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Research Progress on the Adsorption Mechanisms of Biochar for Atmospheric Pollutants

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Abstract

As a carbon-rich porous solid material prepared and formed by pyrolysis of biomass under hypoxic environment, due to the wide range of raw materials and highly developed pore structure, biochar has shown a broad development prospect in the field of atmospheric pollutants. This article systematically explains the research progress of the adsorption mechanism of biochar on atmospheric pollutants. The study of biochar surface adsorption of gaseous pollutants such as SO2, NOx, VOCs and fine particulate matter (PM2.5) is the result of multi-mechanism synergy. Among them, physisorption such as micropore filling and van der Waals force provides basic adsorption ability, and chemisorption such as surface complexation, ion-exchange and hydrogen bond improves adsorption strength and selectivity. The pyrolysis process and the type of raw materials can adjust the specific surface area, pore size, surface functional groups and degree of aromaticity of biochar, which in turn affects the contribution ratio of the adsorption mechanism. The current research focus has changed from the description of a single adsorption mechanism to the quantitative analysis of multi-mechanism synergy, and has developed from the adsorption behavior under ideal conditions in the laboratory to the actual environment. The future research direction should be to carry out in-depth research on the direction of multi-pollutant collaborative control, whole-life cycle safety research and low-cost large-scale application, and promote the theoretical development and practical application of biochar in atmospheric pollution control technology.

Keywords

biochar, atmospheric pollutants, physisorption, chemisorption

1. Introduction

With the continuous development of global industrialization, air pollution has become an increasingly serious global problem [1]. Typical atmospheric pollutants include fine particulate matter (PM2.5), volatile organic compounds (VOCs), ozone (O3), sulfur dioxide (SO2) and nitrogen oxides (NOx), etc., which have a serious impact on the stability of ecosystems and human health. According to data from the World Health Organization, there are more than 3 million premature deaths induced by atmospheric pollutants such as VOCs and fine particulate matter every year [2]. The problem of ozone pollution is also becoming more and more serious. Because the emission of carbon dioxide, VOCs and NOx has the characteristics of low co-benefit and non-linear response, it has caused serious difficulties for multi-target collaborative management

[3]. According to research, it is difficult to achieve the coordinated goal of controlling PM2.5, ozone and carbon dioxide through terminal management and single climate policy. Only through deep pollution control and structural transformation can the atmospheric environment be effectively controlled [3]. According to this control demand, air pollution prevention and control technology needs to be economical, efficient and environmentally friendly. At the same time, it can adapt to the complex situation of coordinated emissions of a variety of air pollutants. Against this background, the development of low-cost, high-efficiency and environmentally friendly new adsorption materials has become the key research direction of air pollution prevention and control [1].

Biochar is a carbon-rich solid material prepared from biomass through pyrolysis under hypoxic environmental conditions. Because of its special physicochemical properties, it has excellent potential in atmospheric pollution control [1]. Compared with porous materials such as activated carbon and metal–organic frameworks, biochar has obvious advantages in resource utilization and surface chemical characteristics. In terms of resources, biochar generally uses livestock manure, straw and other agricultural waste and urban organic solid waste as precursor raw materials to realize waste utilization while realizing carbon sequestration. With the European Union, Brazil, the United States, India and China as the main producers, the global generation of biomass waste is about 140 billion tons every year, of which straw incineration accounts for 18% of the world's CO2 emissions [2]. By preparing such waste into biochar, while effectively reducing the environmental load, 0.3-2Gt of carbon dioxide can be sequestered annually by 2050 [2]. In terms of surface chemical characteristics, due to the developed pore structure, rich functional groups and high specific surface area of biochar, it can complete the efficient adsorption of a variety of atmospheric pollutants (such as VOCs, NOx and SO2) through physical actions such as filling pores and complexation reactions, ion-exchange and other chemical reactions [4]. After activation and modification of biochar, such as rice husk biochar, the adsorption amount of NO and SO2 reached 95.7mg/g and 100.2mg/g [2] respectively. At the same time, biochar can realize multiple "adsorption-desorption" cycles through thermal regeneration and other methods, and the application potential is more prominent [1]. However, the application research of biochar in the field of air pollution prevention and control is relatively limited compared with the research in the field of water and soil restoration [1]. The properties of biochar are strongly dependent on the type of raw materials, the temperature and time of pyrolysis, and the modification method, which leads to large differences in the adsorption capacity and mechanism of different studies [4]. On the other hand, the current research has limited understanding of the adsorption and synergistic removal under the coexistence of multiple pollutants, and the research system is not complete [4]. At present, there is a consensus on the physisorption and chemisorption mechanism of biochar, but there are still many problems in the role of surface free radicals in the degradation of pollutants and the catalytic process affected by electron transfer processes [1]. At the same time, the large-scale application of biochar still faces many challenges, such as the possible generation and emission of greenhouse gases in the preparation process, and the introduction of processing technology has the risk of increasing costs and secondary pollution [2].

