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*Review*

# A Comprehensive Evaluation of Adsorption Techniques for Dye Elimination in Wastewater: From Conventional Adsorbents to Nanotechnology

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**Abstract**

The continuous discharge of hazardous synthetic dyes into aquatic environments as a result of rapid industrialization poses a serious threat to both environmental and human health. This review aims to provide a comprehensive and up to date evaluation of adsorption techniques for dye removal from wastewater, with a focus on both conventional and emerging adsorbent materials. The review examines and compares natural materials, such as clays, zeolites, charcoal, and agricultural wastes, as well as engineered and nano scale materials, including carbon nanotubes, graphene, metal organic frameworks, and nanocomposites, for wastewater decolorization. This study presents a critical analysis of published studies from 2018 to 2025, focusing on the performance of various adsorbents under key operational parameters such as pH, temperature, contact time, and adsorbent dosage. The dominant adsorption mechanisms, including electrostatic attraction, ion exchange, and surface complexation, are systematically discussed. Special attention is given to the role of nanotechnology and green synthesis strategies in improving adsorption efficiency and material reusability. The review indicates that nano engineered and hybrid adsorbents generally exhibit superior adsorption performance and represent promising candidates for scalable and environmentally sustainable wastewater treatment applications. Future research should prioritize the development of cost-effective regeneration methods, evaluation using real industrial effluents, and pilot scale studies to facilitate the transition from laboratory research to industrial implementation.

**Keywords:** Adsorption; nano adsorbents; green synthesis; wastewater; dyes.

## 1. Introduction

Freshwater resources are under increasing pressure due to rapid industrial development, population growth, and changing climatic conditions[1]. One of the major contributors to water pollution is the discharge of synthetic dyes from industrial processes. Synthetic dyes, including methylene blue, Congo red, methyl orange, rhodamine B, and crystal violet, are extensively used in industries such as textiles, leather, pharmaceuticals, cosmetics, and food processing. Due to their complex molecular structures, resistance to photodegradation and biodegradation, and

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strong coloration even at low concentrations, these compounds are difficult to remove using conventional wastewater treatment methods[2]. When released into natural water bodies without adequate treatment, dye containing effluents can cause serious environmental impacts, including reduced light penetration, disruption of aquatic photosynthesis, and adverse effects on human and ecosystem health[3]. Various treatment technologies have been developed to address dye pollution, including physical, chemical, and biological processes such as coagulation and flocculation, membrane separation, ion exchange, electrocoagulation, advanced oxidation processes, and biological degradation[4]. Although many of these methods can achieve high removal efficiencies under controlled laboratory conditions, their large scale application is often constrained by high operational costs, secondary waste generation, membrane fouling, incomplete dye degradation, or reduced effectiveness in complex industrial effluents[5]. Consequently, adsorption has received considerable attention as an alternative treatment method due to its operational simplicity, effectiveness, and minimal generation of secondary pollutants[6]. Conventional adsorbents, including activated carbon, clays, zeolites, biochar, and various agricultural by products, have been extensively investigated for dye removal. These materials are generally cost effective and environmentally acceptable; however, they frequently suffer from shortcomings such as restricted adsorption capacity, slow adsorption kinetics, low selectivity toward specific dyes, and challenges related to regeneration and reuse[7]. In response to these limitations, recent research has increasingly focused on the development of advanced adsorbent materials, including nano scale adsorbents, metal organic frameworks, magnetic composites, and hybrid systems. These materials typically exhibit higher surface areas, tunable pore structures, and improved surface chemistry, which enhance their interaction with dye molecules[8]. Despite the growing number of research articles and reviews on dye adsorption, several limitations remain in the existing literature. Many reviews focus on specific classes of adsorbents or report adsorption performance under idealized laboratory conditions, with limited discussion of regeneration efficiency, long term stability, or applicability to real industrial wastewater[9]. Comparative assessments that evaluate conventional, nano based, and hybrid adsorbents under similar experimental conditions remain limited, making it difficult to objectively assess their practical advantages and limitations. Furthermore, unresolved challenges such as adsorbent performance under variable pH conditions, interference from coexisting contaminants, scale up feasibility, and environmental concerns related to nanomaterial use have not been adequately addressed[10]. Although nanotechnology is frequently presented as a promising solution for wastewater treatment, its application in dye removal presents several practical challenges. High synthesis costs, uncertainties associated with material recovery and reuse, and potential environmental risks related to nanoparticle release continue to limit large scale implementation. While green synthesis approaches and sustainable material design have been proposed to mitigate these issues, their integration into adsorption research remains inconsistent and insufficiently evaluated in existing reviews[11]. In this context, the present review examines adsorption based approaches for dye removal from wastewater by considering both conventional and recently developed adsorbent materials reported between 2018 and 2025. The discussion emphasizes adsorption mechanisms, key operational parameters such as pH, temperature, contact time, and adsorbent dosage, as well as issues related to regeneration and environmental sustainability. Particular attention is given to nano engineered and green synthesized adsorbents, with emphasis on their reported performance, limitations, and potential for real world application.

