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Advancements in characterization Techniques, empirical Models, and Artificial intelligence for comprehensive understanding of heavy metal adsorption on sewage sludge biochar

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ABSTRACT

Heavy metal-containing industrial effluents, such as Pb^{2+}, Cd^{2+}, and Cu^{2+}, pose serious threats to the environment and public health since they are not biodegradable and can accumulate over time. Biochar, particularly sewage sludge-derived biochar (SSBC), has arisen as a promising and cost-effective material for heavy metal removal from wastewater due to its high adsorption capacity, large surface area, and rich porous structure. This review explores the use of SSBC for the adsorption of heavy metals, highlighting the impact of pyrolysis temperature on its surface properties, such as specific surface area and functional groups. Characterization techniques, including SEM, FTIR, XRD, XPS, AES, GC–MS, ICP, and ESR, are employed to analyze the chemical and structural properties of SSBC, providing insights into the changes that enhance its adsorption performance. Additionally, Artificial Neural Network (ANN) models are utilized to portend the adsorption efficiency of SSBC, offering a quantitative understanding of the relationship between heavy metal removal efficiency and biochar properties. This review emphasizes the importance of pyrolysis in optimizing SSBC for wastewater treatment and demonstrates how advanced characterization techniques and predictive models can guide the progress of more efficient biochar-based adsorbents for environmental remediation. The results highlight the promising role of SSBC in providing a sustainable remedy for heavy metal contamination in industrial wastewater.

Introduction

The discharge of significant concentrations of heavy metals into surface water from industrial or agricultural sources, known for their poisonous and non-biodegradable nature, leads to groundwater contamination, a constant source of worry. Metals like lead, cadmium, copper, nickel, zinc, and chromium, which are toxic and carcinogenic, can cause severe physical health issues, necessitating their environmental removal. Heavy metals like Pb^{2+}, Cd^{2+}, and Cu^{2+} are frequently found in industrial wastewater. These non-biodegradable substances pose a significant menace to the aquatic environment and public health, as they can accumulate in the food chain. Their contamination, including in acid mine drainage (AMD), is of utmost concern to environmental communities due to their harmful effects on aquatic and human life (Subash et al., Dec. 2023); (Cheng et al., Jan. 2011); (Kılıç et al., Oct. 2013); (Francis et al., Aug. 2023); (Mayilswamy and Kandasubramanian, 2024) Finding cost-effective and efficient technologies for removing heavy metals from polluted water is critical. Previously, a few traditional treatment procedures, such as chemical precipitation, were regularly deployed and optimized for heavy metal removal from water (Janyasuthiwong et al., 2016); (Matlock et al., Nov. 2002). Over the last five years, the consumption or use of existing natural resources has increased alarmingly during the previous two decades, with a 27 billion tonne rise in consumption. One primary byproduct of biological wastewater treatment is waste-activated sludge, which is typically costly to transport and dispose of (Wang, Feb. 2015). Even though a variety of techniques, including ion exchange, ionization, oxidation, polyelectrolyte, coagulation, and biological processes, are employed to treat water contamination, in practice, they have several drawbacks, comprising higher costs, ineffectiveness against all forms of pollutants, solid waste generation, increased land area requirements, hazards to humans and aquatic life, high electricity demands, etc. Adsorption is regarded as the most viable method because it has the potential to eliminate all forms of water pollutants, including organic and inorganic

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matter, from industrial wastewater, sewage water, domestic wastewater, synthetic water, drinking water, surface water, and groundwater, and because it is competent, cost-effective, the convenience of low-cost, globally available adsorbent, flexible in design, user-friendly, and low entropy (Xu and Wang, Jun. 2017).

