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Recent Advances in Cellulose-Based Adsorbents for Removal of Dyes and Heavy Metals from Wastewater

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Abstract

Water pollution caused by industrial effluents containing synthetic dyes and heavy metals remains a major environmental challenge worldwide. Industries such as textiles, mining, and electroplating release contaminants including methylene blue, methyl orange, Pb^{2+}, Cd^{2+}, and Cr^{6+} into aquatic environments, necessitating effective treatment methods. Adsorption has gained significant attention due to its simplicity, high efficiency, low cost, and environmental compatibility. Cellulose-based adsorbents are promising materials because of their abundance, renewability, biodegradability, and excellent adsorption properties. The hydroxyl groups in cellulose facilitate pollutant removal through electrostatic interactions, hydrogen bonding, and complexation. Recent advances in chemical modification, nanocellulose, hydrogels, aerogels, and magnetic cellulose composites have further enhanced adsorption performance and recovery. Despite these developments, challenges related to regeneration, mechanical stability, and large-scale application remain. Overall, cellulose-based adsorbents show strong potential as sustainable and cost-effective materials for wastewater treatment and environmental protection.

***Keywords:** Cellulose-based adsorbents; Wastewater treatment; Dye removal; Heavy metal adsorption; Nanocellulose; Adsorption mechanisms; Cellulose composites; Environmental remediation.*

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1. Introduction

Industrial activities such as textile production, mining, electroplating, and pharmaceutical manufacturing are major sources of water pollution through the discharge of dyes and heavy metals into aquatic environments (Adewuyi, 2020; Zhang *et al.,* 2021; Verma *et al.*, 2026). Rapid industrialization has increased the volume of untreated or poorly treated effluents released into water bodies. Pharmaceutical effluents often contain chemical oxygen demand (COD), biological oxygen demand (BOD), nutrients, suspended solids, and heavy metals that can adversely affect aquatic ecosystems and human health (Iloamaeke *et al.,* 2020). Many of these contaminants are toxic, persistent, and capable of bioaccumulation, creating serious environmental and public health concerns.

Synthetic dyes are among the most problematic industrial pollutants due to their widespread use and resistance to biodegradation. Methylene blue (MB), commonly used in textile, leather, and paper industries, is frequently detected in industrial wastewater (Rial *et al.,* 2024; Husaini *et al.,* 2025a). Other industries also release dyes such as methyl orange (MO), which can reduce light penetration, inhibit photosynthesis, and exhibit toxic, mutagenic, and carcinogenic effects (Latifi *et al.,* 2025). Heavy metals including lead, mercury, cadmium, and arsenic are equally hazardous because of their persistence and potential to cause neurological, renal, and developmental disorders. Although methylene blue is relatively less toxic, high concentrations may still pose risks to humans and aquatic organisms (Zhao *et al.,* 2023).

Several treatment methods, including photocatalysis, coagulation–flocculation, membrane filtration, and biological degradation, have been applied to remove dyes and heavy metals from wastewater (Husaini *et al.,* 2025b; Boukra *et al.,* 2026). However, these technologies often suffer from high costs, low efficiency at low pollutant concentrations, and secondary pollution problems (Akartasse *et al.,* 2022). Consequently, adsorption has emerged as an efficient and economical treatment technology because of its simplicity, high removal efficiency, and potential for adsorbent regeneration and reuse (Husaini *et al.,* 2025c).

Recently, cellulose-based materials derived from lignocellulosic biomass have gained considerable attention as sustainable adsorbents because of their abundance, renewability, biodegradability, and ease of modification (Husaini *et al.,* 2025d; Wang *et al.,* 2020). Advances in nanotechnology have further improved their adsorption performance by increasing surface area and porosity (Islam *et al.,* 2023). Agricultural residues rich in cellulose, hemicellulose, and lignin have also been investigated as low-cost adsorbents (Husaini *et al.,* 2020; Aljeboree *et al.,* 2020; N'diaye *et al.,* 2022). Among these materials, almond seed shells have shown promising performance in removing methylene blue and methyl orange (Hamza *et al.,* 2025). Nevertheless, further studies on regeneration and reusability are required to ensure long-term environmental and economic sustainability.

2. Structure and Properties of Cellulose

2.1 Chemical Structure of Cellulose

Cellulose is the most abundant natural polymer and is widely found in plant cell walls, algae, and some bacteria. It consists of β-D-glucopyranose units linked by β-(1→4)-glycosidic bonds and contains hydroxyl (–OH) groups that form extensive intra- and intermolecular hydrogen bonds, resulting in a highly organized structure with crystalline and amorphous regions (Wang *et al.,* 2020; Chen *et al.,* 2023; Klemm *et al.,* 2022). The crystalline regions provide mechanical strength and thermal stability, while the amorphous regions are more accessible for adsorption and chemical modification (Habibi, 2020; Moon *et al.,* 2021). The hydroxyl groups serve as active sites for the introduction of carboxyl, amino, and sulfonic groups, enhancing pollutant removal through electrostatic attraction, ion exchange, hydrogen bonding, and complexation mechanisms (Chen *et al.,* 2023; Luo *et al.,* 2022). In addition, factors such as surface charge, crystallinity index, and degree of polymerization influence the adsorption efficiency of cellulose-based materials toward heavy metals and synthetic dyes (Zhang *et al.,* 2024; Li *et al.,* 2021).

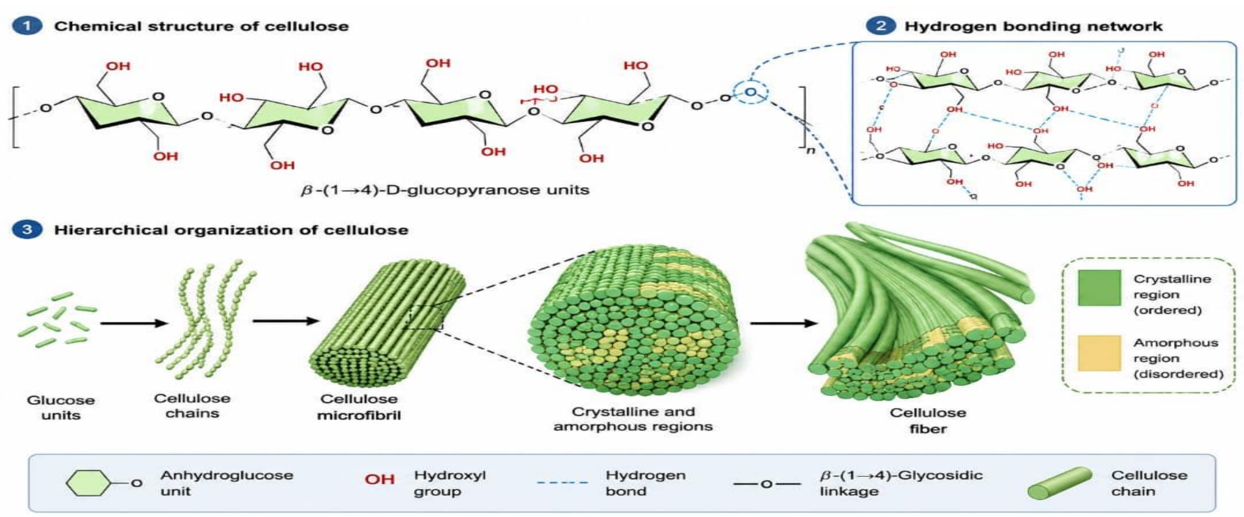

Figure 1: Chemical Structure and Hierarchical Organization of Cellulose Relevant to Adsorption Applications

2.2 Types of Cellulose Materials

Cellulose-derived materials are commonly classified into microcrystalline cellulose (MCC), nanocellulose—including cellulose nanocrystals (CNC) and cellulose nanofibrils (CNF)—and regenerated cellulose based on their production methods and structural dimensions. These forms exhibit distinct physicochemical properties that influence their adsorption performance and suitability for environmental remediation. As a naturally occurring biopolymer, cellulose exists in various structural configurations, each contributing differently to pollutant removal processes and environmental applications.