## 2. Adsorbent Materials

Adsorbents are solid materials used for the removal of harmful chemical contaminants from wastewater. The following characteristics are required for an effective adsorbent material:

High surface area; Presence of appropriate surface functional groups, such as hydroxyl and amine groups; Suitable pore size distribution; High availability and abundance; Good mechanical strength and stability.

Based on where they come from, natural and manufactured adsorbents fall into separate categories. Natural adsorbents are solids that come from natural sources, like coal, clay, wood, and zeolite. Synthetic adsorbents, on the other hand, originate in labs and include nanotubes from carbon, magnetites, and chemicals[11–13].

### *2.1. Natural Adsorbents*

Natural adsorbents have garnered considerable interest in recent years owing to their environmentally favorable characteristics, economic viability, and substantial efficacy in water and wastewater treatment applications. These materials, sourced from agricultural waste (such as rice husks, coconut shells, and banana peels), clays (including bentonite and kaolinite), zeolites, and biochar, have exceptional adsorption capabilities due to their plentiful surface functional groups and porous architectures[14]. Recent improvements have concentrated on altering these materials to enhance their adsorption capabilities by methods such as surface activation, acid/base treatment, and nanoparticle impregnation. Modified bentonite and biochar have shown improved removal efficiency for heavy metals, dyes, and organic pollutants. Additionally, natural adsorbents have increasingly been mixed with magnetic nanoparticles to make it easier to recover and reuse them, supporting sustainable development goals[15]. Research has looked into using natural adsorbents together in mixed treatment systems to improve how well they remove pollutants and keep the process stable. Moreover, improvements in modifying agricultural waste and using nanotechnology have expanded the use of natural adsorbents in various environmental situations[16]. The comparative information presented in Table 1 confirms that although natural zeolites are cost effective and environmentally acceptable, surface modification or hybridization is often required to enhance their dye adsorption capacity and operational stability.

2.1.1. Activated carbon (AC)

Activated carbon is a solid that has a porous structure and is made up of tiny crystals grouped in a graphite grid. There are two different steps in the process of making activated carbon. A carbon based substance is turned into activated carbon by heating it up or using chemicals on it. The process is meant to get rid of most of the non carbon parts, and a part of the first step shows a concentration of carbon. Carbonization is the process of turning carbonaceous matter into pure carbon by heating it. To do this, dense carbonaceous material is used to make finished goods that are very porous. When particles are carbonized and heated to high temperatures, they burn, which gets rid of surface holes through oxidation. To clean water and wastewater. They are granular activated carbon (GAC), powdered activated carbon (PAC), and woven carbon[17].

2.1.2. Clay

Both natural and modified clay forms have shown significant efficacy in the removal of several heavy metals from aqueous solutions. Clay is a naturally occurring material composed mainly of fine grained particles. that may become pliable with enough moisture and harden upon dehydration or heating[18]. It is a naturally occurring soil substance composed of hydrous aluminum phyllosilicates that demonstrates flexibility upon hydration. Clay resources are plentiful in the environment and economically viable[19]. Clay has lately attracted considerable attention for its effectiveness as an adsorbent in the extraction of heavy metals from aqueous solutions. Clay minerals mostly possess negatively charged ions on their surfaces. This property makes them very effective and is often used in the removal of positive ions from wastewater. The efficacy is due to their capacity to promote cation exchange, together with their considerable pore volume and extensive specific surface area[20].

2.1.3. Agricultural Waste

The leftover products from different forestry and agricultural operations are known as agricultural wastes. There are several benefits to using agricultural waste as an adsorbent to treat wastewater, including affordability, accessibility, quick recovery, chemical durability, low manufacturing requirements, sustainability, and conservation. Farm waste and by product adsorbents provide the needed attributes of high porosity and extensive surface area, making them suitable for water treatment operations[21]. Cellulose, lignin, and hemicellulose are the main components of agricultural waste and by products. The ability of an adsorbent to attract and hold onto substances is greater when lignin contains polar functional groups like ethers, aldehydes, ketones, alcohols, acidic compounds, and phenols. Hypothetical existence. Lately, a range of waste materials and agricultural by-products, including clay, rice husk, onion skin, and wheat waste[22].