Biochar, an incipient carbon material made primarily from low-cost biomass remnants, has recently acquired a lot of focus in the scientific community due to its promising potential in a variety of environmental applications such as environmental remediation, soil improvement, carbon sequestration, and water treatment (Kulkarni et al., Nov. 2023); (Brodowski et al., Sep. 2005); (Yao, Mar. 2012); (Inyang et al., Nov. 2010). Wood, agroindustrial or agricultural wastes and residues, urban sludge, the organic part of municipal solid waste, and animal manure can all be biochar precursors. The kind of raw material used, as well as the pyrolysis operational parameters, can all impact the physicochemical qualities of the biochar produced. The physicochemical features of biochar, such as its highly porous structure, high mineral content, large specific surface area, and diverse surface functional groups, make it a viable substitute for traditional adsorbents. When considering sludge management options, pyrolysis presents a viable alternative to the existing methods of landfilling, incineration, or direct agricultural use (Tripathi et al., Mar. 2016); (Regkouzas and Diamadopoulos, Jun. 2019); (Hwang et al., Aug. 2007). The pyrolysis process usually produces biochar, biofuel, and bio-oil from the organic waste while also removing pathogens and decreasing the amount of biosolids. The final product, biochar that has been pyrolyzed from sewage sludge, is plenty of nutrients and elemental carbon. It also has a significant number of bidirectional cations and surface adsorption sites, and it helps improve soil fertilization and eliminate pollutants from wastewater (Chavan et al., Dec. 2024); (Yalasangi et al., Dec. 2024).

Currently, China begets over 25 million tonnes of sewage sludge (80 % humidity) annually from wastewater facilities, which places significant environmental trouble on plant holders and local administrations. In comparison to the present approaches of landfilling, incineration, or direct agricultural use, pyrolysis can potentially be a propitious solution for sludge treatment. As a result, sewage sludge pyrolysis and sludge-derived biochar are gaining increasing interest (Hwang et al., Aug. 2007); (Domínguez et al., Jul. 2006); (Smith et al., Jun. 2009); (Hossain et al., 2010). The primary elements influencing the pyrolysis process and determining the nature and dispensation distribution of carbonization products are carbonization temperature, heating rate, nitrogen flow rate, and carbonization time. Elevating the pyrolysis temperature to above 500 °C leads to increased hydrophobicity, surface area, and micropore volume of the resulting biochar, making it highly suitable for eliminating organic contaminants. However, a biochar with smaller pores, less surface area, and more oxygen-embracing functional groups was produced at a lower pyrolysis temperature ($<$500 °C), making it more appropriate for the elimination of the inorganic contaminants (Keiluweit et al., Feb. 2010); (Van Zwieten, Feb. 2010); (Gole et al., Aug. 2024).

The environmental implications of producing biochar from sewage sludge are both positive and negative. On the plus side, biochar production can lower the volume of sewage sludge, reduce landfill use, and convert waste into a valuable product for applications such as heavy metal adsorption, soil enhancement, and carbon sequestration. However, this method raises considerable environmental issues, particularly the possible release of hazardous chemicals during pyrolysis. Sewage sludge frequently contains high levels of heavy metals, such as mercury, cadmium, and lead, which can evaporate during pyrolysis, causing air pollution and secondary contamination. Mercury, in particular, offers a significant environmental problem since its volatilization necessitates sophisticated emission control systems to prevent its release into the atmosphere. The presence of mercury in the resulting biochar may further restrict its usage in agricultural or environmental applications, making the process both economically and environmentally problematic (Zhou, Jun. 2024); (Ghorbani, Oct. 2022).

Furthermore, the energy-intensive aspect of biochar manufacturing raises concerns regarding greenhouse gas emissions, especially if the process uses non-renewable energy sources. To counteract these impacts, cleaner and more efficient pyrolysis methods, as well as strategies for capturing and treating volatile emissions, are required. Addressing these environmental concerns is crucial to ensuring that biochar production from sewage sludge is both sustainable and profitable (Zhou, Jun. 2024).

Despite these problems, biochar produced from sewage sludge offers significant environmental benefits. The technique minimizes the volume of sewage sludge, solving the growing waste disposal problem while converting it into a value-added product. Biochar has showed potential in applications such as carbon sequestration, soil amendment, and wastewater treatment, helping to promote sustainability and environmental rehabilitation. Furthermore, improved pyrolysis technologies and post-treatment processes are being developed to reduce toxic emissions and heavy metal content, so making biochar manufacturing safer and more efficient. With proper management and attention to environmental requirements, sewage sludge biochar has the potential to be a long-term solution for waste management and environmental protection (Zhou, Jun. 2024); (Huang, Feb. 2023).

