Application and Development Prospects of Activated Carbon in Heavy Metal Pollution Treatment

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Abstract. Heavy metal pollution is a serious environmental problem facing the world, posing a serious threat to human health and ecosystems. Activated carbon has attracted much attention due to its ability to adsorb heavy metals efficiently. In this paper, the preparation process of activated carbon is exhaustively described, including the generation of biochar from biomass feedstock and the preparation of activated carbon by physical and chemical activation. Due to its rich pore structure and surface functional groups, activated carbon exhibits excellent heavy metal adsorption properties. Subsequently, the article discusses heavy metal pollution and its treatment technologies, with special emphasis on the application of activated carbon in the removal of heavy metals from water, soil and atmosphere. The application of activated carbon in heavy metal pollution management is promising and is expected to make significant contributions to global environmental remediation in the future.

Keywords: heavy metal pollution, activated carbon, environmental remediation.

1. Introduction

Heavy metal pollution is one of the serious environmental problems currently facing the world, especially in the process of rapid industrialization, which poses a serious threat to water bodies, soil and the atmosphere. Heavy metals, including lead, mercury, cadmium, chromium, arsenic, etc., are widely present in industrial wastewater, waste gas and waste residue, and once they enter the environment, they are extremely difficult to be degraded through natural processes. They tend to accumulate in soil, water and living organisms and are passed on through the food chain, which ultimately poses a threat to human health and ecological environment [1]. The hazards of heavy metal pollution are mainly reflected in its threat to human health, its ability to damage the ecological environment, and the pollution it produces to soil and water bodies. Through respiration, drinking water, and the food chain, heavy metals can enter the human body, damaging the nervous system, liver, and kidneys, and can lead to chronic poisoning or more serious health problems. In addition, heavy metal contamination affects the growth of plants and the ability of animals to reproduce, disrupting the balance of the entire ecosystem while allowing the concentration of pollutants in the food chain to rise cascading down the food chain, ultimately devastating the entire ecosystem.

In the treatment of heavy metal pollution, the commonly used technologies mainly include three methods: biodegradation, chemical transformation and adsorption. Biodegradation converts heavy metals into non-toxic or low-toxic compound forms through various processes such as adsorption, precipitation, leaching, and redox. However, its application is limited due to the more stringent requirements of microorganisms for survival environment [2]. Chemical conversion, on the other hand, utilizes complex processes such as precipitation, ion exchange, chelation, or adsorption to separate heavy metals from the contaminated medium and transfer them into liquid phase drenches, followed by further treatment of these contaminants. However, chemical conversion is costly and the chemicals used may cause secondary pollution problems. In contrast, activated carbon, as an efficient adsorption material, can effectively adsorb heavy metal ions in water and soil due to its rich pore structure and unique surface functional groups [3]. The activated carbon method has several significant advantages, including efficient adsorption, easy operation, low cost and no toxic by-products. Through a combination of physical and chemical adsorption, activated carbon is able to firmly adsorb heavy metal ions in its pores, thus effectively reducing the concentration of pollutants.

This technology is not only simple and easy to control, but also can flexibly adjust the dosage of activated carbon and treatment conditions according to the concentration and nature of different pollutants.

Research on the application of activated carbon in heavy metal pollution treatment has important environmental, economic and social significance. In this paper, the preparation process of activated carbon and its unique characteristics are described in detail, and the specific applications of activated carbon in removing heavy metals from water, soil and atmosphere are discussed in depth.

2. Preparation of activated carbon

The process of preparing activated carbon is to obtain biomass raw materials from the environment, transform them into biochar through pyrolysis and other means, and activate them by physical and chemical methods to finally obtain activated carbon. Biomass raw materials are mainly divided into three categories: mineral raw materials, plant raw materials and plastic raw materials. Among them, mineral raw materials include bituminous coal, lignite, peat, coal tar, coal asphalt, petroleum residue, petroleum asphalt and so on. Plant-based raw materials include traditional high-quality wood, sawdust, charcoal, coconut shell charcoal, palm kernel charcoal. There are also agricultural and forestry by-products and certain food industry wastes including waste wood, bamboo, bark, wind fallen wood, walnut shells, kernels, cotton shells, coffee bean stalks, oil palm shells, bagasse, furfural residue and so on. Plastic feedstocks, on the other hand, contain polyvinyl chloride, polypropylene, furan resins, phenolic resins, polycarbonate, polytetrachloroethylene, etc [4].