2.1.4. Natural Zeolites

Over 40 distinct kinds of natural zeolite have been identified globally. The dominant variants include clinoptilolite, mordenite, phillipsite, chabazite, stilbite, analcime, and laumontite, while the less common forms include offretite, paulingite, barrerite, and mazzite. Clinoptilolite is the principal natural zeolite and is widely used globally[23]. Zeolites are crystalline substances with a three dimensional architecture formed by tetrahedra of silicon and aluminum atoms interconnected by oxygen atoms[24]. The tetrahedra create pathways that help balance water molecules and replace cations, which helps offset the negative charge caused by swapping similar atoms. The aluminum ion is compact enough to reside in the center of a tetrahedron constituted by four oxygen atoms[25]. When $Si^{4+}$ is replaced by $Al^{3+}$, it creates a negative charge in the crystal structure, which is balanced out by cations (like sodium, potassium, or calcium) that can later be replaced by heavy metals. Zeolites have a distinctive chemical formula of Mx/n[AlxSiyO2(x + y)], and their capacity to modify the pH of aqueous solutions is significantly affected by the presence of various cations, including Na, K, Li, Ca, Mg, Ba, or Sr, each demonstrating different charge densities (n) that influence pH levels[26]. These interactions are governed by specific ratios, which vary between 1 and 6 for the y:x ratio and between 1 and 4 for the p:x ratio. Zeolites are known for their unique crystalline structures and are capable of pH modulation through an ion exchange mechanism. Ion exchange efficiency depends on various factors such as the zeolite's framework structure, dimensions, and morphology of the ions, charge density of the zeolite framework, and ionic nature of the exchanged ions[27]. Further, the concentration of exogenous electrolytes has a significant effect on the ion exchange mechanism. These mechanisms have been important in water treatment methods, where zeolites are employed in the removal of specific cations and also in the regulation of pH, hence contributing to the removal of impurities. Herein lies the prospect for zeolite based materials in the provision of sustainable solutions toward water quality control and ecological sustainability[28]. To highlight differences in structure, cation composition, and practical applications, Table 1 summarizes the most commonly reported natural zeolites used in water and wastewater treatment.

**Table 1. Comparative applications and characteristics of major natural zeolites used in water and wastewater treatment**

| Zeolite Type | Chemical Formula | Structure Type | Common Cations | Water Treatment Applications | References |
|---|---|---|---|---|---|
| **Clinoptilolite** | $(Na, K, Ca)_{2-3}Al_3(Al,Si)_2Si_{13}O_{36}\cdot 12H_2O$ | **HEU** | $Na^+$, $K^+$, $Ca^{2+}$ | **Removal of heavy metals, ammonium, and organic pollutants from drinking and wastewater** | **[29]** |
| **Chabazite** | $(Ca,Na_2,K_2)Al_2Si_4O_{12}\cdot 6H_2O$ | **CHA** | $Ca^{2+}$, $Na^+$, $K^+$ | **Adsorption of ammonia and $CO_2$, purification of municipal wastewater** | **[30]** |
| **Mordenite** | $(Na_2,Ca)_4(Al_8Si_{40})O_{96}\cdot 29H_2O$ | **MOR** | $Na^+$, $Ca^{2+}$ | **Adsorption of dyes, phenols, and other organic pollutants from industrial wastewater** | **[31]** |
| **Phillipsite** | $K_2NaCa_2(Si_{10}Al_6)O_{32}\cdot 12H_2O$ | **PHI** | $K^+$, $Na^+$, $Ca^{2+}$ | **Ammonium and phosphate removal from water bodies, improving eutrophication control** | **[32]** |
| **Erionite** | $(Na_2,K_2,Ca)_2Al_4Si_{14}O_{36}\cdot 15H_2O$ | **ERI** | $Na^+$, $K^+$, $Ca^{2+}$ | **Limited due to toxicity; studied for selective adsorption in controlled systems** | **[32]** |
| **Analcime** | $NaAlSi_2O_6\cdot H_2O$ | **ANA** | $Na^+$ | **Used in water softening and trace metal adsorption** | **[33]** |
| **Heulandite** | $(Ca, Na_2)_5Al_9Si_{27}O_{72}\cdot 24H_2O$ | **HEU** | $Ca^{2+}$, $Na^+$ | **Adsorption of radioactive elements and heavy metals from contaminated waters** | **[32]** |

2.1.5. Biochar

Biochar is an economical and reliable material generated by the carbonization of biomass in an oxygen deprived environment. Presently, research has been favoring biochar as an adsorbent material owing to its better properties relative to other adsorbents, including activated carbon. The advantages include a large surface area that helps remove pollutants more effectively, a cost effective way to refresh it, and a unique structure that sets biochar apart from other adsorbents. Also, biochar reduces greenhouse gas emissions and global warming potential (GWP) while enhancing agricultural productivity [35].

*2.2. Synthetic Adsorbents*

Synthetic adsorbents are manmade materials designed to remove chemicals from liquids, gases, or solutions. They are effective for wastewater treatment due to their tailored properties. Common synthetic adsorbents include zeolites, nanoparticles, and polymer composites[36].