It was imperative to actively search for safer, more affordable, and ecologically friendly alternatives to prevent the discharge of heavy metals into the surrounding environment and regulate the phenomena of eutrophication in water bodies. Researchers have focused a lot of attention on the adsorption method because of its ease of use, high efficiency, economy, environmental friendliness, and little danger of secondary contamination. The findings of this study are to analyze the pyrolysis temperature and characterization techniques like X-ray photoelectron Spectroscopy (XPS), Fourier-transform infrared spectroscopy (FTIR), Scanning Electron Microscopy (SEM), X-ray diffraction (XRD), Electron spin resonance spectroscopy (ESR), Auger electron spectroscopy (AES), Gas chromatography-mass spectrometry (GC–MS) and inductively coupled plasma (ICP) of sewage sludge biochar. Artificial neural network (ANN) models are also utilized to predict the effectiveness of sewage sludge biochar in adsorbing heavy metals. The SVM-ANN model was the most meticulous and dependable prediction model out of all the ANN models. Characterizing biochar using SEM, FTIR, XRD, XPS, AES, ICP, GC–MS, and ESR provides valuable insights into its structure and functionality, which are essential for understanding its adsorption behavior. SEM is particularly useful for examining the surface morphology and pore structure, offering a clear view of how biochar's porosity and surface area create space for heavy metal adsorption. FTIR complements this by identifying functional groups, like hydroxyl (–OH) and carboxyl (–COOH), that actively bind heavy metals through mechanisms such as ion exchange or surface complexation. Meanwhile, XRD helps to analyze the crystalline structure of biochar, while XPS provides detailed information on its elemental composition and chemical states, both of which contribute to understanding the stability and reactivity of the material. Advanced techniques like AES and ICP allow for precise quantification of elements and trace metals, offering a deeper understanding of how metal ions interact with the biochar surface. GC–MS and ESR provide additional details on the chemical environment and reactive species present, which can further explain biochar's adsorption efficiency. The elucidation of biochar derived from sewage sludge necessitates the employment of specific methodologies to comprehensively ascertain its structural attributes, compositional makeup, and reactivity. Together, these techniques not only paint a comprehensive picture of biochar's properties but also highlight how these characteristics can be tailored to improve its performance in heavy metal removal applications.

Methodology for literature review

The present state, significant issues, and research gaps were investigated using Scopus analysis, and future research paths in this field were predicted. This research sought to examine the current state of literature about Scopus studies. The bibliometric data and a content analysis of the most significant cited publications were used in the study's attempt to identify current research trends, gaps in the literature, and primary research priorities. The patterns of publications between 2012 and 2023 are examined in this section concerning their categories and frequency. The present state and developmental patterns of articles pertaining to Scopus are shown. The distribution of total publications (TP) from December 2021 to the present is shown in **Figure S1(a)**.

By examining the nations' collaborative network, it would be feasible to pinpoint global partnerships, prospective partners, and the principal nations that generated a substantial volume of publications and significantly impacted research on Scopus. Using VOS viewer, a geographical distribution network of articles was created to assess each nation's contribution to the development of Scopus. **Figure S1(b)** represents the countries where the research occurred. Each node represents a country or area; larger nodes would have more articles from the participating nations. Based on the data shown in **Figure S1(b)**, China demonstrated a greater node size and a substantial quantity of articles about Scopus. **Figure S1(c)** represents the various departments in which the research has taken place.

Sewage sludge biochar production and experimental Setup

When given a significant amount of biomass, sludges can undergo thermochemical transformation to produce biochar and other byproducts. The production of biochar can be done using various methods like pyrolysis, hydrothermal carbonization, updraft and downdraft gasification, torrefaction, etc. (Damahe et al., Aug. 2024). The production of biochar by pyrolysis of sewage sludge is a potential end-treatment technique. The temperature of pyrolysis, the rate of heat transfer, the residence duration, the additions, and the kinds of source materials are important factors that affect the characteristics of biochar (Cao, Oct. 2024). Friedrich Bergius introduced the thermochemical transformation method known as hydrothermal carbonization in 1913 to address the coalification of biomass derived from cellulose. It aims to convert large amounts of biomass loaded under high-pressure reactors to form biochar and other components like carbon monoxide. The HTC technique is considered to have a higher yield (between 50% and 80%) than the slow and rapid pyrolysis approaches (Erses Yay et al., 2021); (vom Eyser et al., Jun. 2016). Gasification is a process that turns sewage sludge with low O_2 concentrations so that the feedstock doesn't burn completely and produces flammable gases including CO, H_2, and methane (CH_4) as well as certain oxidation chemicals like CO_2. Tezer et al. (Tezer et al., Mar. 2023) investigated the gasification of sewage sludge in two distinct fixed-bed gasifier types using updraft and downdraft methods. According to reports, the down draft gasifier had the largest volume percentages of H_2, CO, and CH_4 gases, regardless of the gasifying agent (air or pure O_2) utilized. The higher heating value (HHV) attained was between 12.7 and 12.8 MJ/Nm^3 (Tezer et al., Mar. 2023). Torrefaction is a mild thermal treatment process conducted at temperatures between 200 °C and 300 °C in an oxygen-free or low-oxygen environment. It is used to convert sewage sludge into biochar by removing moisture and volatile compounds, enhancing its carbon content and energy density. This process improves the stability, porosity, and hydrophobicity of the biochar, making it more effective for applications like heavy metal adsorption in wastewater treatment (Sobol et al., Aug. 2023). The proximity analysis and ultimate analysis of biochar is done to find out the element composition in biochar (Refer to **supplementary information**).

