



Research Article

Review: The Development of Polymer Use as Adsorbents in Industrial Wastewater Treatment Processes

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Abstract

The utilization of polymers, both synthetic polymers and biopolymers, as adsorbents in industrial wastewater treatment has shown significant progress in recent years. Numerous studies have reported that natural polymers such as cellulose, chitosan, and alginate, as well as synthetic polymers including ion-exchange resins, porous polymeric materials, and polyaniline, exhibit high adsorption capacities toward a wide range of pollutants. These materials have been widely applied in the treatment of wastewater from various industrial sectors, including textile industries (dyes), heavy metals, pharmaceuticals, food and beverage processing, and petrochemical industries containing hydrocarbon compounds. Adsorption occurs through several mechanisms, including ion exchange, complexation or chelation by functional groups such as $-NH_2$, $-COOH$, and $-OH$, hydrogen bonding, as well as π - π interactions and electrostatic forces. Biopolymers offer advantages in terms of sustainability, biodegradability, and relatively low production costs, whereas synthetic polymers are superior in mechanical strength, thermal stability, and higher selectivity toward specific pollutants. Although many studies have reported very high pollutant removal efficiencies, often exceeding 90%, large-scale implementation still faces several challenges, particularly related to process scalability, selectivity toward complex mixtures of pollutants, regeneration capability, and the long-term stability of adsorbents for repeated use. This article comprehensively reviews the literature on the classification and application of polymers as adsorbents, the underlying adsorption mechanisms, their physicochemical properties, and their practical implementation in industrial wastewater treatment. In addition, the challenges encountered, potential solutions, and future development trends of polymer-based adsorbents are also discussed.

Keywords: polymer adsorbents, wastewater, adsorption, industrial wastewater, adsorption efficiency

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1. Introduction

The rapid expansion of the industrial sector has led to a substantial increase in the volume and complexity of wastewater generated. This wastewater contains a diverse range of chemical and biological contaminants that pose significant risks to aquatic ecosystems (Gupta et al., 2022). For example, effluents from textile industries commonly contain sulfonated aromatic dyes that are persistent and resistant to natural degradation processes. In contrast, wastewater from metal-based industries often carries hazardous heavy metals such as lead (Pb), chromium (Cr), and cadmium (Cd), which are highly toxic and prone to bioaccumulation in aquatic

ecosystems (Sahu et al., 2025). In addition, the presence of pharmaceutical residues and hydrocarbon compounds originating from petrochemical industrial activities further intensifies environmental pollution.

As the complexity of industrial wastewater management continues to grow, the need for effective and adaptable treatment technologies becomes increasingly critical. In this regard, adsorption is widely recognized as a promising treatment method due to its operational simplicity, high flexibility, and efficient pollutant removal performance (Gupta et al., 2022; Sahu et al., 2025). Moreover, the application of polymers as adsorbent materials offers distinct advantages in terms of physicochemical properties, including well-developed porous structures that enhance adsorption, tunable specific surface areas, and the presence of active functional groups that can be readily modified to improve affinity toward specific target pollutants (Alam et al., 2025). Collectively, these characteristics highlight the strong potential of polymer-based adsorbents to enhance the efficiency and effectiveness of industrial wastewater treatment processes.

Synthetic polymers, such as sulfonated polystyrene resins, have been widely applied in ion-exchange systems for the removal of charged species and heavy metals (Elfeghe et al., 2022). Despite their high performance, concerns regarding environmental persistence and sustainability have driven the exploration of alternative materials. In this context, biopolymers such as chitosan and alginate have emerged as promising candidates due to their biodegradability, renewability, and competitive adsorption capacities (Amiri et al., 2023). However, their practical application in industrial scale systems remains limited by factors such as mechanical stability, regeneration efficiency, and performance in multi-pollutant environments.

Therefore, this review aims to provide a comprehensive and critical analysis of recent developments in polymer-based adsorbents for industrial wastewater treatment. Unlike previous review studies, this work emphasizes the integration of polymer structure, adsorption mechanisms, pollutant characteristics, and industrial application contexts to provide a more holistic understanding of adsorption performance. Furthermore, this review distinguishes between laboratory-scale findings and their applicability in real industrial systems, highlighting current limitations and identifying future research directions for the development of more efficient and sustainable adsorption technologies.