2.2.1 Microcrystalline Cellulose (MCC)

Microcrystalline cellulose (MCC) is produced through partial acid hydrolysis of cellulose, a process that removes the amorphous portions while retaining the crystalline regions. MCC is characterized by good mechanical strength, chemical stability, and moderate surface area, making it an appropriate support material for chemical modification and composite preparation (Kumar *et al.,* 2024). However, its relatively limited porosity and surface accessibility may reduce adsorption efficiency unless additional functionalization is carried out.

2.2.2 Nanocellulose (CNC and CNF)

Nanocellulose has gained considerable attention as an advanced adsorbent because of its nanoscale dimensions, high specific surface area, and abundance of surface hydroxyl groups. It mainly exists in two forms: cellulose nanocrystals (CNC) and cellulose nanofibers (CNF). CNC consists of highly crystalline rod-shaped nanoparticles with outstanding mechanical properties, whereas CNF comprises flexible and interconnected nanofibers containing both crystalline and amorphous domains. Due to their large surface area and adjustable surface chemistry, nanocellulose materials exhibit remarkable adsorption capacities for dyes and heavy metals (Yang *et al.,* 2024). Moreover, chemical treatments such as TEMPO-mediated oxidation can introduce carboxyl groups onto the surface, thereby enhancing the binding affinity for metal ions.

2.2.3 Cellulose Derivatives (e.g., CMC and Cellulose Acetate)

Cellulose derivatives such as carboxymethyl cellulose (CMC) and cellulose acetate possess improved solubility, processability, and functionalization potential compared to native cellulose. Among these derivatives, CMC is particularly important because it contains negatively charged carboxylate groups that enhance the adsorption of cationic pollutants via electrostatic interactions and ion-exchange mechanisms (Kumar *et al.,* 2024; Luo *et al.,* 2022). The availability of different cellulose forms and derivatives provides researchers to tailor adsorbent properties for specific environmental remediation applications and targeted pollutant removal.

3. Preparation and Modification of Cellulose-Based Adsorbents

3.1 Physical Modification

Physical modification is often used to enhance the adsorption properties of cellulose without altering its chemical composition. Common methods include milling, grinding, sieving, carbonization, and activation, which increase surface area, pore volume, and surface roughness, thereby improving the availability of adsorption sites (Patel, 2021; Singh *et al.,* 2022; Berrahou *et al.,* 2026). Carbonized cellulose materials exhibit enhanced adsorption due to their porous structures, while ball milling reduces crystallinity and increases amorphous regions, promoting better adsorption performance.

However, physical modification alone generally offers limited selectivity toward specific pollutants, making further chemical functionalization necessary for improved efficiency.

3.2 Chemical Modification

Chemical modification significantly enhances the adsorption performance of cellulose by introducing functional groups that interact strongly with pollutants. Common methods include oxidation, amination, and sulfonation, which introduce carboxyl (–COOH), amino ($-NH_2$), and sulfonic acid ($-SO_3H$) groups, respectively. These modifications improve the adsorption of dyes and heavy metals through electrostatic attraction, ion exchange, and complexation mechanisms. Aminated cellulose shows high affinity for Pb(II) and Cu(II), while carboxylated cellulose is particularly effective for cationic dye removal (Khan *et al.,* 2022; Luo *et al.,* 2022; Chen *et al.,* 2023). Recent studies have also employed graft copolymerization to attach synthetic polymers onto cellulose chains, producing hybrid materials with enhanced adsorption capacity, selectivity, and stability (Li *et al.,* 2021; Benahmed *et al.,* 2022; Zhou *et al.,* 2023).

3.3 Composite Formation

The development of cellulose-based composites has significantly expanded the applicability of cellulose materials in wastewater treatment by improving their structural integrity and functional performance. The preparation of composite and hybrid cellulose materials involves combining the inherent properties of cellulose with those of other functional materials to produce synergistic effects that enhance overall efficiency (Abu Rub *et al.,* 2023; Deng *et al.,* 2024). Among these materials, cellulose–metal oxide composites utilize the catalytic activity and high reactivity of metal oxides, enabling improved pollutant removal through both physical adsorption and chemical interactions. In addition, polymer–cellulose hybrid materials incorporate synthetic or biodegradable polymers into the cellulose matrix, thereby enhancing mechanical stability, flexibility, and durability, which are essential for practical environmental remediation applications (Husaini, 2026).

3.3.1 Magnetic Cellulose Composites

Magnetic cellulose composites are prepared by incorporating magnetic nanoparticles, such as Fe_3O_4, into cellulose matrices to produce adsorbents that can be easily separated from aqueous solutions using an external magnetic field (Zhang *et al.,* 2024). These materials combine high adsorption efficiency with simple recovery and reusability, making them suitable for practical and large-scale wastewater treatment applications.

3.3.2 Nanoparticle-Loaded Cellulose

Cellulose materials can also act as support matrices for various nanoparticles, including metal oxides such as TiO_2 and ZnO, graphene oxide, and carbon nanotubes. The incorporation of these nanoparticles significantly improves adsorption performance by increasing surface area, providing additional active sites, and promoting synergistic interactions between the cellulose matrix and nanoparticles (Husaini, 2023a; Singh *et al.,* 2022).

