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Review

Recent progress in the production and application of biochar and its composite in environmental biodegradation

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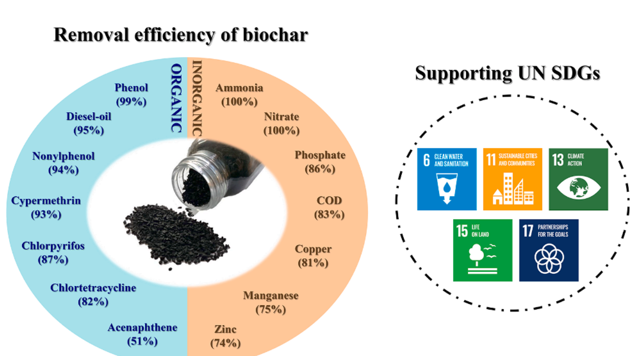
HIGHLIGHTS

- Pyrolysis is one of the most promising methods to produce porous biochar.
- Advanced technologies shorten process time and improve biochar quality.
- Kinetics of pollutant removal is important for degradation and mechanism study.
- The SA of bacteria-immobilized biochar ranges from 10 to 470 m^2/g.
- Bacteria-immobilized biochar shows high pollutants removal efficiency (43–100%).

GRAPHICAL ABSTRACT



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ABSTRACT

Over the past few decades, extensive research has been conducted to develop cost-effective and high-quality biochar for environmental biodegradation purposes. Pyrolysis has emerged as a promising method for recovering biochar from biomass and waste materials. This study provides an overview of the current state-of-the-art biochar production technology, including the advancements and biochar applications in organic pollutants remediation, particularly wastewater treatment. Substantial progress has been made in biochar production

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through advanced thermochemical technologies. Moreover, the review underscores the importance of understanding the kinetics of pollutant degradation using biochar to maximize its synergies for potential environmental biodegradation. Finally, the study identifies the technological gaps and outlines future research advancements in biochar production and its applications for environmental biodegradation.

1. Introduction

In recent years, growing concerns on environmental pollution and waste management have prompted the need for sustainable and innovative solutions (Tan et al., 2023). Environmental biodegradation, specifically related to water pollutants, is a pressing issue often associated with industrialization (Usman and Balsalobre-Lorente, 2022). Various pollutants pose ecological challenges and negatively impact human and ecosystem (flora and fauna) health, as they have been linked to various issues from biodiversity loss to adverse health effects on humans, including cancer, neurodevelopmental disorders, and cardiovascular diseases (Briffa et al., 2020). The release of persistent organic/inorganic pollutants, heavy metals, etc., and greenhouse gases into the environment is a global issue that contributes to environmental degradation (Ahmad et al., 2022). In addition, various emerging pollutants such as microplastics, pharmaceuticals, and personal care products are forthcoming and threatening as they are not effectively captured or treated by conventional remediation techniques. Hence, addressing waste disposal and exploring sustainable solutions to mitigate environmental pollution is critical.

With the increasing urbanization trend, waste management has taken centre stage with ever-greater significance. However, traditional waste management methods and pollutant remediation have been proven less effective than desired, indicating the need for shifting towards more sustainable and efficient techniques (Malinauskaite et al., 2017). One commonly employed solution in waste management is landfilling, the most unsustainable dumping practice widely adopted, creating many issues. Landfills are a notable source of leachate - a pollutant-rich liquid that contaminates groundwater and surface water (Kabir et al., 2023). The high levels of organic and inorganic pollutants in leachate pose a complex and challenging treatment problem. With the diverse and inherited characteristics, it is a great challenge in waste management that requires innovative solutions. While much work has been done and ongoing efforts are ongoing to improve practices in waste disposal and minimize environmental impacts, there is still room for optimism, particularly with respect to biowaste.

