International Journal of Biological Macromolecules 224 (2023) 1337–1355

Contents lists available at ScienceDirect

International Journal of Biological Macromolecules

journal homepage: www.elsevier.com/locate/ijbiomac

Review

Cellulose-based materials and their adsorptive removal efficiency for dyes: A review

Abida Kausar [a], Sadia Tul Zohra [a], Sana Ijaz [a], Munawar Iqbal [b,*], Jibran Iqbal [c], Ismat Bibi [d], Shazia Nouren [e], Noureddine El Messaoudi [f], Arif Nazir [g]

[a] Department of Chemistry, Government College Women University Faisalabad, Pakistan
[b] Department of Chemistry, Division of Science and Technology, University of Education, Lahore, Pakistan
[c] College of Natural and Health Sciences, Zayed University, P.O. Box 144534, Abu Dhabi, United Arab Emirates
[d] Institute of Chemistry, The Islamia University of Bahawalpur, Bahawalpur, Pakistan
[e] Department of Chemistry, Government College Women University, Sialkot, Pakistan
[f] Laboratory of Applied Chemistry and Environment, Faculty of Sciences, Ibn Zohr University, 80000 Agadir, Morocco
[g] Department of Chemistry, The University of Lahore, Lahore, Pakistan

ARTICLE INFO

Keywords:
Modified cellulosic materials
Dyes adsorption
Wastewater treatment

ABSTRACT

Dyes are emerging as harmful pollutants, which is one of major issues for the environmentalists and there is a urgent need for the removal of dyes from the effluents. In this context, the adsorption technology has been extensively used as an effective tool for the removal of dyes from the aqueous phase. This technique uses low-cost adsorbents and the cellulosic material is a biodegradable, cost-effective and renewable polymer, which is not soluble in the majority of solvents because of its crystalline nature and hydrogen bonding. Currently, the modified cellulosic materials for the removal of dyes from wastewater gained much attention. Moreover, the application of cellulose for water treatment can be utilized for controlling pollution and have high economic viability and availability. This review signifies the use of cellulose-based adsorbent for dyes adsorption from wastewater. The key advancement in the preparation and modification of cellulose-based adsorbents is discussed and their adsorption efficiencies are compared with other adsorbents for removal of dyes and adsorption conditions are also considered for the same. The studies reporting cellulose-based adsorption from 2003 to 2022 are included and their various properties are compared for the efficient removal of dyes. The modified cellulosic materials cellulose is a highly effective adsorbent for the remediation of effluents.

1. Introduction

In recent decades, rapid industrialization and an immense rise in the population have caused serious contamination of water resources [1]. Water contamination has become an alarming environmental problem and has attracted global attention, mostly as diverse pollutants enter water bodies due to anthropogenic activities [2]. There are different types of pollution and dyes are one of the major categories of pollutants (Fig. 1) [3,4]. When dyes enter into the aquatic systems, they make it inappropriate for use and often it becomes hard to treat such water. Because the molecular structure of dyes is complex and many dyes being used in industry have a synthetic origins, which are highly stable and difficult to degrade naturally [5].

Dyes are the compounds that are colored and extensively used in cosmetics, printing and plastic industries for coloring products and as a result, a huge amount of colored wastewater is generated. Dyes production and its usage in textile and other industries result in the direct production of dyes containing colored wastewater [6]. According to an estimate, manufacturing operations discharge 2 % of dyes, while textile and related industries discharge 10 % of dyes in the effluent [7]. The wastewater containing toxic dyes is not acceptable under the respective environmental regulations [8]. The dye molecules persist in the aquatic environments due to their low biodegradability, stability to photolysis and oxidizing agent [9].

There are two types of dyes that are natural and synthetic. The natural sources are plants, animals, minerals and insects without any chemical treatment [10,11]. Synthetic dyes are synthesized chemically, which are highly stable and toxic to living organisms. Commercial

* Corresponding author.
E-mail address: bosalvee@yahoo.com (M. Iqbal).

https://doi.org/10.1016/j.ijbiomac.2022.10.220
Received 28 July 2022; Received in revised form 12 October 2022; Accepted 24 October 2022
Available online 26 October 2022

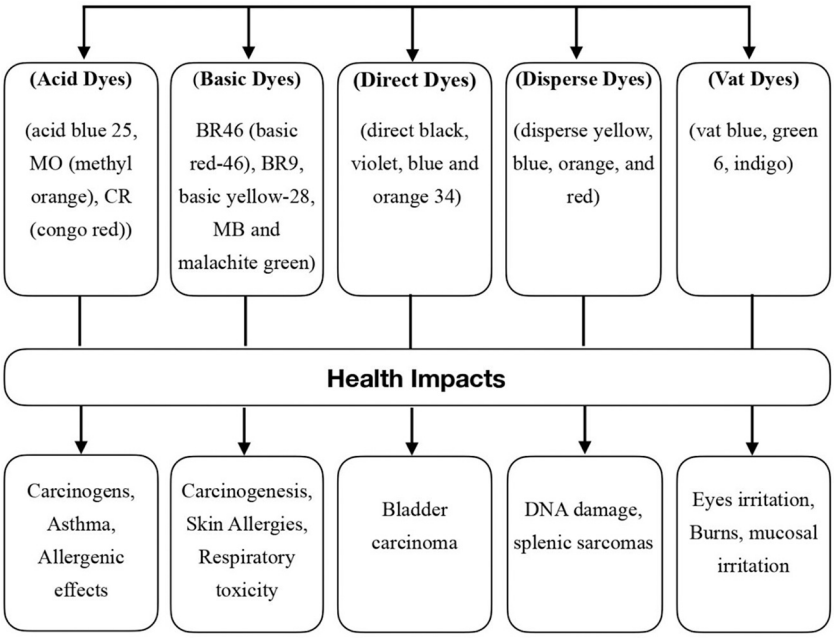

Fig. 1. Hazardous effects caused by different classes of dyes.

Table 1
Impacts of different pollutants on air, water and soil.

Impact on air quality	Wet process in industries produce gaseous pollutants and resultantly, air pollution occurs by the emission of different types of gases such as CO_2, NO_2, SO_2 etc. [23]. Heavy metals from petroleum combustion, paper processing plants and nuclear power stations cause air pollution which then causes DNA damage and cancer in humans by inhalation of polluted air [24].
Impact on water quality	Operations, i.e., printing, dyeing and finishing in textile industry turns 2,000,000 REF tons of dyes to effluents each year. Increased demands of products which are dyed by using synthetic dyes generate wastewater. Mostly synthetic dyes cause cancer and can also cause an allergy to the malignant tumor [25]. Heavy metals dangerously affect marine species i.e. fishes. Heavy metals can enter in their bodies via body surface, gills and digestive tract. Inorganic mercury and bacterial activity causes methyl mercury formation that is poisonous [26,27]
Impact on soil quality	When textile effluents enter into soil even for short period of time cause decrease in organic matter, calcium, magnesium, potassium, ammonium and phosphorus content, H_2O soluble salts. High amount of effluents i.e. textile results in decreased germination [28–30] Heavy metals are non-degradable and are not degraded by microbial or chemical degradation. They change soil properties like color, pH and porosity and so affect soil quality [24]

synthetic dyes can be classified in different ways. Classification can be done concerning color, structure and methods of application [12]. However, because color nomenclature involves complexities from the system of chemical structure, classification based on application is feasible [5]. Fig. 1 represents different health effects that are based on classification. Dyes can also be classified generally based on charge when dissolved in the aqueous medium, i.e., cationic, anionic and non-ionic dyes. One another source of water pollution is heavy metals (metals and metalloids having a density of $>4 \pm 1$ g/cm^3, e.g. Hg, Cu, Co, Ni, Zn, Al, As, Pb, etc) [13–16], which are also toxic contaminants and have an adverse impact on health (Table 1) [17].

1.1. Environmental impacts of textile dyes

The synthetic dyes used in industry are described as organic molecules that are stable to oxidizing agents, heat and light and are resistant to aerobic digestion. Discharge of colored effluents has toxic effects on living organisms [18–22]. The release of dyes effluent affects aquatic communities as the breakdown of dye products can be toxic for some organisms in the aqueous systems due to the toxic nature of byproducts (Table 1). It also prevents light penetration, which affects the photosynthesis process and hampers the aquatic life ecosystems. Resultantly, the biological cycle of the stream is disturbed and the value of environmental aesthetics is declined. The noticeable concentration of dyes in water and textile effluent is 1 mg/L and 10–200 mg/L, respectively. Different physicochemical parameters from textile dyeing industries concerning National Environmental Quality Standard (NEQS) are presented in (Table 2). It is indicated that in different cities of Pakistan like Faisalabad and Karachi, the situation is very alarming for the environment as compared to the permissible limit set by NEQS. Photolytically and chemically stable dyes are highly persistent in a natural environment. These properties may result in the bioaccumulation of toxic substances that can ultimately enter into the food chain and affect human beings. Synthetic dyes cause cancer and may also cause an allergy to the malignant tumor. Majority of the commercially used synthetic dyes are resilient to photodegradation and biodegradation. The most common hazard associated with inhalation of dye is respiratory problems and

Table 2
Effluents physicochemical parameters from textile dyeing industries collected from some areas.

Areas	pH	Temperature °C	COD (mg/L)	BOD (mg/L)	TDS (mg/L)	TSS (mg/L)	References
Faisalabad	8–14	–	590 to 880	211 to 487	2700 to 4200	66	[31]
Karachi	7.5–11.55	36 to 49.2	115 to 705	85 to 653	2469 to 7295	934 to 1875	[32]
Standard (NEQS)	Up to 40 6 to 9	150	200	80	3500	150	[32]

NEQS = National Environmental Quality Standard.

Table 3
Pros and cons of different separation techniques [4,41].

Techniques	Advantages	Disadvantages
Chemical methods		
Ozonation	Ozone can be used in the gaseous form and it is not involved in any increase in the waste water volume. Sludge is not generated.	Its half-life is shorter (twenty min) Cost of the operation is very high
Photochemical		
Sodium hypochlorite (NaOCl)	No sludge production and bad odors are highly reduced.	By-products are formed. Aromatic amines are released.
Electrochemical destruction	Initiation and acceleration of the cleavage of azo-bond Sludge is not buildup and chemicals are not consumed.	Rate of removal of dyes decreases directly due to higher flow rates.
Fenton Reagent	Price of reagent is low. Efficiency of procedure high.	Sludge production and issues while disposing.
Biological methods		
Aerobic biodegradation	Cost for operation is low, useful for azo-dyes removal	Microorganisms grow due to appropriate environment, reduced speed of process
Anaerobic biodegradation	By-products are means of the energy resources	More treatment is needed under aerobic environment, release H_2S and CH_4
Physicochemical methods		
Adsorption	A large variety of the dyes can be removed efficiently.	Surface area for some adsorbents is relatively low and cost of the adsorbents is high.
Membrane filtration	All dyes are effectively removed.	A very concentrated sludge is generated.
Ion exchange	Adsorbents are not lost, instead they are regenerated.	Method is not efficient for all of the dyes, i.e., disperse dyes are not removed.
Irradiation	At the scale of lab, oxidation is effectively done.	Large concentration of dissolved oxygen is needed.
Electrocoagulation	It is feasible from economic point of view.	Need further treatments by filtration and flocculation and sludge production.

they also affect the immune system. Dyes also cause skin irritation, blocked or itchy noses, sore eyes and sneezing [8,20].

1.2. Wastewater treatment methods

The dyes are non-biodegradable. Therefore, primary as well as secondary conventional systems are not suitable for the treatment of these effluents [20,33–38]. Some investigations have focused on the development of treatment processes for dye wastewater, such as advanced oxidation and biological processes. For the former, it has been found that it may be effective in reducing COD and removing suspended solids, but is ineffective for the removal of color from wastewater. For the latter, because of the complex composition of dye wastewater and higher organic load, the dye wastewater cannot be efficiently treated and purified. Different treatment techniques, including flocculation/coagulation, biological treatment, advanced oxidation processes, ozonation, adsorption and membrane filtration have been employed for the removal of dyes from the wastewater (Table 3). However, because of high operating cost, little performance and environmental impact, such methods are impossible for an industrial application. Due to relatively low removal efficiencies and high operating costs using the mentioned processes, there are various limitations of every method based on design, efficiency and cost [11,39,40]. But adsorption, in comparison

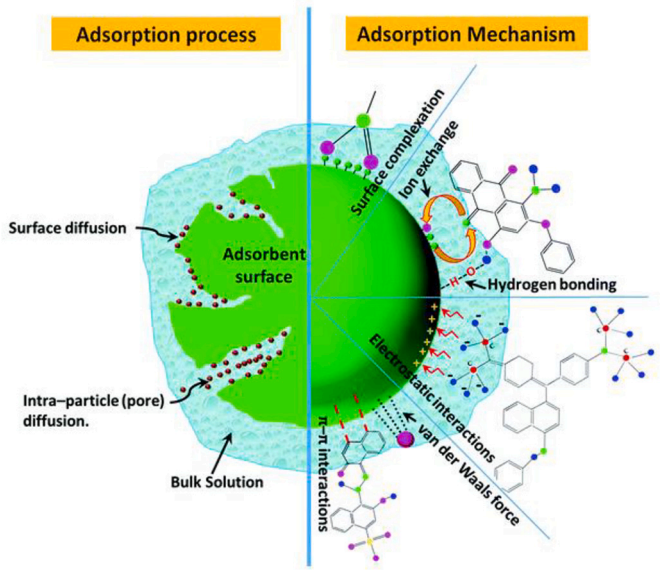

Fig. 2. Different adsorption mechanisms involved in dyes removal [48].

with others, is proved to be the most suitable method in many aspects. A summary of the advantages and disadvantages is described in Table 3.

The method of adsorption is more competitive than all other processes due to its easy accessibility, economical and higher rate of pollutant removal. Search for such adsorbents that fulfill industrial water treatment criteria and all of its standards are also low cost, eco-friendly, have high efficiency and their availability is possible at a large scale [42–46]. Adsorption of dyes on the surface of the adsorbent occurs by different mechanisms, i.e., hydrogen bonding, π-π interactions, electrostatic attraction and hydrophobic interaction (Fig. 2). Anionic dyes i.e. MO and CR adsorption occur through the processes of ion exchange and electrostatic attraction while Rhodamine dye is adsorbed through intermolecular interactions [47]. The mechanism of surface complexation is associated with the binding of ions with different surface functional groups present on the adsorbent surface and electrostatic interaction between the surfaces of adsorbent-adsorbate [48].

Different adsorbents are being used for dyes removal from wastewater like commercial activated carbon, ion-exchange resins, cellulose-based materials commercial activated alumina, silica gels, etc. [19–21,33,42,49]. Commercial activated carbon is much more expensive. The main drawback of activated carbon is rapid saturation and regeneration of this activated carbon becomes expensive and loss of adsorbent occurs. Ion exchange resins are advantageous as adsorbent is not lost on regeneration, but such materials are also expensive like activated carbons [39,44,50,51].

Cellulose-based materials, due to their large abundance, ease in use, availability, low cost and physicochemical characteristics with the particular structures are widely used and are efficient as compared to other adsorbent materials, i.e., commercial activated carbon which is much more expensive (20–22 US $ per kg) [52]. Various types of biomass including algae, fungi, yeast and bacteria have provided efficient adsorbents for wastewater treatment, i.e., many enzymes are available for mineralization as well as degradation of the dyes released from textile industries into water bodies [53]. The desired characteristics of adsorbents are better to meet by the cellulose-based adsorbents, as adsorption capacity of commercial cellulose, cotton fibers, bagasse, rice straw and sawdust for removal of MB, Congo red, Drimarine Yellow HF-3GL, Malachite green and anionic dye is reported to be up to 97, 94, 89.95, 92 and 97 (%), respectively [54] [55]. Table 4 shows the adsorption capacities for dyes of different adsorbent types. The development of cellulose-based adsorbent is one the ongoing research topic,

Table 4
Adsorption capacities of dyes using different adsorbents.