Pyrolysis is a common means of converting biomass feedstocks into biochar, which specifically refers to a series of physical or chemical changes that occur when polymeric substances are heated under anaerobic or anoxic conditions. Pyrolysis treatment of plant fiber raw materials can obtain three parts: solid carbon, pyrolysis oil and gas. The solid carbon can be used as the raw material of biochar for the preparation of activated carbon. Currently, the main treatment methods for biochar are physical activation, chemical activation and physical-chemical activation. Physical activation method refers to contacting the biochar raw material with activation gases such as water vapor, flue gas, carbon dioxide or air at a high temperature of 800-1000℃. At the same time, the redox reaction occurs and leads to the ablation and gasification of the charcoal and the creation of pores. This method has the production characteristics of producing raw materials from a wide range of sources, producing a complete range of activated carbon, and having an abundance of activation furnace types. The chemical activation method refers to the preparation of activated carbon by mixing various carbon-containing raw materials with chemicals uniformly and going through the processes of carbonization, activation, recycling of chemicals, rinsing and drying at a certain temperature. The production characteristics of this method include low energy consumption, easy control of the properties of the activated carbon, and high specific surface area of the resulting activated carbon product. Physical-chemical activation method refers to the combined application of physical and chemical activation methods, using the carbonization tail gas of the physical method to supply heat for the chemical method production, realizing the production process without coal consumption, and obtaining both physical and chemical activated carbon [5].

3. Application of activated carbon

Activated carbon effectively removes metal vapors and is effective for the treatment of heavy metals already present in the atmosphere as well as for the treatment of fumes emitted from factories. The adsorption properties of activated carbon for different heavy metals and their removal is enhanced by modification methods. It has been found that the adsorption capacity of activated carbon varies depending on the type of heavy metal, but its removal capacity can be significantly improved by physical or chemical modification. In particular, the modified activated carbon showed superior performance when treating higher concentrations of heavy metals.

3.1. Adsorption of airborne heavy metals by activated carbon

In the application of activated carbon in air pollution control, including the removal of heavy metals. There are various modification techniques for activated carbon, such as acidification, alkalization and gas phase modification, and their effectiveness in the removal of gaseous pollutants. The removal capacity of activated carbon can be significantly improved by the techniques, especially when dealing with complex gas mixtures. Effect of different modification methods on the removal of heavy metals from air by activated carbon. The results of the study show that activated carbon treated by modification exhibits significant advantages in the removal of specific heavy metals, especially for some difficult-to-remove heavy metals, and the modified activated carbon provides higher removal efficiency and longer service life [6].

Mechanisms of heavy metal removal by activated carbon in the atmosphere, including physical adsorption and chemical reaction, were analyzed with respect to the removal effect of activated carbon under different conditions of use. It was shown that activated carbon not only removes heavy metals by surface adsorption, but also enhances its removal ability by chemical reaction with heavy metals. The removal effect of activated carbon on heavy metals in gases and the factors affecting it are about the type of activated carbon, the use conditions and the operating parameters have an important influence on its removal performance. By optimizing these factors, the effectiveness of activated carbon in treating heavy metals in gases can be further improved [7].

3.2. Adsorption of heavy metals in water by activated carbon

Activated carbon is widely used in the field of water treatment due to its large specific surface area and good adsorption performance. It mainly removes heavy metal ions from water through physical adsorption and chemical reaction. These characteristics make it excellent in removing heavy metals such as lead, cadmium, chromium, mercury and copper. There are differences in the removal ability of activated carbon for different heavy metal ions [8]. The removal of lead ions by activated carbon is remarkable and the removal rate can reach more than 90%. The removal effect of activated carbon on cadmium ions is also very superior, and different types of activated carbon show different removal efficiencies. In order to enhance the removal performance of activated carbon, researchers have used various modification methods. Modified activated carbon can significantly improve the removal of specific heavy metal ions investigated the removal of copper ions by modified activated carbon. The results showed that the modification treatment significantly increased its adsorption capacity [9]. The mechanisms of heavy metal removal from water by activated carbon mainly include physical adsorption, chemical reaction and ion exchange. The study of revealed that the main mechanism of activated carbon in removing mercury ions is the formation of insoluble compounds through chemical reactions [10]. Ion exchange is also an important mechanism for the removal of heavy metal ions, especially effective in the treatment of aluminum ions.