The adsorption process is highly regarded as a practical method for eliminating various water pollutants from different sources, such as industrial and domestic wastewater and drinking water. This is due to its effectiveness, cost efficiency, adaptable design, availability of low-cost and globally accessible adsorbents, minimal energy demands, simple regeneration of specifically used adsorbents, and overall user-friendliness. Chemical engineering uses the adsorption process as a separation technique, wherein one or more gaseous or liquid components from one phase congregate or concentrate at the surface of one more phase, ultimately completing the separation process (Xu and Wang, Jun. 2017).

Fig. 1 represents the adsorption mechanism in biochar. In an adsorption method, contact within the adsorbent and adsorbate is achieved by continuous fixed bed, continuous fluidized bed, continuous moving bed, batch treatment, and pulsed bed. Apart from batch as well as fluidized bed adsorption treatment, the other techniques have limitations such as a significant area need, a more incredible amount of adsorbent required, feed channeling, high cost, pre-requisite storage of adsorbent, and non-uniform residence duration (Bryukhov and Ulrikh, 2022).

Batch mode adsorption studies give critical operating parameters and useful operational information regarding individual adsorbents. The benefits of fixed-bed columns over batch studies include operating them individually, in a sequence, or simultaneously (Albroomi et al., Jul. 2017). Fixed-bed height, flow rate, and breakthrough curve are some factors used in column mode investigations. These methods for eliminating contaminants from water and wastewater are the most popular because they are dependable, effective, and efficient (Gupta, 2009). Further information about batch and column adsorptions used in various adsorption experiments is mentioned in Table 1.

Conventional characterization techniques for heavy metal adsorption

Sludge-based biochar's ultimate use is recognized to be significantly influenced by a wide range of morphological, structural, and chemical properties. To ensure biochar is properly evaluated before its application, it is crucial to perform a detailed characterization using advanced analytical tools such as X-ray photoelectron spectroscopy (XPS), X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), and scanning electron microscopy (SEM). These techniques provide valuable insights into the structural, chemical, and surface properties of biochar, which are essential for determining its suitability for specific purposes (Y. Wang, H. Li, and S. Lin, "Advances in the Study of Heavy Metal Adsorption from Water and Soil by Modified Biochar,", 2022).

SEM

SEM is a highly sophisticated instrument used for examining surface phenomena in materials. When an electron beam with high energy is directed at a sample in SEM, it provides valuable details about the material's chemistry, topography, composition, grain orientation, morphology, and crystallographic information. Consequently, SEM is an indispensable tool for material characterization (Skubiszewska-zi, 2015). Considering the conditions of pyrolysis, increasing the process temperature results in a more well-defined surface morphology of the biochar. Additionally, the porous structure becomes more prominent, improving accessibility for adsorbate particles to enter the pores. Table 2 represents the SEM analysis of sewage sludge biochar. Using SEM, biochar was characterized at 400 °C, 600 °C, and 800 °C for pyrolysis. The findings are displayed in **Figure S2**(a, b, c). It was possible to see that the 400SS's morphology was rough, consisting of block formations with numerous fractures. But 600SS had a far smoother surface structure with only a few tiny particles sprinkled here and there. The 600SS morphology was more hierarchical and regular than the 400SS morphology.

