

Research Progress on the Application of Biochar in Adsorbing Organic Pollutants from Wastewater

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Abstract. With the rapid development of industrial activities, the amount of organic pollutants in wastewater has increased significantly. These pollutants have a profoundly detrimental impact on both the environment and human health. Biochar has shown great potential in removing organic pollutants because of its porous structure and active surface groups. This paper reviews the main methods for preparing biochar, the ways to improve its properties, the mechanisms behind the adsorption process, and its application in treating polluted water. The future development of biochar in this field is also discussed.

Keywords: Biochar, organic pollutants, adsorption, wastewater treatment, modification.

1. Introduction

Industrial and agricultural work has caused the release of a significant amount of wastewater with organic pollution [1]. This water often contains harmful substances such as dyes, pesticides, and leftover medications. These substances do not break down easily. They can remain in water or soil for an extended period and may harm people, animals, and plants. Some are also hard to remove, which makes the cleaning work more difficult. People have tried various methods, including adding chemicals, allowing solids to settle, and using potent cleaning agents. But these methods do not always work well. The problem is more challenging to solve when the pollution level is low or when various types of waste are mixed. People are now seeking new methods that are safer and more effective. One possible way is to use biochar. It has a large surface area, many small holes, and active spots that can catch harmful substances. These features help it remove dyes, drug remains, and hormone-like chemicals. Biochar can remain useful for an extended period, making it a viable option for treating contaminated water in the future.

2. Preparation Methods of Biochar

Biochar is a carbon-rich material. It is made by heating plant waste or other natural materials in the absence of oxygen. This process produces a black, light substance with many small holes. Common materials used to make biochar include crop waste, wood pieces, fruit shells, animal waste, and sewage sludge [2]. Biochar can be derived from a wide variety of sources within the food chain, including rice husks, straw, sugarcane residues, grape pomace, peanut shells, pig manure, and cow dung. Among these, agricultural straw has attracted significant attention due to its high production volume. It is estimated that China produces over 900 million tons of straw annually, accounting for more than 16% of the global straw output and ranking first worldwide. According to Li and Wang, the average annual carbon sequestration potential of converting crop straw into biochar in China is approximately 0.96×10^8 tons, which could play a significant role in mitigating climate change [3].

Additionally, the sugar and alcohol industries produce large quantities of bagasse, a fibrous byproduct of sugarcane processing. In China, sugarcane production amounts to approximately 123 million tons annually, yielding about 5.2 million tons of bagasse. Animal manure, another biomass source from the food production stage, increased from 1.7 billion tons in 1995 to 2.8 billion tons in 2006.

At the consumption stage of the food chain, household food waste also represents a significant biomass source. In Finland, it has been reported that households generate approximately 130 million kilograms of food waste each year.

These materials are inexpensive and readily available, making biochar a cost-effective and eco-friendly solution for pollution management. The amount of carbon and the structure of biochar mainly depend on the type of material and how it is made [3]. People can produce biochar in various ways, including heating without oxygen (pyrolysis), using hot water, burning with limited oxygen, or applying microwave heat [4]. Each method gives biochar different features. The technique is often chosen based on the material's moisture content and the type of biochar required for the application.

3. Modification Techniques of Biochar

Biochar can remove some harmful substances on its own. But it still has some problems. To help it work more effectively, many researchers have found ways to improve it [5]. Biochar has garnered widespread attention as a low-cost, biocompatible, and efficient adsorbent for removing various contaminants from water. Its physicochemical properties, and thereby its adsorption performance, can be significantly enhanced through modification techniques. Numerous studies have focused on improving the adsorption capacity of modified biochar and investigating the underlying mechanisms of adsorption. However, a comprehensive and systematic analysis of the different modification approaches and their specific effects on various types of contaminants remains limited.

This review integrates recent research on the adsorption behavior of modified biochar toward diverse pollutants. It classifies modification strategies into three main categories: physical, chemical, and composite modifications. Physical modifications primarily aim to enhance the specific surface area and pore structure of biochar. Chemical modifications introduce additional functional groups that facilitate targeted interactions with contaminants. Composite modifications combine the advantages of different functional materials to enhance adsorption and further performance.

