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Metal Oxide-Based Biochar Composites for Wastewater Treatment Applications

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ABSTRACT
This briefly summarizes the purpose of the literature review, its main elements, methods of analysis, and main conclusions. The purpose of this literature review is to summarize the present applications of novel metal oxide based biochar composites in wastewater treatment. The study identified different effects of different metal oxide-based biochar composites for treating wastewater, bringing more options for treating wastewater.

KEYWORDS
Metal oxides; Biochar; Wastewater treatment; Literature review; Composites

1 Introduction

With the development of industry, water pollution caused by wastewater discharge has become a concern. Adsorbents are a good solution, but most of them are costly.

Biochar is a carbon-rich solid material produced by pyrolysis of biomass under anoxic conditions, which has a large specific surface area, a solid carbon structure, a wide range of raw material sources, and shows good catalytic activity and stability under both acidic and alkaline and neutral conditions. Meanwhile, biochar is a cheap and easy-to-obtain adsorbent material with excellent performance, which is widely used in the field of degradation of water environment pollutants due to its environmental friendliness and wide source.

Biochar-based composites constructed on the basis of metal oxides such as TiO2 , iron oxide, MnO2 and biochar have excellent adsorption properties and are widely used in the degradation of pollutants in water.

2 Characterization and preparation of biochar with metal oxides

Biochar can be prepared from biomass pyrolysis, which is a process in which biomass raw materials are heated in an anaerobic or low-oxygen environment to cause internal decomposition to form biochar, bio-oil and pyrolysis gas. Most of the research results show that the pyrolysis process of biomass can be divided into three stages: drying and preheating stage, volatilization and analysis stage, and carbonization stage [6]. The first stage generally occurs between room temperature and 130°C, when the internal structure of biomass is rearranged and a large amount of water is lost; the second stage occurs between 130 and 450° C, when cellulose, hemicellulose, lignin and other solids absorb a large amount of heat and decompose, and volatilization is analyzed; and the third stage mainly occurs after 450°C, when the biochar is slowly formed and char-rich residues are produced. Pyrolysis temperature is considered to be the most critical factor affecting the properties of biochar, which has a large impact on biochar yield and physicochemical properties [7]. Generally, as the pyrolysis temperature increases, the biochar yield decreases, the pH increases, the aromatic carbon structure and nanopore size increase accordingly, and the number of oxygen-containing functional groups, such as C-O and O-H bonds, decreases and the number of basic functional groups increases in the biochar. According to the rate of heating, the pyrolysis process can be divided into slow pyrolysis and fast pyrolysis. At low temperatures, different acceleration rates will have an effect on the biochar yield, which can be neglected at high temperatures.

2.1 TiO2/biochar composites

TiO2-loaded biochar composites can be prepared from different biochar sources and applied to the field of wastewater treatment to obtain better removal results Sol-gel, hydrolysis, hydrothermal/solvent-thermal, ultrasonic and other methods of preparation are able to prepare TiO2/biochar composites, and are able to remove the pollutants in the wastewater, such as methyl orange, antibiotics, phenol, and activated blue 69.

2.2 Iron oxide-biochar composites

Luyen et al [35] developed a cost-effective magnetic biochar (MBC) nanocomposite using rice husk biochar and iron oxide nanoparticles as precursors and applied it for the removal of crystalline violet (CV) from aqueous solution.

2.3 MnO2/biochar composites

Tan et al [45] prepared iron and manganese oxide modified biochar composites from rice straw biochar.

2.4 Other oxide-biochar composites

The combination of biochar with other oxides for the preparation of composites can also significantly increase the specific surface area, improve the pore size, regulate the surface functional groups, increase the adsorption sites, and improve the adsorption and degradation of pollutants. MgO, ZnO, ZrO2 , γ-Al2O3, and graphene oxide have also been used for the preparation of biochar-based composites [50-51].

3 Adsorption properties and applications of metal oxide-based biochar composites

3.1 TiO2 /biochar composites

TiO2 nanomaterials dispersed on the surface of biochar can increase the specific surface area of the catalyst and the number of active sites; on the other hand, based on the porous structure and adsorption ability of biochar, it can enrich the pollutant molecules around the TiO2 particles, which can greatly improve the degradation efficiency of the organic pollutants in the environmental medium.

Biochar has good electrical conductivity and electron transport ability, which can reduce the recombination of photogenerated electron-hole pairs in the photocatalytic process and accelerate the degradation process of organic pollutants.

Based on the energy band theory of semiconductors, biochar can synergistically reduce the band gap width of TiO2 . A Ti-O-C bond can be formed between biochar and TiO2 , and when TiO2 is modified by C doping, C acts as a photosensitizer, and the band gap energy of TiO2 is sensitized by doped C. The band gap energy is reduced, and the photoresponsive range of the composite material will be shifted from UV region to visible region, which can effectively promote the degradation of organic molecules [22]. The photocatalytic oxidation experiments showed that the decolorization efficiency for methyl orange was 96.88% and the mineralization efficiency was 83.23%.