Dyes	Nano activated carbon [56]	Adsorbents from algal biomass Spirulina sp. [57]	Adsorbents from bacterial biomass Aureispira sp. (CCB-QB1) [58]	Commercial cellulose [59]	Cellulose from citrus peel [60]	Thiourea modified sugarcane bagasse cellulose (commercial) [61]
Methylene Blue	28.09 mg/g	90.90 mg/g			200–923 mg/g	632.9 mg/g
Congo Red			1.48 mg/g	298.98 mg/g		

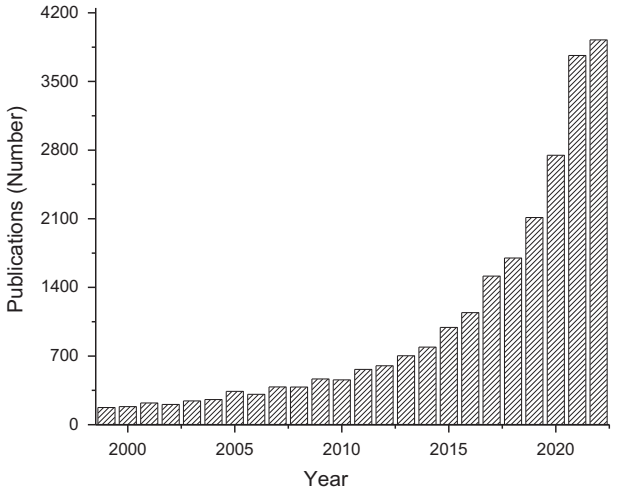

Fig. 3. Trend in cellulose-based adsorption studies published (Source: Scopus, keyword: Cellulose, adsorption, dye, Accessed September 8, 2022).

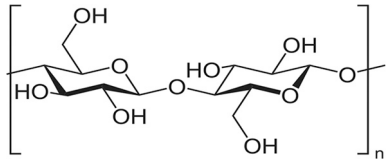

Fig. 4. Structure of cellulose [41].

as mentioned in Fig. 3, the number of publications is increasing in the respective field, which needs a lot more research and innovation for the development of commercial cellulose-based adsorbent.

2. Cellulose

Cellulose is a stable polymer of glucose and is linked to the linear chains comprising about twelve thousand residues. It is the most abundant as well as a renewable polymer that has worldwide availability. It plays a structural role in the primary cell wall in green plants and different forms of algae, as well as oomycetes. It is considered the most common compound which is organic and is widely present on earth [62]. All plant materials contain about 33 % cellulose (wood 40–50 % and cotton 90 %). For its usage in industries, it is chiefly acquired from pulps of wood and cotton [63]. Moreover, cellulose has wide applications as starting material in various types of chemical conversions, for the production of films and threads. It is also involved in the production of a wide range of cellulose derivatives which are used in different areas of industrial units and at the domestic level. The cellulose, along with many of its modified structures has been created in the form of another category of sorbents which are adaptable for dyes removal from aqueous media [20].

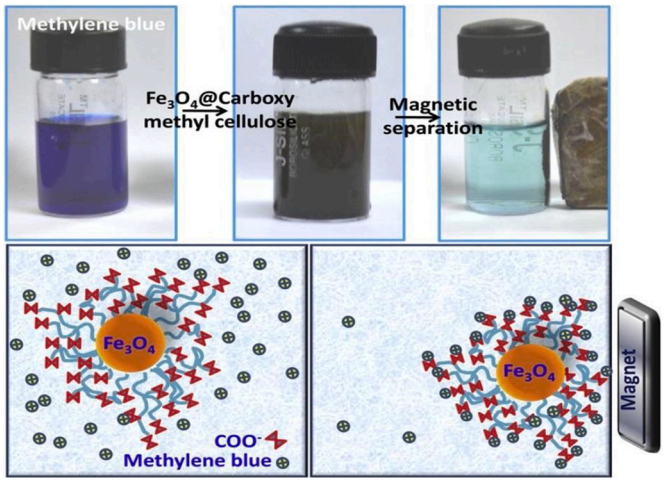

Fig. 5. Top - MB mixed with nanoparticles of methyl cellulose before and after removing dye, Bottom - MB captured by the nanoparticles of MC [67].

2.1. Structure of cellulose

Cellulose is formed from D-glucose molecules, having an average molecular weight of about 100,000 and condensed via β (1 → 4)–glycosidic linkages and has three OH groups in each unit of hydroglucose, that convey different sorption sites which are active and enhance the ability for removal of the dyes. The cellulosic molecule structure is shown in Fig. 4. It is hydrophobic and is also not soluble in many organic solvents and is biodegradable. Cellulose can be broken into its glucose molecules by treating with concentrated acids at higher temperature [41].

Cellulose has two functional groups named hydroxyl and methylol (in each unit). It has an ordered structure as there are no branching or side chains. It is a semicrystalline in nature, i.e., has both amorphous and crystalline phases. No matter it is linear and comprises two types of OH groups, primary OH in methylol group at 6th carbon and secondary OH group at 3rd and 4th carbons, both of these are hydrophilic and did not dissolve in H_2O and other common solvents because of strong hydrogen bonding, present between cellulose chains. As a result, hydrogen bonding between chains of cellulose and van der Waals attraction between molecules of glucose form the crystalline nature of cellulose [64].

It is exciting to observe that, at both terminals of the cellulose chain, OH groups act differently, i.e., C-1 terminal of the cellulose is reducing, while C-4 OH group of the same chain is non-reducing [65]. Cellulose have large number of polar H and O atoms, that play role in intermolecular and intramolecular hydrogen bonding, between the same and the nearby chains, and give stiffness to the cellulose chains [66]. Cellulose is effective adsorbent due to its abundance, easy availability and low cost, which has vast applications in the treatment of wastewater. However, the technology of water treatment currently faces three main problems. Firstly, there is difficulty in scaling up the current laboratory treatment processes to industrial level. Secondly, most of the industrial adsorbents are porous particles with macro sizes for increasing surface area and adsorption efficiency, but the process of diffusion within particles limits the adsorption capacity and rate also. Thirdly, the separation is achieved

Table 5
Different sources of cellulose with percentage content [65].

Sources of cellulose	Cellulose content
Hairs of cotton seed-the purest cellulose source	(90–99 %)
Cereal straw	Barley, 48 % Oat, (44 to 53 %) Rice, (43 to 49 %) Rye, (50 to 54 %) Wheat, (49 to 54 %)
Bast fibers	Kenaf, (47 to 57 %) Jute, (60 to 65 %) Flax and Ramie, (70 to75%) Hemp, (75–80 %)
Canes	Bamboo, (40 to 55 %) Bagasse, (33 to 45 %)
Leaf fibers	Sisal Fibers, (55 to 73 %)
Wood	(40 to 50 %)

with more ease when the preparation of cellulose beads is made with magnetic properties using a magnetic field. But, few studies have reviewed the possibility to include magnetic nanoparticles, i.e., magnetite –Fe_3O_4 into beads of cellulose to make them efficient cellulose-based adsorbents (Fig. 5) [67]. On heating, cellulose partially decomposes due to hydrogen bonds that exist between the cellulose molecules. The intermolecular hydrogen bonding also makes that high-concentration cellulose solution too viscous to extrude easily. Therefore, further research on biomass development is needed to cope with these issues.

2.2. Cellulose classification

Cellulose fiber can be categorized classified into 2 types of fibers.

1. Natural fibers, i.e., jute and cotton and 2. Man-made fibers, i.e., (i) Viscose, (ii) Modal, (iii) Lyocell and others.

2.2.1. Natural cellulose sources

Cellulose can be obtained from sources, like animals, plants that grown annually, microbes, and woods. They include softwoods and hardwoods, seed fiber (cotton), bast fibers (ramie, flax, jute, hemp), bamboo and bagasse, *Valonica ventricosa*-an algae, and *Acetobacter xylinum*-a bacteria [65]. Mainly cellulose is obtained from the ligno-cellulosic substances, in forests, having wood as the main and essential source (Table 5). Other resources include agricultural residues and water plants. In plants, it exists in mixture form having hemicelluloses, lignins and comparably small amounts of extractable [68].

2.2.2. Commercial cellulose

The fibers of cellulose are obtained from natural cellulose. Commercial cellulose manufacturers focus on harvesting sources, i.e., wood and in nature highly purified sources such as flax, cotton, hemp, jute, etc. [63]. Cellulose has driven our attention toward its phenomenal behavior in adsorption process. Because it is most abundant and can be found in agro-waste, which makes it more economical and valuable. Its hydrophilic nature, insolubility in neutral water pH conditions and abundance of OH functional groups, make it more proficient toward adsorption. A large number of the hydroxyl groups assist the fusion of the distinct chemical moieties, which adsorb different pollutants from aqueous media [69]. A variety of sources can be used to obtain raw materials of cellulose, i.e., modal is obtained from the beech trees, wood fiber gives rayon, seaweed is the source of SeaCell, etc. Fiber from the viscose rayon is obtained by mixing of cellulose in alkali solution and then precipitating it in the solution of carbon disulfide for the generation of cellulose xanthate. Lyocell is generated by direct dissolution of the cellulose in *N*-methyl morpholine-N-oxide solvent. To get these fibers, the reduction of cellulose is carried out into a viscous mass to a fairly pure form and fibers are then formed using the process of extrusion via spinnerets. Therefore, finished products with slight differences in characteristics are obtained by the manufacturing process in contrast to the natural sources of material [70].

Table 6
Cellulose types and sources used in wastewater treatment [73].

Cellulose types	Alternative names	Sources	Size and synthesis
MFC-Micro fibrillated cellulose)	(Microfibrillated cellulose nanofibrils), (Microfibrils nanofibrillated cellulose)	(Sugar beet), (Potato tuber), (Hemp), (Wood)	5 to 60 nm in diameter, Mechanical pressure, prior to or/and after treatment with enzymes or/and chemicals.
CNC-cellulose nano crystals	(Nanocrystalline cellulose), (Whiskers), (Rod-like cellulose), (Microcrystals)	(Tunicin), (wheat straw), (Wood), (Avicel), (Cotton), (Ramie), (Flax), (Mulberry bark)	5 to 70 nm in diameter, 100 to 250 nm long Cellulose from the bacteria and algae acid hydrolysis from different sources
CNF-cellulose nano fibrils	(Nano-fibrillated cellulose)	(Algae), (Wood), (Cotton), (Hemp), (Flax), (Wheat straw), (Few bacteria), (Ramie), (Sugar beet), (Potato Tuber), (Tunicin)	5 to 100 nm in diameter, Several microns long Direct production by bacteria or isolation through cellulose feedstock homogenization
BNC-bacterial nano cellulose	(Microbial cellulose), (Bio cellulose), (Bacterial cellulose)	(Sugars having less molecular weight), (alcohols)	20 to 100 nm in diameter Synthesis using bacterial

Table 7
Chemical composition of agro-waste for cellulose, lignin and hemicellulose production.

Agriculture residue	Cellulose (%)	Hemicelluloses (%)	Lignin (%)	References
Rice husk	45	19	19.0	[74]
Bagasse	55.2	16.8	25.3	[75]
Ground nutshell	38.3,	27.6	21.1	[76]
Onion skin	41.1 ± 1.1	16.2 ± 0.6	38.9 ± 1.3	[77]
Mulberry barks	37.38 ± 2.31	25.32 ± 2.45	9.99 ± 0.82	[78]
Banana	63–64	10	5	[79]
Wheat straw	48.8	35.4	17.1	[74]
Garlic straw	41	18	6.3	[80]
Yellow birch	47	31	21	[74]
Softwood	45–50	25–35	25–35	[81]
Newspaper	40–55	18–30	25–40	[82]
Corn cobs	45	35	15	[83]
Sponge gourd fiber	66.59	17.44	15.46	[84]
Palm shell	29.7	–	53.4	[85]
Coir	32–43	10–20	43–49	[63]

2.3. Chemical and physical properties of the cellulose

The plant cell wall is a chief source of cellulose. Being a structural polymer, it gives mechanical strength to the cells of plants. Presence of nano fibrillar components provides specific strength to many species of plants. Wood and all lignocellulosic materials have the property of providing a high value of strength to weight ratio [71]. Nowadays, cellulose isolation and its characterization along with diverse use of various forms of the cellulose, i.e., crystallites, nanofibers, nanocrystals (nanowhiskers) and nanofibrils are the attaining attention of the researchers [72].

Unique methods used for the production of different forms of cellulose include top-down methods which include different physical,

Table 8
Modification of cellulose with different chemical reagents by utilizing methods of esterification for various pollutants.

Adsorbent	Adsorbate	Agents for Modification	Adsorption capacity (mmol/g)	pH	References
Cellulose	Malachite green	Maleic anhydride ($C_4H_2O_3$), glycidyl methacrylate, thiourea (sulfur, carboxyl, amino)	0.36	9.0	[89]
Cellulose (bagasse)	Zn(II), Cd(II), Pb (II)	Hydrochloric acid, chlorine, nitric acid, sodium hydroxide tartaric, oxalic and citric acids	0.12, 0.13, 0.17	5.0	[90]
Commercial Cellulose	Cd(II)	Succinic anhydride ($C_4H_4O_3$) + Sodium bicarbonate (Carboxylate)	1.65	8.0	[91]
Cellulose (Cotton)	Au(III)	H_2SO_4	6.21	–	[92]
Commercial Cellulose	Cu(II), Cd(II) Pb (II)	Succinic anhydride, (Carboxyl)	0.47, 0.76, 0.99	5.5–6.0	[93,94]

Table 9
Use of different chemical reagents for modification of cellulose by process of halogenation.

Adsorbent	Modifying agents	Adsorbate	Adsorption capacity (mmol/g)	References
Cellulose powder	(Trimethylammonium chloride (C_3H_9N) (Amino))	Cr(VI)	1.38	[89]
Commercial Cellulose	(Phosphorous oxychloride (Amine (Cell-N-S)), (Thiol (Cell-N-S))	Hg(II), Hg (II)	0.19, 0.04	[97]
Cellulose powder	Thionyl chloride ($SOCl_2$) modified (Chloride)	Cu(II), Co (II), Ni (II), Zn(II)	0.10, 0.09, 0.07, 0.07	[95]

Table 10
Modification of cellulose utilizing variety of chemical reagents by method of oxidation.

Adsorbent	Adsorbate	Modifying agents (pollutant binding groups)	Adsorption capacity (mmol/g)	References
Cellulose powder	Ni(II), Cu (II)	Sodium metaperiodate ($NaIO_4$) (carboxyl)	3.13, 3.70	[100]
Softwood pulp cellulose	Cd(II), Ni (II)	Nitrogen tetroxide (N_2O_4) (carboxyl)	0.28, 0.16	[101]
Nanocellulose	Methylene blue	TEMPO-oxidation (carboxyl)	2.40	[102]

chemical or enzymatic approaches for isolation from different sources, i.e., from wood, wood pulp, cotton and agricultural residues. Bottom-up method to produce nanofibrils of cellulose. It is important to know that cellulose-based substances can be used as cheap forms of adsorbents and their tendency to eliminate pollutants may be affected due to chemical treatment. Commonly, unmodified cellulosic forms are less efficient for adsorption capacities than modified forms of cellulose. Various chemicals, i.e., organic and mineral acids and bases, different oxidizing agents, and some organic compounds are being utilized for modification purposes (Tables 6 and 7) [73].

3. Modification of the cellulose

Modification of cellulose is done chemically to get many useful derivatives for the treatment of wastewater [46,49,86]. A lot of research is conducted by researchers in this area. The efficiency of the wastewater treatment can be enhanced by using derivatives, specifically for removing heavy metals and dyes. Forms of cellulose that are extensively used include powder and fiber forms. The chemical modification provides high capacities of adsorption in comparison to its unmodified counterparts. Methods used for its modification include esterification, halogenations and etherification, grafting and oxidation, etc. Different modifying agents can be used, i.e., organic basses and the acids, organic and inorganic compounds, some oxidizing agents and minerals etc. Composite beads are formed by combining it with other materials. Nanofibers, nanocrystals, and crystallites can be obtained by the method of modification. Further research is still required for exploring the synthesis approaches for modified adsorbents, which are cellulose-based materials for dyes adsorption from wastewater on large scale.

3.1. Esterification

The adsorption capacities of modified cellulose (esterification) are shown in Table 8. Citric acid was converted into its anhydride by Low et al. [87] using heat, which may react further with cellulosic OH groups in the pulp of wood, for ester linkage formation. In this way, COOH groups are introduced into wood pulp and the esterification process enhances the percentage of carboxylic content in the wood fiber, which ultimately increases the adsorption of dyes. Using this process, Marchetti et al. [88] modified the wood pulp. Reaction was carried out using catalysts with succinic anhydride. The acid value determined by titration relates directly to the binding capacity of Cd(II) in sawdust with 169 mg/g capacity.