This research focuses on the research progress of the adsorption mechanism of biochar on atmospheric pollutants, focusing on the four aspects of the structural characteristics of biochar, the adsorption mechanism, the influencing factors of biochar adsorption of major atmospheric pollutants and the challenges faced by current research. This research can promote the theoretical development and practical application of biochar in atmospheric pollution control technology, help to analyze the current research progress of biochar to remove typical atmospheric pollutants and clarify the future development direction, hoping to provide theoretical reference for biochar to control the atmospheric environment.

2. Structural Characteristics of Biochar

The main components of biochar include C, H, O and N, S, P, K and other elements [5], among which the content of C element is the highest, generally more than 60%, followed by H and O. Pore structure is the core structural feature of biochar. According to the size, pores can be divided into three categories: macropores (>50nm), mesopores (2~50nm) and micropores (<2nm) [6]. Micropores can increase the specific surface area and pore capacity of biochar, and enhance its ability to adsorb small molecular substances (such as heavy metal ions and organic small molecule pollutants). The mesopores are a channel for transporting small molecular organic matter, which can hold pollutants with large diameters. Macropores / transport channels, which improve the contact efficiency between biochar and soil, water and gas, and also provide space for the growth of microorganisms. Through the pore system of "large pores-mesopores-micropores", biochar can provide effective transmission channels, storage space and reaction sites. At the same time, there are also rich functional groups on the surface and pores of biochar, which gives biochar the ability of chemisorption and catalytic activity [2]. These agonal groups are mainly formed by pyrolysis at medium and low temperatures below 500°C, so that biochar has surface charge and chemical reaction activity, and can fix heavy metal ions and nutrients through complexation, ion-exchange, etc.

The carbon matrix of biochar is different from the regular crystal structure of graphite. It is an irregular carbon structure with high aromaticity and stability formed by the condensed aromatic ring of the sheet layer through random stacking [7]. The degree of condensation of the aromatic ring is related to the temperature of pyrolysis. When the temperature rises, the degree of condensation of the aromatic ring increases, improving the orderliness of the arrangement, but the whole is still in a chaotic state of random stacking [8]. This aromatic ring structure is the fundamental reason for the chemical inertness of biochar and its ability to survive in the soil for hundreds to thousands of years. At the same time, the process of pyrolysis (temperature, heating rate, residence time) and the selection of precursor raw materials (straw, sludge, manure, etc.) also have a decisive relationship with the structural characteristics of biochar. Normally, when the temperature of pyrolysis is higher than 600°C, biochar will be produced with a large specific surface area, higher degree of aromaticity, but fewer functional groups; in low-temperature pyrolysis, biochar will have rich functional groups, but weak pore development.

3. Adsorption Mechanism

3.1 Physisorption

When the particulate matter enters the pore, the microporous structure of biochar has an obvious physical interception effect on fine particulate matter. The mesopores act as a diffusion channel, so that the particles can enter the deeper adsorption site. After activation treatment, the microporous structure of biochar reaches 86%, and the adsorption capacity of particulate matter is significantly improved [9]. Micropore filling means that particles entering the micropore are captured by the superposition of the potential energy of the pore wall on the molecule. Compared with mesopores and large pores (surface covering is the main adsorption), micropores are mainly filled with pores, showing an l-type adsorption isotherm (Langmuir type). The maximum adsorption capacity is determined by the volume of micropores. When the micropores are filled, the adsorption also enters the stable period. The molecular sieving effect refers to the selection of particles of a specific size according to the size of the aperture, and the particles with a molecular dynamics diameter larger than the aperture are separated. The van der Waals force is the main driving force of physisorption. It is the interaction between the surface atoms and particles of biochar. The van der Waals force is weak, but due to the huge specific surface area of biochar, it can still form a considerable adsorption effect.

π-π accumulation is the main mechanism of biochar adsorption and conversion of aromatic pollutants. Biochar is pyrolyzed at high temperature, and the condensed aromatic ring of the sheet layer is randomly stacked to form an irregular carbon structure with high aromaticity and stability, with a stable π electron system. At the same time, there is also a π electron system for polycyclic aromatic hydrocarbons on the surface of the particle. When the two π electron systems meet, they will produce a strong affinity and stacked together in a face-to-face parallel way, thus forming a stable π-π interaction [10].

3.2 Chemisorption

The interaction of surface functional groups refers to the polar groups on the surface of biochar, which can complex with oxygen-containing hydroxyl groups on the surface of biochar, form hydrogen bonds and acid-base neutralization [11]. For example, the oxygen-containing groups on the surface of biochar can form weak chemical bonds with electronegative atoms (O, N) and H atoms in pollutants, thus fixing pollutants. Oxygen-containing active groups such as carboxyl groups, hydroxyl groups and carbonyl groups can form coordinate bonds with metal ions and polar molecules through coordinated reactions, effectively fixing heavy metal ions.

