Research Progress of Biochar for Water Pollution Control

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Abstract. As an emerging carbon material, biochar has received great attention from scholars in recent years. This paper focuses on the application of three kinds of biochar in water pollution control engineering and their degree of control on organic matter and heavy metal pollution in water. The paper discusses sludge-based biochar, agricultural biomass matrix biochar, and clay mineral/biochar composites. The paper concludes that most biochar materials are at the experimental exploratory research stage and there is limited research on their commercial applications. The paper describes the mechanisms of how biochar can control organic and heavy metal pollution and discusses the advantages and limitations of biochar in controlling these two types of pollutants and the future direction of biochar. The aim of this paper is to help researchers understand the role of biochar in water pollution control engineering and to establish the relevant knowledge framework and logic more effectively. It is hoped that after reading this paper, readers will be able to explore and discover suitable biochar materials or biochar composites for water pollution control engineering.

Keywords: Biochar; water pollution control; carbon reduction; application.

1. Introduction

Biochar is a solid material containing a large amount of aromatic hydrocarbons, which is produced by cracking biomass matrix materials under fully anaerobic or oxygen-limited conditions at different temperature ranges. Biochar has a large specific surface area and high ion exchange capacity, which can effectively absorb organic pollutants and heavy metal pollutants. Currently, carbon emission is a pressing global issue, and the concepts of peak carbon and carbon neutrality are deeply rooted in people's minds [1-2]. For most of the scholars, the utilization of bio-based materials for valuable and efficient carbon utilization has become the preferred method.

This new material has also been heavily utilized as an effective method for controlling water pollution. Currently, there are various techniques available for the elimination of organic pollutants and heavy metals from the aquatic environment, such as redox, chemical precipitation, ion exchange, membrane separation, electrochemical, and adsorption. Biochar, as an emerging material, has attracted the attention of scholars due to its wide range of sources and strong adsorption capacity [2-5].

This paper focuses on the application of biochar matrix in water pollution control. It was found that biochar used for water pollution control mainly includes sludge-based biochar [6], biochar extracted from agricultural biomass [7], and clay mineral/biochar composites [8]. In addition, this paper summarizes the research progress of biochar in controlling two major types of pollutants in water, i.e., organic pollutants and heavy metal pollutants, and outlines the advantages and disadvantages of biochar.

2. Biochar for Water Pollution Control

There are various ways to use biochar in water pollution control. This chapter will analyze three types of biochar commonly used in water pollution control, as well as their advantages, disadvantages, and preparation methods.

2.1. Sludge-based Biochar

Sludge is an unavoidable by-product of industrial and domestic wastewater treatment processes. The surface of biochar made from it is characterized by the presence of a layer of sludge on the surface of the biochar. There are many pores on the surface of biochar made from sludge, which can strongly adsorb heavy metals, microorganisms and organic matter in wastewater. With the rapid development of human scientific and technological progress, the spread of more advanced industries and urbanization has led to an increasing amount of contaminated sludge in water purification systems as well as in natural water bodies. The annual production of sludge in China reached 60 million tons in 2019, and it is expected to reach 75.38 million tons during the 14th Five-Year Plan period [9, 10]. Therefore, compared with the general landfill disposal method, sludge carbonization and reuse are effective sludge disposal method. Therefore, how to utilize municipal sludge efficiently, economically, and safely has become the current problem of municipal sludge treatment in China. According to Hu Yao et al. [6] there are three types of sludge biochar pyrolysis: traditional pyrolysis, microwave pyrolysis and hydrothermal method. According to Table 1, several processes were evaluated from the point of view of low carbon and environmental protection: hydrothermal method was superior to microwave heating method than traditional heating method [6]. From the evaluation of process complexity: traditional pyrolysis is the simplest, hydrothermal method has average process complexity, and microwave pyrolysis is the most complex. However, due to the sensitivity of sludge carbonization to temperature, the three methods should be evaluated comprehensively according to the requirements and characteristics of the desired products in order to select the optimal solution.

Table 1. Comparative analysis of three preparation methods [6].

Method of preparing sludge biochar	Principle	Preparation conditions	Vantage	Drawbacks
Conventional pyrolysis	Direct heat decomposition	300-1000°C	Simple process, high product porosity, large production scale, few processing limitations	Low yield, high energy consumption
Microwave heating method	Electrical energy is converted to microwave radiation and then converted to heat energy	550-700°C	Uniform product properties, high porosity, uniform heating, high efficiency, energy saving and environmental protection	Complex process operation, small production scale
Hydrothermal method	Pyrolysis using high pressure water vapor	≤350°C	Low energy consumption, environmentally friendly.	Low level of aromatization, low porosity, poor stability

2.1.1 Sludge biochar modification

The modification of sludge biochar can be categorized into two types of modification. One category is adsorption modification and the other is catalytic modification. The common modifications included in each category are shown by Table 2.