3.2. Halogenation

One of the techniques used for the modification of cellulose is halogenation (Table 9). Chloro-deoxycellulose was synthesized by Tashiro and Shimura [95], by reaction of thionyl chloride with cellulose powder in dimethylformamide as solvent. Functionalization of chlorodeoxy cellulose was carried out with thiourea, thiosemicarbazide, thioacetamide, hydrazine, ethylenediamine and hydroxylamine. Nevertheless, its synthesis was not easy because of the comparatively low reactivity of thionyl chloride with cellulose. Aoki et al. [96] used 6-bromo-6-deoxycellulose for the synthesis of 6-deoxy-6-merca-ptocellulose along with its S-substituted derivatives. Cellulose and Cl had lower reactivity than cellulose and Br. Adsorption behavior of some functional groups i.e. Amino (−NH2), carboxyl (-COOH), mercapto (-SH) isothiouronium, and some additional OH groups for metallic ions was studied by introducing them into cellulose. Derivatives having COOH groups had adsorption capacity of 104, 36 and 9 (mg/g) for Pb (II), Cu(II) and Ni(II), respectively, which is due to 2-mercaptobutanedioic acid. The adsorption capacity of derivatives with carboxyl (COOH) and amino (NH_2) groups was 28, 22 and 8 (mg/g) for the Pb(II), Cu(II), and Ni(II), respectively, which due to the reaction with the cysteine.

3.3. Oxidation

Oxidation followed by functionalization of cellulose produces reactive cellulose derivatives (Table 10). Dialdehyde cellulose was synthesized by Maekawa and Koshijima [98], using periodate oxidation of the

Table 11
Modification of cellulose with different chemical reagents by etherification method.

Adsorbent	Adsorbate	Agents used for modification	Adsorption capacity (mmol/g)	pH	References
Commercial Cellulose	Hg(II)	Sodium methoxide, epichlorohydrin, polyethyleneimine (amino)	1.44	7	[103]
Cellulose powder	Cu(II), Cr(III)	Acrylonitrile (C_3H_3N), hydroxylamine (H_3NO)-amidoxime	3.76, 3.90	5	[104]

cellulose. Milde acidified sodium chlorite was used for further oxidation of dialdehyde cellulose. A 100 % oxidized 2, 3-dicarboxy cellulose was soluble in H_2O, while the one which was only 70 % oxidized was insoluble in H_2O. Latter was studied for heavy metal adsorption capacity and the uptake levels achieved for Cu(II) and Ni(II), which were 236 mg/g and 184 mg/g, respectively. Later on, derivatives of cellulose hydroxamic acid were synthesized by Maekawa and Koshijima [99], from the dialdehyde cellulose, which was prepared in the previous method of periodate oxidation and their adsorption capacities for heavy metals were studied. The adsorption of Cu(II) was 246 mg/g for the same.

3.4. Etherification

Cellulose ethers are commonly prepared when alkali cellulose is reacted with organic halides (Table 11). This etherification reaction was used by Navarro et al. [103] for the modification of porous cellulose. For this, cellulose carrier was first reacted with the sodium methylate and alkali cellulose was prepared. Organic halide (epichlorohydrin) was then reacted with alkali cellulose, which yielded epoxy groups, which were reactive. These groups were functionalized with a chelating agent (polyethyleneimine). The adsorption capacity of obtained adsorbent-(Cell-PEI) was 2.5, 38 and 12 (mg/g) for Co(II), Cu(II) and Zn(II), respectively. Saliba et al. [104] used amidoxime groups for chemical modification of sawdust by reacting acrylonitrile and sawdust using etherification, for the addition of cyano groups in the structure of cellulose. Amidoximation of cyano groups was carried out by reacting it with hydroxylamine. The adsorption capacity of amidoximated sawdust was 188 and 246 (mg/g) for Ni(II) and Cu(II), respectively [105]. Modified adsorbents for heavy metal adsorption with their method of adsorption are listed in Table 11. Methods of Etherification discussed in the following section used direct modification methods for the production of cellulose-based adsorbents. In an alternative method, the second polymer (a long branch) was grafted on the molecule of cellulose. In this way, cellulose is imparted with significant properties, which are otherwise deficient in the native celluloses. Such grafting probabilities will be reviewed in the next section.

3.5. Monomer grafted cellulose based adsorbents

A process that involves the formation of the branched copolymer by covalent attachment of side chain grafts, with the main chain of the polymer backbone is called graft copolymerization. The extent of polymerization graft is known as the yield of grafting. Yield is determined gravimetrically in the form of mass percent increase following the copolymer preparation. Side chain grafts as well as backbone may be either homopolymer or copolymer. Free radicals or ionic chemical groups at active sites initiate reactions of polymerization [106]. Various methods, i.e., radiations of high energy, chemical and photochemical techniques have been used for initiation or activation of cellulose backbone [107]. Methods for initiation involving free radicals have become most popular owing to their workability. Free radicals can be produced either by the method of decomposition of the chemical initiator or by using ultraviolet light. During the method of copolymerization, radicals are formed either on the backbone of cellulose or on the monomer that has to be grafted. Homopolymerization of monomer occurs due to the generation of radicals on the monomer. This is the reason that initiators having the capability to generate radicals at various sites on the backbone of cellulose are markedly preferred [108]. A summary of the modification methods of cellulose is summarized in Table 12.

3.6. Organic and inorganic treatment for cellulose modification

EDTA dianhydride has been used to improve the adsorption capability of mercerized (Alkaline cellulose fiber) as well as non-mercerized cellulose because such celluloses can be chelated with EDTA. In an aqueous environment, lignocellulose gained from the cotton pellets are utilized for arsenic removal. In this method, cotton pellets are treated with ferric chloride. The adsorbent has the capacity of five times regeneration, after which it decreases by about 11.5 %. A high percentage of cellulosic materials present in wastes can be modified and used for adsorption of the dyes and heavy metals. Chemical modification of three such materials was carried out via phosphorylation and successive loading of the iron for gel formation. The adsorption efficiencies of various cellulose-based adsorbents are displayed in Table 13. Cellulose in sponge form is often loaded with iron for enhancement of adsorption capacity for arsenic. Similar research was carried out by Gurgel et al. [93] using mercerized cellulose. Mercerization of cellulose was carried out by the use of sodium hydroxide, followed by its washing with distilled water and then acetone, after which it was dried and stored. Cellulose was then reacted under reflux of pyridine with succinic anhydride. Heavy metal adsorption for Cu(II), Cd(II), and Pb(II) were 30.4, 86, and 205.9 (mg/g), respectively. Mercerized cellulose was further modified with triethylenetetramine by Gurgel et al. [93] for

Table 12
A comparison of modification methods for synthesis of cellulose-based adsorbents.

Method of modification	Method type	Advantages	Disadvantages	References
Grafting of monomers	Photo-grafting	Light sources of ultraviolet light are easily available. Reaction is selective	Adsorption capability is low	[107]
	High energy radiation grafting	Ionization sources have commercial availability. Reaction is simple as well as flexible.	Demand of photoenergy is high. Equipment are required for production of photoenergy	[109]
	Chemical initiation grafting	Adsorption capability is high	Chemicals are used in large amount and method is complex.	[110]
Direct chemical modification methods	Esterification	Adsorption capability is high and is largely used for purification of water	Method is complex and chemicals are consumed in large amounts	[111]
	Halogenation	Moderate capacity of adsorption	Needs toxic chemicals	[112]
	Oxidation	Capacity of adsorption is high	Large amount of chemicals is consumed	[101]
	Etherification	High adsorption capacity	Synthetic pathway is complex	[104]
	Silynation	Method is simple with high adsorption capacity	Low adsorption capacities	[113]
	Alkaline treatment	Simple method of synthesis, extensively studied method for water purification, Low manufacturing costs	Low adsorption capacities	[114]

Table 13
The adsorption efficiencies of various cellulose-based adsorbent.

S. No	Cellulose source	Composite	Dye	pH	Efficiency	Isotherm	Kinetic	Thermodynamics	Single dye	Binary dye	Characterization	Ref.
1	Carboxymethycellulose (Commercial)	Polyvinyl alcohol/ Na-alginate/ rice husk	Direct Orange-3GL, Direct Orange-26, Direct Blue-67, Direct Red-31,	12	80–90 %	Langmuir	2	–	–	–	FTIR, SEM	[120]
2	Commercial cellulose	Polypyrrole	Congo red	2	85 %	Langmuir	2	En	298.98 mg/g	–	FESEM, XRD, FTIR, BET, TGA, NMR	[59]
3	Bagasse	Clay	Drimarine Yellow HF-3GL	2	88.64 %, 89.95 %	Redlich Peterson	2	Ex	–	–	FTIR, TGA, EDX, SEM and XRD	[121]
4	Rice straw	Carbon nanomaterial hybrid aerogel	Methylene Blue, Congo Red	–	80 %	Langmuir	2	–	1178.5 MB 585.3 mg/g CR	Adsorption of Methylene Blue was lower and the CR was higher	FE-SEM, FTIR	[122]
5	Citrus peel	Calcium alginate	CV, MB	3-11	50–150 mg/g	Langmuir	1	Ex	MB 200–923 CV 187–881 mg/g	MB 795.14 CV 884.11	FTIR, DRX, BET, SEM	[60]
6	Poplar chips	Sodium alginate beads	MB	3–7	309–1180 mg/g	Langmuir	2	–	1181 mg/g	–	FESEM, FTIR	[123]
7	Laboratory filter paper	Bentonite	Congo Red	7	–	Langmuir	2	Ex	45.77 mg/g	–	SEM-EDX, XRD, FTIR, TGA	[124]
8	Cotton fibers	–	Congo Red, MB	6	94 %, 42 %	Freundlich	2	–	300.8 CR, 98.7 MB mg/g	–	FTIR, SEM, XPS	[125]
9	Commercial cellulose	Chitosan/SWCNT/ Fe_3O_4/TiO_2	Methylene Blue and Congo Red	3	–	Redlich-Peterson	2	–	15 and 20 %	–	TEM, SEM, FTIR, XRD, TGA, BET	[126]
10	Commercial cellulose	Carbon/ montmorillonite	Methylene Blue	8	–	Redlich-Peterson	2	–	138.1 mg/g	–	SEM, XRD, TGA, FTIR	[127,128]
11	Pineapple peel	Magnetic diatomite hydrogels	Methylene Blue	2–6	90 %	Langmuir	2	–	101.94 mg/g	–	FTIR, XRD, SEM, TGA	[129]
12	Waste printed papers	–	Hydroxynaphthol l Blue and Congo Red	2–3	–	Langmuir	1	En	0.1700 and 0.1564 mmol/g	–	FTIR, SEM, TEM	[130]
13	Commercial cellulose	–	Methylene Blue and Methyl Violet	9	–	Langmuir	2	–	497.5 and 840.3 mg/g	197.2 mgg^{-1},677.2 mg g-1	FTIR, XRD, TGA	[131]
14	Sisal fiber	Activated carbon	Methylene Blue	6.9	–	Langmuir	2	En	103.66 mg/g	–	FTIR XRD, TGA, SEM	[132]
15	Sugarcane bagasse	Montmorillonite	Auramine O, Amido Black 10 B	3–7	–	Langmuir	2	AO En, Ab is Ex	1336.2, 232.0 mg/g	1.41,4.95 mg/g	SEM, FTIR, BET	[133]
16	Sugarcane bagasse	–	Methylene Blue	–	98.32 %	Langmuir	2	En	9.41 mg/g	–	SEM	[134]
17	Bamboo powder	ZnO	Methylene Blue, MG	–	93.55 %, 99.02 %		2	–	46.77 MB and 49.51 MG mg/g	–	SEM, TGA, FTIR	[54]
18	Bacterial cellulose	Ca-montmorillonite	Methylene Blue	8–10	–	Langmuir	2	–	338.8 mg/g	–	SEM, FTIR	[135]
19	Commercial (carboxymethycellulose)	–	Methylene Blue	11	–	Freundlich	2	–	756 mg/g	–	SEM, FTIR	[136]
20	Carboxymethycellulose	Organo-bentonite	Red 2BENW	5.2	–	Freundlich	2	–	91.14 %	–	FTIR, SEM, XRD, TGA, BET, BJH	[137]
21	Constructing wood cellulose	Montmorillonite hydrogels	Methylene Blue	7	–	Freundlich	1	–	277 mg/g	–	SEM, TEM, FTIR	[138]

(*continued on next page*)

Table 13 (*continued*)

S. No	Cellulose source	Composite	Dye	pH	Efficiency	Isotherm	Kinetic	Thermodynamics	Single dye	Binary dye	Characterization	Ref.
22	Cellulose	Bentonite-zeolite	Brilliant Green	4–5.6	–	Langmuir	2	En	90.09 mg/g	–	FTIR, BET, PSD, XRF, SEM, EDX	[139]
23	Rhizomes of *Alpinia nigra*	Montmorillonite	Eosin Y	–	50–150 mg/g	Langmuir	2	Ex	199.9 mg/g	–	FTIR, XRD, HNMR, SEM, BET	[140]
24	Commercial Cellulose	Montmorillonite	MB	8–10	60–160 mg/g	Redlich-Peterson	2	–	138.1 mg/g	–	XRD, FTIR, SEM, TGA	[127]
25	Commercial cellulose	Fe-amino clay	MB, Chrysoidine G	10	–	Langmuir	2	–	438 and 791 mg/g	–	SEM, FTIR, XPS, XRD, XRD, HRTEM, TGA	[141]
26	Commercial cellulose	Polyvinyl alcohol, ZSM-5 zeolite	MB	–	97 %	Freundlich	2	–	7.83 mg/g	–	FTIR, XRD, TGA, SEM	[142]
27	Rice husk	–	Malachite Green, CV, CR	7, 2.2	–	Langmuir	2	–	4.42 MG, 9.57 CV, 15.54 CR (mg/g)	–	FESEM, FTIR, XRD	[143,144]
28	Mesquite woods	Fe_3O_4	MB	7	–	Langmuir	2	–	1225 mg/g	–	FTIR, XRD, TGA, SEM, TEM	[145]
29	Filter paper	Microfibrillated cellulose	Methylene Blue	–	–	Langmuir	2	Ex	303 mg/g	–	SEM, FTIR, BET, TGA	[146]
30	Sugarcane and soursop residues	–	Methylene Blue	5.16	90.4 %	Redlich-Peterson a	2	–	–	–	SEM	[147]
31	Thiourea modified sugarcane bagasse cellulose (commercial)	Carboxymethyl cellulose	Methylene Blue, Crystal Violet	> 7	–	Langmuir	2	Ex	632.9 and 574.7 mg/g	555.6 and 427.4 mg/ g	FTIR, XRD, SEM, TGA	[61]
32	Rice husk (graft copolymers of cellulose)	–	Malachite Green, Crystal Violet, Congo Red dye	2.2–7	–	Langmuir	2	–	4.42 for MG,9.57 for CV, 15.54 for CR	–	FESEM, FTIR, XRD	[143]
33	Trimellitated sugarcane bagasse	–	Safranin-T, Auramine-O	4.5–7	41–51 %	Langmuir	2	Ex	0.638 mmol g-1 1.230 mmol g-1	–	FTIR, SEM	[148]
34	Cellulose filament (commercial)	Poly (N-isopropylacrylamide-*co*-acrylic acid)	Methyl Violet	7	–	Langmuir	2	En	226.02 mg/g	–	AFM, FTIR, SEM, TGA	[149]
35	Waste printing paper	–	Hydroxynaphthol Blue and Congo Red	2, 3		Langmuir	1	En	0.1700 and0.1564 mmol/g	–	SEM, TEM, FTIR	[130]
36	Commercial cellulose	k-carrageenan/ activated montmorillonite	MB	6	98 %	Langmuir	2	–	12.25 mg/g	–	FTIR, SEM, TGA	[150]
37	Cotton	$Fe(OH)_3$	Congo Red	7	–	Langmuir	2	–	689.65 mg/g	–	SEM, TEM, XRD, FTIR, BET	[151]
38	Rice straw (cellulose nanofibril aerogels)	–	Malachite Green	–	92 %	Langmuir	2	–	212.7 mg/g	–	FESEM, FTIR, XRD	[152]
39	Carboxymethycellulose (commercial)	Bentonite	Congo Red and Methyl Orange	–	87 %	Langmuir	2	Ex	110.7 mg/g	–	SEM, TEM, XRD, TGA, FT-IR	[153]
40	Carboxylated cellulose (commercial)	Trimellitic anhydride (CTA)	Auramine-O and Safranin-T	4.5, 7	44.61 %, 78.87 %	Langmuir	2	Ex	(2.841) and (3.691), (5.443) and (4.074) mmol/ g	1.230 And 3.728 mmol g^{-1}	EDX, FTIR, SEM, TGA	[154]
41	Commercial cellulose	Clay hydrogel (montmorillonite)	MB	1–11	96.6 %, 98 %	Langmuir	2	–	100 mg/g	–	FTIR, TEM,	[155]

(*continued on next page*)

Table 13 (*continued*)