The review compares the adsorption efficiency of each modification type for heavy metals, inorganic salts, and organic pollutants. It also presents a systematic analysis of the adsorption mechanisms corresponding to each class of contaminants. Ultimately, the review highlights current challenges and offers recommendations for the future development and application of biochar-based adsorbents.

These methods alter the surface, increase its size, and introduce groups that help capture organic pollutants. After these changes, biochar becomes more effective in cleaning contaminated water. There are three main types of changes: physical, chemical, and mixed. Physical changes are easy and cheap. They include heating, using steam, adding carbon dioxide, or using sound waves. These steps can create new pores or enlarge existing pores. This gives more space for harmful substances to stick. Some steps also clean the surface by removing ash or unclogging blocked pores. This helps biochar work better and last longer. These methods do not need strong chemicals. They are safer for the environment and cost less. They are a good choice for cleaning a large amount of wastewater.

4. Types of Organic Pollutants and Adsorption Mechanisms

Wastewater contains a variety of harmful organic substances. Some common examples include dyes such as methylene blue and rhodamine B, farm chemicals like glyphosate and dichlorvos, and pharmaceutical residues like sulfonamides and tetracyclines. Other harmful substances, like phenols and hormone-like compounds, are also often found in dirty water [6]. These chemicals do not break down fast. They can remain in water for an extended period and may harm people, animals, and the environment. Most of them come from factories, farms, drug makers, and homes. Their chemical bonds are strong, so normal cleaning steps cannot easily remove them. Some of these pollutants are found in tiny amounts, but they can still cause strong effects on living things [7]. Others can build up slowly in the body and may lead to health problems later.

Biochar can help remove these harmful substances from water in several simple ways [8]. One way is by static charge. If the surface of biochar has a negative charge, it can attract pollutants with a positive charge, such as dye molecules. Another way is called π - π interaction. This happens when

ring parts of a pollutant stick to the carbon rings in biochar [9]. These links help the waste stay on the surface. Biochar can also form hydrogen bonds if it has surface groups, such as hydroxyl or carboxyl groups [10]. If the pollutant has no charge, it can still be held by hydrophobic forces [11]. If metal parts are added to biochar, they can also bind pollutants by forming special bonds with them [12]. The results can vary with changes in pH, temperature, or salt level in the water [13].

5. Application Examples and Effect Analysis

Numerous studies have demonstrated that biochar can effectively remove harmful organic substances from wastewater. It performs well in laboratory tests and real-world treatment projects [14]. Different types of biochar have been utilized to purify water contaminated with dyes, agricultural chemicals, and residual pharmaceuticals [15]. In each case, the results were good. This indicates that biochar is effective in many cases. It can be used for various types of dirty water and meets multiple cleaning needs.

For dye-polluted water, biochar made from rice husks and treated with chemical steps can remove rhodamine B up to 250 milligrams per gram of biochar [16]. In some tests, over 95 percent was removed. Bamboo-based biochar is also used to take out methylene blue. Its adsorption follows the Langmuir model. This means the dye forms a single, complete layer on the surface of the biochar. It also follows the pseudo-second-order model. This means the process depends on the amount of dye in the water and the number of free spots on the biochar.

For water contaminated with pesticides, biochar made from sludge has been used to remove chemicals such as dichlorvos and glyphosate [17]. These biochars work well in acidic water. They stay strong for a long time, which helps with long-term use. Pesticides are harmful and can move quickly through water, so it is essential to stop them early. Biochar can prevent these dangerous substances from entering rivers or seeping deep into the ground.

Drug waste is a big problem. Substances like tetracycline and sulfamethoxazole can harm people and water animals [18]. Biochar can be combined with chitosan to enhance its effectiveness. This type of biochar yields better results [19]. It has more active spots and surface groups. These help it form strong bonds, like hydrogen or π - π bonds, with drug molecules. This improved biochar works better than normal biochar.

Some companies use biochar in real treatment. A pharmaceutical factory utilized magnetic biochar made from coconut shells to treat its wastewater. It removed 93 percent of the pollution. The same material was reused five times and still worked well. This shows that biochar is strong and can be reused. It also saves money and reduces waste, which is particularly beneficial for large projects.