2. Methodology

This research was conducted in the form of a systematic literature review and was carried out through four main stages: the preparation stage, literature review, data collection, and data analysis, as illustrated in Figure 1.

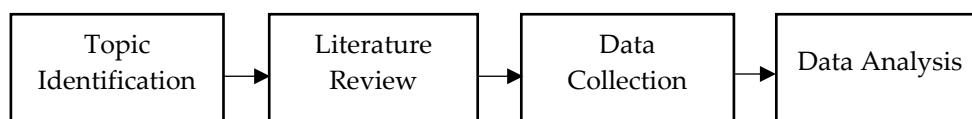


Figure 1. Framework of the review process

2.1 Topic identification phase

The preparation phase commenced with the definition of the review scope, focusing on the application of synthetic polymers and biopolymers as adsorbents in industrial wastewater treatment. During this phase, the objectives of the literature review were explicitly established, accompanied by the formulation of a conceptual framework and a coherent structure for the discussion. This structure encompasses the classification of polymer-based materials, the fundamental adsorption mechanisms, their applications in various industrial sectors, as well as the associated challenges and future development perspectives. Furthermore, the theoretical basis of the review was reinforced through an examination of fundamental adsorption principles and the relevant characteristics of industrial wastewater, thereby ensuring that the discussion is well-founded and systematically presented.

2.2 Literature review phase

The literature review phase was conducted through a systematic examination of scientific publications relevant to the topic, utilizing several leading academic databases, including Google Scholar, Scopus, and

Web of Science. The literature search was performed using keywords such as “polymeric adsorbents,” “biopolymer adsorbents,” and “adsorption wastewater treatment,” along with other related terms to ensure comprehensive coverage of the research scope. The selection of articles was not arbitrary but was based on their relevance, scientific impact, and contribution to the advancement of polymer-based adsorption technologies. Priority was given to studies that are frequently cited, published in reputable peer-reviewed journals, and that provide significant insights into adsorption mechanisms, material development, and industrial applications. In addition, recent publications were emphasized to capture the latest technological developments and research trends in this field.

The literature selection process was conducted systematically following the PRISMA guidelines, as illustrated in Figure 2.