2.2.1. Synthetic Zeolites

The most prevalent mineral components found in nature, silica and alumina, are the main raw materials utilized in the production of zeolite. Because clay minerals contain large amounts of silicon and aluminum, they dissolve readily in alkaline solutions and form zeolites. This has led to their widespread use in the synthesis of zeolites. Various zeolite kinds (A, X, N, P, etc.) have been produced with kaolin as an aluminosilicate precursor. Byproducts may serve as a viable source for zeolite manufacturing. Coal fly ash (CFA), which contains a lot of both crystal and non-crystal aluminosilicate, works well as a starting material for making zeolites[37].

2.2.2. Nanoparticles

Nano adsorbents are nanoparticles derived from organic or inorganic substances that have a considerable affinity for adsorption. Due to their extensive surface area, elevated porosity, and reactive surfaces, They are highly effective in removing various types of pollutants. The nanoadsorbents ensure no dangerous payload release while exhibiting exceptional efficiency and speed[38]. One of the most important characteristics of nano adsorbents is regeneration. A regeneration process, which separates the adsorbate from the nanoparticles after adsorption, can recover the same nanoparticles. Metal oxides, polymer based combinations, and carbon compounds are examples of synthetic nano adsorbents, very efficient at removing various contaminants like dyes, heavy metals, and medications. Controlled form and tailored surface chemistry enhance their adsorption kinetics and selectivity[39]. Many times, these materials are prepared with specific functional groups, enhancing their capacity to interact better with the pollutants they intend to catch, improving their effectiveness and reusability[40]. Polymer coated graphene oxide and magnetic nanocomposites are favored due to their excellent solubility in liquids, ease of recovery using magnetic methods, and high efficacy in pollution capture. Lastly, improved efficiency and reusability of nano carbon based adsorbents for water filtration have been addressed by recent studies. Modified carbon nanoparticles have been found highly efficient and reusable to eliminate organic contaminants and heavy metals from water, making them suitable for repeated adsorption procedures[41].

*2.3. Hybrid Adsorbents*

Hybrid adsorbents are increasingly employed for wastewater treatment owing to their efficiency in removing a broad range of contaminants. These materials usually exhibit the ideal combination of organic and inorganic components. They have a large surface area, tunable pore geometries, and the ability to select the substances with which they interact[42]. Hybrid adsorbents in wastewater treatment may selectively remove pollutants such as heavy metals, dyes, pharmaceuticals, and organic compounds. They show better adsorption capacity, selectivity, and reusability than conventional adsorbents[43]. Hybrid adsorbents can be modified to meet specific treatment requirements, making them promising materials for wastewater treatment for sustainable and effective wastewater remediation. Researchers from several fields, including adsorbent development, have explored the potential combination of natural and synthetic materials. This technology has resulted in hybrid adsorbents that, for some applications, improve performance by incorporating the best features of both natural and synthetic materials[44]. Examples include the combination of natural materials like chitosan, zeolites, and activated carbon with man made polymers or small particles in wastewater treatment to enhance their chemical affinity and increase their longevity. Chitosan, a natural material, may be modified or mixed with synthetic polymers to render it more robust and resistant to chemicals that will give rise to its enhanced efficiencies in cleaning up pollutio[45]. The mixing of natural zeolites with synthetic materials, such as polymers or nanoparticles, can enhance their heavy metal and organic pollutants sorption capability in wastewater treatments. Consequently, the synergistic effects of such mixtures bestow unique characteristics onto the adsorbents, hence their potential to effectively eliminate particular pollutants in wastewater and thus enhance water treatment efficiency[46].

*2.4 Critical Comparison and Benchmarking of Adsorbents for Dye Removal*

Different classes of adsorbents have been reported for dye removal; however, direct comparison among them is often limited by differences in experimental conditions and evaluation methods. Many studies focus mainly on adsorption capacity under optimized laboratory conditions, which does not always reflect practical performance in real wastewater systems. Natural adsorbents such as clays, agricultural wastes, zeolites, and biochar are widely available and cost effective, but they generally show moderate adsorption efficiency and slower kinetics, often requiring modification to improve performance and regeneration[9]. Synthetic adsorbents provide better control over surface properties and adsorption stability, although higher production costs may limit their large scale use. Nano adsorbents usually exhibit high adsorption capacity and rapid dye uptake due to their large surface area and active sites; however, concerns related to cost, recovery, and environmental safety remain[36]. Hybrid adsorbents combine features of different materials and often achieve improved performance and reusability, making them a promising compromise between efficiency and practical applicability. Overall, meaningful evaluation of adsorbents requires comparative analysis based on common performance criteria rather than isolated performance indicators. From a practical perspective, scale up feasibility, material cost, and applicability to real industrial wastewater remain critical challenges for adsorption based dye removal[47]. Although nano adsorbents and hybrid materials often demonstrate superior adsorption capacities under laboratory conditions, their large-scale implementation is constrained by high synthesis costs, complex regeneration procedures, and uncertainties related to material recovery. In contrast, natural adsorbents offer economic and operational advantages but generally require surface modification to achieve competitive performance[42]. Furthermore, many reported studies rely on synthetic dye solutions, which do not adequately represent the complexity of real wastewater containing competing ions, organic matter, and fluctuating pH. These factors must be considered when evaluating adsorbents for industrial deployment. Several studies provide quantitative data that allow comparison between different adsorbent classes. In general, nano adsorbents report higher adsorption capacities, often in the range of a few hundred milligrams per gram, compared with many conventional or unmodified materials. This improvement is mainly linked to their large surface area and the presence of active surface sites[48]. Adsorption mechanisms are commonly examined using kinetic and isotherm models, supported by surface analyses such as FTIR, which indicate that electrostatic interactions, surface complexation, and π–π interactions play key roles depending on the dye and adsorbent properties[49]. However, many of these results are obtained under controlled laboratory conditions using single component dye solutions. In real wastewater systems, the presence of competing ions, organic matter, and variable pH can significantly reduce performance. In addition, the environmental and safety aspects of nano adsorbents require careful attention, particularly regarding particle release and reuse. Approaches such as immobilization or magnetic separation have been proposed to address these concerns and improve practical applicability[49].