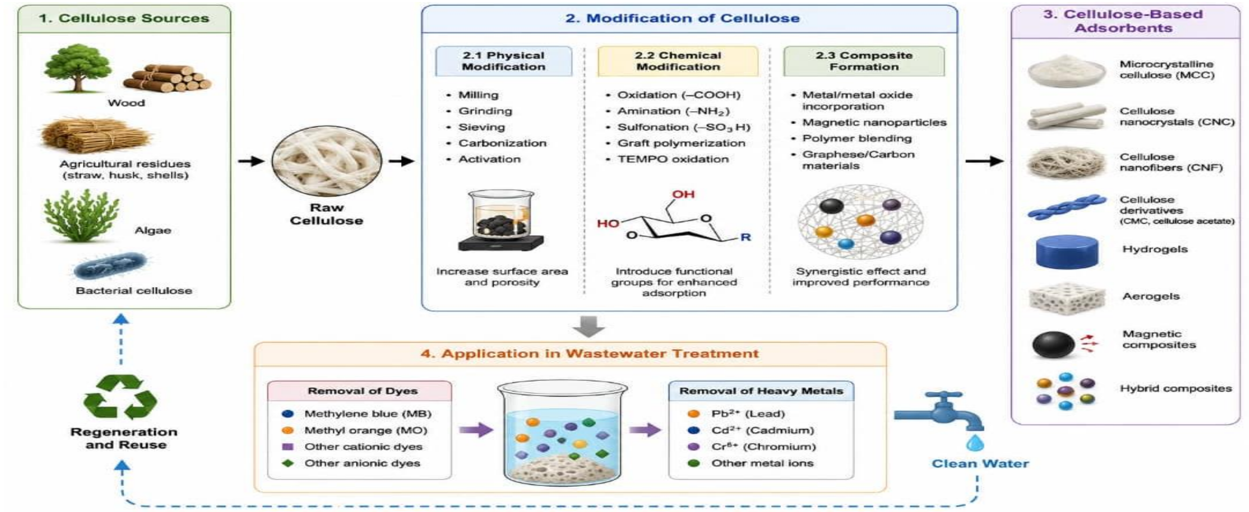

Figure 2: Preparation, Modification, and Classification of Cellulose-Based Adsorbents for Wastewater Treatment

4. Adsorption Mechanisms

4.1 Physical Adsorption

Physical adsorption, commonly known as physisorption, refers to the accumulation of pollutant molecules on the surface of an adsorbent through weak intermolecular forces such as van der Waals forces and dipole–dipole interactions (Wang and Guo 2023). Since no new chemical bonds are formed during this process, physical adsorption is generally reversible. The efficiency of physisorption is strongly influenced by the surface characteristics of the adsorbent, including surface area, pore volume, and pore size distribution, because larger and more porous surfaces provide a greater number of adsorption sites (Sun *et al.,* 2023). Highly porous materials such as activated carbon and biochar are therefore particularly suitable for this mechanism. In addition, factors such as temperature and pressure affect the adsorption process, with lower temperatures generally favoring physical adsorption. Owing to its fast and energy-efficient nature, physisorption usually dominates the early stage of pollutant removal (Deng and Su 2025; Husaini, 2023b).

4.2 Chemical Adsorption

Chemical adsorption, also known as chemisorption, involves the formation of strong covalent or ionic bonds between pollutant molecules and the functional groups present on the adsorbent surface (Liu *et al.,* 2023). Unlike physical adsorption, chemisorption is often more selective and may be irreversible because of the strength of the chemical interactions involved. This mechanism requires relatively higher activation energy and depends greatly on the surface chemistry and reactivity of the adsorbent material. Functional groups such as hydroxyl, carboxyl, carbonyl, and amino groups are essential in promoting these interactions (Zhou *et al.,* 2024). Chemisorption enhances the stability of adsorbed contaminants and is particularly important in applications requiring long-term pollutant retention. In many modified and functionalized adsorbents, chemisorption significantly contributes to the overall adsorption capacity (Li *et al.,* 2025).

4.3 π–π Interactions

π–π interactions occur between the electron-rich π-electron systems of aromatic structures present in both adsorbents and adsorbates. This mechanism plays an important role in the adsorption of organic contaminants containing aromatic rings or conjugated double bonds (Mian *et al.,* 2025). Adsorbent materials such as activated carbon and biochar contain graphitic and aromatic structures that promote π–π stacking interactions. As a result, these interactions improve the adsorption affinity for pollutants such as dyes, pharmaceutical compounds, and other aromatic organic substances. The effectiveness of π–π interactions is influenced by factors including surface aromaticity, chemical modification, and the presence of electron-donating or electron-withdrawing functional groups on the adsorbent surface (Zhao *et al.,* 2025).

4.4 Electrostatic Interactions

Electrostatic interactions are based on the attraction between oppositely charged species in aqueous solutions. The extent of this interaction largely depends on the surface charge of the adsorbent and the ionization state of the adsorbate, both of which are highly affected by the solution pH (Husaini, 2025). Under specific pH conditions, the adsorbent surface may acquire either a positive or negative charge, thereby promoting the adsorption of contaminants carrying opposite charges. This mechanism is particularly important for the removal of ionic pollutants such as heavy metal ions and charged organic compounds. Moreover, the ionic strength of the solution and the presence of competing ions can significantly influence the effectiveness of electrostatic attraction (Husaini, 2025).

4.5 Hydrogen Bonding

Hydrogen bonding is a secondary adsorption mechanism that occurs between hydrogen atoms attached to electronegative atoms, such as oxygen or nitrogen, and lone pair electrons on neighboring electronegative atoms. This interaction contributes to the adsorption of polar organic compounds and helps stabilize the adsorbed layer on the adsorbent surface (Sun *et al.,* 2023). Functional groups including hydroxyl, carboxyl, and amino groups increase the potential for hydrogen bond formation. Although hydrogen bonds are weaker than covalent bonds, their combined effect can substantially improve adsorption efficiency, especially when they operate alongside other mechanisms such as electrostatic attraction and π–π interactions (Zhou *et al.,* 2024).

4.6 Electron Transfer

Electron transfer mechanisms involve the movement or exchange of electrons between the adsorbent and adsorbate, leading to the formation of charge-transfer complexes or redox reactions (Hassan and Baghban, 2025). This mechanism is especially relevant for pollutants with strong electron-donating or electron-accepting characteristics. Adsorbents modified with metals or reactive functional groups can significantly enhance electron transfer processes and improve adsorption performance (Li *et al.,* 2025). In some cases, electron transfer not only increases adsorption efficiency but also promotes the degradation or transformation of pollutants into less harmful forms. Consequently, this mechanism is highly important in advanced adsorption technologies and hybrid wastewater treatment systems (Deng and Su, 2025).

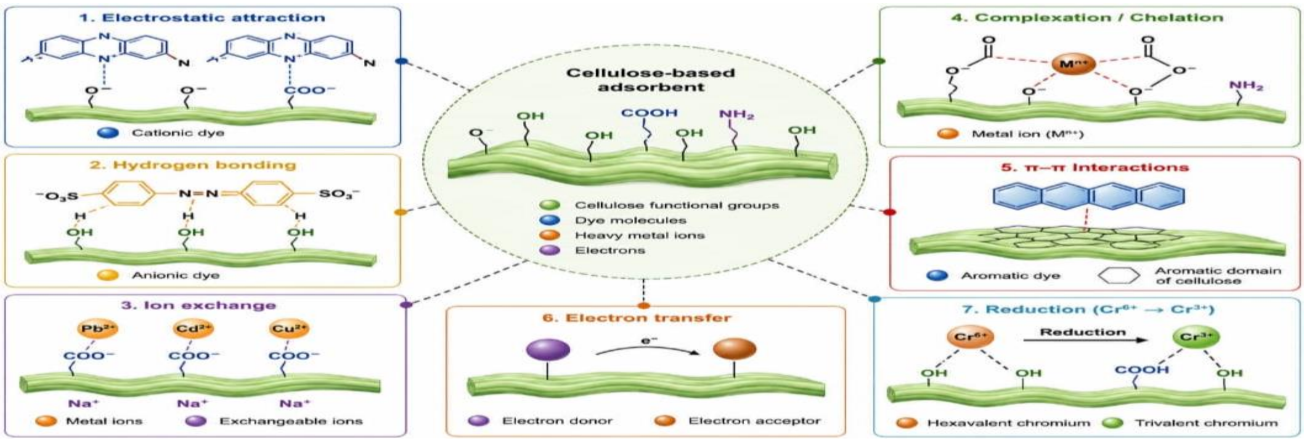

Figure 3: Adsorption Mechanisms of Dyes and Heavy Metals on Cellulose-Based Adsorbents