Additionally, the porosity rises due to the many compact particles that immediately cover the 800SS surface shape. The different adsorption capacities may be caused by raw biochar's surface properties and pore architectures at various pyrolysis temperatures. Higher temperature has been related to an increase in the activation energy for microporosity growth, which in turn causes the generation of more

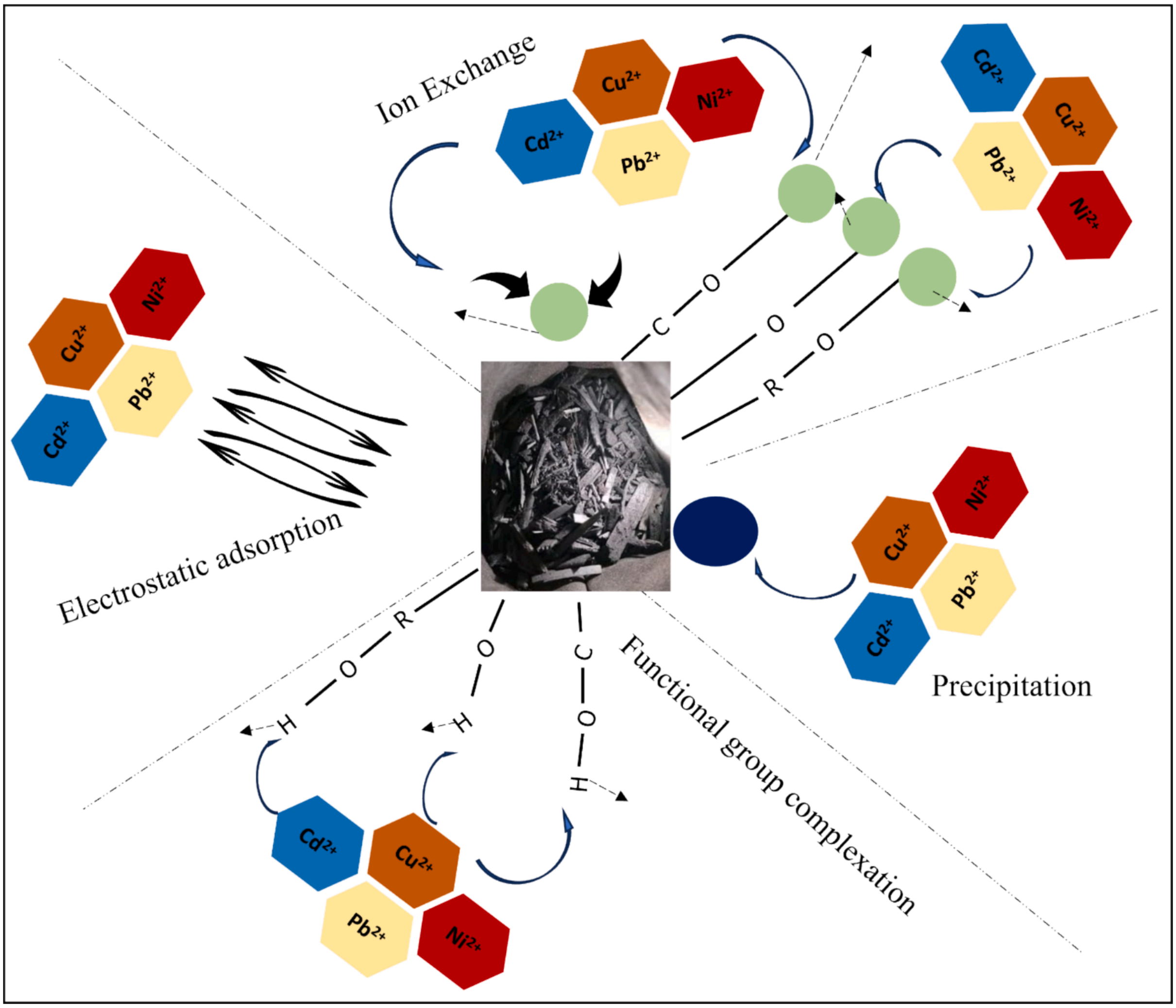

Fig. 1. Adsorption mechanism of biochar. Reprinted with permission from the copyright (Khiari et al., 2019) 2017, Elsevier.

micropores, according to earlier research (Yavari et al., Jul. 2017). The impact of temperature during pyrolysis on the shape of the as-prepared biochar was examined by analyzing SEM images of WSBC. It was discovered that when the pyrolysis temperature varied, the biochar structure was altered. At higher temperatures, biochar's arrangement and surface appearance seem more complicated. Whereas the structure of biochar tended to become rougher as the pyrolysis temperature rise, the surfaces of WSBC were smooth at 400 °C (Ho et al., 2017).