Biomass waste has long been a challenge for disposal due to its abundance and inherited nature. However, they have been transformed into valuable resource such as biochar through various advanced scientific and technological methods termed waste-to-wealth bioconversion. Converting biomass into biochar is a potential environmental remediation solution to mitigate pollution and promote a healthier, cleaner, and more sustainable future (Yek et al., 2022). This is a timely yet imperative challenge, as it can potentially transform waste management practices and the environment simultaneously (Foong et al., 2023). Pyrolysis-derived biochar from biomass represents a carbon-rich product increasingly recognized for carbon sequestration with its superior properties such as porosity, surface area, and chemical stability (Yek et al., 2022). The uniqueness and unparalleled characteristics of biochar have become an attractive option for environmental and agricultural applications.

The biochar market has steadily gained attraction, with a projected CAGR of 12.1% from 2023 to 2030 at about USD 1.2 billion (Research, 2023). This impressive growth is primarily attributed to the increased applications of biochar for carbon sequestration; its relevance in contemporary environmental remediation is thus established. Progress in biochar production technology has significantly impacted its biodegradation potential. For instance, the synergy between biochar and bacteria has enhanced biodegradation rates, leading to more efficient pollutant removal (Jiang et al., 2023). Additionally, optimization attempts in the pyrolysis process are expected to yield biochar with improved adsorption capabilities (Yek et al., 2022). With refined production and application techniques, biochar can be more advantageous now in various applications to mitigate the pollution. Research primarily focuses on identifying the fundamental mechanisms that govern the interaction between biochar and pollutants while addressing current challenges in fully harnessing its potential for environmental biodegradation. Overall, biochar offers a promising solution to environmental pollution, with a bright future ahead.

Biochar production and its potential to support bacterial growth and activity are critical for biodegradation. Biochar derived from nutrient-rich biomass exhibits certain features that encourage bacterial colonization and rejuvenation (Zhang et al., 2023a). These attributes include a porous structure that provides refuge and surface area for bacteria to inhabit. Furthermore, they are nutrient-dense and contain bioavailable compounds that can provide energy and nutrients to bacteria for survival in biowastes. For example, nutrient-rich biochar could be produced from manure or sewage sludge (Buss et al., 2022). Alternatively, biochar could be treated with nutrient-rich solutions to impart bacterial growth with necessary nutrients (Marcińczyk et al., 2022). However, additional research is required to understand the symbiosis between biochar and bacteria communities and optimize the biochar production process to cater for biodegradation applications of specific pollutants, enabling more effective and targeted remediation of polluted environments.

The use of biochar in modern wastewater treatment strategies presents significant environmental benefits. Applying biochar in wastewater treatment facilities improves contaminant removal efficiency and reduce environmental impact (Li et al., 2022a). Biochar effectiveness for pollutant removal depends on various factors such as pH of the environment, pollutant concentration, and contact time between biochar and the contaminant. In-depth research on these variables and their effects on biodegradation is necessary to develop effective biochar-based remediation strategies (Lv et al., 2022). A comprehensive understanding of the biodegradation kinetic parameters involved in biochar application is critical for optimizing its efficacy in removing pollutants.

Furthermore, biochar has been found to provide a favourable habitat for microbial communities which can aid in the degradation of organic pollutants. This lends support to the use of biochar in biodegradation applications. The versatility of biochar extends to the treatment of wastewater from a variety of sources including natural and anthropogenic sources such as rivers, agricultural run-off, aquaculture, industrial effluents (Amalina et al., 2023), and recently petroleum spill adsorption (Ariyanti et al., 2023). The documented ability of biochar to adsorb a wide range of pollutants, including heavy metals, pesticides, nitrogen, phosphorus, and organic pollutants, underscores its potential to enhance water quality and safeguard aquatic ecosystems (Lv et al., 2022).

This review assesses the latest advancements in developing and applying biochar and its composites for environmental biodegradation. This study provides a detailed overview of the current state of research, achievements, and challenges encountered in this field. Biochar and its composites possess unique physicochemical properties that offer multifunctionality, which has resulted in extensive research into its potential role in environmental remediation. There is a pressing need for further exploration on enhancing biochar and its composites for cost-effective environmental biodegradation. The aspects requiring attention include the production of biochar, biochar-pollutants-microorganisms synergistic interaction, optimization of biochar application in different environmental contexts, and assessment of the