5. Removal of Dyes Using Cellulose-Based Adsorbents

5.1 Types of Dyes

Dyes are complex organic substances extensively utilized in industries including textiles, leather processing, cosmetics, pharmaceuticals, and paper production. Large quantities of these dyes are often released into aquatic environments without sufficient treatment, causing serious environmental and public health problems because of their toxic nature, persistence, and resistance to biodegradation (Aanchal and Basu, 2020; Hassan *et al.,* 2023). Based on their ionic characteristics, dyes are commonly grouped into cationic (basic) dyes and anionic dyes, and this classification strongly affects their interaction with adsorbent materials.

5.1.1 Cationic Dyes (e.g., Methylene Blue)

Cationic dyes such as methylene blue (MB) are widely studied pollutants because of their potential health risks, including respiratory irritation, eye damage, and mutagenic effects (Kausar *et al.,* 2023).

Cellulose-based adsorbents exhibit strong affinity toward these dyes due to the presence of hydroxyl (–OH) and carboxyl (–COOH) groups, which facilitate adsorption through electrostatic attraction and hydrogen bonding (Qiao *et al.,* 2021). Chemical modifications such as TEMPO-mediated oxidation and carboxylation further enhance adsorption capacity by increasing active binding sites and surface area. Modified cellulose materials have achieved adsorption capacities exceeding 100 mg/g for methylene blue (Iwuozor *et al.,* 2021). Adsorption is generally more effective under alkaline conditions (pH 7–9), where the cellulose surface becomes more negatively charged, strengthening dye–adsorbent interactions (Hamidon *et al.,* 2022).

5.1.2 Anionic Dyes (e.g., Methyl Orange)

Anionic dyes such as methyl orange (MO) are more difficult to remove with unmodified cellulose because electrostatic repulsion occurs between the negatively charged dye molecules and the cellulose surface (Iwuozor *et al.,* 2021). To improve adsorption, cellulose is often modified through amine functionalization, polymer grafting, or the addition of cationic surfactants, which introduce positively charged binding sites (Kausar *et al.,* 2023). Methyl orange adsorption mainly occurs through electrostatic attraction, ion exchange, and hydrogen bonding, with optimal performance typically observed under acidic conditions (pH 3–5). Recent cellulose-based hydrogels, nanocomposites, and magnetic adsorbents have demonstrated enhanced adsorption rates and reusability due to their high porosity and accessible active sites (Hamidon *et al.,* 2022; Aanchal and Basu, 2023).

5.2 Adsorption Performance

The adsorption performance of cellulose-based adsorbents is strongly influenced by surface modification. Native cellulose generally shows limited adsorption capacity due to its low surface area and fewer active sites. Chemical modification significantly enhances dye removal efficiency, often achieving removal rates above 90% (Suteu *et al.,* 2021). Cellulose-based beads and hydrogels also exhibit high adsorption capacities because of their improved porosity and increased availability of functional groups (Hamidon *et al.,* 2022). Advanced techniques such as nanostructuring and chemical grafting further improve adsorption kinetics, capacity, and reusability of cellulose-based materials (Zhang *et al.,* 2024).

5.3 Factors Affecting Dye Removal

5.3.1 pH

The pH of the solution is one of the most important factors influencing dye adsorption because it affects both the surface charge of the adsorbent and the ionization behavior of dye molecules. At alkaline pH values, cellulose surfaces become increasingly negatively charged, which favors the adsorption of cationic dyes such as methylene blue through stronger electrostatic attraction. In contrast, acidic conditions promote protonation of the adsorbent surface, thereby enhancing the adsorption of anionic dyes. This pH-dependent adsorption behavior has been extensively discussed by (Hamidon *et al.,* 2022; Zhang *et al.,* 2024).

5.3.2 Contact Time

Contact time plays a significant role in determining the adsorption rate and the time required for the system to reach equilibrium. In most cellulose-based adsorption systems, dye uptake occurs rapidly during the initial stage because of the large number of available active sites on the adsorbent surface. As adsorption progresses, the rate gradually decreases until equilibrium is attained. (Suteu *et al.,* 2021) observed that dye adsorption onto cellulose-based adsorbents generally follows pseudo-second-order kinetic behavior, suggesting that chemisorption is the predominant mechanism. Depending on the adsorbent properties and dye concentration, equilibrium can be achieved within a few minutes to several hours.

5.3.3 Adsorbent Dosage

Adsorbent dosage is another important factor affecting dye removal efficiency. Increasing the amount of adsorbent introduces more active sites for dye binding, thereby improving overall removal efficiency. However, after reaching an optimum dosage, the adsorption capacity per unit mass may decline due to particle agglomeration and overlap of adsorption sites. (Suteu *et al.,* 2021) reported that although increasing adsorbent dosage enhances total dye removal, excessive dosage may reduce adsorption efficiency on a gram basis, highlighting the importance of dosage optimization for industrial and practical applications.

6. Removal of Heavy Metals Using Cellulose-Based Adsorbents

6.1 Common Heavy Metals

Heavy metals such as lead (Pb^{2+}), cadmium (Cd^{2+}), and chromium (Cr^{6+}) are considered some of the most dangerous contaminants present in wastewater because of their high toxicity, persistence, non-biodegradable nature, and ability to accumulate in living organisms (Singh *et al.,* 2022; Haroon *et al.,* 2025). These pollutants are mainly generated from industrial activities such as mining operations, electroplating, battery production, and textile manufacturing. Continuous exposure to heavy metals can result in serious health complications, including kidney failure, neurological disorders, and cancer-related diseases.

6.2 Removal of Lead (Pb^{2+})

Lead is recognized as one of the most harmful heavy metals commonly detected in industrial effluents. Cellulose-derived adsorbents, particularly oxidized and carboxylated cellulose materials, exhibit excellent affinity toward Pb^{2+} ions because of the strong interaction between lead ions and oxygen-containing functional groups present on the adsorbent surface (Garba *et al.,* 2020). Research has shown that nanocellulose and cellulose-based composite materials can achieve adsorption capacities greater than 200 mg/g for lead removal, demonstrating performance comparable to or even better than traditional adsorbents such as activated carbon (Qiao *et al.,* 2021).

