Applications of Porous Activated Carbon Produced from Waste Biomass for Wastewater Treatment

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Abstract. Activated carbon is a porous carbon material possessing excellent physical and chemical properties. Activated carbon produced from waste biomass offers a viable approach for wastewater treatment. Current research focuses extensively on enhancing the adsorption capacity of modified activated carbon towards multiple wastewater pollutants. This review elaborates on the differences between physical and chemical activation in preparing porous activated carbon, then further analysed the influence of elemental composition on the specific surface area of biomass feedstock under varying conditions. In terms of specific surface area and pore structure, chemical activation proves more effective in enhancing the overall performance of activated carbon. This paper further explores the influence mechanisms of porous activated carbon on wastewater pollution-related parameters, systematically elucidating its primary mechanisms of action in pollutant removal processes. This study centres on the preparation of activated carbon from waste biomass for wastewater treatment. Its objective is to encourage scholars to develop novel activated carbon materials or modification methods that enhance adsorption performance for wastewater pollutants while ensuring material stability and treatment efficiency.

1 Introduction

Nowadays, the world faces challenges of rapid population growth, accelerated urbanization, and expanding industrial activities; much water is discharged into the environment without proper treatment. The literature indicates that the textile industry releases over 8×10^5 tons of synthetic dyes into aquatic ecosystems annually, with azo dyes accounting for 60-70% of this total [1]. Increasingly, developing nations are establishing manufacturing and industrial facilities; many plants often discharge untreated wastewater directly into aquatic environments, intensifying water resource pressures in these regions. This is because factories discharge vast quantities of wastewater into the environment without a comprehensive environmental management system, leading to a global health risk crisis and ecological imbalance.

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Industrial wastewater typically contains pollutants such as dyes, heavy metal ions and pharmaceutical waste. If discharged into water bodies without systematic treatment, these wastewater contaminants pose a significant threat to ecosystems.

Over the past decade, numerous methods have emerged for removing pollutants from wastewater, including chemical membrane separation, porous activated carbon adsorption, and photocatalytic degradation. Among these, research on porous activated carbon has remained a focal point for scientists due to its versatility in composition. Because derived from diverse biomass sources and has a wide range of preparation temperatures, properties, carbonization levels, specific surface areas, pore sizes and electrical conductivities. Numerous studies indicate that pore size plays a critical role in the adsorption of many pollutants. The purpose of this review is to discuss the preparation process of porous activated carbon and its applications in wastewater treatment. Additionally, the impact of porous activated carbon derived from different biomass sources on wastewater treatment is examined. Finally, the contributions of porous activated carbon in the field of wastewater treatment will be discussed in detail.

2 Method for preparing porous activated carbon from waste biomass

There are two methods for producing porous activated carbon. The one-step process and the two-step process. The one-step process simultaneously completes pyrolytic carbonization and the activation reaction. The two-step process involves carrying out the one-step process in separate stages to generate activated carbon. The activation process is a critical step in the preparation of porous activated carbon, involving complex chemical reactions between the activator and the biomass. Its activation effects primarily manifest in two aspects: pore formation and doping. Consequently, the activation stage yields porous activated carbon products with significantly increased specific surface area and porosity. Therefore, the two-step method is generally the preferred approach. First, the raw material undergoes a specific pretreatment process (dehydration/air-drying, crushing, and screening, etc.), followed by pyrolysis. The pyrolysis products then undergo simple processing to yield the final product.

2.1 Physical activation

Physical activation produces activated carbon with varying pore sizes. Using two different carrier gases—water vapor (H_2O) and carbon dioxide (CO_2)—at high temperatures yields activated carbon with distinct pore structures. For instance, CO2 primarily generates microporous activated carbon, H2O increases pore size and produces mesoporous activated carbon. During the physical activation process, residual volatile substances and tar present in biochar are decomposed through gasification or the Boudouard reaction. The generation and release of gases create new pores or enlarge existing ones on the surface of biochar, resulting in activated carbon with high porosity.

2.2 Chemical activation

In chemical activation, chemicals ($KOH/K_2CO_3/ZnCl_2/H_2NO_3$) are typically used as modifiers to weaken or break the chemical bonds between residual lignocellulosic components in biochar [2]. For instance, CO_2 and H_2O are removed during subsequent pyrolytic heat treatment, yielding activated carbon with a well-developed porous structure. The resulting activated carbon must also undergo acid washing to eliminate any residual traces of chemical activators that may remain in the material. Activated carbon produced using alkaline chemical reagents (such as KOH) increases micropore density and specific surface area [3], while acidic chemical reagents (such as H_2NO_3) significantly enhance micropore and interstitial structures while substantially increasing specific surface area [4]. Therefore, preparation under different conditions results in porous activated carbon possessing distinct pore structures, specific surface areas, and surface oxygen-containing functional groups.