**Table 2. Comparative Assessment of Adsorbent Classes for Wastewater Treatment Applications[50].**

| Adsorbent Class | Scale up Potential | Cost Consideration | Performance in Real Wastewater |
|---|---|---|---|
| Natural Adsorbents | High | Low | Moderate; affected by competing ions |
| Synthetic Adsorbents | Moderate | Medium to high | Stable but cost limited |
| Nano Adsorbents | Low to moderate | High | Often reduced outside lab conditions |
| Hybrid Adsorbents | Moderate | Medium | Improved stability and reusability |

## 3. Nanoparticles used as Adsorbents for Wastewater Remediation

Wastewater treatment uses various nano adsorbents. They have been shown to be quite effective in eliminating contaminants from water. However, it's difficult to compare their effectiveness directly because many factors come into play, like the size and shape of the nanoparticles, specific conditions (like pH, temperature, and how long the reaction lasts), and how the experiments are set up (whether done in batches or columns). Nano adsorbents can be categorized into the following classes[49].

*3.1 Metal Oxide Nanoparticles*

Metal oxide nanoparticles like TiO2, ZnO, Fe3O4, and Al2O3 are widely studied for their great ability to attract and hold onto substances, thanks to their large surface area, stability, and active sites. For instance, magnetite (Fe3O4) nanoparticles are commonly used to remove dyes and heavy metals because they can be easily modified on their surface and can be recovered using magnets. Also, $TiO_2$ nanoparticles can break down organic pollutants when exposed to UV light, which makes them useful for treating wastewater[51].

*3.2 Carbon Based Nanomaterials*

Another important class of nano adsorbents is activated carbon nanoparticles, graphene oxide (GO), and carbon nanotubes (CNTs). They are very efficient in adsorbing heavy metals and organic pollutants because of their remarkable surface area, π–π interactions, and adjustable surface chemistr[53]. Research has demonstrated how effectively graphene oxide composites can remove dyes, such as rhodamine B and methylene blue, from aqueous environments. Moreover, multi walled carbon nanotubes (MWCNTs) have the capability to sequester many contaminants, including metals, dyes, and pharmaceuticals, because of their hollow, porous architecture and potential for chemical modification[54].

*3.3 Nano Clays and Layered Double Hydroxides (LDHs)*

Big spaces between layers and the ability to swap ions make nanostructured clays (like bentonite and montmorillonite) and LDHs affordable and good for the environment as adsorbents. They are often used to get rid of metal ions and cationic dyes. As stated by [20], Mg Al LDH treated with bio waste more effectively adsorbed Pb(II) and Cd(II) from wastewater. Also, modified bentonite nanoparticles work better at attracting and holding onto pollutants like Congo red and heavy metals, especially when they are treated with acid or surfactants[55].

*3.4 Metal Organic Frameworks (MOFs)*

MOFs are nanoporous materials that are solid and made up of metal ions that are linked to organic ligands. Advanced adsorbents can be engineered with highly tunable pore structures and exceptionally large surface areas. Studies such as [22] have demonstrated that zirconium based metal–organic frameworks are capable of adsorbing a wide range of dyes, including Congo red and methyl orange, even under acidic conditions. Also, copper and iron-based MOFs have shown promise in removing stubborn organic toxins while breaking them down catalytically. This capability makes them useful for cleaning up wastewater in two ways[56].

*3.5 Biopolymer Based Nanoparticles*

Nanoparticles originating from biopolymers, including chitosan, cellulose, and alginate, are attracting interest due to their biodegradability and low toxicity. These materials often have a strong affinity for dye molecules and metal ions via functional groups like amines and hydroxyls. Chitosan nanoparticles mixed with silver showed more than 90% effectiveness in getting rid of lead ions from industrial waste. Recent improvements include biopolymer nanocomposites that are linked together and hybrid systems that use metal oxides, which make them stronger and easier to use multiple times[57].