6.3 Removal of Cadmium (Cd^{2+})

Cadmium is a highly toxic heavy metal associated with severe health effects, including kidney damage and skeletal disorders. The adsorption efficiency of cellulose-based materials for Cd^{2+} removal can be significantly improved through surface modification with functional groups such as thiol, amine, and carboxyl groups, which enhance metal binding through chelation mechanisms (Frontiers Review, 2021). Several studies have reported that cadmium adsorption onto modified cellulose materials follows the Langmuir adsorption isotherm and pseudo-second-order kinetic model, indicating monolayer adsorption and the dominance of chemisorption processes (Garba *et al.,* 2020).

6.4 Removal of Chromium (Cr^{6+})

Chromium generally exists in two major oxidation states, Cr^{3+} and Cr^{6+}, with hexavalent chromium (Cr^{6+}) being the more toxic and carcinogenic form. The removal of Cr^{6+} using cellulose-based adsorbents involves both adsorption and reduction processes, where toxic Cr^{6+} ions are converted into the less harmful Cr^{3+} form. Modified cellulose materials, including amine-functionalized cellulose and cellulose nanocomposites, have demonstrated high chromium removal efficiency due to improved electrostatic interactions and enhanced redox properties (Aanchal and Basu, 2023).

6.5 Adsorption Mechanisms of Heavy Metals on Cellulose

Cellulose-based adsorbents are highly suitable for heavy metal removal because they contain abundant functional groups such as hydroxyl (–OH), carboxyl (–COOH), and amine (–NH_2) groups that readily interact with metal ions. The major adsorption mechanisms involved include ion exchange, electrostatic attraction, complexation or chelation, and surface precipitation. These mechanisms collectively contribute to the strong attachment of heavy metal ions onto cellulose matrices (Qiao *et al.,* 2021; Kausar *et al.,* 2023).

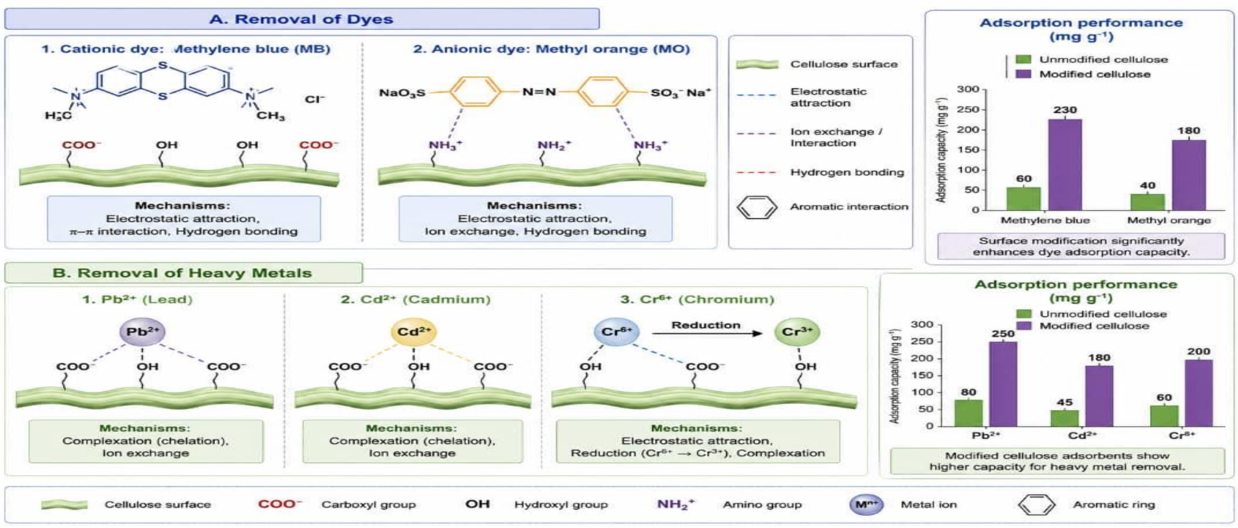

Figure 4: Performance of Cellulose-Based Adsorbents for the Removal of Dyes and Heavy Metals from Wastewater

7. Characteristics Influencing Adsorption

7.1 Surface Area and Porosity

The adsorption efficiency of materials such as biochar and activated carbon largely depends on their surface area and pore structure. A larger surface area provides more active sites for pollutant adsorption, while well-developed pores enhance contaminant diffusion into the adsorbent matrix (Qin *et al.,* 2023; Kong *et al.,* 2025). Micropores are effective for trapping small organic molecules, whereas mesopores and macropores are more suitable for larger contaminants. Adsorbents with hierarchical pore structures generally exhibit improved adsorption capacity and faster kinetics because they facilitate efficient pollutant transport within the material (Salahat *et al.,* 2023; Kong *et al.,* 2025). Therefore, optimizing surface area and pore distribution is crucial for enhancing wastewater treatment performance.

7.2 Functional Groups

The adsorption behavior of adsorbents is strongly influenced by the type and abundance of surface functional groups. Groups such as hydroxyl (–OH), carboxyl (–COOH), carbonyl (C=O), and amine (–NH_2) facilitate adsorption through hydrogen bonding, electrostatic attraction, π–π interactions, and metal complexation (Mahmoud and Leick, 2023). Surface modification methods, including oxidation, acid or alkali treatment, and metal doping, can enhance the number and activity of these groups, thereby improving adsorption capacity and selectivity (Park *et al.,* 2025). Such modifications enable efficient removal of dyes, pharmaceuticals, and other contaminants, while also improving adsorbent regeneration and long-term stability during repeated use (Mahmoud and Leick, 2023).

7.3 pH and Solution Chemistry

The pH of the solution plays a critical role in adsorption processes because it affects both the charge of the adsorbent surface and the ionization state of pollutants (Dai *et al.,* 2024). Under acidic conditions, positively charged adsorption sites tend to favor the removal of negatively charged contaminants, whereas alkaline conditions promote deprotonation of the adsorbent surface and improve adsorption of positively charged species (Liang *et al.,* 2024). Additionally, the presence of dissolved salts, competing ions, and natural organic matter may either enhance or hinder pollutant adsorption by influencing the interaction between contaminants and adsorption sites (Dai *et al.,* 2024).

7.4 Temperature and Ionic Strength

Temperature influences adsorption by affecting molecular motion, interaction energy, and binding forces between pollutants and adsorbents. In endothermic systems, higher temperatures often enhance adsorption, whereas exothermic systems may exhibit reduced adsorption efficiency with increasing temperature (Hou *et al.,* 2023). Ionic strength also plays a key role, particularly for charged pollutants, as high ion concentrations can weaken electrostatic interactions and reduce adsorption performance (Wen *et al.,* 2025). Additionally, both temperature and ionic strength can affect adsorbent regeneration, structural stability, and reusability over repeated cycles (Sun *et al.,* 2024). Understanding these factors is essential for optimizing adsorption systems under real environmental conditions.