XRD

Information on the crystalline components and composition of the biochar-based adsorbent is obtained by XRD analysis. It includes the interaction of X-rays with materials, which leads to X-ray beams diffraction and forming a particular diffraction pattern. The differences in biochar crystallization before and after the process were explained by XRD **Figure S3**(**b**), Following Cu(II) adsorption on modified biochar (nBC700-Cu), the diffraction peaks of $CuFe_2O_4$, CuO, and $C_4H_6CuO_4$. were discovered. The peaks showed that nBC700 could effectively compound Cu (II) on the biochar surface (Zhao, May 2020).

At pyrolysis temperatures ranging from 400 to 1000 °C, **Figure S3**(**a**) displays the XRD spectrum of SBC. SiO_2, which originates from the sewage sludge, was indicated by the typical peak at $2\theta = 26.6^\circ$. The distinctive CaS peak was seen at reduced temperatures during pyrolysis (400–600 °C), but at higher temperatures (700–1000 °C), the peak vanished, and a new CaS characteristic peak at $2\theta = 31.4^\circ$ emerged. Lu et al. investigated XRD patterns to evaluate the potential of chemical precipitation for Pb^{2+} sorption, analyzing both the original and Pb-loaded SDBCs at pH levels of 3 and 5 (Lu et al., 2012) as Table 3 shows the XRD analysis of Sewage sludge biochar.

FTIR

The FTIR method is applied to study the functional groups in biochar and sludge samples. This method makes it possible to analyze the biochar's chemical structure and physical condition quickly, precisely, and effectively. The fewer and weaker peaks observed in biochar compared to activated carbon suggest a less dense distribution of functional groups on its surface, with a low presence of specific compounds like carboxyl, ketone, lactone, and aldehyde. These findings emphasize the need to modify biochar to enhance its properties (Kulkarni et al., 2023). **Figure S4** displays the FTIR spectrum of sewage sludge biochar. Artificial Neural Networks (ANN) can use the structural and chemical characteristics of biochar, identified through techniques like FTIR, to accurately predict its adsorption efficiency under varying conditions. This integration of experimental insights and computational modeling bridges the gap between material characterization and practical application.

FTIR analysis is used to identify and confirm the surface functional groups of the synthesized biochar within the wave number range of 400 to 4000 cm^{-1}. The spectra were recorded at a resolution of 4 cm^{-1} within this range to study changes in functional groups at different

Table 1

Information regarding the various parameters used for the adsorption experiments.

