Recent Advances in Activated Carbon Applications for Water Treatment

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Abstract. Activated carbon has long been recognized as one of the most effective adsorbents for water purification due to its high specific surface area, adjustable pore structure, and rich surface functional groups. In recent years, it has been widely applied in the removal of organic dyes, heavy metal ions, and emerging pollutants from wastewater, showing strong adsorption capacity and good regeneration potential. This paper systematically reviews the adsorption mechanisms of activated carbon, including physical adsorption, electrostatic interaction, ion exchange, and π–π stacking effects, and highlights how factors such as pore size distribution, surface chemistry, and functional modification influence adsorption efficiency. Special attention is given to modification strategies, such as chemical activation, surface oxidation, and composite material synthesis, which have been proven to enhance removal performance and extend service life. At the same time, the economic cost and environmental sustainability of activated carbon preparation and regeneration are analyzed, with a focus on challenges such as resource consumption and secondary pollution. Current applications still face shortcomings in achieving high efficiency at low cost, large-scale regeneration, and environmentally friendly disposal. Future research should therefore prioritize the development of green preparation technologies, synergistic adsorption–catalysis processes, and sustainable regeneration methods, providing theoretical and practical references for the optimized application of activated carbon in water treatment systems.

Keywords: Activated Carbon; Water Purification; Adsorption Mechanism; Heavy Metals; Organic Dyes.

1. Introduction

Industrial development has resulted in increasing water pollution by both heavy metals (e.g., Cd^{2+}, Pb^{2+}) and organic dyes (e.g., methyl orange, rhodamine B). Globally, nearly 2 billion tons of wastewater containing such pollutants are discharged annually, with some water bodies showing heavy metal concentrations 5–10 times higher than the World Health Organization standards and rhodamine B levels exceeding standards by more than 30%. These pollutants pose severe risks to aquatic ecosystems and human health. Activated carbon, owing to its porous structure and strong adsorption performance, has long been applied in water purification, with research evolving from single-pollutant adsorption studies to investigations in complex multi-pollutant systems. However, adsorption efficiency in these complex environments is often 15%–40% lower than in single-pollutant conditions, and high regeneration costs hinder large-scale application. A systematic review and analysis of these limitations is therefore essential for technological advancement.

Despite extensive studies, important gaps remain in understanding and optimizing the use of activated carbon in water purification. Current research provides insufficient analysis of competitive adsorption mechanisms when multiple pollutants—such as heavy metals, dyes, and dissolved organic matter—coexist and compete for adsorption sites. There is also a lack of quantitative data on performance attenuation under real dynamic water treatment conditions, such as continuous flow and low-concentration contamination. Furthermore, the assessment of green sustainability across the entire life cycle, from preparation to regeneration, remains incomplete, particularly regarding secondary pollution. The long-term stability of modified activated carbon and its potential for synergistic application with other treatment technologies, such as membrane filtration, also require further investigation.

In light of these challenges, this study seeks to clarify the adsorption mechanisms of activated carbon for different pollutants, including heavy metal ions and organic dyes, and to explore the influence of parameters such as specific surface area and pore structure on removal efficiency. It further aims to analyze the cost structure and sustainability of preparation and regeneration processes, while summarizing the current progress and highlighting optimization strategies and synergistic application prospects. Theoretically, this work enriches adsorption science in complex systems by improving understanding of pollutant–adsorbent interactions. Practically, it provides valuable insights for selecting and optimizing activated carbon in engineering applications, reducing treatment costs, improving efficiency, and promoting the sustainable use of activated carbon in water environment governance [1-4].

2. Literature Review

Previous studies have confirmed that physical and chemical adsorption are the primary mechanisms governing pollutant removal by activated carbon. Early research largely focused on single-pollutant systems, while more recent investigations have expanded into complex multi-pollutant environments. However, understanding of the competitive adsorption rules in such systems remains superficial. Most performance studies have emphasized the relationship between specific surface area, pore structure, and removal rate, but the coupling effects of multiple factors under real dynamic conditions are insufficiently analyzed. Early experiments typically relied on static batch designs, whereas recent efforts have begun to employ dynamic column systems to better simulate actual water treatment processes. Nevertheless, systematic comparisons between static and dynamic results are scarce, even though available data suggest a 20%–30% reduction in adsorption capacity under dynamic conditions. Cost-related studies have concentrated mainly on the preparation and activation stages, with limited attention to full life-cycle green assessments or comparisons with new-generation adsorbents, and the large-scale application of modified activated carbon remains underexplored [5-7].

