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Progress in the Application of Biochar in the Treatment Process for Selected Pollutants in Slaughterhouse Wastewater

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Abstract. With the large-scale development of slaughterhouses, the wastewater they generate has become a significant source of pollution, if not managed properly, it may lead to eutrophication of water bodies, ecological damage, and even pose risks to human health. Biochar, as a low-cost, environmentally friendly adsorbent material, has garnered significant attention from researchers. Research into the treatment of wastewater using biochar has gradually commenced, yet systematic analysis of its application within specific high-pollution wastewater treatment processes, such as those employed in slaughterhouses, remains inadequate. This paper analyses the characteristics of slaughterhouse wastewater, summarises the core properties of biochar, and then reviews case studies of biochar and its modified and composite variants in treatment processes for primary pollutants within slaughterhouse wastewater, and analyses the mechanisms by which biochar removes relevant pollutants, revealing that modified biochar and its composite materials not only offer low cost, ease of preparation, and environmental friendliness, but also demonstrate highly effective results when applied in relevant pollutant treatment processes. This study aims to provide valuable insights for optimising treatment processes for high-concentration organic wastewater from slaughterhouses and similar facilities, and to advance the application of biochar and its modified materials in environmental processes such as wastewater resource recovery.

1 Introduction

Water pollution is becoming increasingly severe, emerging as one of the five major threats facing the Earth's ecological environment. With the continuous advancement of human civilisation, vast areas across the globe are currently grappling with severe water pollution issues. According to World Health Organisation data, approximately three million people die each year from water pollution-related diseases. Moreover, due to the diverse sources of pollution—including industrial effluent, agricultural contamination, and domestic sewage—the pollutants vary considerably, making remediation efforts considerably more challenging. Recently, with the expansion of slaughterhouse operations, the wastewater generated by these

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facilities has become a significant source of environmental pollution that cannot be overlooked. The water exhibits a weakly acidic pH, a reddish-brown colour, and an unpleasant fishy odour. It is characterised by high levels of organic pollutants [1], ammonia nitrogen concentrations, substantial suspended solids content, and potential contamination with pathogens [2], oils, and other pollutants. If improperly treated, it poses a serious threat to aquatic ecosystems and human health. Biochar, as an emerging material for the resourceful utilisation of biomass, is a solid product primarily composed of carbon, hydrogen, oxygen and other elements. It is produced through the high-temperature pyrolysis or incomplete combustion of carbon-rich biomass under anaerobic conditions, exhibiting highly aromatic characteristics [3]. Owing to its high specific surface area, porous structure, and presence of active sites, coupled with its raw materials predominantly being waste biomass such as straw and wood chips, it serves as an adsorbent material in wastewater treatment processes. It participates in wastewater treatment through adsorption, as a biological carrier, and via catalytic action, demonstrating significant potential in nitrogen and phosphorus removal from water bodies and COD degradation. It is cost-effective, environmentally friendly, and sustainable. Research into the treatment of wastewater using biochar has gradually gained momentum in recent years. By analysing case studies of biochar application in slaughterhouse wastewater treatment processes, this paper provides valuable insights for optimising the treatment of slaughterhouse or similar wastewater streams through the use of biochar and its modified derivatives.

2 Characteristics of slaughterhouse wastewater and the pollution it causes

2.1 Sources

The primary sources of slaughterhouse wastewater include, first, washwater from livestock pens; second, water used for pre-slaughter washing of animals; third, bloodwater from the cutting room and wastewater from washing off entrails during the slaughter process. Additionally, wastewater is generated during high-temperature dehairing and skinning of livestock, as well as from processes such as fat extraction and boning [1, 2, 4].

2.2 Characteristics and primary contaminants

Slaughterhouse wastewater contains substantial quantities of animal hair, skin flakes, meat trimmings, bloodstains, and offal debris, undigested livestock feed, faeces, fats, and proteins. Generally free of heavy metals and toxic chemicals, its primary pollutants are: BOD_5 (five-day biochemical oxygen demand) concentrations of 350–1000 mg/L and CODcr (chemical oxygen demand) concentrations of 800–3000 mg/L, NH_3-N (ammonia nitrogen) concentration of 80–200 mg/L, SS (suspended solids) concentration of 500–2500 mg/L, and animal and vegetable oils. It exhibits a reddish-brown colour and is accompanied by a distinct fishy odour [5, 6].