When the surface charge of biochar is opposite to that of charged particles, electrostatic interaction will occur (in essence, Coulomb force). The properties of the surface charge of biochar are affected by the pH value, which determines the dissolution state of the official group. Therefore, the surface charge state of biochar can be adjusted by adjusting the PH value of the solution, and then the electrostatic adsorption intensity can be controlled.

4. Influential Factors

The chemical composition of the precursor material of biochar is different from the microstructure, which affects the pore structure of biochar [12]. For example, wood cellulose has a natural fiber bundle structure, which is conducive to the formation of a developed pore structure after pyrolysis. The high content of ash in animal manure will affect the development of micropores in biochar. Different temperatures of pyrolysis lysis will also affect the properties of biochar. Low-temperature pyrolysis can retain the functional group, which is conducive to chemisorption, while high-temperature pyrolysis promotes high aromaticity and is conducive to the development of pores, greatly increasing the specific surface area, which is conducive to physisorption [7,13]. When the temperature is too high, it will cause the micropores collapse.

The basis of physisorption is the specific surface area and pore structure. The large specific surface area and appropriate pore size can provide sufficient space for pollutants, and also directly affect the adsorption capacity of biochar. surface functional groups are the decisive factors of chemisorption. The formation of hydrogen bonds, complexing reaction and neutralization reaction determine the adsorption direction and adsorption intensity [11]. Changes in temperature will also affect the adsorption performance of biochar. The adsorption process is usually an exothermic reaction, and the driving force of the physisorption process is mainly the van der Waals force. Therefore, when the temperature rises, the molecular movement intensifies, which makes it difficult for the molecule to be adsorbed and reduces the adsorption capacity. However, chemisorption involves the formation of chemical bonds. A suitable temperature increase can improve the chemisorption rate [11], but too high will still lead to a decrease in the adsorption capacity.

In real life, atmospheric pollutants are mixtures, so there will be a variety of pollutants competing for limited adsorption sites. The size of the competitiveness is affected by the polarity, size and the strength of the interaction force of pollutant molecules. Molecules with strong polarity first occupy polar positions, and those with a molecular diameter smaller than the microporous diameter are more likely to enter micropores, and priority is given to adsorption on molecules with stronger interaction on the surface of biochar [14].

5. Facing Challenges

There is still a lack of understanding of the synergistic relationship between physisorption such as micropore filling, van der Waals force and the formation of hydrogen bonds, and the synergistic relationship of chemisorption such as complex reactions under the actual situation, and which mechanism dominates. The structure-effect relationship of biochar is difficult to establish due to the lack of complete correlation, which makes the production process more difficult. On the other hand, the insufficient pyrolysis process of biochar may cause volatile organic matter (VOCs) to exist in biochar, posing the risk of air pollution. Research shows that at 400℃, the concentration of volatile organic matter measured by biochar prepared from manure as a precursor is 73.4μg/g at 50℃, but it drops to 4.96μg/g at 700℃ [15]. The current research on the relationship between the preparation cost and the adsorption efficiency of biochar modification is unclear, and there is a lack of evaluation of service life and regeneration cost. The difference in precursor materials directly affects the final product, resulting in differences in performance.

6. Future Outlook

The main challenges faced by the research on biochar adsorption of atmospheric pollutants are insufficient fundamental understanding, lack of safety risk assessment and unknown cost. Therefore, the future development direction of this field should be to realize the quantitative distinction between physisorption and chemisorption, and analyze the impact of different surface sites on the total adsorption capacity of biochar. Research the modification method that consumes less energy and requires fewer reagents and the regeneration process that extends the service life of biochar to reduce costs.

At the same time, improve the pyrolysis process, reduce the residue of volatile organic matter in biochar, and establish a strict risk assessment system for secondary pollution that may occur in the production process. Pre-treatment of the precursor to reduce the content of harmful substances in the final product. Assess the risk of the re-release of adsorbed pollutants due to environmental changes during the use of biochar, and analyze the risk of harm to the environment of degradation products generated during use.

7. Conclusion

Biochar has formed a relatively complete theoretical system in the field of adsorption of atmospheric pollutants. Physisorption such as micropore filling, van der Waals force and π-π interaction makes biochar have basic adsorption ability. Chemisorption based on hydrogen bonds and complex reactions enhances adsorption intensity and adsorption selectivity. The adsorption capacity is determined by the specific surface area and pore size. The type of of the functional group determines the direction of chemisorption, and π-π interaction is affected by the degree of aromaticity. The difference in the pyrolysis process directly affects the characteristics of biochar. Low-temperature pyrolysis can retain the function group, which is conducive to chemisorption. As the temperature rises, the pores play a dominant role and lead the physisorption. The future research direction should gradually shift from single adsorption to multi-mechanism synergy, transition from the ideal conditions of the laboratory to the actual application environment, accurately design the physicochemical properties of biochar according to the characteristics of target pollutants, achieve high adsorption efficiency, strong adsorption selectivity, and provide better solutions for atmospheric pollutant control.

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Conflicts of Interest

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