S. No	Cellulose source	Composite	Dye	pH	Efficiency	Isotherm	Kinetic	Thermodynamics	Single dye	Binary dye	Characterization	Ref.
42	Kepok banana peel	–	Procion dye	5	–	Langmuir	–	–	15.585 mg/g	–	FTIR, SEM-EDS	[156]
43	*Posidonia oceanica*	–	Basic Blue 9, Acid Blue 25	3.5	–	Langmuir	2	–	0.955, 0.370 mg/g	–	XRD, FTIR	[157]
44	Mulberry branches	–	Acid Blue 93, MB	9	200–250 mg/g	Freundlich,	2	–	1372 mg/g	78.5 % AB 93, 73.3 % MB	SEM, FTIR, BET	[158]
45	Commercial cellulose	Sodium alginate	MB	–	97 %	Langmuir	2	Ex	256.41 mg/g	–	FESEM	[159]
46	Commercial cellulose hardwood kraft pulp	–	Reactive Light Yellow K-4G, Acid Red GR,CR 4BS	7–8	–	Langmuir	2	–	555.6 mg/g	–	AFM, FTIR, XRD	[160]
47	CCF (CAC)	APE/bentonite	Brilliant Green	3–5	95 %	–	2	–	52.63 mg/g	–	SEM, XRF, EDX, FTIR, UV–vis	[161]
48	Commercial cellulose	Graphene oxide	MB	10.59	89 %	Langmuir	2	Ex	70.03 mg/g	–	FTIR, XRD, SEM	[162]
49	Commercial cellulose (acrylic acid and carboxymethyl cellulose)	–	Methyl Orange, Disperse Blue 2BLN, Malachite Green		84.2 %, 79.6 %, 99.9 %	Temkin	2	–	147.9 mg/g	–	SEM, FTIR	[163]
50	Commercial cellulose	Polyacrylamide	MB	5	90 %	Langmuir	2	–	326.08 mg/g	–	FESEM	[164]
51	CarboxymethyCellulose	Montmorillonite item and cross-linked by PEGDA	Cationic dye Lauths Violet	–	–	–	–	–	85.4496.06 %	–	FTIR, SEM	[165]
52	Commercial cellulose	polyaniline	RBBR RO, RV, RBK	3	82 %	Langmuir	1	–	420.40, 606.99, 402.36, 310.62 mg/g	–	XRD, FTIR, SEM, TGA	[166]
53	Commercial cellulose	–	Basic fuchsine and Malachite Green	6, 6.5	85 %, 90 % BF & MG	Langmuir	2	Ex	1155.76 BF, 458.72 MG mg/g	–	XRD, FTIR, SEM, TGA	[167]
54	Carboxymethy cellulose (commercial)	Organic montmorillonite	Congo Red	9.6	–	–	–	–	171.37 mg/g	–	SEM, XRD, TGA FTIR, TEM	[168]
55	Commercial cellulose (cellulose acetate composites)	Montmorillonite	Acid scarlet G	5.5	–	Langmuir	1	En	85.7 mg/g	–	FTIR, SEM, TGA, XRD	[89]
56	Lignocellulose-g-poly (acrylic acid)	Montmorillonite	Methylene blue (MB)	10	83.40 %	Langmuir	2	–	1994.38 mg/g	–	XRD, TEM, FTIR, SEM.	[169]
57	Platanus xhispanica plant tree leaves (lignocellulos)	Montmorillonite clay	Methyl Orange	–	–	Freundlich	2	–	3.374 mg/g	–	FTIR, TGA, SAXS	[170]
58	Lignocellulose	Montmorillonite	Congo Red	4	–	Langmuir isotherm	2	En	52.75 mg/g	–	FTIR, XRD	[171]
59	Commercial Cellulose	$Fe_3O_{4/}$ activated carbon	Congo Red	4–9.5	20 mg/g	Langmuir	2	Ex	66.09 mg/g	–	XRD, BET, TGA, SEM, VSM	[172]
60	Palm flower (lignocellulosic waste biomass activated carbon)	–	Amido Black	2.3	–	Freundlich	2	En		–	SEM, BET	[173]
61	*Posidonia oceanica*	–	Acid Yellow 44	2–3	–	Freundlich	2	–	0.028 mmol/g	–	SEM	[174]
62	Waste-newspaper	Graphene oxide	Methylene Blue and Congo Red	–	235.6 % MB, 70.2 % CR	Langmuir	2	–	65.4 to 154.1 MB 128.6 μmol/g CR	–	FTIR, TEM, SEM, TGA	[175]
63	Orange peel	–	Congo Red, Procion Orange and Rhodamine B	5, 3, 3	–	Langmuir and Freundlich	1	–	22.4, 1.3 and 3.22 mg/g	–	–	[176]

(*continued on next page*)

Table 13 (*continued*)

S. No	Cellulose source	Composite	Dye	pH	Efficiency	Isotherm	Kinetic	Thermodynamics	Single dye	Binary dye	Characterization	Ref.
64	Sawdust	–	Anionic dye (E102, Acid Yellow 23 (Ay23), FD and C Yellow 5)	3	97 %	Dubinin-Radushkevich	2	En	4.71 mg/g	–	FTIR, SEM	[177]
65	Microcrystalline cellulose	–	Methylene Blue	4–10	–	Langmuir	2	Ex	4.95 mg/g	–	BET, FESEM, FTIR	[178,179]
66	Carboxymethycellulose	Carboxylated graphene oxide	Methylene Blue	10	91.1 %	Langmuir	2	Ex	183.15 mg/g	–	FTIR, TGA, SEM, XPS, BET	[180]
67	Cellulose micro crystalline	Aminoethanethiol	Red Reactive	2 and 9	–	Langmuir	2	–	78, 26 mg/g	–	XRD, TGA, FTIR,	[181]

*1 = Pseudo 1ST order kinetic model and *2 = Pseudo 2nd order kinetic model, Ex = exothermic, En = Endothermic.

analysis of any enhancement in cellulose adsorption capacity. Consequently, it was investigated that cellulose modified with triethylenetetramine had less adsorption capacity. In another study, Hokkanen et al. [113] utilized carbonate containing hydroxyapatite (CHA) and used this modified cellulose to adsorb Cd(II) and Ni(II). The results of this analysis were positive. Divalent cations, i.e., Zn(II), Pb(II), Co(II), Cd(II), Ni(II) and Cu(II) were also adsorbed by using organic compound made by modification of cellulose with thionyl chloride, followed by the ethylene sulfide and ethylenediamine. Reactivity and efficiency of metal adsorption were increased by this type of chemical modification.

Zhou et al. [115] used maleic anhydride for cellulose modification and it resulted in increased efficiency of Hg(II) adsorption. Grafting of cellulose using radiations was also carried out for the synthesis of microspheres of cellulose adsorbent for Cr(VI) adsorption using styrene. The adsorption capacity of this adsorbent was 123.4 mg/g. In the same way, etherification, oxidation, and modification of cellulose to Schiff was carried out by Kumari et al. [73], where lysine was used for the adsorption of Hg ions from the water.

3.7. Treatment with acids

Oak sawdust was used as an adsorbent for Cr, Cu and Ni adsorption by Argun et al. [90]. Oak sawdust was pretreated with HCl. Sawdust, a lignocellulosic material is widely available and is used as an adsorbent for treatment of wastewater. Meena et al. [116] studied adsorption of Hg (II), Cr(VI), Pb(II) and Cu(II) using sawdust from the tree *Acacia arabica*. Hydroxyethyl-cellulose was grafted with the acrylic acid by Cavus et al. [117] using poly(ethylene glycol diacrylate)-cross-linking agent, for adsorption of Cd(II), Cu(II) and Pb(II) ions.

3.8. Alkali treatment

Cellulose beads are formed and treated with iron oxyhydroxide to remove arsenite as well as arsenate from the aqueous solutions and the prepared adsorbent was also regeneratable up to 4 adsorption cycles. Shukla et al. [118] used jute fibers to remove Ni(II), Cu(II) and Zn(II). Agricultural by-products as biopolymers have functional groups, which offer high adsorption capacities. Biomaterials also have such functional groups that can undergo chemical modification to enhance their adsorption efficiencies. Jute fibers contain 12 to14 percent lignin and 58 to 63 % cellulose. Their 2 new forms were developed by modification. One form is produced by dye loading and the other was developed by oxidizing it with NaOH. These modified forms of the jute fibers were proved to be more efficient than raw counterparts and system efficiency was also affected by pH of the medium. A direct relation of adsorption capacity was observed with pH, i.e., at low pH, the adsorption capacity was decreased. Jute fiber-based adsorbent was regenerated by treating it with NaOH.

3.9. Cellulose composites

For wastewater treatment, different materials have been combined with cellulose. Modification of cellulose can be done to use as an adsorbent using sodium montmorillonite (NaMMT). A composite biomaterial called cellulose montmorillonite is a modified product. It is highly efficient for the removal of Cr(VI) from the aqueous solutions. Using NaOH, regeneration of adsorbent is possible up to 10 cycles. Composites of CTS/cellulose were also produced by binding cellulose with chitosan, which is used for removal of the heavy metals and dyes from wastewater. Cellulose nanowhiskers were also used to improve the adsorption capacity of acrylic acid-based hydrogel, which enhanced a 20 % adsorption capacity of composites of MB removal (Fig. 6) [119]. The adsorption efficiencies of various cellulose-based adsorbent are depicted in Table 13.

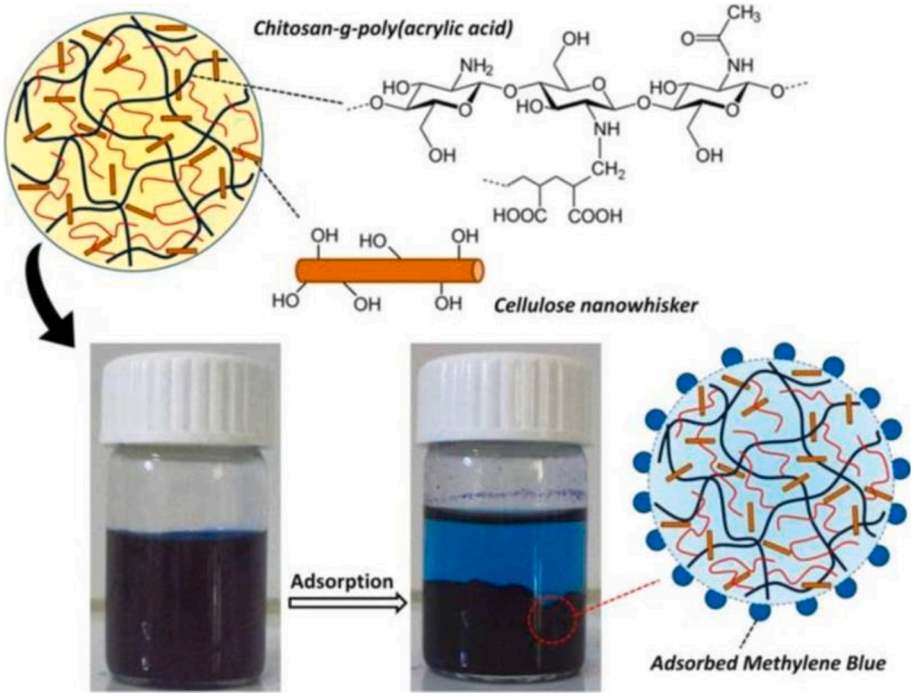

Fig. 6. Adsorption of MB dye on cellulose nanowhisker composite [119].

4. Effects of pH on adsorption

The most significant factor which influences adsorbent capacity in the treatment of wastewater is solution pH. The efficiency of the adsorption depends on pH of the solution because changes in pH result in changes in the extent of ionization of the molecule being adsorbed and change occurs on the surface of the adsorbent [182]. As a consequence, with the change in pH of the solution, the adsorption rate changed significantly. When the pH of a solution is low, the dye removal percentage for anionic dyes increases, whereas, for cationic dye adsorption, dyes removal percentage may decrease. On contrary, when the pH of the solution is in the basic range, then anionic dye removal is declined, whereas for the cationic dye percentage of dye removal is increased. Low adsorption of cationic dyes at low pH was due to a large number of hydrogen ions striving for adsorption sites and in this way, hydrogen ions compete with the cationic ions. When pH is high, ionization of functional groups takes place on the adsorbent surface, it increases cationic adsorption by electrostatic attraction. When dyes are anionic, low pH furnishes higher adsorption because the adsorbent surface is charged positively and can adsorb anionic dyes easily [183].

For comprehending the adsorption mechanism, the point of zero charge, pH_{pzc} is a basic parameter. Value of pH_{pzc} signifies the adsorption ability of adsorbents and the type of active sites. When pH > pH_{pzc}, the different functional groups exist, i.e., carboxyl (COO-) and hydroxyl (OH-) and the adsorption of cationic dyes occur. However, the adsorption of anionic dyes is promising when pH < pH_{pzc} as the surface of the adsorbents has positive charge [183].

The effect of pH on the adsorption of dyes is reported in Table 13. Literature survey highlights that optimization of pH is dependent on the cellulose source being used and dyes nature, i.e., Wang and Wang [168] performed the adsorption at 9.6. Also, [127,169] optimized the pH value from 2 to 10 to remove methylene blue (MB) from the lignocellulose-g-poly(acrylic acid)/montmorillonite composite and the cellulose/montmorillonite, respectively. At pH 2, the adsorption was minimum for all dyes. By increasing pH, adsorption capacity increased and in the pH 8–10 range, maximum adsorption was achieved. The composite lignin-containing cellulose nanocrystals/sodium alginate beads were used to remove MB dye. pH effect on dye removal was observed by varying the pH of MB solution in 3–11 range. The adsorption of MB by LCNCs/SA beads increased significantly from 261.9 to 309.9 mg/g when pH was increased from 3 to 7, and later, it become steady. When solution pH values were increased, more ions were adsorbed on the surface of LCNCs/SA beads [123].

5. Kinetics study

Different mechanisms to control the adsorption process include diffusion control or mass transfer and chemical reaction, and these mechanisms are useful for establishing kinetic models. Dye adsorption kinetics is imperative while selecting the best conditions to operate a batch process, which is full scale. Kinetic study of adsorption illustrates how the uptake rate of solute controls the time of residence of the adsorbate at the interface of solution. This rate becomes significant when the adsorption system is designed and calculated from the kinetic study [184,185]. Sorption energy is fundamental for picking the ideal working conditions for sorbent-sorbate collaboration and is a huge aspect of plotting the sorption process. So, to investigate the efficiency of the sorbent and to study the controlling component of the sorption, pseudo first and second order kinetics models and the intraparticle models are considered. The removal of AR-42 dye on CMC/O-bent composite followed the pseudo-second order kinetics [137]. The kinetic study of organophilic composite montmorillonite/cellulose acetate to remove Eosin Y followed the pseudo-second order versus pseudo first order based on the calculated and experimental values [140]. For CR dye removal, pseudo-second order kinetic was better fitted [171].

Also, Mohammed et al. [186] studied pseudo-first, second orders and intraparticle diffusion models for kinetics analysis of MB dye sorption onto beads of composite cellulose nanocrystal (CNC)– alginate hydrogel. Adsorption kinetics and its mechanism were best described in terms of the model intraparticle diffusion and pseudo-second order kinetics model. The values of R^2 for pseudo-first order kinetics was less than those of pseudo-second order. Pseudo-second order kinetics model fitted excellently with regression coefficient (R^2 = 0.999). Similarly, Kausar et al. [121] applied pseudo second order kinetic model for study of kinetic data of the sorption of dye Drimarine Yellow HF-3GL onto the composite cellulose and clay. Liu et al. [158] applied pseudo second-

order to study the kinetics of sorption of MB and acid blue 93 dyes from the binary and single systems using a cellulose-based adsorbent. The R^2 values for MB and AB-93 dyes in the case of pseudo-second order model of kinetics were 0.998, which is higher than the ones obtained from pseudo-first order model. A review of kinetic studies (Table 13) shows that pseudo-second order kinetics model is better fitted to dye adsorption data on the cellulose-based adsorbents versus other models.

6. Equilibrium study

Equilibrium study, the adsorption isotherm is the basic need for understanding the adsorption nature of the adsorbate on to the respective adsorbents. The concentration of adsorbate shows dynamic equilibrium with adsorbent interface in solution. Analysis of equilibrium data helps in developing mathematical models, which helps in the illustration of results quantitatively. The assumptions of such models of equilibrium can help in the prediction of ions adsorption together with providing significant data on the mechanism of the adsorption [20,187]. Since, the concentration at equilibrium is dependent on temperature, which is performed at a specific temperature. Many isotherms, i.e., Langmuir, Freundlich, Dubinin-Radushkevich (DR), Redlich-Paterson, Sips and Halsey isotherms are widely used in adsorption studies. Each model of equilibrium explains different adsorption characteristics; however, the most favorable methods are the Langmuir and the Freundlich. The ideal model of a monolayer is the Langmuir isotherm [188], which explains that a monolayer can be formed by adsorbed molecules and every adsorbed molecule possesses exactly the same energy for the adsorption of adsorbate ion. Multilayer adsorption is demonstrated by the Freundlich isotherm [189]. Commonly, Freundlich model describes the adsorption performance of the species which are particularly interactive or the organic component of materials that have a porous structures and a large number of activated carbons [190].