2.3 Harms

Slaughterhouse wastewater can cause severe visual and olfactory discomfort to humans. If discharged without proper treatment, it may result in high concentrations of organic pollutants and excessive nitrogen and phosphorus levels in water bodies. This can cause eutrophication, leading to algal blooms in freshwater and red tides in seawater. Such conditions adversely affect the normal growth and development of aquatic flora and fauna.

Furthermore, ammonia nitrogen may accelerate microbial proliferation within water supply pipelines, thereby compromising disinfection efficacy during water treatment processes and ultimately posing risks to human health. The pathogens and microbial contamination within the wastewater, along with organic impurities, readily foster the proliferation of mosquitoes, flies, E. coli, and other bacterial pathogens, posing threats to human and animal health. If discharged onto farmland, the salts and pathogens may cause crop lodging and reduced yields, while simultaneously contaminating soil and groundwater [5-7].

3 Biochar and its application cases

3.1 Characteristics and modification of biochar

Biochar is a low-cost, readily prepared, and environmentally friendly adsorbent material. Possessing high porosity, abundant surface functional groups and active sites, it can participate in the treatment process of both inorganic and organic pollutants in wastewater [8]. The pores of biochar activated through physical or chemical methods are optimised to become abundant and uniformly arranged, thereby increasing its specific surface area and enhancing its adsorption capacity. Owing to its porous structure, biochar also serves as a carrier for microorganisms, while its electrochemical properties promote microbial metabolism and accelerate electron transfer, facilitating biological oxidation and reduction processes. The oxygen-containing functional groups and free radicals on its surface can serve as active sites for catalysis, promoting the chemical oxidation of organic pollutants. Consequently, it finds extensive application in fields such as the adsorption and degradation of organic pollutants in water bodies. Slaughterhouse wastewater represents a typical example of organic effluent. Regarding biochar modification, MA et al. propose two primary methods [9], firstly, impregnating prepared biochar with chemical agents or co-precipitating it with metals for modification. Secondly, directly mixing biomass with modifying reagents before undergoing high-temperature pyrolysis. Modified biochar exhibits increased specific surface area, pore volume, and functional group density, significantly enhancing its adsorption capacity and potentially improving performance in water pollutant removal applications. Biocarbon modification is generally categorised into two approaches: surface structural modification, which alters the pore structure to increase specific surface area and thus adsorption capacity; and surface chemical modification, which modifies surface functional groups to create additional adsorption sites and improve adsorption efficiency.

3.2 Applications in wastewater treatment

3.2.1 Removal and recovery of nitrogen and phosphorus

Biochar is an environmentally friendly adsorbent material with practical applications in the removal and recovery of nitrogen and phosphorus from water bodies.

WANG et al. proposed that the process of biochar removing nitrogen and phosphorus from water is typically achieved through multiple synergistic mechanisms [10].

The nitrogen removal mechanism primarily encompasses electrostatic attraction, whereby when the solution pH exceeds the biochar's zero charge point, the negatively charged biochar surface attracts ammonium ions through electrostatic forces. Concurrently, ion exchange occurs, whereby ammonium ions are adsorbed by displacing other cations with lower affinity for biochar surface sites.

The mechanism for phosphorus removal primarily involves the aforementioned electrostatic attraction and ion exchange, alongside ligand exchange and surface precipitation, and so on.

As an environmentally friendly adsorbent, biochar demonstrates significant application potential in the removal and recovery of nitrogen and phosphorus from water bodies. The majority of biochar adsorbing nitrogen or phosphorus can be reused after undergoing desorption.

3.2.2 Removal of organic matter and ammonia nitrogen

Concurrently, certain moulded composite materials derived from biochar maintain high pollutant removal efficiency during recycling. Zhang et al. observed that biochar nonwoven fabric retained over 96.33% ammonia nitrogen removal efficiency after 11 consecutive usage cycles [11]. In their experimental microwave-biochar process for treating high-concentration ammonia nitrogen wastewater, the biochar nonwoven fabric primarily leverages the ‘thermal effect’ of microwave radiation. Under microwave irradiation, electromagnetic energy converts to thermal energy, rapidly polarising polar molecules such as water and ammonia in the solution. Friction between these molecules generates heat, causing the internal solution temperature to rise sharply. This facilitates the transfer of ammonia molecules from the solution phase to the gas phase. Biochar, with its substantial specific surface area and microporous structure, rapidly absorbs microwave radiation energy, accelerating the entire process. Concurrently, a ‘non-thermal effect’ catalyses the process, coupled with microwave heating, enabling an ‘adsorption-desorption’ mechanism that simultaneously promotes the volatilisation of NH from the wastewater.