8. Adsorption Isotherms, Kinetics, and Thermodynamics

Adsorption isotherm, kinetic, and thermodynamic investigations are important analytical tools used to explain the interaction mechanisms between adsorbates (dyes or heavy metals) and cellulose-based adsorbents. These studies provide valuable information regarding adsorption capacity, surface characteristics, adsorption rate, and energy changes occurring during the adsorption process (Musah *et al.,* 2022; Hamidon *et al.,* 2022).

8.1 Adsorption Isotherm Models

Adsorption isotherm models describe the equilibrium relationship between the adsorbate concentration in solution and the quantity adsorbed on the adsorbent surface. These models are essential for evaluating adsorption capacity and understanding surface behavior of adsorbents (Jiang *et al.,* 2025). Among the various isotherm models, the Langmuir and Freundlich models are the most widely applied in cellulose-based adsorption systems.

8.1.1 Langmuir Isotherm Model

The Langmuir isotherm model assumes that adsorption occurs as a monolayer on a homogeneous adsorbent surface containing finite and identical active sites. The model further assumes that there is no interaction between adsorbed molecules (Li *et al.,* 2020; Hamidon *et al.,* 2022). This model is extensively used to evaluate dye and heavy metal adsorption onto cellulose-based materials because it can estimate the maximum adsorption capacity of the adsorbent. The linear form of the Langmuir equation is given as:

$$\frac{C_e}{q_e} = \frac{1}{bq_{max}} + \frac{C_e}{q_{max}}$$ **Eqn. 1**

Where:

C_e = equilibrium concentration of adsorbate in solution (mg/L)

q_e = amount of adsorbate adsorbed at equilibrium (mg/g)

q_{max} = maximum monolayer adsorption capacity (mg/g)

b = Langmuir adsorption constant related to adsorption energy or affinity (L/mg)

A good agreement with the Langmuir model suggests monolayer adsorption on uniform adsorption sites and is often associated with chemisorption mechanisms (Singh *et al.,* 2022). Recent studies have shown that modified cellulose materials such as nanocellulose and functionalized cellulose composites frequently follow the Langmuir model during the removal of Pb^{2+}, Cd^{2+}, and methylene blue, indicating strong affinity and uniform binding sites.

8.1.2 Freundlich Isotherm Model

The Freundlich isotherm model describes adsorption on heterogeneous surfaces with non-uniform distribution of adsorption energy. Unlike the Langmuir model, it assumes multilayer adsorption and is commonly applied to complex adsorption systems (Musah *et al.,* 2022). The linear form of the Freundlich equation is expressed as:

$$\log q_e = \log K_f + \frac{1}{n} \log C_e$$ **Eqn. 2**

Parameters of the Freundlich Equation

Where:

q_e = amount adsorbed at equilibrium (mg/g)

C_e = equilibrium concentration of adsorbate in solution (mg/L)

K_f = Freundlich constant indicating adsorption capacity

n = adsorption intensity constant

$\frac{1}{n}$ = heterogeneity factor indicating adsorption favorability

Values of ($1/n < 1$) indicate favorable adsorption conditions. In cellulose-based adsorbents derived from agricultural wastes, Freundlich behavior is often observed due to the presence of heterogeneous functional groups such as hydroxyl (–OH) and carboxyl (–COOH) groups. This behavior suggests multilayer adsorption and surface heterogeneity.

8.2 Adsorption Kinetic Models

Adsorption kinetic models are used to evaluate the rate of adsorbate uptake and identify the mechanisms controlling the adsorption process.

8.2.1 Pseudo-First-Order (PFO) Model

The pseudo-first-order model assumes that the adsorption rate is proportional to the number of unoccupied adsorption sites. It is generally associated with physisorption processes (Revellame *et al.,* 2020). The linear form of the PFO equation is:

$$\log (q_e - q_t) = \log q_e - \frac{k_1}{2.303} t \quad \textbf{Eqn. 3}$$

Where:

q_e = amount adsorbed at equilibrium (mg/g)

q_t = amount adsorbed at time (t) (mg/g)

k_1 = pseudo-first-order rate constant (min^{-1})

t= adsorption time (min)

Although the PFO model is useful for describing certain adsorption systems, many studies involving cellulose-based adsorbents report poor fitting of experimental data, especially for heavy metal adsorption, due to inaccurate prediction of equilibrium adsorption capacity.

8.2.2 Pseudo-Second-Order (PSO) Model

The pseudo-second-order model assumes that adsorption occurs mainly through chemisorption involving electron sharing or electron exchange between adsorbent and adsorbate molecules. It is currently the most widely used kinetic model for cellulose-based adsorption systems. The linear form of the PSO equation is

$$\frac{t}{q_t} = \frac{1}{k_2 q_e^2} + \frac{t}{q_t} \quad \textbf{Eqn. 4}$$

q_t= amount adsorbed at time t (mg/g)

q_e = amount adsorbed at equilibrium (mg/g)

k_2 = pseudo-second-order rate constant (g/mg·min)

t = adsorption time (min)

The PSO model usually provides better correlation with experimental adsorption data than the PFO model (Hamidon *et al.,* 2022). However, recent studies suggest that the excellent fit of the PSO model may not always indicate pure chemisorption, but may also involve diffusion-controlled mechanisms and surface heterogeneity. In cellulose-based adsorbents, PSO kinetics are commonly linked to the presence of abundant functional groups such as hydroxyl and carboxyl groups, which facilitate ion exchange and surface complexation processes.

8.3 Thermodynamic Studies

Thermodynamic studies are used to determine the feasibility, spontaneity, and thermal nature of adsorption processes. The main thermodynamic parameters evaluated include Gibbs free energy change (ΔG^0), enthalpy change (ΔH^0), and entropy change (ΔS^0).

The relationship between Gibbs free energy and equilibrium constant is expressed as:

$(\Delta G^0) = - RT \text{ In } K_c$ **Eqn. 5**

ΔG^0 = Gibbs free energy change (kJ/mol)

R = universal gas constant (8.314 J/mol·K)

T = absolute temperature (K)

K_c = equilibrium constant

The Van't Hoff equation used for determining enthalpy and entropy changes is given as:

$\text{In } K_c = \frac{\Delta S^0}{R} - \frac{\Delta H^0}{RT}$ **Eqn. 6**

ΔH^0 = enthalpy change (kJ/mol)

ΔS^0 = entropy change (J/mol·K)

R = universal gas constant

T = absolute temperature (K)

K_C = equilibrium constant

Negative ΔG^0 values indicate that adsorption occurs spontaneously, while positive ΔH^0 values suggest an endothermic process in which adsorption increases with temperature; negative ΔH^0 values indicate exothermic adsorption (Singh *et al.,* 2022). Positive ΔS^0 values reflect increased randomness at the adsorbent–solution interface. Thermodynamic parameters also help distinguish adsorption mechanisms, with physisorption generally characterized by $\Delta H^0 < 40$ kJ/mol and chemisorption by $\Delta H^0 > 40$ kJ/mol. Studies on cellulose-based adsorbents commonly report negative ΔG^0, positive ΔH^0, and positive ΔS^0, confirming spontaneous and thermodynamically favorable adsorption. Combined isotherm, kinetic, and thermodynamic analyses provide valuable insight into adsorption mechanisms and support the optimization of cellulose-based materials for wastewater treatment (Hamidon *et al.,* 2022; Musah *et al.,* 2022).

