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Production of biochar from rice straw and its application for wastewater remediation – An overview

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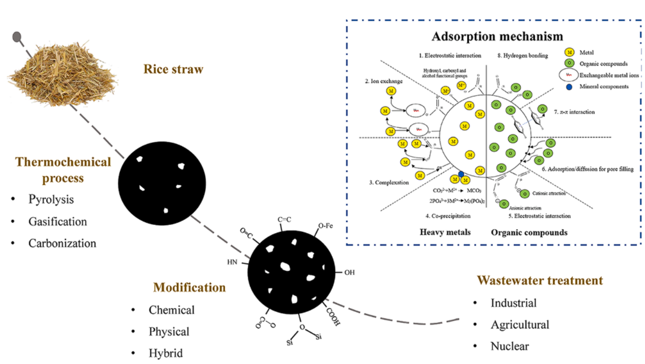
HIGHLIGHTS

- Various synthesis and modification techniques of rice straw biochar are reviewed.
- Pyrolysis is the most established and prominent method to produce biochar.
- Acid-modified biochar is effective for metal ions and organic compounds removal.
- More understanding of the adsorption mechanism for other contaminants is needed.
- Recyclability and stability of biochar are essential for wastewater treatment.

GRAPHICAL ABSTRACT



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ABSTRACT

The valorization of biochar as a green and low-cost adsorbent provides a sustainable alternative to commercial wastewater treatment technologies that are usually chemical intensive and expensive. This review presents an in-depth analysis focusing on the rice straw-derived biochar (RSB) for removal of various types of contaminants in wastewater remediation. Pyrolysis is to date the most established technology to produce biochar. Subsequently, biochar is upgraded via physical, chemical or hybrid activation/modification techniques to enhance its adsorption capacity and robustness. Thus far, acid-modified RSB is able to remove metal ions and organic compounds, while magnetic biochar and electrochemical deposition have emerged as potential biochar

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modification techniques. Besides, temperature and pH are the two main parameters that affect the efficiency of contaminants removal by RSB. Lastly, the limitations of RSB in wastewater remediation are elucidated based on the current advancements of the field, and future research directions are proposed.

1. Introduction

The increase in world population has culminated the food demand substantially, including rice being the most important grain crop globally. As a result of intensive rice farming to cater the demand, massive amounts of rice straw (600–1000 MT) are generated annually as agricultural waste (Bhatnagar et al., 2022). This solid biomass waste can be transformed to cheap and environmental-friendly biochar that can be upgraded and engineered to be valorized in a plethora of applications, such as adsorbents (Singh et al., 2020b), fertilizers (Dinh et al., 2022), catalysts (Lee et al., 2020) and soil conditioners (Liu et al., 2022). With this, the dual advantage of circular bioeconomy and efficient handling/management of crop residues can be pursued.

Biochar can be derived from rice straw via a variety of thermochemical conversion routes, including pyrolysis (Zong et al., 2021), torrefaction or carbonization (Tan et al., 2021), hydrothermal liquefaction (Harisankar et al., 2021) and gasification (Pei et al., 2020). The properties of the biochar produced depend heavily on the process conditions, such as pressure, temperature, reactor configurations, as well as the catalysts used. Generally, pristine rice straws have high ash content (8.5–20.4%) as compared to other straw types such as wheat straw (5.0–8.5%), barley straw (7.4%), corn straw (5.1–7.9%) and sugarcane straw (4.1%) (Wang et al., 2020). Silica oxide is the main constituent of the ash in the presence of other oxides such as aluminium oxide and calcium oxide (Singh and Patel, 2022). Other elemental contents of rice straw include ~40% carbon, ~30% oxygen, ~5–6% hydrogen, ~1% nitrogen and <0.2% sulfur (Wang et al., 2020). The characteristics and properties of several straw-type biomass are compared and summarized in Table 1. Generally, these straw-type biomass contain comparable elemental composition (C, H, N, S, O) and are having low moisture content of <10%, rendering them a suitable pyrolysis feedstock for biochar production. In addition, the moderate fixed carbon content of rice straw (as compared to other straw-type biomass such as sugarcane straw and wheat straw with <10% of fixed carbon) is also a favourable feature for carbon-based adsorbent synthesis (Nawaz and Kumar, 2021).

