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Evaluation of Adsorbent Materials for Phenol Removal from Industrial Effluents: A Review

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Abstract

Phenol is a common pollutant in industrial wastewater that, even at low concentrations, poses serious threats to the environment and human health. Among the biological and physicochemical methods available for phenol removal, adsorption stands out due to its simplicity and operational ease. This method offers significant advantages over conventional techniques, including the ability to remove organic pollutants even at low concentrations and the potential for using natural waste materials as adsorbents. However, the success of this technique depends fundamentally on the selection of a suitable adsorbent material. Given the continued efforts by the scientific community to develop new materials for this purpose, it is essential to review those already tested for phenol removal to identify which material classes and specific materials show the most promise. This study compares the phenol adsorption capacity of different adsorbent materials based on recent publications (2019-2024). Parameters such as BET surface area, pH of the phenol solution, and contact time were also identified and collected from the literature for each material, enabling future analyses to explore possible correlations between adsorption capacity and these parameters. Sustainable and alternative materials, such as biochars and activated carbons, demonstrated high efficiency, even with lower surface areas, while chemical modifications and solution pH were found to be important, though not sole, factors for performance. Composite and magnetized materials, such as Fe_3O_4/ZIF-8, also showed promising potential, though with lower adsorption capacities than activated carbons. The results reinforce the viability of adsorption as a treatment method for phenol-contaminated effluents and highlight the importance of optimizing materials to further enhance phenol removal in a sustainable and efficient manner.

Keywords: phenol removal; adsorption; industrial wastewater; activated carbon; biochar

1. Introduction

Among various industrial pollutants, phenol stands out due to its significant presence in effluents from industries such as oil refineries, coke production, dyeing, pharmaceuticals, and others. The discharge of large volumes of wastewater containing phenol into water bodies significantly contributes to environmental contamination, even at low concentrations [1-3]. In water, phenol, even at concentrations of 5-25 mg/L, can be lethal to fish, and levels as low as 0.5 mg/L are sufficient to alter the taste of drinking water [4]. According to the United States Environmental Protection Agency (EPA), phenol is classified as a priority pollutant, with a maximum permissible concentration of 0.1 mg/L in wastewater [5]. In addition to its environmental impact, phenol is known for its toxicity to humans and animals, being linked to diseases affecting the liver, kidneys, gastrointestinal tract, and central nervous system [6].

With the growing global concern over environmental contamination, the development of efficient and sustainable pollutant removal technologies has become essential. Among the current methods for phenol removal, processes such as precipitation, coagulation, flocculation, biological treatments, redox reactions, ion exchange, membrane separation, reverse osmosis, and adsorption are noteworthy. Adsorption, in particular, has gained significant attention due to its operational simplicity and low cost.

However, phenol concentrations in industrial effluents vary widely depending on the source (Table 1). This variability underscores the importance of developing adsorbent materials capable of efficiently removing phenol across this wide range of concentrations. Aligned with this, the feasibility of adsorption technology for phenol removal largely depends on the availability of materials with high adsorption capacity and selectivity for this compound. In this context, several adsorbents have been synthesized and tested, making it crucial to compile the most recent research to guide the development of optimized materials.

Table 1. Phenol Concentration in Industrial Effluents.

Phenol Source	Phenol (ppm)	Ref.
Petroleum processing	40~185	[7]
Fabrics	100~150	[7]
Wood manipulation	50~953	[7]
Fiberglass	40~2564	[7]
Coke oven	30~1000	[8]
Pharmaceuticals, paint, etc.	0.1~1600	[9]

This work aims to gather and compile adsorption capacity data reported in recent literature (2019-2024) on adsorbent materials used for phenol removal from aqueous solutions. Additionally, relevant parameters such as BET surface area, pH of the phenol solution, and contact time, are presented.

2. Methodology

This systematic review aimed to compare the phenol adsorption capacities of different adsorbent materials reported in the scientific literature. Articles presenting experimental data on phenol adsorption isotherms, published between 2019 and 2024, were considered. The databases used for the search included ScienceDirect, Scientific Electronic Library Online (SCIELO), Multidisciplinary Digital Publishing Institute (MDPI), CAPES journals, and Google Scholar. Only full-text articles published in English were included, while abstracts, conference papers, monographs, dissertations, and theses were excluded from the review.

2.1. Selection criteria

To be included, articles needed to report phenol adsorption isotherms at 298 K, with adsorption capacity data for an equilibrium concentration of 100 ppm. Articles that did not provide experimental isotherms or data under the specified conditions were excluded. Additional information, such as BET surface area, solution pH, and contact time, when available, was included for comparative purpose.

2.2. Data analysis

The data extracted from the selected articles were organized in a comparative table, highlighting the adsorption capacity of the materials under standardized conditions (100 ppm and 298 K), along with any additional parameters, when available. In cases where adsorption isotherm data were presented only in graphical form and it was challenging to precisely identify the adsorbed quantity at 100 ppm, the data capture software DigitizeIt was used to accurately determine the corresponding values.