*3.6 Magnetic Nanocomposites*

Magnetic nanocomposites combine magnetic cores (like Fe3O4) with useful nanomaterials, such as silica, polymers, or carbon compounds, to improve their ability to separate and adsorb substances [25]. made a magnetic GO@Fe3O4 composite that effectively removes antibiotics and dyes, allowing for simple recovery using magnetic separation. These materials provide a significant benefit in post-treatment recovery and regeneration, facilitating numerous reuse cycles and minimizing secondary waste production in treatment systems[58].

## 4. Adsorption Mechanisms

The adsorption method has been extensively used to eliminate natural and organic pollutants from the environment. Adsorption is the process whereby molecules from one phase adhere to the surface of another phase, resulting in a chemical interaction or interphase formation. Based on the type of interaction between adsorbents and adsorbates, we categorize adsorption extraction into two types: physisorption and chemisorption. Physisorption happens through weak van der Waals forces, while chemisorption occurs when contaminants attach to surfaces because of functional groups[59]. Adsorption is often considered the most commonly used method for removal compared to other techniques, owing to its cost effectiveness and operational simplicity[60]. Adsorption processes involve the way wastewater, which contains substances that can stick to surfaces, interacts with a very porous solid material. Intermolecular forces make this interaction possible, which creates an adsorbate and an adsorbent. Adsorption is often regarded as the most used method for elimination due to its cost effectiveness and operational ease[61]. The adsorbent's capability for the adsorption process is contingent upon the following characteristics.

- Quantity of adsorbent used
- Concentration of pollutants in sewage
- Temperature (T)
- pH
- Contact time(t)
- Adsorption Capacity (mg/g)

The presence of oils, greases, and suspended particles also affects adsorption efficacy. When industrial effluents interact with adsorbents, contaminants attach to the surfaces of the adsorbents, creating a state of equilibrium. The adsorption isotherm and kinetic models assess the effectiveness of the adsorption process[62]. The porosity, surface area, polarity, and functional groups present on the adsorbent's surfaces also influence its effectiveness. Adsorbents may be rejuvenated by desorption. Consequently, the regenerated adsorbents may also be used for adsorption and further applications. Adsorbent regeneration may be accomplished by several methods, including electrochemical regeneration, thermal regeneration, and pressure swing techniques [63].

Table 3 provides a comparative overview of commonly reported adsorbents, highlighting not only adsorption capacity and effective pH ranges but also key operational parameters such as contact time and temperature. These parameters play a decisive role in evaluating the practical applicability of adsorption systems. Advanced materials such as graphene oxide, magnetic nanocomposites, and Zr-based metal–organic frameworks exhibit high adsorption capacities and shorter equilibrium times, reflecting faster adsorption kinetics under controlled laboratory conditions. In contrast, conventional adsorbents such as activated carbon and biochar demonstrate broader pH tolerance and stable performance across wider temperature ranges, particularly in real wastewater matrices. The inclusion of contact time and temperature data underscores that high adsorption capacity alone is insufficient to assess real-world feasibility, as operational efficiency, energy requirements, and treatment duration are equally critical. This comparison reveals a persistent gap between laboratory-scale performance and practical wastewater treatment conditions, emphasizing the need for future research to prioritize operational optimization alongside material development.

**Table 3. Summarizes the adsorption capacities, pH ranges, contact time, and Temperature performance in synthetic and real wastewater of selected adsorbents reported in the literature.**

| Adsorbent | Adsorption Capacity (mg/g) | pH Range | Contact time (t) | Temperature (T) | Wastewater Type | Reference |
|---|---|---|---|---|---|---|
| Activated Carbon | 150–320 | 4–9 | 30–180 min | 25–40 °C | Synthetic / Real | 64 |
| Bentonite Clay | 40–120 | 5–8 | 60–240 min | 25–35 °C | Synthetic | 65 |
| Biochar | 80–250 | 3–9 | 45–180 min | 25–50 °C | Synthetic / Real | 66 |
| Graphene Oxide | 200–450 | 4–8 | 15–90 min | 25–40 °C | Synthetic | 67 |
| Magnetic Nanocomposite | 180–400 | 5–9 | 30–120 min | 25–45 °C | Real | 68 |
| Zr-based MOFs | 300–500 | 3–7 | 10–60 min | 25–35 °C | Synthetic | 69 |

*4.1 Chemical Adsorption*

Chemical adsorption transpires via the establishment of chemical bonds via the sharing or exchange of electrons between the adsorbate and the adsorbent[64]. We are able to describe how certain functional groups on the adsorbent surface interact with the adsorbate ions. Compared to physical adsorption, this irreversible mechanism works better at comparatively high temperatures. Depending on the energy changes that take place during the adsorption process, chemisorption may be either exothermic or endothermic. The chemistry and variety of the material that attracts other substances, the properties of the substances being attracted, and the environment of the water solution all affect the complex interactions between the active parts on the surfaces of the attracting materials and the substances being attracted[65]. A schematic representation of the chemical adsorption process is shown in Figure 1[66].