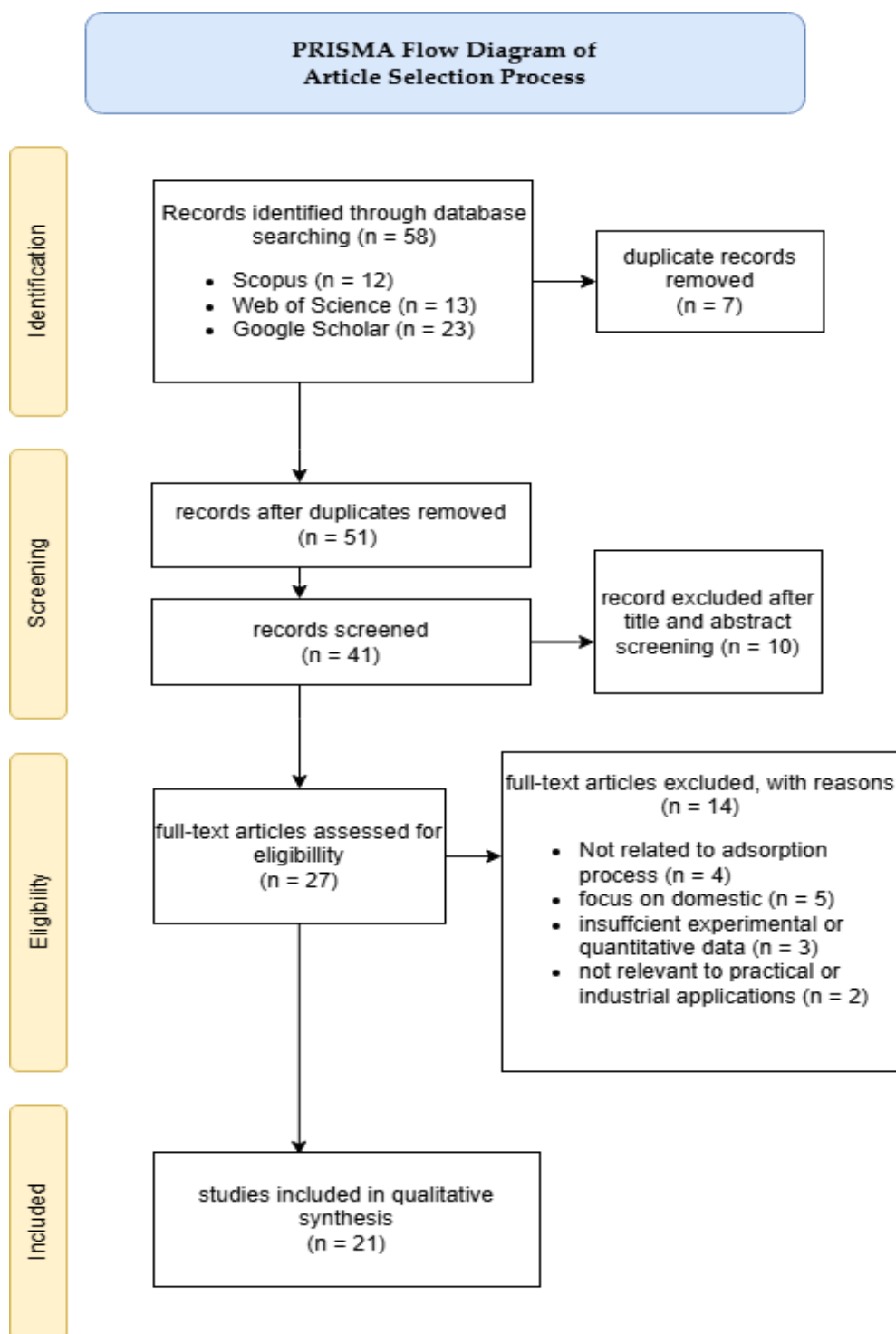


Figure 2. PRISMA flow diagram of the literature selection process

A total of 58 articles were initially identified through database searching using Google Scholar, Scopus, and Web of Science. After removing duplicate and irrelevant records, 41 articles remained for the screening stage. During the screening process based on titles and abstracts, a number of articles were excluded due to their lack of relevance to polymer-based adsorption and industrial wastewater treatment. Subsequently, 27 full-text articles were assessed for eligibility. Among these, several articles were further excluded due to reasons such as insufficient experimental data, non-industrial application focus, or lack of relevance to adsorption processes.

Finally, a total of 21 articles met the inclusion criteria and were selected for further analysis in this review. This systematic selection process ensures that the included studies are relevant, reliable, and representative of recent developments in polymer-based adsorption technologies.

2.3 Data collection phase

The data collection phase was conducted through the systematic extraction and organization of information from the selected literature to obtain relevant data supporting the objectives of this review. A total of 21 articles published between 2019 and 2025 were analyzed, which were retrieved from major academic databases, including Google Scholar, Scopus, and Web of Science. The data gathered included the types and characteristics of pollutants in industrial wastewater, the types and properties of polymeric adsorbents, the reported adsorption mechanisms, as well as key performance indicators such as adsorption capacity and pollutant removal efficiency. In addition, information regarding the application of polymer-based adsorption technologies at both laboratory and industrial scales was also collected. All data used in this review were derived exclusively from published literature and did not involve direct experimental work, ensuring that the analysis is fully based on existing empirical studies. This approach enhances the transparency, representativeness, and reliability of the review.

2.4 Data analysis

The data analysis phase was conducted through a critical and comparative examination of the data obtained from the selected literature. To ensure a systematic and transparent selection process, inclusion and exclusion criteria were applied. The inclusion criteria comprised: (1) studies focusing on polymer-based adsorbents, including both synthetic polymers and biopolymers; (2) applications related to industrial wastewater treatment; (3) studies reporting adsorption performance parameters such as adsorption capacity and removal efficiency; and (4) articles published in peer-reviewed journals within the period of 2019–2025.

The exclusion criteria included: (1) studies not related to adsorption processes; (2) studies focusing on domestic or non-industrial wastewater; (3) articles lacking sufficient experimental or quantitative data; and (4) studies not relevant to practical or industrial applications. Based on these criteria, the selected articles were analyzed to evaluate the performance of different polymeric adsorbents, identify their strengths and limitations, and assess their suitability for various industrial wastewater characteristics. The findings were then systematically synthesized to construct a comprehensive and critical narrative. Furthermore, this analysis was used to identify existing research gaps and to propose future research directions in polymer-based adsorption technologies.