The AR-42 dye adsorption onto composite showed heterogeneous adsorption suggesting that the Freundlich model is more suitable [137]. To remove Eosin Y, composite organophilic montmorillonite-cellulose acetate revealed that Freundlich model did not fit well because of small 1/n values. Instead of this Langmuir model fitted better based on the correlation coefficient value for both isotherm models [140]. LNC/MMT nanocomposite was used for CR dye removal and the Langmuir model was more suitable than other models applied [171]. Similarly, for the removal of MB dye, composite cellulose nanocrystal (CNC)–alginate hydrogel beads were applied and results revealed that the Langmuir isotherm model fitted better than the others. Values of R^2 observed were near unity from the linear form of the Langmuir model as compared to those calculated from the Freundlich model, which indicates that the Langmuir model explains the process of adsorption very well. A study of adsorption isotherm showed that process of adsorption was better described by Langmuir isotherm versus Freundlich isotherm [159]. Aichour and Boudiaf [60] studied CV and MB dyes onto cellulose/calcium alginate composite and Freundlich and Langmuir isotherms were applied to the adsorption data. For MB dye, the maximum adsorption capacity for CPAA-A composite and CPAA powder was 923.07 and 200.01 (mg/g), respectively. For CV dye, the removal was 881.36 and 187.77 (mg/g) for beads of CPAA-A composite and CPAA powder, respectively. The R^2 values explain monolayer and homogeneous distribution on the adsorbent surface. The Langmuir explained well the CV and MB adsorption onto the said adsorbent. The equilibrium studies of adsorption of dyes verify that Langmuir isotherm and Freundlich are better fitted to the adsorption dyes onto the cellulose-based adsorbents (Table 13).

7. Thermodynamic study

A significant factor in process of dye removal is temperature. Wastes are released at a different temperature from the industries, which need to be studied to understand the adsorption nature of the adsorbates. To build up probability and response nature, it is valuable to study the adsorption process thermodynamically [33,44,49,184]. Temperature as well as adsorption nature can be used to determine distinctive factors of thermodynamics based on ΔS°, ΔH° and ΔG° parameters [191]. Exothermic as well as endothermic nature is described in reported data with the help of thermodynamic investigation of adsorption of dyes onto cellulose-based adsorbents. If adsorption extent is increased with temperature, then it is an endothermic process. It occurs the reason that with temperature, the movement of dye molecules increases and as a result, more active sites become available for adsorption. On the other hand, if adsorption capacity decreases with temperature, then the adsorption process is exothermic. The reason for this decrease in adsorption is the reduction in attractive forces between active sites of the adsorbent and the dye species [12].

Thermodynamic features give information regarding energy changes occurring in the process of adsorption. Values of ΔH° and ΔG° were positive and negative, respectively at various temperatures, which show that adsorption was spontaneously occurring as an endothermic process. Positive ΔS° values show that there is a considerable affinity between adsorbent and adsorbate, which represents a greater degree of

Table 14
FT-IR analysis of various cellulose-based adsorbent for the removal of dyes.

Composites	Bands (cm^{-1})	Vibrations	Functional groups	References
Cellulose/ montmorillonite	33,900	Stretching	(O—H)	[133]
	2900	Stretching	(C—H)	
	1018	Stretching	(C—O)	
Cellulose/clay	3372	Stretching	C-C	[121]
	1106 and 1435	Stretching	C-O	
	778	Stretching	Fe-Fe-OH	
	1035	Stretching	Si-O	
Nanocrystalline cellulose/ montmorillonite	3630	Stretching	(O—H)	[124]
	3320	Stretching	(O—H)	
	1633	Bending	(O—H)	
	1425	Bending	(C—H)	
	1038	Stretching	Si-O-Si	
	908	Stretching	Al-Al-OH	
	522	Bending	Al-O-Si	
Carboxymethyl cellulose/ organobentonite	1446	Stretching	-COO gp	[137]
	1600	Asymmetric	-COO gp	
Cellulose/ Montmorillonite	2900	Stretching	O-H groups	[127]
	3431, 3625 and 1640	Stretching		
Cellulose-montmorillonite	3379	Stretching	O-H	[193]
	2902	Stretching	-CH	
	794	Stretching	Si-O	
Celluloacetate-organophillic montmorillonite	2919	Asymmetric.	(-C-H bond)	[140]
	2850	Symmetric	(-C-H bond)	
	1486	Bending	(-C-H bond)	
CA/OMMT	2850	Symmetric	$-CH_2$	[89]
	2920	Asymmetric stretching	C-H	
Carboxymethyl cellulose/ bentonite	1085.5, 794.3 and 1035.7	Stretching	Si- O and Si-O –Si	[153]
	3629.4 and 916.6	Stretching and bending	O—H group	
	1367.5	Stretching	C-N	
Carboxymethyl cellulose/organic montmorillonite	1600	Asymmetric	COO-	[168]
	1446	Stretching symmetric	COO-	
	2922	Symmetric	$-CH_3$	
	2850	Symmetric	$-CH_2$	
	1024	Asymmetric stretching	Si- O	
Cellulose based citrus peel/ calcium alginate	2927	Stretching	C-H	[60]
	1026	Stretching	C-OH	
	660	Stretching	C-Cl	

randomness at the interface of adsorbent and solution [60].

Zhou et al. [89] studied the removal of anionic dyes onto CS/OMMT composite. The results indicated that the respective process was an endothermic and spontaneous process because after using CA/OMMT 60 % for the sorption of ASG standard enthalpy change give a positive value of 24.8 kJ/mol. For the adsorption of Congo red onto LNC/MMT, negative ΔG° values at various temperatures indicate spontaneous behavior of the sorption process. A positive ΔH° revealed endothermic sorption. Positive ΔS° value shows increase in randomness at the interface of solution and solid [171].

For both binary and single sorption of the dyes (CV and MB) on cellulose/calcium alginate composite were performed, the ΔG° value was negative, at different temperature values, demonstrating that adsorption of CV and MB dyes is spontaneous and ΔH° negative value indicates that the process of adsorption of CV and MB are exothermic [60]. Similarly, Mohammed et al. [159] performed anionic dye elimination onto cellulose nanocrystal–alginate hydrogel beads composite. The dye removal reduced from 77 to 69 % by increasing the temperature from 25 to 55 °C. Negative ΔG° values represent the spontaneity of sorption process. When the temperature was increased, ΔG° also increased, indicating a reduction in adsorption with temperature. Negative ΔH° values show that the process of adsorption was exothermic. Thermodynamic studies show that process of sorption can be exothermic or endothermic for the adsorption of dyes onto cellulose-based adsorbents (Table 13).

8. Characterization

There are different methods that have been used to portray the adsorbents and the adsorption process can be better understood by characterization of the adsorbents [33,42,43,45,49,184,192]. The SEM, XRD, TGA, FTIR and TEM have been applied in this regard. FT-IR information about the functional group and how this functional group responds during the sorption process. The difference between the sorbent functional groups before and after the experiment is also provided by FTIR and the change in the functional groups is due to the adsorption process that is attached to specific functional groups (Table 14). In this regard, [130] studied the MMT and NCC and found that the binding is due to the hydroxyl group in MMT. The C—H in nanocrystalline cellulose shows the band at 1425–1427 cm^{-1}. The carbonyl group shows the band in the range of (1650–1750 cm^{-1}), which after adsorption appeared at 1550–1600 cm^{-1} as an arene group. For Na-bentonite, a band at 3630 cm^{-1} of O—H was observed and 3442 cm^{-1}H-bonding, 1094 and 1038 cm^{-1} Si—O stretching, 1630 cm^{-1}H-O-H bending. CTAB modified bentonite showed a band at 2922 cm^{-1} and 2852 cm^{-1} for the symmetric and asymmetric vibrations of CH_3 and CH_2, respectively [137]. At 2927 cm^{-1}, a peak was observed due to the presence of the C—H group of alkanes in FTIR spectra of the composite beads of calcium alginate-CA and CPAA-A. At 1624, 1642 and 1614 (cm^{-1}), strong peaks were observed for amide and alkyl carbonate. At 1026 cm^{-1}, and 660 cm^{-1}, peaks indicate the presence of stretching of C-OH in alcoholic group and stretching of C—Cl of the group alkyl halide [60]. At 3431, 3625 and 1640 (cm^{-1}), absorbance bands are observed due to OH group in FT-IR spectra of the CMt due to Mt. and band at 2900 cm^{-1} disappeared showing entire destruction of cellulose and entrance of carbonaceous material on Mt. surface [127]. FT-IR spectra of the LCNCs/SA beads showed changes in the peak positions, especially shifting from 1415 cm^{-1} (Na-alginate) to 1436 cm^{-1} (Ca-alginate) for symmetric carboxylate (–COO–) group [123]. The CMC showed 1446 and 1600 (cm^{-1}) bands for –COO group for symmetric and asymmetric, respectively [137]. The cellulose acetate revealed acetylation due to bands of ester group C = 0, –CO– stretching of acetyl and C—H stretching in the group $–OCOCH_3$ at 1742.7, 1239.4 and 1364 (cm^{-1}), respectively [140]. The LNC lignocellulose showed absorption bands at 1164, 1032 and 112 (cm^{-1}) for C-O-C and C—O due to vibration [171]. Strong bands at 3379 and 2902 (cm^{-1}) are due to O—H stretching and C—H stretching in the structure of cellulose, respectively [193].

Table 15
Characterization of various cellulose-clay/sodium alginate composite by TGA.

Composites	Temperature	Reason	References
CA/OMMT	320–400 °C	Thermal degradation of CA and decomposition of surfactant	[89]
Organophilic montmorillonite/ cellulose acetate	110 °C	Decomposition of polymer chains	[140]
Cellulose–bentonite	30–600 °C	Thermal stability of the prepared hydrogels	[124]
Cellulose/clay	163,466 °C	Composite are stable at high temperature	[121]
Carboxymethyl cellulose/ bentonite	25–500 °C	Elimination of the water molecules from carboxylic group of polymeric chain	[153]
Carboxymethyl cellulose/organic montmorillonite	500 °C	Degradation mechanism of alkyl ammonium ion clay modifier	[168]
Cellulose/ montmorillonite	490 °C	Carbon decomposition	[127]
Carboxymethyl cellulose/organo-bentonite	400 °C	Thermal decomposition	[137]

Table 16
Characterization of various cellulose-based composite by XRD analysis.

Cellulose composites	2Θ (degree)	References
Cellulose based citrus peel/calcium alginate	2Θ = 21.36°	[60]
Carboxymethyl cellulose/organo-bentonite	2Θ = 4.62°	[137]
Carboxymethyl cellulose/organic montmorillonite	2Θ = 4.43°	[168]
CA/OMMT	2Θ = 2.89°	[89]
Cellulose/montmorillonite	2Θ = 5.67°	[127]
Organophilic montmorillonite/cellulose acetate	2Θ = 4.180°	[140]
Cellulose–bentonite	2 Θ = 20.2°	[124]
Cellulose−Clay	2θ = 7.1°	[155]
Cellulose/Clay	2θ =12.04°	[121]
Carboxymethyl cellulose/ bentonite	2θ =7.40°	[153]
Lignocellulose-g-poly(acrylic acid)/montmorillonite	2θ =5.83°	[169]

Another technique, TGA provides information on a specific temperature, the stability of the adsorbent and the weight loss of sorbent (Table 15). In the TGA study, a sample is heated at a specific temperature and a change in mass with temperature was observed. The thermal stability of organophilic montmorillonite/cellulose acetate was studied and used to remove Eosin Y, which showed the polymer degradation in the temperature range of 110–400 °C. Moreover, 400–700 °C is the last stage where the crystalline region is completely degraded [140]. The composite showed stability at higher temperatures and weight loss of 2.17 and 53 (%) was observed at 163 °C and 466 °C for cellulose-clay composite-I and cellulose-clay composite-II, respectively [121]. The cellulose/montmorillonite composite TGA analysis showed a band between 250 °C and 490 °C which revealed carbon material decomposition [127]. Also, the CMC/O-bent composite degradation started at 400 °C and degraded up to 800 °C. The reason behind this can be due to the effect of alkyl ammonium degradation that played a role of a barrier for heat protection and the thermal stability of the composite was increased on the whole due to the presence of inner silicates [137].

To find structural and change in crystallinity, XRD analysis has been employed (Table 16). It can also predict variations in the sorbent structure [194]. The CMt composite XRD analysis revealed the layered structure. XRD showed that 2θ decreased from 5.89° to 5.67° because carbon was intercalated in Mt. [127]. The XRD analysis of bentonite showed a peak at 6.93° which was reduced after surface modification and the resultant peak was at 4.96°. The CMC/O-bent showed structurally different material of composite after the removal of AR42 dye [137]. The organophilic montmorillonite/cellulose acetate showed a

Table 17
Characterization of various cellulose-clay/sodium alginate composite by SEM.

Cellulose composite	Structure	Pore size	Ref.
Organophilic montmorillonite/ cellulose acetate	Dense structure with pores	–	[140]
Cellulose/montmorillonite	Rough with blunt edge	1 μm	[127]
Cellulose/montmorillonite hydrogels	Clay with cellulosic network	200 nm	[138]
Lignocellulose-g-poly(acrylic acid)/montmorillonite	Coarse surface with microporous structure	5 μm	[169]
Carboxymethyl cellulose/ organic montmorillonite	Large surface area with no. of pores	5 μm	[168]
CA/OMMT Macroporous	Paper-like shape	–	[89]
Cellulose/bentonite-50 μm	Zeolite Microporous with sandwiched bentonite	50 μm	[139]
Cellulose based citrus peel/ calcium alginate	Heterogeneous and Rough surface	2 mm	[60]
Cellulose–bentonite	Sponge-like macroporous structure	–	[124]
CA/OMMT	Macroporous structure	–	[89]
Lignin-containing cellulose nanocrystals/sodium alginate	Rough and fold surface and the porous internal structure	100 μm	[123]
Cellulose nanocrystal–alginate	Smooth and porous surface	3 mm	[159]
Cellulose/montmorillonite mesoporous composite beads	Number of pores on the surfaces of beads were noticed	–	[133]
Cellulose/Clay	Rough and porous surface	–	[121]

peak at 15.28°, which was reduced to 10.160° on acetylation and the clay peak shifted to 4.7, which was originally at 5.770° [140]. The alginate, CPAA and CP and CPAA-A exhibit amorphous structure and the peak was detected at 21.36°, the large peak of CP and CPAA was observed in the XRD pattern, which indicates that samples have low crystallinity [60].

To evaluate structural ordering, morphologies, cracks and particles attached to adsorbent surfaces and cavities, SEM analysis is carried out (Table 17). SEM analysis indicated large differences before and after the clay treatment. It was revealed that some critical changes on the surface of clay have occurred after dye adsorption [195]. The LCNCs/SA beads have a rough and fold surfaces and a porous internal structure, which can help to improve the adsorption performance [123]. SEM characterized nanocellulose as a needle-like crystalline structure. NCC and MMT mixed up and form composite NcMMT (a fragile film). NCC have small-sized molecules made a composite with large-sized molecule MMT. Because cellulose was short-sized, their surface was smooth, less porous and the spacing between each cellulose was narrow [196]. The CCF was prepared from cellulosic and non-cellulosic material having intra-fibrous pores. The coated mixture of APE and bentonite on CCF was used as a sorbent for the treatment of wastewater. The CAC showed a heterogeneous structure [197]. Also, the CMt showed a flat structure of Mt. with a flood of carbon particles. Finally, CMt showed roughly with a blunt edge due to the stream of carbon particles [127].