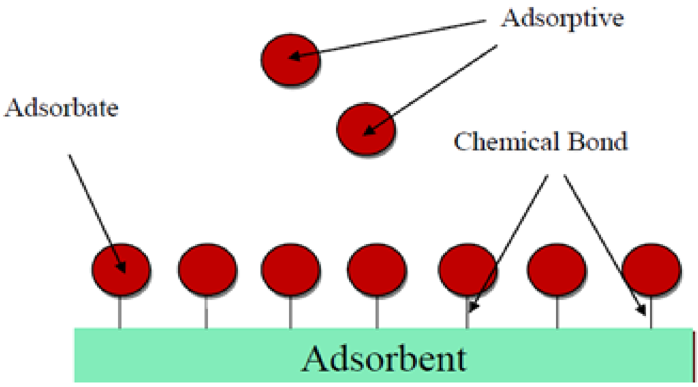


**Figure 1. Schematic representation of the chemical adsorption process**

*4.2 Physical Adsorption*

Physical adsorption, or physisorption, is a weak process where there are only slight attractive forces between the substance being adsorbed and the surface it sticks to. The forces that keep the adsorbate in place come from interactions between positive and negative charges, weak attractions, and van der Waals forces. Physisorption is an easily reversible phenomenon. The balance of physical adsorption is quickly reached, depending on the size of the pores on the surface and the size of the tiny holes in the solid adsorbent. The speed of physisorption is inversely correlated with the molecular weight of the adsorbate [67].

The type of raw material and how it's prepared, like the temperature used for modification and carbonization, are important factors that influence the surface pores of activated carbon adsorbents. Also, the way the surface interacts with different functional groups can help with physical adsorption, especially by attracting heavy metals to the carbon surface through electrical forces and ion dipole interactions. Figure 2 illustrates a schematic of the physical adsorption process[68].

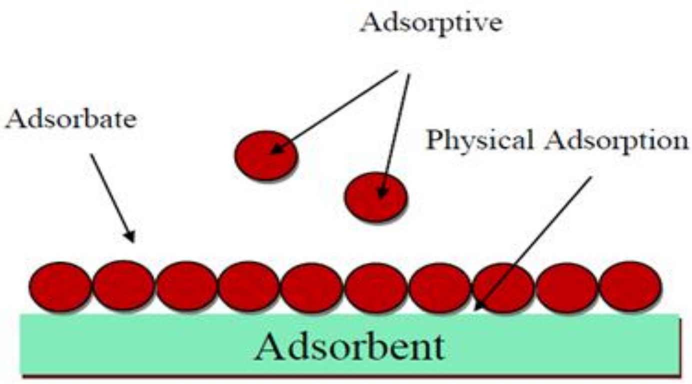


**Figure 2. Schematic representation of the physical adsorption mechanism.**

Figure 3 schematically summarizes the principal adsorption mechanisms governing dye removal from aqueous systems, including electrostatic interactions, ion exchange, and surface complexation. These mechanisms are illustrated in relation to key physicochemical factors such as surface charge distribution, the presence of exchangeable ions, and the nature and density of surface functional groups, all of which critically influence adsorption efficiency and selectivity[9]. Electrostatic attraction or repulsion between dye molecules and the adsorbent surface is shown to depend strongly on solution pH and the point of zero charge, while ion exchange processes involve the replacement of counterions on the adsorbent surface by dye species. Surface complexation is depicted as the formation of specific chemical interactions between dye molecules and active functional groups, contributing to stronger and more stable adsorption. In addition, Figure 3 presents a classification of adsorbents into natural, synthetic, nano engineered, and hybrid materials, providing a unified visual framework that links material type to dominant adsorption mechanisms and performance characteristics. This integrated representation facilitates comparison across different adsorbent classes and highlights how material design and surface chemistry govern adsorption behavior in dye removal applications[4].