9. Recent Advances in Cellulose-Based Adsorbents

Recent years have seen remarkable advancements in the development of cellulose-based adsorbents due to the increasing demand for sustainable, efficient, and cost-effective technologies for wastewater treatment. Current innovations mainly focus on the nanostructuring, surface functionalization, and hybridization of cellulose materials in order to improve their adsorption performance toward dyes and heavy metals.

9.1 Nanocellulose-Based Materials

Nanocellulose materials, such as cellulose nanocrystals (CNCs) and cellulose nanofibers (CNFs), are promising adsorbents due to their high surface area, excellent mechanical properties, and abundant hydroxyl groups. Their nanoscale structure provides more accessible active sites, resulting in superior adsorption performance compared with bulk cellulose (Si *et al.,* 2022; Jiang *et al.,* 2023). Surface functionalization with carboxyl, amino, and thiol groups further enhances the adsorption of heavy metals such as Pb^{2+}, Cd^{2+}, and Cr^{6+}. Nanocellulose can also be fabricated into membranes, beads, and films for water treatment applications. Recent developments focus on integrating nanotechnology and green synthesis approaches to produce highly efficient and recyclable adsorbent materials (Yang *et al.,* 2024).

9.2 Magnetic Cellulose Composites

Magnetic cellulose composites are attractive adsorbents because they can be easily recovered from treated water using an external magnetic field, eliminating the need for complex separation processes. These materials are typically produced by incorporating magnetic nanoparticles such as Fe_3O_4 into cellulose matrices. The resulting composites exhibit high adsorption efficiency, easy recovery, and good reusability. Recent studies have improved the distribution and stability of magnetic nanoparticles within cellulose structures, enhancing both adsorption performance and durability. Magnetic cellulose composites have demonstrated effective removal of dyes and heavy metals, while hybrid magnetic nanocellulose materials offer the combined benefits of high surface area and magnetic separability for large-scale wastewater treatment applications (Qiao *et al.,* 2021).

9.3 Cellulose Hydrogels and Aerogels

Cellulose-based hydrogels and aerogels are highly porous three-dimensional materials with excellent water absorption and adsorption properties. Their large surface area and interconnected pore structures facilitate rapid pollutant diffusion and efficient adsorption. Hydrogels are particularly effective for removing dyes and heavy metals due to their swelling ability, which enhances contact between pollutants and active sites. Aerogels, on the other hand, possess ultra-lightweight structures and extremely high porosity, resulting in high adsorption capacities. Functionalized cellulose hydrogels, especially those combined with graphene oxide or metal oxides, have shown improved adsorption kinetics and reusability. Nanocellulose-derived gels are also regarded as environmentally friendly and scalable materials for wastewater treatment applications (Qiao *et al.,* 2021).

9.4 Hybrid Bio-Adsorbents

Hybrid bio-adsorbents are developed by combining cellulose with other functional materials such as chitosan, activated carbon, metal oxides, and graphene-based compounds. These hybrid systems exploit synergistic interactions to improve adsorption efficiency. For example, cellulose–chitosan composites enhance adsorption due to additional amino groups, whereas cellulose–graphene composites provide increased surface area and improved conductivity. Recent findings indicate that hybridization significantly enhances adsorption capacity, pollutant selectivity, mechanical stability, and regeneration efficiency. Moreover, hybrid cellulose materials exhibit multifunctional properties, allowing the simultaneous removal of dyes, heavy metals, and other organic contaminants from wastewater (Jiang *et al.,* 2023).

10. Advantages of Cellulose-Based Adsorbents

10.1 Low Cost

Cellulose-based adsorbents possess several advantages over conventional materials such as activated carbon, synthetic resins, and metal oxides. Since cellulose is obtained from abundant natural resources including agricultural residues, wood, and plant biomass, its production cost is relatively low. The utilization of agricultural by-products and waste biomass further minimizes production expenses while promoting waste valorization and sustainable resource utilization (Husaini, 2024; Garba *et al.,* 2020).

10.2 Renewable and Biodegradable

Cellulose is a renewable, biodegradable, and environmentally benign biopolymer. Unlike many synthetic adsorbents, cellulose-based materials do not contribute to secondary environmental pollution after disposal. Nanocellulose materials, in particular, offer additional advantages associated with green chemistry due to their biocompatibility and minimal ecological impact (Si *et al.,* 2022).

10.3 High Adsorption Efficiency

The excellent adsorption performance of cellulose-based materials is mainly attributed to the abundance of hydroxyl groups, large surface area—particularly in nanocellulose—and the possibility of tailoring surface chemistry through modification techniques. These characteristics facilitate strong interactions between pollutants and adsorbents through mechanisms such as electrostatic attraction, ion exchange, hydrogen bonding, and complexation. Studies have demonstrated that nanostructured cellulose materials often outperform many conventional adsorbents in the removal of dyes and heavy metals (Qiao *et al.,* 2021; Jiang *et al.,* 2023).

10.4 Ease of Modification

One of the major strengths of cellulose lies in its chemical versatility. The presence of reactive hydroxyl groups enables straightforward chemical modification using various treatment methods. Common modification approaches include carboxylation, amination, polymer grafting, and nanoparticle incorporation. These modifications improve adsorption capacity, selectivity, and recyclability of cellulose-based adsorbents. Recent studies particularly emphasize surface engineering and hybridization strategies for designing cellulose materials targeted toward specific pollutants (Yang *et al.,* 2024).

11.0 Challenges and Limitations

11.1 Scale-Up Challenges

Despite their excellent laboratory performance, large-scale application of biomass-derived adsorbents such as biochar and activated carbon remains challenging (Liu *et al.,* 2024). Commercial production requires consistent feedstock quality and careful control of pyrolysis or activation processes to maintain uniform adsorbent properties. Variations in biomass composition can lead to differences in surface area, pore structure, and functional groups, affecting treatment efficiency and reliability (Sangamnere *et al.,* 2024). Furthermore, integrating these materials into existing wastewater treatment systems may require engineering modifications and process optimization. Economic viability, energy demands, and environmental sustainability during large-scale production also remain significant barriers to commercialization (Wang *et al.,* 2024).

11.2 Regeneration Issues

The regeneration and reuse of biomass-based adsorbents are critical for ensuring both economic and environmental sustainability. However, repeated adsorption–desorption cycles often result in pore blockage, reduction in surface area, and degradation of active functional groups, leading to a gradual decline in adsorption performance (Zhao *et al.,* 2025). Thermal regeneration techniques can recover adsorption capacity effectively, but they usually require high energy input and increase operational costs. Similarly, chemical regeneration methods may produce secondary pollutants that require additional treatment before disposal. Certain contaminants, particularly persistent organic pollutants, strongly adhere to adsorption sites, making complete regeneration challenging. Therefore, the development of regeneration approaches that are efficient, low-cost, and environmentally friendly remains essential for the long-term application of these materials in wastewater treatment systems (Wang *et al.,* 2024).