3.3. Adsorption of heavy metals in soil by activated carbon

Activated carbon, a widely used adsorbent, has shown remarkable results in the removal of heavy metals from soil. Studies on modified activated carbon have found that optimizing the pore structure and surface chemistry of activated carbon can significantly improve its adsorption capacity for heavy metals such as lead, cadmium and copper. In addition, compositing activated carbon with other materials such as biochar or nanomaterials can further enhance its efficiency in removing heavy metals [11]. Composite materials not only increase the specific surface area of activated carbon, but also improve its removal of heavy metals through synergistic effects. The performance of activated carbon in removing heavy metals from soil, its excellent removal ability for heavy metals such as lead, cadmium and copper [12]. Meanwhile, studies have shown that activated carbon based composites exhibit higher treatment efficiency in treating heavy metals in soil, and these new composites, such as functionalized nano-activated carbon, have wider application prospects [13]. In practice, activated carbon is used in various forms, depending on the degree and type of soil pollution. According to research, the application methods of activated carbon include mixed application and

surface mulching. Mixed application is usually used in highly polluted areas, where activated carbon is thoroughly mixed with the soil to ensure its uniform distribution and maximize the remediation effect. In mildly contaminated areas, topdressing is more cost-effective. The choice of different application methods not only affects the remediation effect, but also directly influences the economic cost [14]. Another important consideration is the treatment life of activated carbon, which may become saturated during treatment, resulting in a reduction of its adsorption capacity. Therefore, periodic replacement or regeneration of activated carbon is required to maintain its effectiveness. For this reason, researchers are exploring more economical production methods and regeneration techniques for activated carbon, such as thermal and chemical regeneration methods [15].

Although activated carbon has shown remarkable effects in soil heavy metal pollution treatment, it still faces some challenges. First, the production cost of activated carbon is relatively high, which limits its application in large-scale remediation. Second, the saturation problem of activated carbon requires effective regeneration techniques to solve. In recent years, researchers have proposed innovative approaches, such as utilizing waste as a raw material to produce low-cost activated carbon, and developing novel activated carbon composites to improve their economics and treatment efficiency. In addition, future research should focus on the environmental impact and long-term stability of activated carbon. Although activated carbon performs well in the short term, its long-term effects and impact on the ecosystem need to be further evaluated. Therefore, the development of new environmentally friendly activated carbon materials and the evaluation of their long-term application effects will be an important direction for future research.

4. Summary

As an effective material for heavy metal pollution treatment, activated carbon can be widely used in water, soil and atmosphere by virtue of its unique pore structure and chemical properties, showing remarkable adsorption effects on various heavy metals such as lead, mercury and cadmium. Through physical and chemical modification, the adsorption capacity of activated carbon can be significantly enhanced, especially when dealing with high concentrations and complex mixtures of pollutants. Activated carbon's high specific surface area and rich pore structure make it excellent at adsorbing harmful components in gases. By introducing activated carbon into the exhaust gas treatment system, heavy metal vapors and particulate matter in the exhaust gas can be effectively captured and removed. Activated carbon has the advantage of efficient removal in treating heavy metal pollution in water. The pore structure of activated carbon can effectively capture heavy metal ions in water and improve the removal efficiency. The use of activated carbon has a low cost and is suitable for large-scale water purification. It is easy to operate, and the removal of heavy metals can be realized under relatively simple operation by putting activated carbon into the water or adopting an activated carbon filtration system. In the field of soil remediation, the application of activated carbon not only helps to reduce heavy metal contamination in the soil, but also provides organic matter to the soil and improves soil quality. Activated carbon is able to remove heavy metal ions from the soil through physical adsorption, thereby reducing the concentration of heavy metals in the soil while improving the soil structure. Activated carbon is a source of organic matter, which is conducive to increasing the soil's porosity and water-holding capacity. Moreover, the application of activated carbon can also promote the activity of microorganisms in the soil, improve soil fertility, and contribute to the healthy growth of plants. Since activated carbon is a relatively environmentally friendly material, its use does not introduce other harmful substances and has a low impact on the environment. And the cost of activated carbon is low, showing high economy in large-scale application. As a multifunctional and environmentally friendly material, activated carbon has great potential for application in heavy metal pollution control.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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