Table 2. Sludge biochar modification classification [6].

Type of modification	Modification method
Adsorption modification	Modification Methods Magnetic material modification, nanomaterial modification, acid modification, alkaline modification, organic material modification, solid material modification
Catalytic modification	Persulfate system, Fenton system, photocatalytic system

2.1.2 Limitations of sludge biochar

At present, the adsorption and catalytic modification of sludge-based biochar are mostly in the laboratory stage, lacking economic cost analysis and matching with the actual situation [6]. There is no detailed Life Cycle Assessment (LCA) process to determine whether the modification or preparation of sludge-based biochar will cause more pollution to the environment (water bodies), which has not been identified.

2.2. Agricultural Biomass Substrate Biochar

China is a large agricultural production and consumption country. China's annual crop residue production is about 600-800 million tons, accounting for about half of the total biomass resources in China [7] Therefore, the traditional in situ burning of agricultural biomass is a great waste of carbon resources. Therefore, the traditional on-site burning of agricultural biomass is a great waste of carbon resources, and using it as a substrate for carbonization and fixation will be an effective way to reduce carbon emissions of resources.

2.2.1 Types of agricultural biomass substrate biochar

According to the research of Hu et al. [8] it is known that the current agricultural biomass carbon is mainly the following celery stalk biomass charcoal, date palm magnetic biocarbon, modified cotton straw, cassava straw cationic adsorbent, modified rice husk ash adsorbent, wheat straw biocarbon, bamboo flake biocarbon, modified cationic wheatgrass straw biocarbon, beet residue, sugarcane bagasse, peanut shells mixed biocarbon, bamboo , bagasse biochar clay composites, wheat straw biochar-graphene composites, magnetic wood chip biochar, oxygenated functional group modified rice straw biochar, manganese oxide modified biochar, corn stover biochar, pine biochar, pig manure biochar composite biochar, sesame straw biochar [7].

2.2.2 Usage in water pollution control

Biochar prepared from agricultural biomass is mainly used as anion/cation adsorbent and organic matter pollution adsorption in water pollution control due to the characteristics of biomass matrix rich in cellulose, lignin and hemicellulose [7].

2.2.3 Limitations of biochar preparation from agricultural biomass

Biochar composite adsorbent surface functional groups are complex, the removal of pollutants is affected by a variety of mechanisms, and most of the current research remains at the stage of epigenetic analysis [4]. The effective recycling of biomass resources and charring process lacks a complete system and process flow compared to sludge-based biochar, and commercial application studies have not been identified. And same as sludge-based biochar, there is no complete LCA evaluation study for this process.

2.3. Clay Mineral/Biochar Composite Materials

Clay minerals and biocarbon materials are widely used in wastewater treatment processes due to their low cost and easy availability. According to Huang et al. [11] these composites have a certain adsorption effect on heavy gold ions, dyes, antibiotics, and nutrient-rich salts in wastewater.

2.3.1 Types

Composites used for heavy metal adsorption in water treatment are as follows: montmorillonite/corn stover, Aconite/de-siliconized rice, Dendrobite/coconut shells, Vermiculite/hickory wood, Bentonite/hollow lotus seed, Zeolite/sludge, Bentonite, Fontschauerite, Cigarette wastes, Bentonite and Corncobs. Composites used for dye adsorption in water pollution: montmorillonite/bamboo, silica silt/carboxymethyl cellulose, bentonite/kelp, augite/bagasse, augite/rice husk. Antibiotic removal: montmorillonite/wheat straw, montmorillonite/municipal solid waste, montmorillonite/cow dung and wheat straw, montmorillonite/corn cobs, montmorillonite/cauliflower leaves, montmorillonite/municipal garbage, Aberdeen/potato stems, Aberdeen/straw, Aberdeen/vegetable leaves, Aberdeen/rice husk. Removal of eutrophic salts are: montmorillonite/bamboo, vermiculite/algae, zeolite/water hyacinth, bentonite/cotton stalks [11].

2.3.2 Limitations of use in water pollution control

It has been shown by a number of studies that there are fewer studies on the differences in the disposal and stability of clay mineral/biochar composites as well as their disposal methods and whether they produce secondary contamination. Again, these studies do not have LCA evaluations.

3. Application of biochar to water pollution

At present, biochar is mainly used in water pollution control engineering for organic matter pollution and heavy metal pollution prevention through adsorption principle.