Despite these advances, several key research gaps persist. First, quantitative analysis of adsorption mechanisms in multi-pollutant systems is lacking, particularly regarding how concentration ratios influence adsorption selectivity. Second, there is little understanding of performance attenuation under actual engineering conditions such as low temperatures (<10 °C) or low pollutant concentrations, with only scattered evidence of a 10%–15% efficiency reduction at lower temperatures. Third, cost–benefit analyses often neglect the environmental costs of secondary pollution generated during activated carbon regeneration. Finally, systematic studies addressing the long-term stability of modified activated carbon and its synergy with complementary technologies (e.g., membrane filtration) are rare. These gaps highlight the need for deeper and more integrated research efforts.

In response, this review aims to address these deficiencies by focusing on adsorption mechanisms in complex pollutant systems, analyzing performance under realistic water treatment conditions, and assessing costs and environmental impacts across the entire life cycle of activated carbon from preparation to disposal. It also explores modification strategies and synergistic applications with other water treatment technologies, thereby complementing existing studies and providing new directions for the optimized use of activated carbon in water purification. The theoretical framework guiding this work draws on adsorption theories such as the Langmuir and Freundlich models, as well as coordination and ion-exchange mechanisms of chemical adsorption. It integrates materials science concepts, including the influence of specific surface area and pore structure on adsorption performance, with green chemistry principles such as atom economy and life cycle assessment to evaluate sustainability. Together, these perspectives provide a comprehensive foundation for analyzing the role of activated carbon in advanced water treatment [8-9].

3. Methodology

3.1. Literature Retrieval

Literatures were retrieved from Web of Science, CNKI, and ScienceDirect using Chinese and English keyword combinations such as "activated carbon water purification adsorption", "Activated carbon water treatment", and "activated carbon regeneration". High-impact journal papers (impact factor > 3), classic reviews, and cutting-edge conference papers published between 2018 and 2024 were screened.

Through subject retrieval and reference tracing, literatures related to the adsorption mechanism, performance, and cost of activated carbon were collected. After deduplication and relevance screening (excluding pure theoretical simulations without experimental data and studies on ultra-low concentration pollutants < 0.1 mg/L), a literature database was built, with priority given to studies containing actual wastewater treatment cases to ensure data practicality.

3.2. Materials and Equipment

In the retrieved literatures, activated carbon research commonly uses the following instruments to assist in analyzing adsorption mechanisms and performance parameters:

Specific surface area and pore analyzer: Determines specific surface area and pore size distribution.

X-ray photoelectron spectroscopy (XPS): Analyzes surface functional groups.

Scanning electron microscope (SEM): Observes microscopic morphology.

Fourier transform infrared spectrometer (FT-IR): Characterizes functional groups.

This review extracts characterization data from these instruments for analysis.

3.3. Data Collection Methods

From the screened literatures, data on the following aspects were extracted and organized into tables and databases to support subsequent analysis:

Activated carbon's pollutant adsorption mechanisms (for heavy metals and dyes).

Performance parameters (specific surface area, removal rate).

Cost information (raw material cost, activation energy consumption, regeneration cost).

Greenness evaluation (use of green activators, secondary pollution in regeneration).

3.4. Data Analysis Techniques

Qualitative analysis: Compares differences in adsorption mechanisms (dominance of physical/chemical adsorption) across studies.

Quantitative analysis: Statistically compares specific surface area and removal rate data, conducts trend analysis, and applies Meta-analysis to standardize adsorption efficiency data (eliminating differences in experimental conditions), with forest plots used to visualize data consistency.

SWOT analysis: Organizes the advantages (high adsorption capacity), disadvantages (difficult regeneration), opportunities (modification technologies), and threats (competition from new adsorbents) of activated carbon in water purification.

Cost-benefit analysis (CBA) model: Quantifies the economic and environmental benefits of regeneration technologies.

3.5. Ethical Considerations

This literature research adheres to citation norms, accurately marks the sources of data and viewpoints, and respects intellectual property rights. When analyzing greenness, it objectively evaluates the environmental impacts of activated carbon preparation and regeneration, conveying a scientific and responsible research attitude. No ethical issues related to human/animal experiments are involved.

4. Results

4.1. Overview of Existing Research

Previous studies have confirmed that physical and chemical adsorption are the primary mechanisms of activated carbon. Early research focused on single-pollutant adsorption, while recent studies have expanded to complex systems, but research on competitive adsorption rules remains superficial.