9. Conclusion

This review gives quick insight into the removal of dyes using cellulose-based adsorbents. Cellulose is an eco-friendly, renewable, lost-cost and highly efficient with a remarkable adsorption efficiency, i.e., commercial cellulose, cotton fibers, bagasse, rice straw and sawdust showed adsorption efficiencies up to 97, 94, 89.95, 92, and 97 (%) for removal of MB, CR, DYHF-3GL, MG and anionic dye, respectively. It is observed the adsorption the dye onto various cellulose-based adsorbents is highly dependent on the initial concentration of dye, solution pH, adsorbent dose and temperature. For characterization of the cellulose before and after dyes adsorption, different techniques have been utilized, FTIR (functional group), SEM (structural ordering, morphologies), TGA (thermal stability) and XRD (structural analysis). Chemical and physical modifications have been performed for the modification of cellulosic material for the enhancement of dyes adsorption. Modifications and pretreatments of cellulose biopolymers are proved to be involved directly in the enhancement of their adsorption capacity. For the treatment of wastewater, cellulose-based adsorbents are highly feasible and also, these are regeneratable and recyclable. Chemical modifications improve the adsorption capacity of the cellulose-based adsorbents, which functionalized the surface of the adsorbent and create more active binding sites for an effective uptake rate of the adsorbate. Based on these findings, it is revealed that the cellulose-based adsorbents have the potential for the removal of dyes from the effluents. However, there is also a need to develop more innovative techniques for the modification of cellulosic materials for sequential application to enhance the dyes removal efficiencies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] S. Hokkanen, A. Bhatnagar, M. Sillanpää, A review on modification methods to cellulose-based adsorbents to improve adsorption capacity, Water Res. 91 (2016) 156–173.
[2] A. Bhatnagar, M. Sillanpää, Utilization of agro-industrial and municipal waste materials as potential adsorbents for water treatment—a review, Chem. Eng. J. 157 (2010) 277–296.
[3] F.M.D. Chequer, J.P.F. Angeli, E.R.A. Ferraz, M.S. Tsuboy, J.C. Marcarini, M. S. Mantovani, D.P. de Oliveira, The azo dyes disperse red 1 and disperse Orange 1 increase the micronuclei frequencies in human lymphocytes and in HepG2 cells, mutation Research/Genetic toxicology and environmental, Mutagenesis 676 (2009) 83–86.
[4] S. Dawood, T. Sen, Review on dye removal from its aqueous solution into alternative cost effective and non-conventional adsorbents, journal of, Chem. Process. Eng. 1 (2014) 1–11.
[5] V. Gupta, Application of low-cost adsorbents for dye removal–a review, J. Environ. Manag. 90 (2009) 2313–2342.
[6] X.S. Wang, Y. Zhou, Y. Jiang, C. Sun, The removal of basic dyes from aqueous solutions using agricultural by-products, J. Hazard. Mater. 157 (2008) 374–385.
[7] S. Allen, G. Mckay, J.F. Porter, Adsorption isotherm models for basic dye adsorption by peat in single and binary component systems, J. Colloid Interface Sci. 280 (2004) 322–333.
[8] M. Iqbal, M. Abbas, A. Nazir, A.Z. Qamar, Bioassays based on higher plants as excellent dosimeters for ecotoxicity monitoring: a review, Chem. Int. 5 (2019) 1–80.
[9] Q. Sun, L. Yang, The adsorption of basic dyes from aqueous solution on modified peat–resin particle, Water Res. 37 (2003) 1535–1544.
[10] M. Shahid, F. Mohammad, Recent advancements in natural dye applications: a review, J. Clean. Prod. 53 (2013) 310–331.
[11] A. Ayach, S. Fakhi, Z. Faiz, A. Bouih, A. Benkdad, M. Benmansour, A. Laissaoui, M. Adjour, Y. Elbatal, I. Vioque, G. Manjon, O. Aitmalek, in: Adsorption of methylene blue on bituminous schists from Tarfaya-Boujdour, 3, Chemistry International, 2017, pp. 442–451.
[12] M.T. Yagub, T.K. Sen, S. Afroze, H.M. Ang, Dye and its removal from aqueous solution by adsorption: a review, Adv. Colloid Interf. Sci. 209 (2014) 172–184.
[13] M. Sasmaz, G.U. Senel, E. Obek, Boron bioaccumulation by the dominant macrophytes grown in various discharge water environments, Bull. Environ. Contam. Toxicol. 106 (2021) 1050–1058.
[14] A. Sasmaz, B. Sasmaz, J.R. Hein, Geochemical approach to the genesis of the oligocene-stratiform manganese-oxide deposit, Chiatura (Georgia), Ore Geol. Rev. 128 (2021), 103910.
[15] M. Sasmaz, G.U. Senel, E. Obek, Strontium accumulation by the terrestrial and aquatic plants affected by mining and municipal wastewaters (Elazig, Turkey), Environ. Geochem. Health 43 (2020) 1–14.
[16] M. Sasmaz, E. Öbek, A. Sasmaz, Bioaccumulation of cadmium and thallium in pb-zn tailing waste water by Lemna minor and Lemna gibba, Appl. Geochem. 100 (2019) 287–292.
[17] A. Mohammed, A. Kapri, R. Goel, Biomanagement of Metal-Contaminated Soils, Environmental Pollution. Springer, Netherlands (online), 2011.
[18] A. Goshadrou, A. Moheb, Continuous fixed bed adsorption of CI acid blue 92 by exfoliated graphite: an experimental and modeling study, Desalination 269 (2011) 170–176.

[19] G. Jalal, N. Abbas, F. Deeba, T. Butt, S. Jilal, S. Sarfraz, Efficient removal of dyes in textile effluents using aluminum-based coagulants, Chem. Int. 7 (2021) 197–207.
[20] K.M. Elsherif, A. El-Dali, A.A. Alkarewi, A. Mabrok, Adsorption of crystal violet dye onto olive leaves powder: equilibrium and kinetic studies, Chem. Int. 7 (2021) 79–89.
[21] A. Chham, E. Khouya, M. Oumam, A. Abourriche, S. Gmouh, S. Mansouri, N. Elhammoudi, N. Hanafi, H. Hannache, The use of insoluble mater of moroccan oil shale for removal of dyes from aqueous solution, Chem. Int. 4 (2018) 67–77.
[22] M.A. Jamal, M. Muneer, M. Iqbal, Photo-degradation of monoazo dye blue 13 using advanced oxidation process, Chem. Int. 1 (2015) 12–16.
[23] R. Mia, M. Selim, A. Shamim, M. Chowdhury, S. Sultana, M. Armin, M. Hossain, R. Akter, S. Dey, H. Naznin, Review on various types of pollution problem in textile dyeing & printing industries of Bangladesh and recommandation for mitigation, Journal of Textile Engineering & Fashion Technology 5 (2019) 220–226.
[24] J. Briffa, E. Sinagra, R. Blundell, Heavy metal pollution in the environment and their toxicological effects on humans, Heliyon 6 (2020), e04691.
[25] I. Anastopoulos, A. Mittal, M. Usman, J. Mittal, G. Yu, A. Núñez-Delgado, M. Kornaros, A review on halloysite-based adsorbents to remove pollutants in water and wastewater, J. Mol. Liq. 269 (2018) 855–868.
[26] M. Zaynab, R. Al-Yahyai, A. Ameen, Y. Sharif, L. Ali, M. Fatima, K.A. Khan, S. Li, Health and environmental effects of heavy metals, Journal of King Saud University-Science 34 (2022), 101653.
[27] C.H. Walker, R. Sibly, D.B. Peakall, Principles of ecotoxicology, CRC Press2005.
[28] P. Chhonkar, S. Datta, H. Joshi, H. Pathak, Impact of industrial effluents on soil health and agriculture-Indian experience: Part I-Distillery and paper mill effluents, 2000.
[29] G. Nagda, A. Diwan, V. Ghole, Seed germination bioassays to assess toxicity of molasses fermentation based bulk drug industry effluent, electronic journal of environmental, agricultural and food, Chemistry 5 (2006) 1598–1603.
[30] S. Ramana, A. Biswas, S. Kundu, J. Saha, R. Yadava, Effect of distillery effluent on seed germination in some vegetable crops, Bioresour. Technol. 82 (2002) 273–275.
[31] S. Nosheen, H. Nawaz, K.-U. Rehman, Physicochemical characterization of effluents of local textile industries of Faisalabad-Pakistan, Int. J. Agric. Biol. 2 (2000) 232–233.
[32] S. Imtiazuddin, M. Mumtaz, K.A. Mallick, Pollutants of wastewater characteristics in textile industries, J Basic App Sci 8 (2012) 554–556.
[33] A.M. Awwad, M.A. Amer, Adsorption of Pb(II), Cd(II), and Cu(II) ions onto SiO2/kaolinite/Fe2O3 composites: modeling and thermodynamics properties, Chem. Int. 8 (2022) 95–100.
[34] C.P. Ukpaka, B.T.X. Degradation, The concept of microbial integration, Chem. Int. 3 (2017) 8–18.
[35] C. Ukpaka, E. Wami, Degradation biokinetics of used and fresh lube oils in contaminated soil environment, Chem. Int. 3 (2017) 494–507.
[36] F. Minas, B.S. Chandravanshi, S. Leta, Chemical precipitation method for chromium removal and its recovery from tannery wastewater in Ethiopia, Chem. Int. 3 (2017) 392–405.
[37] K. Djehaf, A.Z. Bouyakoub, R. Ouhib, H. Benmansour, A. Bentouaf, A. Mahdad, N. Moulay, D. Bensaid, M. Ameri, Textile wastewater in Tlemcen (Western Algeria): impact, treatment by combined process, Chem. Int. 3 (2017) 414–419.
[38] K.B. Daij, S. Bellebia, Z. Bengharez, Comparative experimental study on the COD removal in aqueous solution of pesticides by the electrocoagulation process using monopolar iron electrodes, Chem. Int. 3 (2017) 420–427.
[39] K. Legrouri, E. Khouya, H. Hannache, M. El Hartti, M. Ezzine, R. Naslain, Activated carbon from molasses efficiency for cr (VI), pb (II) and cu (II) adsorption: a mechanistic study, Chem. Int. 3 (2017) 301–310.
[40] M. Iqbal, R.A. Khera, Adsorption of copper and lead in single and binary metal system onto Fumaria indica biomass, Chem. Int. 1 (2015) 157b–163b.
[41] M.A.M. Salleh, D.K. Mahmoud, W.A.W.A. Karim, A. Idris, Cationic and anionic dye adsorption by agricultural solid wastes: a comprehensive review, Desalination 280 (2011) 1–13.
[42] A.M. Awwad, M.W. Shammout, M.W. Amer, Fe(OH)3/kaolinite nanoplatelets: equilibrium and thermodynamic studies for the adsorption of pb (II) ions from aqueous solution, Chem. Int. 7 (2021) 90–102.
[43] A.M. Awwad, M.W. Amer, M.M. Al-Aqarbeh, TiO2-kaolinite nanocomposite prepared from the jordanian kaolin clay: adsorption and thermodynamic of Pb(II) and Cd(II) ions in aqueous solution, Chem. Int. 6 (2020) 168–178.
[44] A.M. Alkherraz, A.K. Ali, K.M. Elsherif, Removal of pb (II), zn (II), cu (II) and cd (II) from aqueous solutions by adsorption onto olive branches activated carbon: equilibrium and thermodynamic studies, Chem. Int. 6 (2020) 11–20.
[45] M. Alaqarbeh, M. Shammout, A. Awwad, Nano platelets kaolinite for the adsorption of toxic metal ions in the environment, Chem. Int. 6 (2020) 49–55.
[46] E.C. Jennifer, O.P. Ifedi, Modification of natural bentonite clay using cetyl trimetyl-ammonium bromide and its adsorption capability on some petrochemical wastes, Chem. Int. 5 (2019) 269–273.
[47] K. Shen, M. Gondal, Removal of hazardous rhodamine dye from water by adsorption onto exhausted coffee ground, J. Saudi Chem. Soc. 21 (2017) S120–S127.
[48] S. Dutta, B. Gupta, S.K. Srivastava, A.K. Gupta, Recent advances on the removal of dyes from wastewater using various adsorbents: a critical review, Materials Advances, 2021.
[49] A.M. Awwad, N.M. Salem, M.W. Amer, M.W. Shammout, Adsorptive removal of pb (II) and cd (II) ions from aqueous solution onto modified hiswa iron-kaolin clay: equilibrium and thermodynamic aspects, Chem. Int. 7 (2021) 139–144.
[50] M. Fazal-ur-Rehman, Current scenario and future prospects of activated carbon preparation from agro-industrial wastes: a review, Chem. Int. 4 (2018) 109–119.
[51] S. Jafarinejad, Activated sludge combined with powdered activated carbon (PACT process) for the petroleum industry wastewater treatment: a review, Chem. Int. 3 (2017) 368–377.
[52] E. Menya, P. Olupot, H. Storz, M. Lubwama, Y. Kiros, Production and performance of activated carbon from rice husks for removal of natural organic matter from water: a review, Chem. Eng. Res. Des. 129 (2018) 271–296.
[53] S. De Gisi, G. Lofrano, M. Grassi, M. Notarnicola, Characteristics and adsorption capacities of low-cost sorbents for wastewater treatment: a review, sustainable, Mater. Technol. 9 (2016) 10–40.
[54] Y. Guan, H.-Y. Yu, S.Y.H. Abdalkarim, C. Wang, F. Tang, J. Marek, W.-L. Chen, J. Militky, J.-M. Yao, Green one-step synthesis of ZnO/cellulose nanocrystal hybrids with modulated morphologies and superfast absorption of cationic dyes, Int. J. Biol. Macromol. 132 (2019) 51–62.
[55] C. Anushree, J. Philip, Efficient removal of methylene blue dye using cellulose capped Fe3O4 nanofluids prepared using oxidation-precipitation method, Colloids Surf. A Physicochem. Eng. Asp. 567 (2019) 193–204.
[56] N.J. Vickers, Animal communication: when i'm calling you, will you answer too? Curr. Biol. 27 (2017) R713–R715.
[57] R. Kausar, Methylene blue adsorption isotherm on spirulina sp. Microalgae biomass coated by silica-magnetite, in: IOP Conference Series: Materials Science and Engineering, IOP Publishing, 2020, p. 012019.
[58] N. Hasyimah, G. Furusawa, A. Amirul, Biosorption of a dye and heavy metals using dead cells of filamentous bacterium, aureispira sp. CCB-QB1, Int. J. Environ. Sci. Technol. 18 (2021) 1627–1636.
[59] T. Shahnaz, V. Padmanaban, S. Narayanasamy, Surface modification of nanocellulose using polypyrrole for the adsorptive removal of Congo red dye and chromium in binary mixture, Int. J. Biol. Macromol. 151 (2020) 322–332.
[60] A. Aichour, H. Zaghouane-Boudiaf, Single and competitive adsorption studies of two cationic dyes from aqueous mediums onto cellulose-based modified citrus peels/calcium alginate composite, Int. J. Biol. Macromol. 154 (2020) 1227–1236.
[61] Y. Pan, X. Shi, P. Cai, T. Guo, Z. Tong, H. Xiao, Dye removal from single and binary systems using gel-like bioadsorbent based on functional-modified cellulose, Cellulose 25 (2018) 2559–2575.
[62] M. Tsegaye, B.S. Chandravanshi, S. Feleke, M. Redi-Abshiro, Enhanced cellulose efficiency of pressurized hot water pretreated highland ethiopian bamboo (Yushania alpina): a potential feedstock for ethanol production, Chem. Int. 7 (2021) 53–61.
[63] A.A. Sundarraj, T.V. Ranganathan, A review on cellulose and its utilization from agro-industrial waste, Drug Invent. Today 10 (2018) 89–94.
[64] D.W. O'Connell, C. Birkinshaw, T.F. O'Dwyer, Heavy metal adsorbents prepared from the modification of cellulose: a review, Bioresour. Technol. 99 (2008) 6709–6724.
[65] D. Klemm, Comprehensive cellulose chemistry, Wiley-Vch1998.
[66] V. Kocherbitov, S. Ulvenlund, M. Kober, K. Jarring, T. Arnebrant, Hydration of microcrystalline cellulose and milled cellulose studied by sorption calorimetry, J. Phys. Chem. B 112 (2008) 3728–3734.
[67] M. Zirak, A. Abdollahiyan, B. Eftekhari-Sis, M. Saraei, Carboxymethyl cellulose coated Fe3O4@ SiO2 core–shell magnetic nanoparticles for methylene blue removal: equilibrium, kinetic, and thermodynamic studies, Cellulose 25 (2018) 503–515.
[68] M.S. Hasanin, A.H. Hashem, A. El-Sayed, S. Essam, H. El-Saied, Green ecofriendly bio-deinking of mixed office waste paper using various enzymes from rhizopus microsporus AH3: efficiency and characteristics, Cellulose 27 (2020) 4443–4453.
[69] G. Crini, Non-conventional low-cost adsorbents for dye removal: a review, Bioresour. Technol. 97 (2006) 1061–1085.
[70] H.J. Koslowski, R. Bauer, Dictionary of man-made fibers: terms, figures, trademarks, International Business Press, 1998.
[71] D. Hon, Cellulose and its Derivatives, Polysaccharides in medicinal applications. Marcel Dekker, New York, 1996.
[72] I. Siró, D. Plackett, Microfibrillated cellulose and new nanocomposite materials: a review, Cellulose 17 (2010) 459–494.
[73] A. Jamshaid, A. Hamid, N. Muhammad, A. Naseer, M. Ghauri, J. Iqbal, S. Rafiq, N.S. Shah, Cellulose-based materials for the removal of heavy metals from Wastewater–An overview, ChemBioEng Reviews 4 (2017) 240–256.
[74] F. Martí-Ferrer, F. Vilaplana, A. Ribes-Greus, A. Benedito-Borrás, C. Sanz-Box, Flour rice husk as filler in block copolymer polypropylene: effect of different coupling agents, J. Appl. Polym. Sci. 99 (2006) 1823–1831.
[75] W.G. Trindade, W. Hoareau, I.A. Razera, R. Ruggiero, E. Frollini, A. Castellan, Phenolic thermoset matrix reinforced with sugar cane bagasse fibers: attempt to develop a new fiber surface chemical modification involving formation of quinones followed by reaction with furfuryl alcohol, Macromol. Mater. Eng. 289 (2004) 728–736.
[76] S. Bano, Y.S. Negi, Studies on cellulose nanocrystals isolated from groundnut shells, Carbohydr. Polym. 157 (2017) 1041–1049.
[77] J.-W. Rhim, J.P. Reddy, X. Luo, Isolation of cellulose nanocrystals from onion skin and their utilization for the preparation of agar-based bio-nanocomposites films, Cellulose 22 (2015) 407–420.
[78] R. Li, J. Fei, Y. Cai, Y. Li, J. Feng, J. Yao, Cellulose whiskers extracted from mulberry: a novel biomass production, Carbohydr. Polym. 76 (2009) 94–99.
[79] A.K. Mohanty, M. Misra, L.T. Drzal, Natural fibers, biopolymers, and biocomposites, CRC Press2005.
[80] F. Kallel, F. Bettaieb, R. Khiari, A. García, J. Bras, S.E. Chaabouni, Isolation and structural characterization of cellulose nanocrystals extracted from garlic straw residues, Ind. Crop. Prod. 87 (2016) 287–296.

