21.	Congo Red	Na-Bentonite	35.84	199
22.	Methylene Blue	Bentonite	157	200
23.	Methylene Blue	Spent activated clay	127.5	201
24.	Methylene Blue	Fibrous clay minerals	85	202
25.	Methylene Blue	Pyrophyllite	70.42	203

Biopolymers and Microbial Biomass: In addition to being biodegradable, biopolymers are polymers made from biobased components.[204] An increasing number of research have focused on the possible applications of biopolymers, such as proteins and chitosan, in novel materials like adsorption.[205]

Utilizing biopolymers and dormant and dead biomass, biosorption is an efficient method for removing dye molecules from diluted aqueous solution.[206] In this instance, biological sorbents are utilized to remove colors from solutions, such as chitosan, peat, yeast, chitin, fungus, or microbial biomass.[207] The following Table 5 lists several biopolymers, microbial biomass, and their maximal capacity for dye adsorption.

Table 5. Biopolymers and Microbial Biomass and their maximum capacity towards adsorption

S.No.	Dyes	Biopolymers and Microbial Biomass	Maximum adsorption capacity Q_m (mg/g)	References
1.	Methylene Blue	Modified clay/chitosan composite	259.8	208
2.	Acid Orange	Chitosan grafted with diethylenetriamine	60.2	209
3.	Acid Green	Chitosan grafted with diethylenetriamine	4.37	209
4.	Acid Red	Chitosan/bentonite hybrid composite	362	210
5.	Methylene Blue	Chitosan/bentonite hybrid composite	497	210

6.	Methylene Blue	Cellulose/carboxymethylated chitosan	761	211
7.	Eosin-Y	Chitosan/PVA	53	212
8.	BO 16	Chitosan/Zeolite A	305.8	213
9.	Reactive Blue 5	Chitosan grafted with polypropylene imine	6250	214
10.	Remazol Red 198	Chitosan grafted with polypropylene imine	5855	214
11.	Acid orange 10	Chitosan	922.9	215
12.	Acid red 73	Chitosan	728.2	215
13.	Acid red 18	Chitosan	693.2	215
14.	Acid green 25	Chitosan	645.11	215
15.	Indigo Carmine	Chitosan	71.8	216
16.	Reactive red 5	Green alga	555.6	217
17.	Methylene blue	Dead rimosus	34.34	218
18.	Methylene blue	Caulerpalentillifera	417	219
19.	Methylene blue	Sargassummuticum	279.2	220
20.	Methylene blue	Dead macro fungi (F)	232.73	221
21.	Methylene blue	Dead macro fungi (P)	204.38	222
22.	Methylene blue	Algae Gelidium	171	222
23.	Methylene blue	Duckweed	144.93	223
24.	Methylene blue	Algal waste	104	224
25.	Methylene blue	Green alga	40.2	224
26.	Methylene blue	The brown alga	38.61	225
27.	Reactive orange 16	Rhizopusarrhizus	190	226
28.	Reactive orange 4	Rhizopusarrhizus	150	226
29.	Direct red 28	Aspergillus niger	14.72	227
30.	Disperse red 1	Aspergillus niger	5.59	228
31.	Acid blue 29	Aspergillus niger	13.82	229
32.	Acid blue 29	Living fungus	6.63	229

33.	Methylene blue	Living fungus	1.17	230
34.	Methylene blue	Dead fungus	18.54	230
35.	Indigo Carmine	Glutaraldehyde cross-linked chitosan	1.8	231

CONCLUSION

This critical review explained different types of dyes based on their chemical structure, functional groups, charge on their particle in aqueous solution, their toxic effect and examined the existing technologies used for dye removal and assessed their effectiveness and limitations. In dye removal, chemical methods such as advanced oxidation and coagulation, have also shown notable potential. However, their application can be cost-prohibitive and may generate secondary pollutants or sludge that require proper disposal. Physical methods, such as adsorption and filtration, have shown promise in removing dyes from wastewater. However, their effectiveness may be constrained by various parameters, including pH, dye content and temperature. A comprehensive investigation was conducted to examine the adsorption of dyes utilizing multiple accessible adsorbents and proven to be viable approach for the treatment of wastewater. Through this critical review, we have gained valuable insights into the diverse range of adsorbents and their performance in dye removal. Also, this review indicates that different adsorbents, such as clay minerals, activated carbon, zeolites, agricultural wastes and metal oxides exhibit varying degrees of effectiveness in adsorbing dyes. Despite the advancements made in adsorption technology, several challenges remain. The limited availability and high cost of certain adsorbents hinder their large-scale application.

Emerging technologies, such as nanomaterial-based approaches, hold promise for more efficient and sustainable dye removal. However, further research is needed to address concerns regarding the long-term effects and environmental impact of these technologies. Overall, the removal of dyes from effluent is a complicated problem that requires a multidisciplinary approach. Continued research and innovation in this field are essential to develop more efficient, inexpensive and sustainable methods for dye removal, ultimately contributing to the preservation and protection of water resources.

ACKNOWLEDGEMENTS

We thank the anonymous referees for their useful suggestions.

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