3.2 Iron oxide-biochar composites

Magnetic biochar-iron oxide composites (MBCs) prepared from agricultural wastes had high adsorption capacity for metal ions such as lead, chromium, copper, and other pollutants in water such as tetracycline, methylene blue, and crystal violet [42]. It was found that the adsorption efficiency of the fabricated magnetic biochar on crystal violet solution at pH= 6.0 could reach 99.02%, with a maximum adsorption capacity of 185.6 mg/g. The adsorption capacity of MBC increased rapidly with the increase in the concentration of crystal violet, from 25 mg/L to 250 mg/L, and was saturated at 250 mg/L, with a capacity of 185.6 mg/g. The adsorption capacity of MBC was increased from 10 mg/L to 250 mg/L, with a capacity of 185.6 mg/g. The adsorption capacity of MBC increased from 10 mg/g to 25 mg/L, with a maximum capacity of 185.6 mg/g; The adsorption capacity was 185.6mg/g. The amount of MBC increased from 10mg/25mL to 25mg/25mL, and the adsorption capacity also increased from 130mg/g to 164.6mg/g, and reached saturation. The adsorption behavior of the sample MBC on the simulated pollutants of crystal violet was in accordance with the Langmuir isotherm model; Khan et al[41] used corn stover powder as the raw material for the preparation of MBC and investigated the performance of MBC for the removal of Cd2+ from the wastewater. The results showed that the MBC successfully solidified iron particles, the iron species formed inner-sphere complexes with oxygen-containing groups and increased the number of oxygen-containing groups, and the affinity of MBC for Cd2+ was higher than that of other adsorbents, with the highest adsorption capacity of 46.90 mg/g. Numerous studies have shown that iron oxide-biochar composites have strong adsorption capacity, magnetic recycling capacity, and catalytic stability, and can still maintain a strong adsorption capacity for many repetitive experiments. multiple repetitions of the experiments can still maintain a high degradation rate.

3.3 MnO2 / Biochar Composites

The modified biochar/ferromanganese composite had increased specific surface area, smaller pore size and increased surface alkaline functional group content compared with the single system biochar, which not only improved the adsorption capacity of Cd2+ ions in wastewater, but also it was found that the biochar-ferromanganese composite could be regenerated in nitric acid solution after adsorption of Cd2+ . The adsorbent still showed high Cd2+ ion removal capacity after 3 times of reuse; Li et al [49] modified the biochar with potassium permanganate and loaded MnO2 particles on the surface and in the pores of the biochar to form a microporous biochar composite material, which provided more adsorption sites for the physical adsorption of the pollutants in water, and the highest adsorption capacity of Cd2+ ion was up to 81.10 mg/g, and the highest adsorption rate was 14.0 ml/min. The maximum adsorption capacity for Cd ion was 81.10mg/g, and the maximum adsorption rate was 14.46g/(mg-h), which increased the adsorption performance by 1.02 times compared with that of the single-system biochar material.

3.4 Other oxide-biochar composites

For the removal of pollutants in water such as phosphate, sulfamethoxazole and methyl orange, fluoride, sulfadimethylpyrimidine, etc., the degradation effect can also reach more than 90% [52-53]. Other oxide-biochar composites not only have high adsorption rate and adsorption capacity, but also have the advantages of environmental protection, high cost effect, high selectivity, etc., which have good application prospects in the field of water pollution treatment.

4 Research trends and future perspectives

Current research on metal oxide-based biochar composites primarily focuses on enhancing adsorption efficiency, optimizing synthesis methods, and exploring multifunctional applications. Future studies should prioritize the development of multi-metal oxide composites to leverage synergistic effects, which could further improve pollutant removal capabilities and catalytic stability. Additionally, green synthesis techniques, such as low-energy pyrolysis and solvent-free modifications, need to be refined to align with sustainable production goals. Emerging technologies, including machine learning-driven material design and in-situ regeneration strategies, hold promise for accelerating the discovery of high-performance composites and reducing operational costs. Practical challenges, such as scalability and long-term environmental impacts, must also be addressed through pilot-scale trials and life-cycle assessments. Integrating these composites with advanced wastewater treatment systems (e.g., membrane filtration or electrochemical processes) could unlock their full potential in addressing complex pollution scenarios.

5 Conclusion

In summary, metal oxide-based biochar composites exhibit remarkable potential for wastewater treatment due to their high adsorption capacity, recyclability, and adaptability to diverse pollutants. TiO_2, Fe_3O_4, and MnO_2 composites demonstrate exceptional efficiency in degrading organic dyes, heavy metals, and pharmaceuticals, often exceeding 90% removal rates. The integration of biochar's porous structure with metal oxides enhances active site availability and electron transfer, while magnetic properties facilitate easy recovery. However, challenges remain in scaling up production and ensuring long-term stability under real-world conditions. Future work should focus on optimizing synthesis protocols, validating performance in industrial settings, and assessing ecological risks. By bridging laboratory innovations with practical applications, these composites could become cornerstone materials in sustainable water purification technologies.

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