3. Result and Discussion

3.1 Classification of polymers

Adsorbent polymers can generally be classified into two main groups, namely synthetic polymers and biopolymers, each offering distinct advantages depending on the application conditions. Synthetic polymers, such as sulfonated polystyrene, polyaniline, and acrylic-based polymers, are widely utilized due to their high mechanical strength, tunable surface properties, and stability under extreme operating conditions, including high temperature, varying pH, and complex wastewater composition. These characteristics make synthetic polymers more suitable for industrial-scale applications, particularly in systems containing high concentrations of pollutants or multi-component contaminants, where durability and consistent performance are required. In contrast, biopolymers such as chitosan, alginate, cellulose, and starch are increasingly

explored as sustainable alternatives due to their biodegradability, renewability, and environmentally friendly nature (Amiri et al., 2023).

Biopolymers are particularly effective in low to moderate pollutant concentrations and in applications where environmental impact and cost efficiency are prioritized. For example, chitosan exhibits strong adsorption of heavy metal ions through chelation mechanisms due to the presence of amino and hydroxyl functional groups, making it suitable for wastewater with relatively simpler compositions.

Table 1. Classification of adsorbent polymers in industrial wastewater treatment

Category	Material	Type	Targeted Pollutant	Dominant Mechanism	Reference
Synthetic	Sulfonated polystyrene	Synthetic	Pb(II), Cu(II)	Ion exchange	(Lau et al., 2023)
Synthetic	Acrylic copolymer	Synthetic	Reactive dyes	Electrostatic adsorption	(Zhang et al., 2022)
Synthetic	Polyaniline	Synthetic	Cr(VI)	Redox-complexation	(Duhan & Kaur, 2020)
Biopolymer	Chitosan	Chitin	Pb(II), Cd(II)	Chelation	(Tandekar et al., 2022)
Biopolymer	Alginate	Algae	Heavy metals	Ion exchange	(Wang et al., 2021)
Biopolymer	Modified cellulose	Biomass	Dyes	Hydrogen bonding	(Zhao et al., 2019)

Synthetic polymers generally possess advantages such as high porosity and good mechanical strength, whereas biopolymers offer benefits in terms of abundant availability and biodegradability. For instance, chitosan contains amino and hydroxyl functional groups that play a crucial role in binding contaminants, while synthetic polymer resins can be engineered to incorporate sulfonate or amino groups to enhance surface functionalization and interactions with target pollutants.

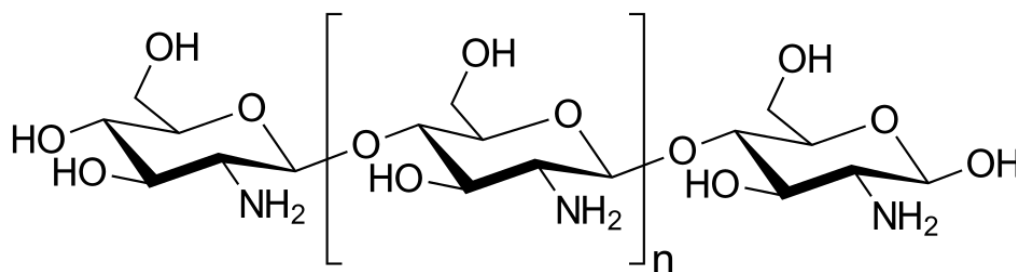


Figure 3. Chemical structure of chitosan, a polysaccharide polymer composed of β -(1 \rightarrow 4)-linked D-glucosamine (amino groups) and N-acetyl-D-glucosamine (acetyl groups).

As one of the most extensively studied biopolymers, chitosan is often modified and applied as an adsorbent for the removal of heavy metals and organic dyes due to the presence of its functional groups, which play an active role in adsorption interactions (Chandra et al., 2023). Chitosan-based adsorbents and their derivatives exhibit high adsorption capacities for both heavy metal ions and organic dye compounds, primarily attributed to the presence of amino and hydroxyl groups in their molecular structure. Moreover, chitosan can be relatively easily modified through various methods, such as silylation or grafting, to enhance its adsorption capacity and mechanical stability.