3. Results and discussions

The research initially identified 597 articles, from which 49 were shortlisted after applying specific filters. In the final stage, experimental data on phenol adsorption were extracted for 19 different materials, along with information on parameters such as BET surface area, pH of the phenol solution, and contact time during the adsorption process, when available. These parameters allow for an analysis of the factors that may influence the adsorption process.

Table 2 compares the performance of different materials in removing phenol from aqueous solution, based on adsorption capacity at 100 ppm and 298 K, and includes the parameters mentioned above. The analysis reveals important trends, such as a positive correlation between BET surface area and adsorption capacity. For instance, materials with higher BET surface areas, like EDTA-4Na modified rice husk activated carbon (2087 m²/g) and corn straw activated carbon (1679 m²/g), showed high adsorption capacities of 236.49 mg/g and 315.64 mg/g, respectively. However, some materials with lower BET surface areas, like pea shell residues (7.07 m²/g), still exhibited good adsorption capacities (89.35 mg/g), suggesting other factors, such as surface chemistry, also play a significant role.

Most materials performed well in solutions with pH values between 6 and 7, such as rice straw biochar (158.62 mg/g, pH 6) and pea shell residues (89.35 mg/g, pH 7). However, no clear direct correlation between pH and adsorption capacity was observed, as materials with varied pH, like EDTA - 4Na modified rice husk activated carbon (pH 5) and Camellia oleifera shell residues (pH 4), still exhibited high performance. This indicates that while pH may influence adsorption, it is not the sole determining factor.

Table 2. Adsorption comparison at 100 ppm and 298 K for different adsorbents.

Material	**BET Surface Area (m^2/g)**	**pH**	**Contact time (min)**	**Adsorption capacity (mg/g)**	**Ref.**
$PbFe_2O_4$ spinel-activated carbon	774.5	7	-	81.65	[10]
Fruit waste from the Ceiba speciosa species	842.0	7	120	130.95	[11]
Pea shells (Pisum sativum)	7.1	7	180	89.35	[12]
Biochars from rice straw	4.1	6	60	158.62	[13]
Shells of Camellia oleifera	596.5	4	-	144.52	[14]
EDTA-4Na-modified activated carbon from rice husk	2087.0	5	240	236.49	[7]
Activated carbon derived from black wattle bark waste	415.0	6.5	1440	43.92	[15]
Enhanced geotextile structure coated with powder-activated carbon (PAC) and Fe_3O_4 nanomaterial	12.5	6	-	31.18	[16]
Activated carbons from penicillin mycelial residues	1369.8	-	40	152.63	[17]
Sewage-based $ZnCl_2$ activated carbon composites intercalated with MgFe	233.8	6	180	70	[18]
Carbon pellets from cigarette butts via thermal treatment	713.0	7	-	137.81	[19]
Organobentonite modified with tallow dihydroxyethyl betaine (TDHEB)	2.0	5	360	5.78	[20]
Activated carbon from sugarcane bagasse	2046.0	6,3	300	84.59	[21]
Spherical activated carbon from kraft lignin	2036.0	-	60	102.73	[22]
Activated carbon from olive stones	667.4	7-9	-	80.96	[23]
Chloromethylated polystyrene	914.0	7	50	82.05	[24]
Regenerable Fe_3O_4/ZIF-8 magnetic composite	1120.7	7	60	129.68	[25]
Activated carbon pellets (ACP-6)	1158.0	7	-	140.39	[26]
Activated carbons from lignin corn straw	1679.0	7.2	-	315.64	[27]

Activated carbons stood out as the class of materials with the highest adsorption capacities, particularly those chemically modified, like rice husk and corn straw activated carbons. Biomass-based materials and agricultural residues, such as pea shells and Camellia oleifera shells, also performed well, suggesting they could be viable low-cost options for phenol removal. In contrast, composite and magnetized materials, like Fe_3O_4/ZIF-8, showed promising potential (129.68 mg/g), though they did not reach the highest adsorption values seen with activated carbons.

These results suggest that chemical modification and material origin significantly influence adsorption capacity, while pH and BET surface area play important roles but are not the sole determinants of performance.

4. Conclusions

This review highlighted various materials studied for phenol removal, with a focus on biomass-derived activated carbons. A positive correlation was observed between BET surface area and adsorption capacity, with chemically modified carbons, like corn lignin activated with KOH, reaching 315.64 mg/g. Materials with lower BET areas, such as pea shells, also performed well, indicating surface chemistry's importance. Composite materials like Fe_3O_4/ZIF-8 showed potential, though with lower adsorption capacities. Regeneration of adsorbents remains crucial for sustainability. Overall, carbon-based materials are effective for phenol adsorption, especially when chemically modified.

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