Many scientists also use models to study the mechanisms by which biochar works. They use the Langmuir and Freundlich models to demonstrate the amount of pollution removed. They use kinetic models, such as pseudo-first-order and pseudo-second-order, to illustrate the rapidity of the process. They also use thermodynamic ideas like Gibbs free energy, heat (enthalpy), and disorder (entropy) to understand energy changes [20]. These models help people understand the process and plan better.

6. Problems and Future Trends

Biochar can effectively purify contaminated water, but certain issues still make it challenging to use in large-scale or long-term systems [21]. These problems stem from the sources of materials, the high cost of treatment, and the difficulty of addressing multiple types of pollution simultaneously.

A significant problem arises from the diverse materials used to produce biochar. It can be made from crop waste, wood, or sludge. Each one yields different results [22]. Even when the same material is used, changes in heating or other steps can alter the final biochar [23]. So, the shape, chemical parts, and pore size are often different. For example, biochar from rice husks may not work the same as biochar from bamboo or sludge, even when made at the same temperature. Because of this, it is challenging to establish a single rule that applies to all types of biochar.

Another problem is that improving biochar often requires significant investment and multiple steps. Chemical changes usually involve strong acids, metal salts, or other hazardous substances. These steps are detrimental to the environment and costly. For small farms, factories, or village systems, this may be too hard or too costly to use. If the price stays high, fewer people will use biochar.

There is also a problem when the water is contaminated with various types of pollution. Real dirty water typically contains organic waste, heavy metals, and substances such as nitrogen or phosphorus [24]. These different substances can all attempt to utilize the same active sites on biochar [25]. This can make each one get removed less. It is also unclear how these substances interact with each other. This makes it difficult to determine how well biochar will perform in real-world water.

A concern is what to do with biochar after it has absorbed the waste. To use it again, it needs to be cleaned. This is now accomplished through heat or strong chemicals, but these can damage the biochar or impair its effectiveness later [26]. Some cleaning steps can also create new pollution. We need safer and easier ways to clean biochar. If cleaning is too tricky or creates new problems, people may be reluctant to use it for a long time.

One way to address these issues is to explore new ideas. A helpful method is to produce biochar in a sustainable manner. These use enzymes, plant parts, or beneficial microbes instead of harmful chemicals [27]. These soft steps are safer and better for the earth.

Another approach is to create new types of biochar that can perform multiple functions. Some of them can remove different types of waste simultaneously. Some can also kill germs or help break down harmful substances faster. This works well when the water has many problems.

Another approach is to utilize tools such as computer models, molecular tests, and machine learning. These tools can help predict how biochar and pollutants interact with each other. They help make better biochar and use less time and money for testing.

One last way is to establish clear rules for producing and utilizing biochar. When people follow the same steps, the results can be trusted. This can help more people utilize biochar in both urban and rural areas. If the quality remains the same and users feel secure, more people will use it for an extended period.

7. Conclusion

Biochar is a cheap and valuable material that helps remove harmful organic substances from dirty water. It is made from crop waste, wood, and other plant materials. These materials are readily available and do not harm the environment. Biochar has a large surface area and numerous small pores. It can hold different pollutants. These include dyes, farm chemicals, and leftover drugs. These pollutants are often hard to clean using standard methods.

Biochar works more effectively when produced correctly. Heating it to high temperatures can cause more pores to form and make it stronger. Changing its surface through heat, chemical treatment, or the addition of other materials can also help. Some types of biochar with added components can simultaneously remove more than one type of pollutant. This is particularly helpful when the water is contaminated with various types of pollution.

Biochar performs well in both laboratory tests and real-world applications. Many studies show that it can significantly reduce waste. It can be used multiple times and still works well, which helps save money. Some people use simple models to study how it works. These models enhance the design and facilitate its use in real-world systems.

There are still some problems. The quality of biochar varies depending on the materials used in its production and the method employed for its production. Some ways to make it better are costly or difficult to use outside the lab. If the water contains a variety of waste, the results may vary. Cleaning used biochar is also not easy and may bring new problems.

In the future, people should develop more efficient methods for producing biochar that are less costly and safer. Making biochar that can perform multiple functions, such as killing germs or treating

water with various types of waste, is also beneficial. Using computer tools can help make better designs. Clear and simple rules for making biochar can help more people trust and use it.

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