Synthetic polymers, such as porous resins like polyaniline, generally possess very high surface areas and are capable of adsorbing aromatic hydrocarbon pollutants through π - π interactions. Meanwhile, other biopolymers such as cellulose and starch are often preferred due to their abundant availability, particularly from biomass waste, as well as their ability to be modified with specific functional groups to enhance adsorption performance. The main advantages of these biomass-based polymers lie in their environmentally friendly nature, suitability as green materials, and potential for sustainable production from renewable resources.

However, the application of biopolymers in industrial systems is often limited by lower mechanical stability, sensitivity to pH variations, and reduced performance in complex multi-pollutant environments. Therefore, while biopolymers are advantageous for green and sustainable treatment processes, synthetic polymers remain more appropriate for harsh industrial conditions requiring high stability and long-term operation. To address these limitations, recent studies have focused on the development of modified biopolymers and hybrid materials, combining the environmental benefits of biopolymers with the structural strength of synthetic polymers. This approach provides a promising pathway for optimizing adsorption performance while maintaining sustainability in industrial wastewater treatment applications.

3.2 Adsorption mechanisms

The adsorption of pollutants on polymer-based adsorbent surfaces can occur through two main mechanisms: physical adsorption (physisorption) and chemical adsorption (chemisorption). The effectiveness of pollutant adsorption by polymers is strongly influenced by the interaction mechanism between the adsorbent surface and the pollutant molecules. These mechanisms can be either physical or chemical, depending on the functional groups present on the polymer and the characteristics of the adsorbed pollutants. To clarify the relationship between the type of adsorption mechanism, functional groups, and target pollutants, Table 2 summarizes the common adsorption mechanisms observed in polymer-based adsorbent systems, along with representative material examples.

Table 2. Adsorption mechanisms of polymers and pollutant interactions

Mechanism	Functional group	Type of interaction	Common pollutant	Example polymer	Reference
Physical adsorption	-OH	Van Der Waals	Dyes	Cellulose	(Haleem et al., 2023)
Chemical adsorption	-NH ₂	Chelation	Pb(II)	Chitosan	(Alkhalidi et al., 2024)
Ion exchange	-SO ₃ H	Electrostatic	Cu(II)	PS Resin	(Khan et al., 2024)
Π - π Interaction	Aromatic Ring	π - π Stacking	Aromatic dyes	Polyaniline	(Liang et al., 2025)
Hydrogen bonding	-OH, COOH	H-Bonding	Pharmaceuticals	PVA	(Z. Hu et al., 2025)

As shown in Table 2, the adsorption performance of polymer-based adsorbents is strongly influenced by the type of functional groups and the dominant interaction mechanisms involved. Adsorbents containing polar functional groups such as hydroxyl (-OH) and carboxyl (-COOH) generally exhibit effective adsorption of polar pollutants through hydrogen bonding and dipole interactions. In contrast, polymers functionalized with amino (-NH₂) and sulfonate (-SO₃H) groups demonstrate higher affinity toward heavy metal ions due to electrostatic interactions and coordination bonding, which contribute to enhanced adsorption capacity and selectivity. Meanwhile, polymers with aromatic structures show improved performance in removing organic dyes and aromatic compounds, primarily due to π - π interactions and hydrophobic effects. These findings indicate that the effectiveness of polymer-based adsorbents is not only determined by their surface area, but also by the compatibility between the functional groups of the adsorbent and the chemical characteristics of the target pollutants. This relationship highlights the importance of material design in optimizing adsorption performance for specific industrial wastewater applications.

Under certain conditions, precipitation adsorption can occur when pollutants form insoluble compounds that subsequently deposit on the adsorbent surface. Another reported mechanism is biosorption, particularly in polysaccharides or microbial extracellular polymers, which proceeds through a combination of ion exchange, complexation, and physical adsorption (Pagliaccia et al., 2022). In addition, hydrophobic interactions play a role in promoting the binding of non-polar pollutant molecules to relatively less hydrophilic adsorbent surfaces. Specifically, the presence of π - π interactions between aromatic rings in polymer structures, such as

polyaniline or aromatic carbon-based adsorbents, and aromatic pollutants can enhance the adsorbent's affinity for dyes and aromatic organic compounds (X. Hu et al., 2022).