3.1. Organic pollution control

The adsorption mechanism of biochar for organic pollutants can be summarized as shown in Fig. 1. Biochar utilizes the abundant micropores and mesopores on its surface to adsorb organic substances. The large specific surface area provides abundant adsorption sites. According to research, the removal of organic pollutants in water bodies is mainly in the following areas: antibiotic wastewater, organic dyes, pesticide wastewater, PCB and polycyclic aromatic wastewater [12].

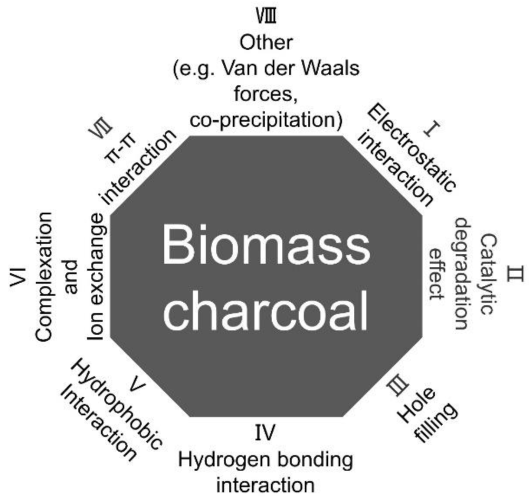

Fig 1. Mechanism of organic pollutant removal by biomass charcoal. (Photo/Picture credit: Original)

3.2. Heavy Metal Pollution Control

For biochar, in general, the pyrolysis temperature increases, the H and O elements decrease, the degree of aromatization of biochar increases, and active functional groups such as -COOH and -OH decrease, all of which are unfavorable to the adsorption of heavy metals. COOH, -OH and other active functional groups decrease, which is not favorable to the adsorption of heavy metals; however, on the other hand, the specific surface area of biochar increases with the increase of pyrolysis temperature. On the other hand, with the increase of pyrolysis temperature, the specific surface area of biochar increases, and the number of adsorption sites increases, which is favorable to the adsorption of heavy metals [2]. However, on the other hand, with the increase of pyrolysis temperature, the specific surface area of biochar increased, and the number of adsorption sites increased, which was in favor of heavy metal adsorption. On the other hand, the increase of specific surface area of biochar with the increase of pyrolysis temperature is favorable for the adsorption of heavy metals. According to the research of Wang et al., the adsorption amount of heavy metals on modified biochar has been improved to some extent, but the degree of improvement is different [2]. The removal effect of heavy metal ions varies with pH, temperature, contact time and dosage. The adsorption of organic pollutants by biomass carbon in water bodies is different from heavy metal pollution. According to the chemical properties of heavy metal ions, in addition to physical adsorption, the method of fixing metal ions, chemical precipitation and other ways to remove. Therefore, the recycling of biochar for heavy metal pollution treatment is relatively complex.

4. Prospects and Suggestions for Future Water Pollution Control by Biochar

Therefore, due to its pollutant removal mechanism for adsorption, how to regenerate and recycle biomass carbon in water pollution control, i.e., pollutant desorption and disposal methods need to be researched and developed. In this paper, we believe that biochar is likely to become a main water treatment device in water pollution control in the future. However, in the face of the current environmental problems that the world is concerned about (global warming), we should take into account the carbon emissions of the corresponding pollution treatment devices. Thus, we should minimize the disturbance and damage to the environment in various aspects. Therefore, LCA evaluation is a necessary study. We should not focus on water pollution control and pollute the rest of the environment.

5. Conclusion

Biochar is a star material in the field of emerging adsorbent materials, which is closely related to carbon emission and environmental protection. In this study, it was found that the main substrates of biochar used in water pollution control projects are sludge substrate, agricultural biochar substrate and clay/mineral biochar substrate, and it was also found that most of the biochar materials are in the stage of experimental exploration and research, and there are fewer studies on the commercialization of the biochar and the existence of the secondary pollution in the process of biochar preparation. In this study, it was shown that biochar can be used to control and remove organic matter and heavy metal pollution in water bodies mainly by adsorption. For heavy metal ions, the reaction sites can be added to the biochar material according to the chemical nature of heavy metal pollution, which can provide better control and removal effects than microporous and mesoporous adsorption. Finding and preparing a biochar material with high commercial value that can simultaneously adsorb and remove two major types of pollutants from water bodies is the future direction of biochar material development and research. That is, LCA life cycle assessment needs to maximize the advantages of LCA evaluation in the direction of carbon reduction. This thesis briefly describes the use and development direction of biochar materials in water pollution control engineering, and puts forward some suggestions for the treatment and prevention and control of organic pollution and heavy metal pollution. This paper argues that all research needs to conduct a complete and comprehensive LCA evaluation, to effectively understand the new and reduced pollutants and thus be able to build a better environmental home for mankind, to achieve the goal of sustainable development of man and nature!

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