Heavy Metal	Feedstock	Adsorption	PyrolysisTemperature (°C)	SurfaceArea (m^2.g^{-1})	Pore Size (cm^3.g^{-1})	C%	Dose (mg)	Time (hr)	Temperature (°C)	pH	AdsorptionCapacity (mg. g^{-1})	Reference
Cd^{2+}	Landfill leachate sludge	Batch	600.00	59.40	19.10	13.74	6.00	2.00	10.00	11.30	723.00	Zhang et al., 2023
Pb^{2+}	Landfill leachate sludge	Batch	600.00	59.40	19.10	13.74	6.00	2.00	10.00	11.30	723.00	
Cd^{2+}	Domestic sewage treatment plant	Batch	500.00	34.80	-	-	1.00	6.00	28.00±2.00	3.00	525.00	Gao, 2019
Cd^{2+}	Municipal sludge biochar	Batch	700.00	27.62 -	4.54	0.40	-	4.00	25.00	5.50	120.24	Wu et al., 2023
Cr^{4+}	Municipal wastewater treatment plant	Batch and column	600.00	-	-	-	2.00	16.00	25.00	4.00	31.53	Fan et al., 2019
Cr^{4+}	Municipal sludge	Batch	500.00	93.19	11.75	-	1.00	5.00	25.00	3.00	178.05	Yu, 2022
Pb^{2+}	Municipal Wastewater Treatment Plant	Batch	400.00	-	-	16.33 ±0.23	4.00	24.00	25.00	1.00-6.00	51.20	Ho et al., 2017
Pb^{2+}	Municipal sewage sludge	Batch	550.00-600.00	12.70 ± 0.70	10.20 ± 0.20	-	5.00	24.00	-	6.60	150.00	Sylwan et al., 2020
Cu^{2+}	Municipal wastewater treatment plant	Batch	500.00	-	-	-	20.00	20.00	25.00	5.20	20.00	Shen et al., 2018
Cu^{2+}	Municipal wastewater treatment plant	Batch	650.00	1175.10	0.69		20.00	48.00	25.00	5.00	18.50	Wei, 2018
Pb^{2+}	Municipal sewage sludge	Batch	400.00	29.58	-	-	0.10	48.00	23.60	5.27	-	Wang et al., 2017
As^{3+}	Municipal sewage sludge	Batch	400.00	29.80	-	-	0.10	48.00	23.60	5.27	-	Wang et al., 2017
Cr^{4+}	Municipal sewage sludge	Batch	400.00	29.80	-	-	0.10	48.00	23.60	5.27	-	Wang et al., 2017
Pb^{2+}	Municipal wastewater treatment plant	Batch	550.00	24.73	-	-	400.00	4.00	25.00	3.50	31.00	Lu et al., 2012
Pb^{2+}	Sewage Treatment Plant	Batch	300.00	7.90	-	-	100.00	36.00	25.00 ± 2.00	5.00	16.80	Zhang et al., 2015
Cr^{4+}	Sewage Treatment Plant	Batch	300.00	7.90	-	-	100.00	36.00	25.00 ± 2.00	5.00	16.80	Zhang et al., 2015
Sb^{2+} and Cr^{4+}	Municipal wastewater treatment plant	Batch	800.00	137.86	-	-	1.60	24.00	30.00	6.50	724.00	Wang, Nov. 2023
Pb^{2+}	Wastewater treatment plant	Batch	800.00	59.38	4.56	-	400.00	24.00	25.0	2.00-6.00	151.52	Tian, Dec. 2022
Cd^{2+}	Wastewater treatment plant	Batch	800.00	59.38	4.56	-	400.00	24.00	35.00	2.00-6.00	109.89	Tian, Dec. 2022
Cu^{2+}	Wastewater treatment plant	Batch	800.00	59.38	4.56	-	400.00	24.00	45.00	2.00-6.00	74.07	Yang, Jun. 2019
Ni^{2+}	Municipal Wastewater Plant	Batch	500.00	24.21	0.08		10.00	24.00	25.00	8.12	20.38	Ifthikar, Aug. 2018
Pb^{2+}	Municipal Wastewater Treatment Plant	Batch	400.00	40.96	11.36	12.24	25.00	24.00	30.00	4.00	239.58	Kang et al., Oct. 2022

(*continued on next page*)

Table 1 (*continued*)

Heavy Metal	Feedstock	Adsorption	PyrolysisTemperature (°C)	SurfaceArea ($m^2.g^{-1}$)	Pore Size ($cm^3.g^{-1}$)	C%	Dose (mg)	Time (hr)	Temperature (°C)	pH	AdsorptionCapacity ($mg. g^{-1}$)	Reference
Hg^{2+}	Municipal Wastewater Treatment Plant	Batch	400.00	40.96	11.36	12.24	25.00	24.00	30.00	4.00	769.23	Kang et al., Oct. 2022
Cu^{2+}	Wastewater Treatment Plant	Batch	700.00	-	-	28.90	15.00	24.00	25.00	4.00	160.57	Zhao, 2020
Cr^{3+}	Wastewater Treatment Plant	Batch	700.00	-	-	28.90	15.00	24.00	25.00	4.00	99.32	Zhao, 2020
Pb^{2+}	Municipal wastewater treatment plant	Batch	350.00	8.20	21.70	18.90	10.00	48.00	25.00	5.00	-	Mourgela et al., 2020
Zn^{2+}	Municipal wastewater treatment plant	Batch	550.00	12.00	13.40	16.00	10.00	48.00	25.00	5.00	-	Mourgela and Regkouzas, 2020
Zn^{2+}	Municipal wastewater treatment plant	Batch	550.00	12.00	13.40	16.00	10.00	48.00	25.00	5.00	-	El Hanandeh et al., Jan. 2021
Ni^{2+}	Municipal Wastewater Treatment Plant	Batch	300.00	-	-	35.80	600.00	48.00		7.10	180.00	Y. Wang, H. Li, and S. Lin, “Advances in the Study of Heavy Metal Adsorption from Water and Soil by Modified Biochar,”, 2022
Cr^{3+}	Municipal sewage Wastewater Treatment Plant	Batch	550.00	31.40	-	70.00	25.00	24.00	25.00±1.00	4.00	98.20	Khiari et al., 2019
Cd^{2+}	Municipal sewage Wastewater Treatment Plant	Batch	550.00	31.40	-	70.00	25.00	24.00	25.00±1.00	4.00	14.30	Khiari et al., 2019
Cu^{2+}	Municipal sewage Wastewater Treatment Plant	Batch	550.00	31.40	-	70.00	25.00	24.00	25.00±1.00	4.00	99.70	Khiari et al., 2019
Pb^{2+}	Municipal sewage Wastewater Treatment Plant	Batch	550.00	31.40	-	70.00	25.00	24.00	25.00±1	4.00	33.70	Khiari et al., 2019