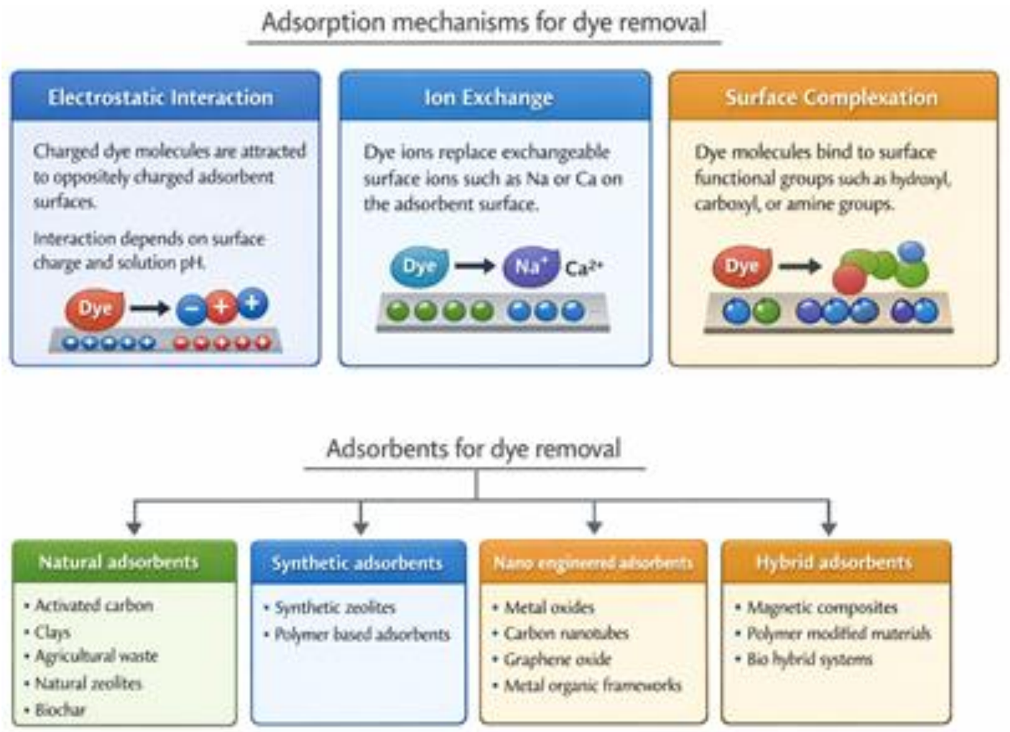


**Figure 3. Schematic illustration of dye adsorption mechanisms and classification of adsorbents.**

## 5. Future prospects

Despite significant advances in adsorbent development, several challenges remain that limit practical application. While nano and hybrid adsorbents demonstrate superior adsorption capacities under controlled conditions, issues such as high production costs, nanoparticle recovery, and environmental safety have yet to be fully addressed. Similarly, conventional adsorbents like clays and biochar offer economic advantages but often require surface modification to achieve competitive efficiency. Future research should focus on developing adsorbents that balance cost, regeneration efficiency, and real-world applicability, particularly under the complex conditions of industrial wastewater. Additionally, scaling laboratory successes to pilot or full-scale systems remains a critical step toward industrial implementation, necessitating comprehensive evaluation of material stability, selectivity, and reusability. By integrating insights from natural, synthetic, and nano-engineered materials, future work can advance adsorption technologies that are both effective and sustainable.

The volume of research on adsorbents for wastewater treatment is increasing, further underlining the urgent need and importance of this field of study. However, there are quite a few major flaws that need further examination and development:

1. The pressing need of the hour is the development of more effective and selective adsorbents to make sure that all pollutants are completely removed, thereby increasing the efficiency of the treatment process as a whole.
2. Economical and regenerable adsorbents: Economic feasibility is one of the main factors affecting the possibility of using various adsorbents on an industrial scale. Thus, the elaboration of economic adsorbents that could be regenerated and applied several times without significant loss of their efficiency is a focus for all future research.

3. Sustainable Alternatives: Development of the adsorbents in an eco-friendly way is a very important factor. This involves using sustainable materials, and the adsorbents as such would not be a cause of environmental contamination.
4. Real Industrial Effluents: Most investigations today use artificial wastewater, which might not simulate the intricacy of real industrial effluents. Because of this fact, research studies using real industrial wastewater will better assess the performance of the adsorbent.
5. Different adsorbents need to be tested under identical conditions by comparative studies. In other words, practicality, efficiency, and cost of various methods of elimination of various pollutants should be checked, so the areas of comparative advantage are highlighted.
6. Future adsorbents should be more stable, especially under fluctuating pH conditions and when subjected to a variety of chemicals commonly encountered in contaminated water, to remove a number of contaminants simultaneously. More importantly, these adsorbents can efficiently remove various pollutants such as hazardous metal ions, organic dyes, and bacterial infections all at once.
7. Pilot and commercial scale applications: The study process from benchtop scale in the laboratory should progress to the pilot and full commercial scale. This means optimization and deployment of the advanced adsorbents into column operations that realistically mimic the process environment.

## 6. Conclusions

Adsorption remains one of the most effective methods for removing dyes from wastewater, offering a balance of efficiency, cost-effectiveness, and sustainability. Traditional adsorbents like activated carbon, clays, and agricultural waste are affordable but limited in performance, while advanced materials nanomaterials, metal organic frameworks, and carbon-based composites provide higher capacity, faster removal, and reusability. Adsorbent efficiency depends on factors such as dosage, dye concentration, pH, contact time, and temperature, as well as surface properties and functional groups. Despite progress, challenges such as cost, regeneration, and real wastewater application remain. Future work should focus on improving selectivity, stability, and practical applicability, bridging the gap between lab studies and real world implementation for sustainable dye removal.

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