3.3 Industrial applications

A clear distinction between laboratory-scale results and industrial-scale applications is essential in evaluating the practical feasibility of polymer-based adsorption technologies. Most studies report high adsorption performance under controlled laboratory conditions, where variables such as pollutant concentration, pH, and temperature are carefully regulated. However, real industrial wastewater systems are significantly more complex, often containing multi-component pollutants, fluctuating conditions, and potential interfering substances that may reduce adsorption efficiency. In addition, factors such as large-scale operation, cost, material regeneration, and long-term stability present further challenges for industrial implementation. Therefore, while laboratory-scale findings demonstrate the potential of polymer-based adsorbents, their practical application at the industrial scale requires further investigation, particularly in terms of performance under realistic conditions, economic feasibility, and operational sustainability.

Table 3. Applications of polymeric adsorbents in various industrial sectors

Sector	Waste type	Polymer	Scale	Efficiency (%)	Reference
Textile	Dyes	Chitosan	Lab	92	(Harimu et al., 2022)
Heavy metals	Pb, Cd	Synthetic resin	Pilot	95	(Khaliq et al., 2025)
Pharmaceutical	Antibiotics	PVA	Lab	85	(Rahman et al., 2025)
Food	Synthetic dyes	Cellulose	Lab	88	(Elzahar & Bassyouni, 2023)
Petrochemical	Aromatic compounds	Polyaniline	Pilot	90	(Hsini et al., 2021)

Adsorbents have been widely applied in the treatment of wastewater across various industrial sectors. In the textile industry, polymers are extensively used to reduce the color intensity of effluents, including those containing both anionic and cationic dyes. For instance, activated chitosan and various polysaccharide-based composites have been reported to effectively adsorb dyes such as methylene blue, crystal violet, and reactive yellow with high efficiency (Ahmad & Ejaz, 2023). Additionally, several studies have also reported the use of porous polymer-based resins capable of removing methylene blue at capacities reaching tens to even hundreds of mg/g, demonstrating excellent adsorption performance.

In the treatment of wastewater containing heavy metals, polymers have also demonstrated high effectiveness against various hazardous ions such as Cr(VI), Pb(II), Hg(II), and Cd(II) (Gupta et al., 2022). Chitosan-melamine composites have been reported to exhibit very high adsorption capacities, reaching up to 618.2 mg/g for Pb(II) and 490.7 mg/g for Hg(II) (Chandra et al., 2023). In the pharmaceutical sector, the use of polymers has increasingly been studied for the removal of drug residues, such as anti-inflammatory compounds and antibiotics, from wastewater. The tunable nature of polymers allows for the more selective and efficient adsorption of organic compounds (Savigni et al., 2025).

Furthermore, the food and beverage industry utilizes polymer-based adsorbents to remove phenolic compounds and pigments before wastewater is discharged into the environment. In the petrochemical sector, polymers are employed to adsorb residual aromatic hydrocarbons and phenolic compounds that have the potential to contaminate water bodies. The development of adsorbent materials also includes the use of polymer-fiber composites and polymer-based hydrogels, which are applied in filtration systems or as alternatives to, or supports for, polymer-based activated carbon. This cross-sector application highlights the important role of polymer adsorbents in liquid purification across various fields, including the pharmaceutical, food and beverage, and biotechnology industries (Khan et al., 2024).

3.4 Case studies and efficiency

Various experimental studies have documented the high performance and efficiency of polymer-based adsorbents. For instance, silica-reinforced chitosan hydrogels and modified starch-based polymer resins have

been reported to achieve pollutant removal efficiencies exceeding 90% under optimal operating conditions (Meetam et al., 2024). A notable example is the chitosan–graphite–melamine adsorbent (GMCS), which exhibited an adsorption capacity for Pb(II) ions of up to 618.2 mg/g (Chandra et al., 2023). Additionally, biopolymer adsorbents such as SFP or plant-based biosorbents have been reported to remove methylene blue dye with exceptionally high adsorption capacities, reaching 803 mg/g (Alam et al., 2025).