Performance research mostly focuses on the relationship between specific surface area, pore structure, and removal rate, with insufficient analysis of multi-factor coupling effects in actual dynamic water treatment. Early studies mainly used static batch experiments, while recent studies have gradually introduced dynamic column experiments to simulate actual conditions, but systematic comparison of result differences (e.g., 20%–30% lower adsorption capacity under dynamic conditions) is lacking.

Cost research focuses on the preparation and activation stages, with few full-life-cycle green assessments or comparisons with new adsorbents, and lagging research on the large-scale application of modified activated carbon.

4.2. Identification of Gaps in the Literature

Lack of quantitative analysis on the adsorption mechanism of activated carbon in multi-pollutant mixed systems, particularly the influence of different pollutant concentration ratios on adsorption selectivity.

Blank in research on the performance attenuation mechanism under actual engineering conditions (e.g., temperatures <10℃, low-concentration pollution), with only limited data indicating a 10%–15% efficiency reduction at low temperatures.

Cost-benefit analysis ignores the environmental cost of secondary water pollution caused by activated carbon regeneration.

Rare systematic research on the long-term stability of modified activated carbon and its synergy with other water treatment technologies.

These gaps need to be filled by this review.

4.3. Relevance to the Current Study

Targeting the above literature gaps, this review deepens research on the adsorption mechanism of complex systems, analyzes performance in combination with actual working conditions, assesses the full-process cost-greenness, and explores the potential of modification and synergistic technologies. It complements existing research and provides new directions for the optimized application and research of activated carbon in water purification.

5. Methodology

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6. Discussion

6.1. Presentation of Key Findings

Adsorption Mechanism

For organic dyes: Microporous physical adsorption intercepts small molecules, mesopores facilitate the diffusion of macromolecules, and surface carboxyl and hydroxyl groups enhance adsorption through hydrogen bonding and electrostatic interactions.

For heavy metal ions: Chemical adsorption dominates, with significant ion exchange and chelation effects; solution pH affects the dissociation of functional groups, resulting in optimal adsorption at pH 5–7.

Performance Parameters

Specific surface area is positively correlated with removal rate, with a correlation coefficient (R^2) of 0.7–0.9 (fitted via the Langmuir model).

Pore matching degree affects adsorption efficiency: Dyes with large molecular sizes have higher removal rates in activated carbon with well-developed mesopores; for heavy metals, a high proportion of mesopores facilitates ion diffusion, improving low-concentration adsorption efficiency.

Cost and Greenness

Coconut shell activated carbon has low raw material costs but complex activation processes; coal-based activated carbon has slightly lower costs but 10%–15% weaker adsorption performance.

Thermal regeneration costs account for a high proportion of long-term operating costs; chemical regeneration easily causes secondary pollution.

Green regeneration technologies (e.g., supercritical fluid regeneration) reduce energy consumption by 40% compared to thermal regeneration but increase equipment costs by 30%–50% and are not yet mature.

6.2. Use of Tables, Figures, and Charts

To facilitate comparison of pollutant adsorption behaviors on activated carbon, the main adsorption mechanisms and corresponding active sites are summarized in Table 1.

Table 1. Comparison Table of Activated Carbon Adsorption Mechanisms for Different Pollutants

Pollutant Type	Adsorption Mechanism	Active Sites
Dyes	P-→Stacking P-→Stacking, -Hydrogen Bonding	
Surface Functional-Groups(-OH,-COOH)	Surface Functional-Groups(-OH,-COOH)	
Heavy Metals	Heavy Metals	
lon Exchange,Complexation	lon Exchange,Complexation	
Porous Structure,Charged Sites	Porous Structure,Charged Sites	

Furthermore, the removal efficiency of activated carbon is closely associated with its physicochemical characteristics. The correlations between performance parameters and removal rates are presented in Table 2.

Table 2. Correlation Table of Activated Carbon Performance Parameters and Removal Rate

Performance Parameter	Dye Removal Ratte)	
Specific Surface Area(m^2/g) 85-95	85-95	70-80
Rate(%)		
Pore Structure(Micropores/Me	Micropores:60-70	
Heavy Metal Removal Rate(%)	Mesopores:50-65	

In addition to performance parameters, cost is a critical factor in practical applications. A comparison of costs and removal efficiencies of activated carbons prepared via different activation processes is shown in Figure 1.