Upon thermochemical treatments, rice straw can be converted to biochar with superior physico-chemical and structural characteristics, including increased carbon content, enhanced surface area, porosity and ion exchange capacity, which make rice straw-derived biochar (RSB) a promising bio-based precursor for adsorbents (Wang et al., 2020). In particular, RSB can be strategically applied for aquaculture wastewater treatment in the context of integrated rice-fish (agri-aquaculture) polyculture systems due to their convenient proximity (Li et al., 2021) and the high feasibility of RSB in removing some pollutant compounds (e.g., phosphorous, ammonia) commonly detected in aquaculture wastewater. Several studies have shown that RSB exhibited promising removal efficiencies towards pesticides (e.g., imidacloprid, atrazine) (Xiang et al., 2020) and pharmaceutical residues (e.g., estrone) (Monga et al., 2022) generated from aquaculture facilities (Kolodziej et al., 2004).

Several review articles on the application of biochar for wastewater treatment are available in the literature. Zeghioud et al. (2022) performed a comprehensive review of the characteristics of biochar derived from various feedstocks and the effects of operating parameters of water treatment that influence the efficiency of organic pollutants removal from wastewater. Similar review article but focusing on biochar derived from municipal solid wastes (MSW) was reported by Li et al. (2022a). Besides, the sustainability aspects (in terms of economic, social and environmental) of biochar for water and wastewater remediation were covered by Kamali et al. (2021). Deng et al. (2021) and Zhuang et al. (2022) also conducted interesting reviews on the performance of biochar for wastewater treatment from the perspectives of ecological benefits and removal mechanisms, respectively, but their scopes were only limited to constructed wetlands and not other types of wastewaters. All these articles have generally spanned a broad range of feedstocks, but the in-depth review of biochar derived from a particular feedstock for wastewater treatment is still lacking and remains as the white space to be addressed and understood.

As such, the main objective of this review is to deep dive into the field of wastewater treatment specifically by RSB. Such thorough and distinct review is still scarce in the literature to the authors' best knowledge. Hence, this review is systematically structured to include various relevant and significant aspects, i.e., preparation of biochar (Section 2), modification or functionalization of biochar (Section 3), performance of pollutants removal from wastewater and the mechanisms involved (Section 4), application of biochar for treatment of various types of wastewaters (Section 5), and lastly the current associated limitations and prospects (Section 6).

2. Preparation of rice straw-derived biochar

Pyrolysis is defined as thermochemical conversion which involves lignocellulosic materials that experience thermal decomposition process with no or limited access of oxygen to produce pyrolysis products such

Table 1
Characteristics and properties of straw-based biomass.

Biomass	Ultimate analysis (%)					Proximate analysis (%)				Structural composition (%)			Reference
	C	H	N	S	O	Moisture	Volatile matter	Fixed carbon	Ash	Hemicellulose	Cellulose	Lignin	
Rice straw	36.2	5.2	0.7	–	40.3	–	–	–	17.6	21.6	31.4	19.1	(Harisankar et al., 2022)
	47.46	6.44	0.83	–	45.15	4.98	81.54	16.46	10.82	–	–	–	(Liu et al., 2021)
Wheat straw	45.5	5.7	1.0	–	47.9	7.1	76.7	9.2	7.0	–	–	–	(Cheng et al., 2019)
Barley straw	45.41	6.10	1.18	–	46.21	4.90	78.80	11.83	6.43	–	–	–	(Ahmed and Hameed, 2018)
Corn straw	45.75	5.93	0.94	0.11	43.69	4.21	–	–	5.91	24.86	39.54	19.30	(Chen et al., 2019)
Sugarcane straw	41.88	5.87	0.47	–	41.72	3.12	87.61	3.22	9.17	12.05	52.60	22.50	(Ferreira et al., 2020)
Rape straw	42.21	5.54	0.42	0.07	51.76	–	–	–	3.69	28.89	45.27	22.15	(Li et al., 2022b)
Mustard straw	54.46	6.29	0.5	–	38.75	3.99	75.55	15.44	5.02	23.12	44.5	21.24	(Nawaz and Kumar, 2021)

"-"denotes not detected/not reported.