Adsorbent performance is a critical parameter for evaluating the potential application of a material in wastewater treatment. Parameters such as adsorption capacity, optimal operating conditions, and adsorbent stability are commonly used as indicators of material effectiveness. Therefore, Table 4 presents a summary of the adsorption performance data of various polymeric adsorbents against industrial wastewater pollutants, including reported adsorption capacities and operational conditions from recent studies, providing a basis for comparative evaluation of material performance.

Table 4. Adsorption performance of polymers against industrial wastewater pollutants

Adsorbent polymer	Pollutant	Adsorption capacity (mg/g)	Optimum pH	Temperature (°C)	Reference
Modified chitosan	Pb(II)	210	5	25	(Alam et al., 2025)
Alginate	Cd(II)	165	6	30	(Kamal et al., 2024)
Acrylic copolymer	Reactive dyes	350	7	25	(de Mello et al., 2022)
Polyaniline	Cr(vI)	280	2	30	(Adeiga & Pillay, 2024)
Cationic cellulose	Methylene blue	190	8	25	(Chen et al., 2022)

High adsorption performance is also demonstrated by chitosan/nano-hydroxyapatite composites, which exhibit a Cd(II) ion adsorption capacity of 127 mg/g. Another study reported that sulfonated polystyrene (SPS) resin synthesized from polystyrene plastic waste can adsorb Pb(II) and methylene blue, although its adsorption capacity is relatively lower compared to other adsorbents. Nevertheless, this material offers advantages in terms of ease of regeneration and the potential utilization of plastic waste (Elfeghe et al., 2022). Overall, these data confirm that polymer-based adsorbents can be engineered to achieve high adsorption capacities, with adsorption kinetics and isotherm characteristics, such as the Langmuir or Freundlich models, making them highly promising for application in industrial wastewater treatment.

3.5 Challenges and future prospects

Despite their promising potential, the use of polymers as adsorbents still faces several challenges that need to be addressed. The main technical challenges include the regeneration and recycling of adsorbents once saturation is reached, the long-term stability of polymer materials under extreme environmental conditions—such as highly acidic or alkaline pH and the presence of strong oxidizers—and the relatively high production costs of functionalized polymers. Additionally, practical challenges relate to the adsorption selectivity in complex solution systems and limitations in scaling up the process for larger industrial applications (Alam et al., 2025). Some types of synthetic polymers also exhibit low degradation rates, requiring careful post-use management to prevent the creation of new environmental issues.

This can be achieved through the development of more innovative materials and technologies. The development of multifunctional polymer composites, for example by integrating antimicrobial nanoparticles or catalytic materials, is expected to provide additional functions such as disinfection and filtration within a single adsorbent material. Furthermore, integrating polymer-based adsorption technology with other treatment processes, such as membrane filtration or photocatalysis, has been proposed as an approach to enhance overall wastewater treatment efficiency. On the other hand, increased utilization of renewable biomass-based polymers is considered to have the potential to reduce the carbon footprint of adsorbent materials while supporting sustainability concepts (Alam et al., 2025). Recent research has also begun focusing on modeling structure–adsorption relationships to design polymers with more selective affinity for target

pollutants. Overall, hybrid material innovation and process optimization are key factors for future research development in the use of polymers as an effective and sustainable solution for industrial wastewater treatment.

4. Conclusion

Polymeric adsorbents represent an effective alternative for industrial wastewater treatment due to their easily modifiable surface properties and high adsorption capacities for a wide range of pollutants. Based on their material type, polymeric adsorbents can be classified into synthetic polymers, such as ion-exchange resins, acrylic copolymers, poly(vinyl alcohol), and polyaniline, as well as biopolymers, including chitosan, cellulose, alginate, and starch. These materials operate through a combination of physical and chemical adsorption mechanisms, as reported in various studies.

Various studies have demonstrated significant adsorption performance, particularly in the removal of heavy metal ions and dyes. Adsorption capacities for Pb(II) ions have been reported to reach hundreds of mg/g, while polymer-based adsorbents also show high effectiveness in dye removal with comparable capacities. The application of polymeric adsorbents spans multiple industrial sectors, including textiles, heavy metal processing, pharmaceuticals, the food and beverage industry, and petrochemicals. This highlights the flexibility and significant potential of polymer-based adsorption technologies in treating wastewater with diverse characteristics.

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