[81] S. Malherbe, T.E. Cloete, Lignocellulose biodegradation: fundamentals and applications, Rev. Environ. Sci. Biotechnol. 1 (2002) 105–114.
[82] R. Howard, E. Abotsi, E.J. Van Rensburg, S. Howard, Lignocellulose biotechnology: issues of bioconversion and enzyme production, Afr. J. Biotechnol. 2 (2003) 602–619.
[83] S. Prasad, A. Singh, H. Joshi, Ethanol as an alternative fuel from agricultural, industrial and urban residues, Resour. Conserv. Recycl. 50 (2007) 1–39.
[84] J. Guimarães, E. Frollini, C. Da Silva, F. Wypych, K. Satyanarayana, Characterization of banana, sugarcane bagasse and sponge gourd fibers of Brazil, Ind. Crop. Prod. 30 (2009) 407–415.
[85] W.M.A.W. Daud, W.S.W. Ali, Comparison on pore development of activated carbon produced from palm shell and coconut shell, Bioresour. Technol. 93 (2004) 63–69.
[86] T.N. Chikwe, R.E. Ekpo, I. Okoye, Competitive adsorption of organic solvents using modified and unmodified calcium bentonite clay mineral, Chem. Int. 4 (2018) 230–239.
[87] K. Low, C. Lee, S. Mak, Sorption of copper and lead by citric acid modified wood, Wood Sci. Technol. 38 (2004) 629–640.
[88] M. Geay, V. Marchetti, A. Clément, B. Loubinoux, P. Gérardin, Decontamination of synthetic solutions containing heavy metals using chemically modified sawdusts bearing polyacrylic acid chains, J. Wood Sci. 46 (2000) 331–333.
[89] C.-H. Zhou, D. Zhang, D.-S. Tong, L.-M. Wu, W.-H. Yu, S. Ismadji, Like composites of cellulose acetate–organo-montmorillonite for removal of hazardous anionic dye in water, Chem. Eng. J. 209 (2012) 223–234.
[90] W.W. Ngah, M.M. Hanafiah, Removal of heavy metal ions from wastewater by chemically modified plant wastes as adsorbents: a review, Bioresour. Technol. 99 (2008) 3935–3948.
[91] B. Belhalfaoui, A. Aziz, E.H. Elandaloussi, M.S. Ouali, L.C. De Ménorval, Succinate-bonded cellulose: a regenerable and powerful sorbent for cadmium-removal from spiked high-hardness groundwater, J. Hazard. Mater. 169 (2009) 831–837.
[92] B. Pangeni, H. Paudyal, K. Inoue, H. Kawakita, K. Ohto, S. Alam, Selective recovery of gold (III) using cotton cellulose treated with concentrated sulfuric acid, Cellulose 19 (2012) 381–391.
[93] L.V.A. Gurgel, O.K. Junior, R.P. de Freitas Gil, L.F. Gil, Adsorption of Cu (II), Cd (II), and Pb (II), From aqueous single metal solutions by cellulose and mercerized cellulose chemically modified with succinic anhydride, Bioresource technology 99 (2008) 3077–3083.
[94] A. Abdelkhalek, S.S. Ali, Z. Sheng, L. Zheng, M. Hasanin, Lead removal from aqueous solution by green solid film based on cellulosic fiber extracted from Banana tree doped in polyacrylamide, Fibers and Polymers (2022) 1–11.
[95] T. Tashiro, Y. Shimura, Removal of mercuric ions by systems based on cellulose derivatives, J. Appl. Polym. Sci. 27 (1982) 747–756.
[96] N. Aoki, K. Fukushima, H. Kurakata, M. Sakamoto, K.-I. Furuhata, 6-Deoxy-6-mercaptocellulose and its S-substituted derivatives as sorbents for metal ions, React. Funct. Polym. 42 (1999) 223–233.
[97] A.M. Donia, A.M. Yousif, A.A. Atia, H.M. Abd El-Latif, Preparation and characterization of modified cellulose adsorbents with high surface area and high adsorption affinity for hg (II), J. Dispers. Sci. Technol. 35 (2014) 380–389.
[98] E. Maekawa, T. Koshijima, Properties of 2, 3-dicarboxy cellulose combined with various metallic ions, J. Appl. Polym. Sci. 29 (1984) 2289–2297.
[99] E. Maekawa, T. Koshijima, Preparation and characterization of hydroxamic acid derivative and its metal complexes derived from cellulose, J. Appl. Polym. Sci. 40 (1990) 1601–1613.
[100] H.A. Rutherford, F.W. Minor, A.R. Martin, M. Harris, Oxidation of cellulose: the reaction of cellulose with periodic acid, J. of res. of the NBS 29 (1942) 131–143.
[101] M. Foglarova, J. Prokop, M. Milichovsky, Oxidized cellulose: an application in the form of sorption filter materials, J. Appl. Polym. Sci. 112 (2009) 669–678.
[102] R. Batmaz, N. Mohammed, M. Zaman, G. Minhas, R.M. Berry, K.C. Tam, Cellulose nanocrystals as promising adsorbents for the removal of cationic dyes, Cellulose 21 (2014) 1655–1665.
[103] R.R. Navarro, K. Sumi, N. Fujii, M. Matsumura, Mercury removal from wastewater using porous cellulose carrier modified with polyethyleneimine, Water Res. 30 (1996) 2488–2494.
[104] R. Saliba, H. Gauthier, R. Gauthier, M. Petit-Ramel, Adsorption of copper (II) and chromium (III) ions onto amidoximated cellulose, J. Appl. Polym. Sci. 75 (2000) 1624–1631.
[105] N.A. Ibrahim, F.H. Abdellatif, M.S. Hasanin, M.M. Abdellatif, Fabrication, characterization, and potential application of modified sawdust sorbents for efficient removal of heavy metal ions and anionic dye from aqueous solutions, J. Clean. Prod. 332 (2022), 130021.
[106] M.M. Nasef, E.-S.A. Hegazy, Preparation and applications of ion exchange membranes by radiation-induced graft copolymerization of polar monomers onto non-polar films, Prog. Polym. Sci. 29 (2004) 499–561.
[107] A. Bhattacharya, B. Misra, Grafting: a versatile means to modify polymers: techniques, factors and applications, Prog. Polym. Sci. 29 (2004) 767–814.
[108] G. Gürdağ, M. Yaşar, M.A. Gürkaynak, Graft copolymerization of acrylic acid on cellulose: reaction kinetics of copolymerization, J. Appl. Polym. Sci. 66 (1997) 929–934.
[109] U.S. Orlando, A.U. Baes, W. Nishijima, M. Okada, Preparation of chelating agents from sugarcane bagasse by microwave radiation as an alternative ecologically benign procedure, Green Chem. 4 (2002) 555–557.
[110] T. Hajeeth, K. Vijayalakshmi, T. Gomathi, P. Sudha, Removal of cu (II) and ni (II) using cellulose extracted from sisal fiber and cellulose-g-acrylic acid copolymer, Int. J. Biol. Macromol. 62 (2013) 59–65.
[111] M. Gurung, B.B. Adhikari, X. Gao, S. Alam, K. Inoue, Sustainability in the metallurgical industry: chemically modified cellulose for selective biosorption of gold from mixtures of base metals in chloride media, Ind. Eng. Chem. Res. 53 (2014) 8565–8576.
[112] Y. Zhou, Q. Jin, T. Zhu, Q. Zhang, T. Ma, Separation of chromium (VI) from aqueous solutions by cellulose modified with D-glucose and quaternary ammonium groups, Cellul. Chem. Technol. 46 (2012) 319.
[113] S. Hokkanen, E. Repo, T. Suopajärvi, H. Liimatainen, J. Niinimaa, M. Sillanpää, Adsorption of ni (II), cu (II) and cd (II) from aqueous solutions by amino modified nanostructured microfibrillated cellulose, Cellulose 21 (2014) 1471–1487.
[114] S.Q. Memon, N. Memon, S.W. Shah, M. Khuhawar, M. Bhanger, Sawdust—A green and economical sorbent for the removal of cadmium (II) ions, J. Hazard. Mater. 139 (2007) 116–121.
[115] Y. Zhou, Q. Jin, X. Hu, Q. Zhang, T. Ma, Heavy metal ions and organic dyes removal from water by cellulose modified with maleic anhydride, J. Mater. Sci. 47 (2012) 5019–5029.
[116] A.K. Meena, K. Kadirvelu, G. Mishra, C. Rajagopal, P. Nagar, Adsorptive removal of heavy metals from aqueous solution by treated sawdust (Acacia arabica), J. Hazard. Mater. 150 (2008) 604–611.
[117] S. Çavuş, G. Gürdağ, M. Yaşar, K. Güçlü, M.A. Gürkaynak, The competitive heavy metal removal by hydroxyethyl cellulose-g-poly (acrylic acid) copolymer and its sodium salt: the effect of copper content on the adsorption capacity, Polym. Bull. 57 (2006) 445–456.
[118] S. Shukla, R.S. Pai, Adsorption of cu (II), ni (II) and zn (II) on modified jute fibres, Bioresour. Technol. 96 (2005) 1430–1438.
[119] B.C. Melo, F.A. Paulino, V.A. Cardoso, A.G. Pereira, A.R. Fajardo, F.H. Rodrigues, Cellulose nanowhiskers improve the methylene blue adsorption capacity of chitosan-g-poly (acrylic acid) hydrogel, Carbohydr. Polym. 181 (2018) 358–367.
[120] H.N. Bhatti, Y. Safa, S.M. Yakout, O.H. Shair, M. Iqbal, A. Nazir, Efficient removal of dyes using carboxymethyl cellulose/alginate/polyvinyl alcohol/rice husk composite: adsorption/desorption, kinetics and recycling studies, Int. J. Biol. Macromol. 150 (2020) 861–870.
[121] A. Kausar, R. Shahzad, J. Iqbal, N. Muhammad, S.M. Ibrahim, M. Iqbal, Development of new organic-inorganic, hybrid bionanocomposite from cellulose and clay for enhanced removal of drimarine yellow HF-3GL dye, Int. J. Biol. Macromol. 149 (2020) 1059–1071.
[122] Z. Yu, C. Hu, A.B. Dichiara, W. Jiang, J. Gu, Cellulose nanofibril/carbon nanomaterial hybrid aerogels for adsorption removal of cationic and anionic organic dyes, Nanomaterials 10 (2020) 169.
[123] M. Ma, Z. Liu, L. Hui, Z. Shang, S. Yuan, L. Dai, P. Liu, X. Liu, Y. Ni, Lignin-containing cellulose nanocrystals/sodium alginate beads as highly effective adsorbents for cationic organic dyes, Int. J. Biol. Macromol. 139 (2019) 640–646.
[124] S.P. Santoso, A. Kurniawan, F.E. Soetaredjo, K.-C. Cheng, J.N. Putro, S. Ismadji, Y.-H. Ju, Eco-friendly cellulose–bentonite porous composite hydrogels for adsorptive removal of azo dye and soilless culture, Cellulose 26 (2019) 3339–3358.
[125] X. Yue, J. Huang, F. Jiang, H. Lin, Y. Chen, Synthesis and characterization of cellulose-based adsorbent for removal of anionic and cationic dyes, Journal of Engineered Fibers and Fabrics 14 (2019), 1558925019828194.
[126] A. ZabihiSahebi, S. Koushkbaghi, M. Pishnamazi, A. Askari, R. Khosravi, M. Irani, Synthesis of cellulose acetate/chitosan/SWCNT/Fe3O4/TiO2 composite nanofibers for the removal of cr (VI), as (V), methylene blue and Congo red from aqueous solutions, Int. J. Biol. Macromol. 140 (2019) 1296–1304.
[127] D.S. Tong, C.W. Wu, M.O. Adebajo, G.C. Jin, W.H. Yu, S.F. Ji, C.H. Zhou, Adsorption of methylene blue from aqueous solution onto porous cellulose-derived carbon/montmorillonite nanocomposites, Appl. Clay Sci. 161 (2018) 256–264.
[128] R.M. Abdelhameed, M. Hasanin, H. Abdel-Gawad, B. Hegazi, Engineering ZIF-8 hybridization by extracted lignin with antibacterial property for uptake of methomyl residues from wastewater, Sep. Sci. Technol. (2022) 1–12.
[129] H. Dai, Y. Huang, Y. Zhang, H. Zhang, H. Huang, Green and facile fabrication of pineapple peel cellulose/magnetic diatomite hydrogels in ionic liquid for methylene blue adsorption, Cellulose 26 (2019) 3825–3844.
[130] J.N. Putro, S.P. Santoso, F.E. Soetaredjo, S. Ismadji, Y.-H. Ju, Nanocrystalline cellulose from waste paper: adsorbent for azo dyes removal, Environmental Nanotechnology, Monitoring & Management 12 (2019), 100260.
[131] Y. Li, X. Hou, Y. Pan, L. Wang, H. Xiao, Redox-responsive carboxymethyl cellulose hydrogel for adsorption and controlled release of dye, Eur. Polym. J. 123 (2020), 109447.
[132] N. Somsesta, V. Sricharoenchaikul, D. Aht-Ong, Adsorption removal of methylene blue onto activated carbon/cellulose biocomposite films: equilibrium and kinetic studies, Mater. Chem. Phys. 240 (2020), 122221.
[133] Y. Pan, H. Xie, H. Liu, P. Cai, H. Xiao, Novel cellulose/montmorillonite mesoporous composite beads for dye removal in single and binary systems, Bioresour. Technol. 286 (2019), 121366.
[134] T.C. Andrade Siqueira, I. Zanette da Silva, A.J. Rubio, R. Bergamasco, F. Gasparotto, E.Aparecida de Souza Paccola, N.Ueda Yamaguchi, Sugarcane bagasse as an efficient biosorbent for methylene blue removal: kinetics, isotherms and thermodynamics, Int. J. Environ. Res. Public Health 17 (2020) 526.
[135] Q. Manzoor, A. Sajid, T. Hussain, M. Iqbal, M. Abbas, J. Nisar, Efficiency of immobilized zea mays biomass for the adsorption of chromium from simulated media and tannery wastewater, Journal of Materials Research and Technology 8 (2019) 75–86.
[136] H. Hosseini, A. Zirakjou, D.J. McClements, V. Goodarzi, W.-H. Chen, Removal of methylene blue from wastewater using ternary nanocomposite aerogel systems:

carboxymethyl cellulose grafted by polyacrylic acid and decorated with graphene oxide, J. Hazard. Mater. 421 (2022), 126752.
[137] A. Leshaf, H. Ziani Cherif, K. Benmansour, Adsorption of acidol red 2BE-NW dye from aqueous solutions on carboxymethyl cellulose/organo-bentonite composite: characterization, kinetic and thermodynamic studies, J. Polym. Environ. 27 (2019) 1054–1064.
[138] Q. Wang, Y. Wang, L. Chen, A green composite hydrogel based on cellulose and clay as efficient absorbent of colored organic effluent, Carbohydr. Polym. 210 (2019) 314–321.
[139] M.S. Shamsudin, S.F. Azha, M. Shahadat, S. Ismail, Cellulose/bentonite-zeolite composite adsorbent material coating for treatment of N-based antiseptic cationic dye from water, Journal of Water Process Engineering 29 (2019), 100764.
[140] M. Goswami, A.M. Das, Synthesis and characterization of a biodegradable cellulose acetate-montmorillonite composite for effective adsorption of eosin Y, Carbohydr. Polym. 206 (2019) 863–872.
[141] M. Rethinasabapathy, S.-M. Kang, I. Lee, G.-W. Lee, S.K. Hwang, C. Roh, Y.S. Huh, Layer-structured POSS-modified fe-aminoclay/carboxymethyl cellulose composite as a superior adsorbent for the removal of radioactive cesium and cationic dyes, Ind. Eng. Chem. Res. 57 (2018) 13731–13741.
[142] R. Sabarish, G. Unnikrishnan, Polyvinyl alcohol/carboxymethyl cellulose/ZSM-5 zeolite biocomposite membranes for dye adsorption applications, Carbohydr. Polym. 199 (2018) 129–140.
[143] R. Kumar, R.K. Sharma, A.P. Singh, Removal of organic dyes and metal ions by cross-linked graft copolymers of cellulose obtained from the agricultural residue, Journal of environmental chemical engineering 6 (2018) 6037–6048.
[144] M.S. Hasanin, Sustainable hybrid silica extracted from rice husk with polyvinyl alcohol and nicotinic acid as multi adsorbent for textile wastewater treatment, Environ. Sci. Pollut. Res. 27 (2020) 26742–26749.
[145] A. Salama, S. Etri, S.A. Mohamed, M. El-Sakhawy, Carboxymethyl cellulose prepared from mesquite tree: new source for promising nanocomposite materials, Carbohydr. Polym. 189 (2018) 138–144.
[146] Y. Li, H. Xiao, Y. Pan, L. Wang, Novel composite adsorbent consisting of dissolved cellulose fiber/microfibrillated cellulose for dye removal from aqueous solution, ACS Sustain. Chem. Eng. 6 (2018) 6994–7002.
[147] L. Meili, P. Lins, M. Costa, R. Almeida, A. Abud, J. Soletti, G. Dotto, E. Tanabe, L. Sellaoui, S. Carvalho, Adsorption of methylene blue on agroindustrial wastes: experimental investigation and phenomenological modelling, Prog. Biophys. Mol. Biol. 141 (2019) 60–71.
[148] R.A. Fideles, G.M.D. Ferreira, F.S. Teodoro, O.F.H. Adarme, L.H.M. da Silva, L. F. Gil, L.V.A. Gurgel, Trimellitated sugarcane bagasse: a versatile adsorbent for removal of cationic dyes from aqueous solution, Part I: Batch adsorption in a monocomponent system, Journal of colloid and interface science 515 (2018) 172–188.
[149] M. Zhang, Y. Li, Q. Yang, L. Huang, L. Chen, H. Xiao, Adsorption of methyl violet using pH-and temperature-sensitive cellulose filament/poly (NIPAM-co-AAc) hybrid hydrogels, J. Mater. Sci. 53 (2018) 11837–11854.
[150] J. Cai, M. Lei, Q. Zhang, J.-R. He, T. Chen, S. Liu, S.-H. Fu, T.-T. Li, G. Liu, P. Fei, Electrospun composite nanofiber mats of Cellulose@ organically modified montmorillonite for heavy metal ion removal: design, characterization, evaluation of absorption performance, Compos. A: Appl. Sci. Manuf. 92 (2017) 10–16.
[151] J. Zhao, Z. Lu, X. He, X. Zhang, Q. Li, T. Xia, W. Zhang, C. Lu, Fabrication and characterization of highly porous fe (OH) 3@ cellulose hybrid fibers for effective removal of Congo red from contaminated water, ACS Sustain. Chem. Eng. 5 (2017) 7723–7732.
[152] F. Jiang, D.M. Dinh, Y.-L. Hsieh, Adsorption and desorption of cationic malachite green dye on cellulose nanofibril aerogels, Carbohydr. Polym. 173 (2017) 286–294.
[153] W. Li, P. Zuo, D. Xu, Y. Xu, K. Wang, Y. Bai, H. Ma, Tunable adsorption properties of bentonite/carboxymethyl cellulose-g-poly (2-(dimethylamino) ethyl methacrylate) composites toward anionic dyes, Chem. Eng. Res. Des. 124 (2017) 260–270.
[154] F.S. Teodoro, M.M.C. Elias, G.M.D. Ferreira, O.F.H. Adarme, R.M.L. Savedra, M. F. Siqueira, L.H.M. da Silva, L.F. Gil, L.V.A. Gurgel, Synthesis and application of a new carboxylated cellulose derivative, Part III: Removal of auramine-O and safranin-T from mono-and bi-component spiked aqueous solutions, Journal of colloid and interface science 512 (2018) 575–590.
[155] N. Peng, D. Hu, J. Zeng, Y. Li, L. Liang, C. Chang, Superabsorbent cellulose–clay nanocomposite hydrogels for highly efficient removal of dye in water, ACS Sustain. Chem. Eng. 4 (2016) 7217–7224.
[156] P.L. Hariani, F. Riyanti, R.D. Asmara, Extraction of cellulose from kepok banana peel (Musa parasidiaca L.) for adsorption procion dye, Molekul 11 (2016) 135–142.
[157] N. Ben Douissa, S. Dridi-Dhaouadi, M.F. Mhenni, in: Spectrophotometric investigation of the interactions between cationic (CI Basic Blue 9) and anionic (CI Acid Blue 25) dyes in adsorption onto extracted cellulose from Posidonia oceanic in single and binary system, 73, Water Science and Technology, 2016, pp. 2211–2221.
[158] L. Liu, Z.Y. Gao, X.P. Su, X. Chen, L. Jiang, J.M. Yao, Adsorption removal of dyes from single and binary solutions using a cellulose-based bioadsorbent, ACS Sustain. Chem. Eng. 3 (2015) 432–442.
[159] N. Mohammed, N. Grishkewich, R.M. Berry, K.C. Tam, Cellulose nanocrystal–alginate hydrogel beads as novel adsorbents for organic dyes in aqueous solutions, Cellulose 22 (2015) 3725–3738.
[160] L. Jin, W. Li, Q. Xu, Q. Sun, Amino-functionalized nanocrystalline cellulose as an adsorbent for anionic dyes, Cellulose 22 (2015) 2443–2456.
[161] S.F. Azha, M. Shahadat, S. Ismail, Acrylic polymer emulsion supported bentonite clay coating for the analysis of industrial dye, Dyes Pigments 145 (2017) 550–560.
[162] H. Shi, W. Li, L. Zhong, C. Xu, Methylene blue adsorption from aqueous solution by magnetic cellulose/graphene oxide composite: equilibrium, kinetics, and thermodynamics, Ind. Eng. Chem. Res. 53 (2014) 1108–1118.
[163] G. Zhang, L. Yi, H. Deng, P. Sun, Dyes adsorption using a synthetic carboxymethyl cellulose-acrylic acid adsorbent, J. Environ. Sci. 26 (2014) 1203–1211.
[164] C. Zhou, Q. Wu, T. Lei, I.I. Negulescu, Adsorption kinetic and equilibrium studies for methylene blue dye by partially hydrolyzed polyacrylamide/cellulose nanocrystal nanocomposite hydrogels, Chem. Eng. J. 251 (2014) 17–24.
[165] E. Karadağ, A. Nalbantoğlu, S. Kundakcı, Ö.B. Üzüm, Highly swollen polymer/clay composite sorbent-based AAm/AMPS hydrogels and semi-IPNs composed of carboxymethyl cellulose and montmorillonite and cross-linked by PEGDA, Polym.-Plast. Technol. Eng. 53 (2014) 54–64.
[166] V. Janaki, K. Vijayaraghavan, B.-T. Oh, A. Ramasamy, S. Kamala-Kannan, Synthesis, characterization and application of cellulose/polyaniline nanocomposite for the treatment of simulated textile effluent, Cellulose 20 (2013) 1153–1166.
[167] Y. Zhou, M. Zhang, X. Hu, X. Wang, J. Niu, T. Ma, Adsorption of cationic dyes on a cellulose-based multicarboxyl adsorbent, J. Chem. Eng. Data 58 (2013) 413–421.
[168] M.-M. Wang, L. Wang, Synthesis and characterization of carboxymethyl cellulose/organic montmorillonite nanocomposites and its adsorption behavior for Congo red dye, Water Science and Engineering 6 (2013) 272–282.
[169] Y. Shi, Z. Xue, X. Wang, L. Wang, A. Wang, Removal of methylene blue from aqueous solution by sorption on lignocellulose-g-poly (acrylic acid)/montmorillonite three-dimensional cross-linked polymeric network hydrogels, Polym. Bull. 70 (2013) 1163–1179.
[170] T. Bunhu, L. Tichagwa, Adsorption of Methyl Orange, Pb2þ and Cd2þ from Aqueous Solution by Composites of Lignocellulose-Montmorillonite Modified with Methacryloxypropyl Trimethoxysilane, 2012.
[171] Y. Zhao, Z. Xue, X. Wang, L. Wang, A. Wang, Adsorption of Congo red onto lignocellulose/montmorillonite nanocomposite, journal of Wuhan University of Technology-mater, Sci. Ed. 27 (2012) 931–938.
[172] H.-Y. Zhu, Y.-Q. Fu, R. Jiang, J.-H. Jiang, L. Xiao, G.-M. Zeng, S.-L. Zhao, Y. Wang, Adsorption removal of Congo red onto magnetic cellulose/Fe3O4/activated carbon composite: equilibrium, kinetic and thermodynamic studies, Chem. Eng. J. 173 (2011) 494–502.
[173] S. Nethaji, A. Sivasamy, Adsorptive removal of an acid dye by lignocellulosic waste biomass activated carbon: equilibrium and kinetic studies, Chemosphere 82 (2011) 1367–1372.
[174] S. Dridi-Dhaouadi, N.B. Douissa-Lazreg, M.F. M'Henni, Removal of lead and yellow 44 acid dye in single and binary component systems by raw Posidonia oceanica and the cellulose extracted from the raw biomass, Environ. Technol. 32 (2011) 325–340.
[175] C. Feng, P. Ren, Z. Li, W. Tan, H. Zhang, Y. Jin, F. Ren, Graphene/waste-newspaper cellulose composite aerogels with selective adsorption of organic dyes: preparation, characterization, and adsorption mechanism, New J. Chem. 44 (2020) 2256–2267.
[176] C. Namasivayam, N. Muniasamy, K. Gayatri, M. Rani, K. Ranganathan, Removal of dyes from aqueous solutions by cellulosic waste orange peel, Bioresour. Technol. 57 (1996) 37–43.
[177] S. Banerjee, M. Chattopadhyaya, Adsorption characteristics for the removal of a toxic dye, tartrazine from aqueous solutions by a low cost agricultural by-product, Arab. J. Chem. 10 (2017) S1629–S1638.
[178] K.B. Tan, A.Z. Abdullah, B.A. Horri, B. Salamatinia, Adsorption mechanism of microcrystalline cellulose as green adsorbent for the removal of cationic methylene blue dye, J. Chem. Soc. Pak. 38 (2016).
[179] M.S. Hasanin, N. Kassem, M.L. Hassan, Preparation and characterization of microcrystalline cellulose from olive stones, Biomass Conversion and Biorefinery (2021) 1–8.
[180] A.S. Eltaweil, G.S. Elgarhy, G.M. El-Subruiti, A.M. Omer, Carboxymethyl cellulose/carboxylated graphene oxide composite microbeads for efficient adsorption of cationic methylene blue dye, Int. J. Biol. Macromol. 154 (2020) 307–318.
[181] L.S. Silva, L.C. Lima, F.J. Ferreira, M.S. Silva, J.A. Osajima, R.D. Bezerra, E. C. Silva Filho, Sorption of the anionic reactive red RB dye in cellulose: assessment of kinetic, thermodynamic, and equilibrium data, open, Chemistry 13 (2015).
[182] F. Saleem, H.N. Bhatti, A. Khan, L.B. Farhat, Z.M. Elqahtani, N. Alwadai, M. Iqbal, Polypyrrole/Magnetic/Tea waste composites for PO43− ions removal: adsorption-desorption, Kinetics, and Thermodynamics Studies, Adsorption Science & Technology 2022 (2022) 4071162.
[183] S. Noreen, U. Khalid, S.M. Ibrahim, T. Javed, A. Ghani, S. Naz, M. Iqbal, ZnO, MgO and FeO adsorption efficiencies for direct sky blue dye: equilibrium, kinetics and thermodynamics studies, J. Mater. Res. Technol. 9 (2020) 5881–5893.
[184] A.M. Alasadi, F.I. Khaili, A.M. Awwad, Adsorption of cu (II), ni (II) and zn (II) ions by nano kaolinite: thermodynamics and kinetics studies, Chem. Int. 5 (2019) 258–268.
[185] A. Babarinde, G.O. Onyiaocha, Equilibrium sorption of divalent metal ions onto groundnut (Arachis hypogaea) shell: kinetics, isotherm and thermodynamics, Chem. Int. 2 (2016) 37–46.
[186] G. Abdulraheem, S. Bala, S. Muhammad, M. Abdullahi, Kinetics, equilibrium and thermodynamics studies of CI reactive blue 19 dye adsorption on coconut shell based activated carbon, Int. Biodeterior. Biodegradation 102 (2015) 265–273.
[187] A. Babarinde, K. Ogundipe, K.T. Sangosanya, B.D. Akintola, A.-O.E. Hassan, Comparative study on the biosorption of Pb(II), Cd(II) and Zn(II) using lemon

grass (Cymbopogon citratus): kinetics, isotherms and thermodynamics, Chem. Int. 2 (2016) 89–102.
[188] I. Langmuir, The adsorption of gases on plane surfaces of glass, mica and platinum, J. Am. Chem. Soc. 40 (1918) 1361–1403.
[189] H. Freundlich, Over the adsorption in solution, J. Phys. Chem. 57 (1906) 1100–1107.
[190] K.Y. Foo, B.H. Hameed, Insights into the modeling of adsorption isotherm systems, Chem. Eng. J. 156 (2010) 2–10.
[191] A. Kausar, H.N. Bhatti, G. MacKinnon, Equilibrium, kinetic and thermodynamic studies on the removal of U (VI) by low cost agricultural waste, Colloids Surf. B: Biointerfaces 111 (2013) 124–133.
[192] M.W. Shammout, A.M. Awwad, A novel route for the synthesis of copper oxide nanoparticles using bougainvillea plant flowers extract and antifungal activity evaluation, Chem. Int. 7 (2021) 71–78.
[193] B. Buyana, B. Aderibigbe, D. Ndinteh, Y. Fonkui, P. Kumar, Alginate-pluronic topical gels loaded with thymol, norfloxacin and ZnO nanoparticles as potential wound dressings, Journal of Drug Delivery Science and Technology 60 (2020), 101960.
[194] T. Anirudhan, M. Ramachandran, Adsorptive removal of basic dyes from aqueous solutions by surfactant modified bentonite clay (organoclay): kinetic and competitive adsorption isotherm, Process Saf. Environ. Prot. 95 (2015) 215–225.
[195] V. Vimonses, B. Jin, C.W. Chow, Insight into removal kinetic and mechanisms of anionic dye by calcined clay materials and lime, J. Hazard. Mater. 177 (2010) 420–427.
[196] S.P. Santoso, L. Laysandra, J.N. Putro, J. Lie, F.E. Soetaredjo, S. Ismadji, A. Ayucitra, Y.H. Ju, Preparation of nanocrystalline cellulose-montmorillonite composite via thermal radiation for liquid-phase adsorption, J. Mol. Liq. 233 (2017) 29–37.
[197] S.F. Azha, L. Sellaoui, M.S. Shamsudin, S. Ismail, A. Bonilla-Petriciolet, A. B. Lamine, A. Erto, Synthesis and characterization of a novel amphoteric adsorbent coating for anionic and cationic dyes adsorption: experimental investigation and statistical physics modelling, Chem. Eng. J. 351 (2018) 221–229.