DAI et al. compared the greywater treatment efficacy of various biochar processes [12], demonstrating that biochar consistently achieved COD removal rates of 80%, with a maximum of 99.84%. Biochar demonstrated favourable removal of NH_4^+-N, achieving a maximum removal rate of 99%. This was attributed to microbial proliferation on the biochar surface, which thickened the biofilm and created both anaerobic and aerobic environments on opposite sides of the membrane. This simultaneous occurrence of nitrification and denitrification facilitated the removal of NH_4^+-N.

ZHANG et al. proposed that biochar [8], as an organic adsorbent, can adsorb organic matter through mechanisms such as pore filling, van der Waals forces, hydrogen bonding interactions, π-π interactions, electrostatic interactions, hydrophobic interactions, catalytic degradation, and complexation. Furthermore, biomass charcoal possesses numerous micropores (<2 nm) and mesopores (2–50 nm), exhibiting a large specific surface area that provides more effective adsorption sites for organic pollutants [13].

3.2.3 Recycling value

Beyond its potential for recycling and reuse, biochar possesses significant regenerative value. Even when its pollutant removal efficiency diminishes after prolonged use, the spent biochar—rich in nutrients such as nitrogen and phosphorus—can be repurposed to enhance soil fertility following the replacement of the substrate to restore the system's treatment efficiency [12]. Should concerns arise regarding potential secondary environmental contamination from trace pollutants or pathogens within the biochar [2], it may be incinerated to generate new energy [14].

3.2.4 Optimise existing processes

The dissolved air flotation process can remove most oils and suspended solids within the flotation tank. WANGD et al. described an integrated design combining mechanical flocculation [15], ozone-biochar contact oxidation, and dissolved air flotation. This patented approach combines mechanical agitation, coagulation, inclined plate sedimentation tanks, and flotation processes, while incorporating ozone into conventional flotation units to form ozonated dissolved air flotation. Powdered bioactive carbon is also added to the system. This integrated design of ozone-activated carbon contact oxidation with dissolved air flotation offers a conceptual approach for synergistically removing the majority of oils and suspended solids within the flotation tank while enhancing adsorption of organic pollutants.

4 Challenges and development

In current slaughterhouse wastewater treatment processes, biochar materials have yet to be deployed on a large scale. Furthermore, the adsorption mechanism and process of biochar are highly complex, and its adsorption performance towards different pollutants is influenced by multiple factors such as ambient temperature and pH levels. Consequently, biochar demonstrates limited specificity in treating particular pollutants. Furthermore, actual wastewater compositions are complex and diverse, containing numerous types of pollutants. The effects of many coexisting ions on the adsorption process of target pollutants remain unclear. Moreover, the possibility cannot be ruled out that biochar may release harmful substances such as organic compounds during practical application, thereby causing secondary pollution.

Future research may further explore the preparation, modification and application of engineered biochar, establishing an efficient and stable integrated biochar-based slaughterhouse wastewater treatment system. Targeting specific pollutants through tailored modification designs to enhance adsorption selectivity, efficiency, and capacity. Research should also explore biochar's practical application in wastewater treatment, recycling, and regeneration to improve operational efficiency and safety. Investigating biochar recovery after adsorbing diverse pollutants, alongside its subsequent harmless treatment and practical reuse, thereby maximising the substantial potential of biochar materials in delivering cost-effective, environmentally sound solutions for pollutant resource recovery.

5 Conclusion

This study investigates biochar and its application in treating pollutants associated with slaughterhouse wastewater, revealing its potential as an ideal material for environmentally sound wastewater treatment. Firstly, biochar offers advantages including low cost, ease of preparation, and environmental friendliness. Secondly, modified biochar can further enhance adsorption performance, while moulded composite materials derived from biochar enable circular reuse. Finally, the core mechanism for treating primary pollutants in slaughterhouse wastewater via biochar exhibits multi-pathway synergistic characteristics. This not only achieves high treatment efficiency but also enables wastewater resource recovery, such as ammonia nitrogen reclamation. This study aims to provide valuable insights for optimising the application of biochar and its modified derivatives in treating slaughterhouse or similar wastewater streams. It is hoped that future research will further explore biochar-based treatment processes for slaughterhouse effluent and other highly polluted wastewater, harnessing its environmental benefits. This approach aligns with the core objectives of carbon neutrality and carbon cycling, thereby supporting the synergistic sustainable development of livestock farming, slaughter industries, and environmental protection.

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