3 Influence of biomass feedstock and methods

3.1 Raw materials

For years, researchers have been working to identify low-cost raw materials, most commonly agricultural residues or woody biomass, as plant-based feedstocks with high lignin content yield substantial amounts of biochar. Examples include cotton stalks, coconut shells, and rice straw. Excessive mineral ash content inhibits the surface structure and reactivity of biochar; its elemental composition, however, influences the formation of surface functional groups, such as double bonds and oxygen/nitrogen-containing groups, which directly determine its adsorption and activation properties. High-temperature pyrolysis promotes the migration of raw material elements toward carbon enrichment while reducing hydrogen and oxygen content. This process enhances the aromaticity of biochar and lowers its polarity. Generally, plant-based biochar exhibits higher carbon and sulfur content than solid waste biochar.

The properties of activated carbon prepared from different biomass feedstocks can lead to significant variations in its adsorption capacity. For instance, oil palm leaves exhibit a specific surface area of 422 m^2/g [5], whereas wheat straw has a specific surface area of 121.72 m^2/g [6].

The biomass determines the minimum pyrolysis temperature required to form a porous structure and influences the adsorption capacity of the activated carbon. This is due to the differing structural characteristics resulting from variations in the content of cellulose, hemicellulose, and lignin within the biomass. During pyrolysis, biomass rich in cellulose and hemicellulose decomposes rapidly, forming the aromatic rings and oxygen-containing functional groups characteristic of activated carbon. However, this method yields a relatively low carbon yield. The decomposition process of lignin is complex and occurs over a broader temperature range. Lignin's aromatic monomers exhibit high thermal stability and substantial fixed carbon content. Consequently, biomass feedstocks with high lignin content yield higher activated carbon production rates.

3.2 Residence time

At low temperatures, increasing gas residence time has little effect on activated carbon yield. However, as the pyrolysis temperature rises, bio-oil production increases while activated carbon yield decreases. At optimal temperatures, extending gas residence time promotes secondary tar cracking and polycondensation reactions, thereby reducing bio-oil yield and enhancing activated carbon yield [7]. However, an excessively long solid residence time leads to decrease in carbon yield due to pyrolysis reactions triggered by ash content [8].

The residence time influences activated carbon yield, though this is largely attributable to variations in feedstock. For instance, under identical temperature and residence time conditions, peanut shells yield the highest activated carbon output among peanut shells, rice husks, and corn stalks [9]. This underscores the necessity of optimising pyrolysis process parameters according to the specific feedstock.

4 The impact of porous activated carbon on wastewater treatment

The development and application of efficient wastewater treatment technologies are of particular importance, as the pollutants in such effluents pose significant hazards to both the environment and human health. Among these, activated carbon adsorption technology proves highly effective in removing organic pollutants, heavy metal contaminants, dye pollutants, and other contaminants from wastewater.

4.1 Impact of organic pollutants

Organic pollutants primarily include organochlorine pesticides, such as aldrin, dieldrin, endrin, chlordane, and heptachlor and polycyclic aromatic hydrocarbons, such as anthracene, benzene, naphthalene, p-nitrotoluene, and pyrene. As well as synthetic dyes, such as methylene blue, Congo red. These organic pollutants exhibit high persistence, toxicity and a tendency to accumulate within living organisms, posing a serious threat to the stability of ecosystems and human health.

The efficiency of activated carbon in removing organic pollutants depends on the interactions between the adsorbate and the physicochemical properties of the carbon. The adsorption process involves both chemical adsorption and multiple physical adsorption mechanisms. Such as, pore diffusion, hydrophobic attraction, electrostatic interactions, π-π electron donor-acceptor interactions, and hydrogen bond formation. These processes are typically facilitated by functional groups on the biochar surface, such as carboxyl (-COOH), hydroxyl (-OH), and alkoxy (-ROH) groups, which provide abundant active binding sites for pollutants [10].