11.3 Lack of Standardization

Another important limitation is the absence of standardized methods for the synthesis, characterization, and evaluation of biomass-derived adsorbents (Liu *et al.,* 2024; Haoufazane *et al.,* 2025). Differences in experimental conditions, including pyrolysis temperature, activating agents, particle size, and adsorption testing procedures, make direct comparison among studies difficult. This inconsistency also limits industrial acceptance and regulatory approval because adsorption performance cannot be reliably predicted under different operational conditions. Consequently, establishing standardized preparation methods, quality control measures, and benchmarking protocols is necessary to improve reproducibility, encourage commercialization, and support the broader implementation of sustainable adsorbent technologies (Sangamnere *et al.,* 2024).

12. Future Perspectives

12.1 Development of Advanced Composites

Future research on cellulose-based adsorbents is focused on developing multifunctional composites with enhanced adsorption efficiency, selectivity, and reusability. Combining cellulose with nanomaterials such as metal oxides, graphene, and metal–organic frameworks (MOFs) can significantly improve adsorption performance by increasing surface area and introducing additional functional groups (Tao *et al.,* 2023; Xiao *et al.,* 2023). Cellulose–MOF composites exhibit tunable porosity and strong affinity for both heavy metals and organic pollutants, while magnetic cellulose composites enable easy recovery after treatment. Similarly, nanocellulose-based hybrid materials offer improved mechanical strength and faster adsorption kinetics. Future studies should emphasize green synthesis routes, cost-effective fabrication methods, and scalable production technologies to support industrial wastewater treatment applications.

12.2 Industrial Applications

Despite the excellent adsorption performance of cellulose-based materials in laboratory investigations, their commercial-scale implementation remains limited. Factors such as poor regeneration efficiency, insufficient mechanical strength, and the high cost of modification continue to hinder industrial application (Kausar *et al.,* 2023; Adegoke *et al.,* 2023). Future research efforts should focus on conducting pilot-scale experiments with real wastewater samples, designing continuous-flow adsorption systems, integrating cellulose adsorbents into existing treatment infrastructures, and improving regeneration efficiency and long-term operational stability. In addition to wastewater treatment, these materials also show promise in areas such as recovery of valuable resources, including precious metals, and removal of pharmaceutical contaminants, thereby expanding their industrial significance (Rocky *et al.,* 2023; Etale *et al.,* 2023).

12.3 Integration with Other Treatment Methods

The integration of cellulose-based adsorption with other treatment technologies represents another promising research direction. Hybrid systems that combine adsorption with membrane filtration, advanced oxidation processes (AOPs), or coagulation–flocculation techniques can overcome the limitations associated with individual treatment methods while improving overall efficiency and reducing operational costs. For instance, adsorption–membrane hybrid systems have proven effective for eliminating trace contaminants and emerging pollutants (Kim *et al.,* 2023; Xiao *et al.,* 2023). Furthermore, integrating adsorption with catalytic degradation processes allows simultaneous adsorption and decomposition of pollutants, resulting in more sustainable and efficient treatment systems.

12.4 Sustainable Design Approaches

Sustainability continues to be a major driving factor in the advancement of cellulose-based adsorbents. Cellulose obtained from agricultural residues such as doum palm, maize, and rice husk provides an eco-friendly and low-cost alternative to conventional synthetic adsorbents (Ivbanikaro *et al.,* 2023). Future material design should emphasize the development of biodegradable and environmentally benign adsorbents, low-energy synthesis techniques, circular economy practices involving reuse and recycling, and reduction of secondary waste generation. In addition, comprehensive life cycle assessment (LCA) studies are necessary to evaluate the environmental impacts associated with the production, application, and disposal of cellulose-based materials. Addressing these sustainability considerations will help align future technologies with global environmental and sustainability objectives.

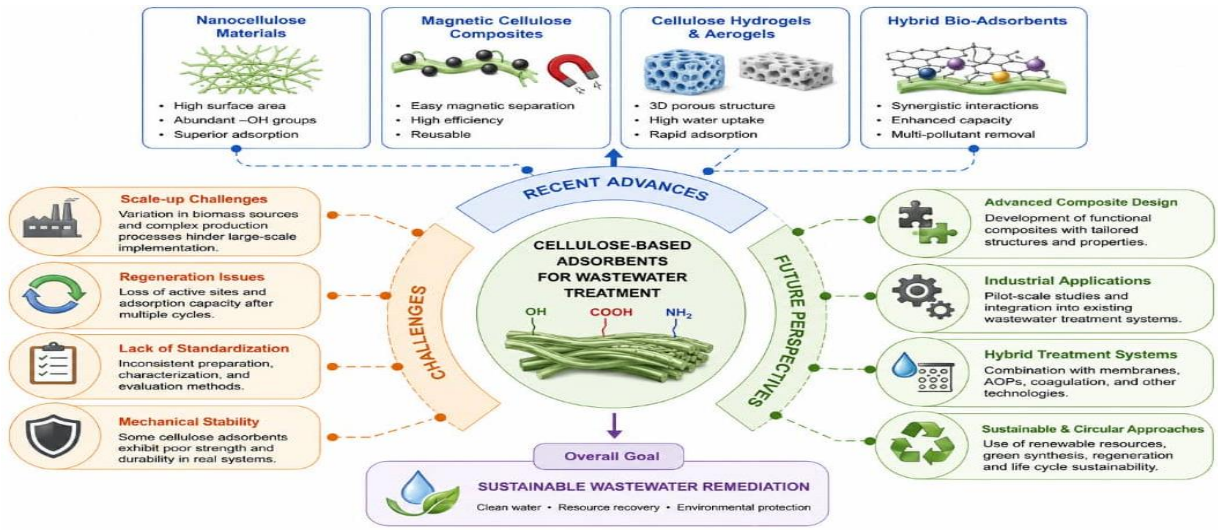

Figure 5: Recent Advances, Challenges, and Future Perspectives of Cellulose-Based Adsorbents in Wastewater Remediation

Conclusion

This review demonstrates that cellulose-based adsorbents are promising materials for the removal of dyes and heavy metals from wastewater due to their abundance, biodegradability, ease of chemical modification, and excellent adsorption properties. The presence of hydroxyl groups and other functional sites enables effective pollutant removal through mechanisms such as electrostatic attraction, hydrogen bonding, and complexation. Recent advances in nanocellulose, hydrogels, aerogels, and magnetic cellulose composites have further enhanced adsorption capacity, selectivity, and reusability. Compared with conventional adsorbents, cellulose-based materials offer lower environmental impact, high removal efficiency, and availability from renewable biomass resources. Nevertheless, challenges related to regeneration, large-scale production, and long-term operational stability still limit their widespread application. Future studies should focus on developing multifunctional hybrid materials, improving regeneration performance, and establishing cost-effective and sustainable production methods. Overall, cellulose-based adsorbents possess strong potential as next-generation materials for wastewater treatment and environmental protection.

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