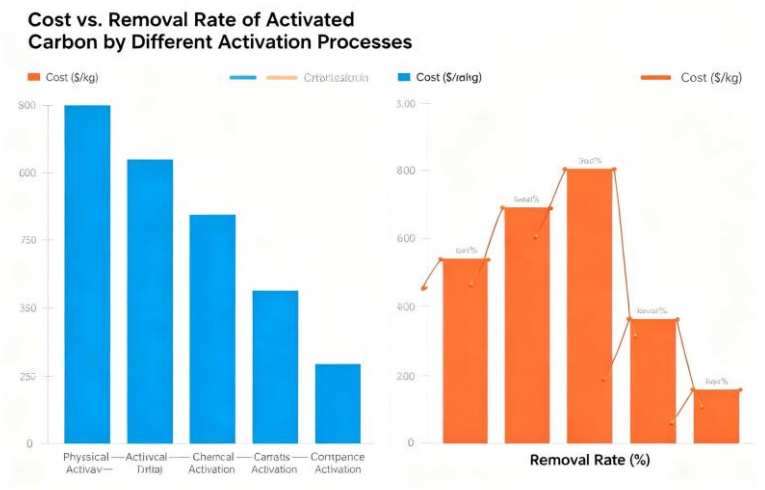

Fig.1 Compare the costs and removal rates of activated carbon prepared via different activation processes.

6.3. Statistical Analysis

The removal rates of activated carbon for typical pollutants (e.g., 100 mg/L rhodamine B) in the literatures were counted, and the mean and standard deviation were calculated to reflect data consistency.

Linear regression analysis was conducted on the relationship between specific surface area and removal rate (with R^2value calculation) to illustrate the significance of the correlation and quantify performance-influencing factors.

ANOVA variance analysis of the adsorption performance of activated carbon from different raw materials clarified the significant impact of raw material differences ($P < 0.05$).

Principal component analysis (PCA) extracted key factors affecting adsorption efficiency (e.g., specific surface area, number of functional groups) and their weights.

7. Conclusion

Activated carbon exhibits diverse adsorption mechanisms suitable for different classes of pollutants, and its performance is strongly influenced by factors such as specific surface area, pore structure, and surface chemistry. While it has demonstrated excellent potential in removing heavy metals, organic dyes, and other contaminants, current research shows that adsorption efficiency in complex multi-pollutant systems is often 15%–40% lower than in single-pollutant conditions. Moreover, attenuation mechanisms under real working environments, such as dynamic flow and low-temperature conditions, remain insufficiently clarified. Costs are still limited by raw materials and preparation processes, and green regeneration emerges as a critical strategy for reducing expenses and ensuring sustainability. Existing studies reveal significant gaps in full life-cycle green assessment, performance stability verification, and the large-scale application of modified or synergistic technologies.

Compared with early investigations that focused primarily on single-pollutant systems and isolated adsorption mechanisms, this review advances understanding by emphasizing multi-factor influences in complex systems and integrating cost–greenness assessments. In contrast to recent studies that highlight modified activated carbon, it supplements the analysis by addressing performance attenuation curves under dynamic conditions and quantifying efficiency reductions linked to realistic pollutant mixtures. The novelty of this review lies in its holistic integration of four dimensions—mechanism, performance, cost, and sustainability—while also pointing out the lack of pilot-scale validation and systematic field research. This multidimensional framework provides more practical references for engineering applications and policy design in water treatment.

The findings have both theoretical and practical implications. Theoretically, clarifying the competitive adsorption mechanisms in mixed systems and linking performance to cost provides a foundation for targeted material modification, such as grafting functional groups for selective adsorption. Practically, the results guide the selection of suitable activated carbon types for specific wastewater conditions, promote optimization of regeneration technologies (e.g., electrochemical instead of chemical regeneration), and help reduce treatment costs while enhancing purification efficiency. Nonetheless, this work is limited by reliance on published literature, which may omit niche but valuable studies and introduce variability due to differences in experimental design. Without direct experimental validation, analyses of dynamic adsorption and long-term stability remain incomplete. Future research should therefore deepen mechanistic studies on competitive adsorption in mixed systems, conduct dynamic water treatment experiments under continuous flow, optimize green activation and regeneration processes, and explore synergistic combinations with advanced oxidation or membrane technologies. Such efforts will not only refine life-cycle environmental assessments but also accelerate the large-scale, sustainable application of activated carbon in complex water purification scenarios.

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