An increase in pyrolysis temperature enhances the specific surface area and pore structure of activated carbon, indicating that carbon prepared under high-temperature conditions is well-suited for removing non-polar organic pollutants. Activated carbon produced at lower temperatures lacks this structural advantage; however, carbon obtained via low-temperature pyrolysis (<500 ℃) retains more oxygen- and hydrogen-containing functional groups, thereby enhancing its adsorption capacity for polar organic pollutants.

4.2 The effects of heavy metals

The density of heavy metal pollutants is at least five times that of the metal content in water, and these heavy metal pollutants are harmful to both humans and the environment. This category includes elements such as cadmium, lead, arsenic, cobalt, mercury, copper, zinc, nickel, and iron. Heavy metals are toxic and carcinogenic, causing various health issues, including allergies, skin irritation, headaches, tumours, and other diseases.

The specific surface area, pore structure, surface functional groups, pH, and cation exchange capacity of activated carbon exert a significant influence on the adsorption of heavy metal pollutants [11]. Methods for removing heavy metal pollutants include surface complexation, ion exchange, precipitation, electrostatic attraction, and physical adsorption. Surface complexation refers to the formation of coordination bonds between metal ions and oxygen-containing functional groups on the surface of activated carbon, thereby adsorbing the heavy metal ions. Ion exchange refers to the process whereby the exchangeable cations originally present on the surface of activated carbon are replaced by heavy metal ions from the solution. Electrostatic attraction is regulated by the pH value of the system, as changes in pH affect the surface charge properties of the activated carbon, thereby influencing the electrostatic forces exerted on heavy metal ions. Furthermore, physical adsorption refers to processes involving the filling of activated carbon pores, hydrogen bonding interactions, and coprecipitation reactions involving mineral salts present within the carbon. Metal ions can be physically captured on the surface and within the pores of activated carbon; consequently, activated carbon with a high specific surface area and well-developed pore structure typically exhibits excellent adsorption capacity for heavy metals.

For example, coconut shell biochar achieved adsorption efficiencies of 94.00% and 42.70% for As and Cr at 45 ℃, while palm kernel shell biochar reached 91.50% and 7.23% for As and Cr at the same temperature [12].

4.3 The effect of dyes

Wastewater pollutants discharged from various dyeing industries contain toxic dyes that adversely affect both human health and aquatic flora and fauna. Among these, biochar has emerged as one of the most effective methods for treating dye-containing wastewater. Various treatment approaches exist, which can be categorized into physical, chemical, and biological processes. These include oxidation remediation, ion exchange, membrane filtration, and precipitation. Research indicates that biochar prepared from rice straw exhibits adsorption capacities of 90.91 mg/g for methylene blue and 44.64 mg/g for crystal violet dye [13]. Activated carbon derived from corn stover demonstrates an adsorption capacity of 164.4 mg/g for Acid Red 18, achieving a removal efficiency of 82.19% [14]. The above findings demonstrate the advantages and potential of biochar in treating dye wastewater.

5 Challenges and future perspectives

With the relentless advance of industrialization and urbanization, factories discharge vast quantities of wastewater pollutants. Consequently, achieving efficient, safe, and economical wastewater treatment has become a matter of significant concern. Simultaneously, water resource issues have emerged as a major challenge in global public health and environmental protection. Against this backdrop, the development of lower-cost, higher-efficiency porous activated carbon materials has become particularly urgent.

The performance of porous activated carbon is influenced by various experimental conditions, including temperature, duration, system pH, and the type of metal ions involved. Therefore, it is necessary to conduct more in-depth research into the key parameters affecting activated carbon performance.

6 Conclusions

This paper elaborates on the effects of physical and chemical activation on the pore size and specific surface area of porous activated carbon. Appropriate residence times and temperatures enhance the yield of activated carbon. Significant performance variations exist between activated carbons produced from different raw materials, with the raw material composition determining the minimum pyrolysis temperature required to form a porous structure, as well as the impact of porous activated carbon on organic pollutants, heavy metal contaminants, and dye pollutants in wastewater. It has been concluded that activated carbon produced using different processes and raw materials exhibits significant variations in both performance and yield.

Therefore, it is necessary to strengthen relevant research to investigate the effects of preparation methods on the performance, yield, and composition of activated carbon. To this end, a comprehensive review of recent relevant literature is required. It is currently challenging to identify an economical process capable of achieving both high yields and high value at an industrial scale. Chemical activation remains the most effective method for enhancing activated carbon properties, yet its industrial application has yet to be widely adopted. Future research efforts should focus on conducting systematic evaluations and benchmarking comparisons of raw materials used in activated carbon production within chemical activation systems.

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