Table 2
SEM analysis of sewage sludge biochar.

SSB	Heavy Metal	Before Adsorption	After Adsorption	Reference
Landfill leachate	Cd (II) and Pb (II)	-	Small particles formed	Zhang et al., 2023
Raw	Cd (II)	-	White granular crystals	Gao, 2019
Raw	Cd (II)	Blocks or lamellar structures with smooth surfaces and no flakes	Flakes appeared and the surface became rough	Wu et al., 2023
nZVI composite	Cr (VI)	-	-	Fan et al., 2019
nZVI-loaded	Cr (VI)	The surface exhibits significant agglomeration, irregularities, and unevenness, characterized by numerous large structures and prominent grooves.	Considerable number of particulate matter on the surface	Yu, 2022
Raw	Pb (II), As (III) and Cr (VI)	-	-	Wang et al., 2017
Raw	Pb (II)	-	New bright zones (arrowed) were discovered in the hollow area.	Lu et al., 2012
Raw	Cr (VI) and Sb (III)	Rough surface and low porosity	Accumulation of particles with size around 100–200 nm	Wang, Nov. 2023
Magnetic	Pb (II), Cd (II) and Cu (II)	-	-	Tian, et al., 2023
Modified	Ni (II)	High surface areas and pore structure	-	Yang, Jun. 2019
nZVI modified	Cu (II)Cr (VI)	Smooth surface and uniform distribution of iron	Attachment of tiny particles resulting in uniform distribution andincreased density of Fe	Kang et al., 2022

Table 3
XRD analysis of sewage sludge biochar.

Sl. No.	Pyrolysis temperature (°C)	Before Adsorption (°)	After Adsorption (°)	Reference
1	1000.00	26.60	31.40	(Wu et al., 2023)
2	500.00	39.74	44.68	(Yu, 2022)
3	700.00	26.60	29.80	(Ho et al., 2017)
4	500.00	20.86, 26.30, 36.55, 42.14, 50.15, 60.00	27.91, 34.79, 39.12, 40.25, 45.90, 54.95	(Yang, Jun. 2019)
5	400.00	21.00	–	(Ifthikar, Aug. 2018)
6	700.00	26.64	42.99, 44.70, 56.60	(Kang et al., 2022)

Table 4
Sewage sludge biochar FTIR data.

Sl no.	Pyrolysis temperature (°C)	Compounds	Before Adsorption (cm^{-1})	After Adsorption (cm^{-1})	Reference
1	500	C-O	1620	1630	(Yu, 2022)
		R-COOH	1430	1410	
2	1000	C–H	866	886	(Wu et al., 2023)
		C-O	1037	1051	
		OH	1420	1433	
		C=O	1615	1643	
3	700	OH	3600	1638	(Ho et al., 2017)
		CH	2915	541	
		CO	1620	785	
4	600	OH	3431	3405	(Fan et al., 2019)
		C–C	1621	1629	
		COOH	1033	1030	
5	550	OH	3420	3620	(Gao, 2019)
		R-O–H	3404	3422	
		C=O	1621	1620	
		C-OH	1032	1039	
6	800	O–H	3640	3646	(Tian, et al., 2023)
		C=O	1788	1796	
		C-N	1510	1498	
7	400	N–H	1573	1565	(Ifthikar, Aug. 2018)
		O–H	3447	3425	
		O-C=O	1413	1384	

pyrolysis temperatures. The FTIR results revealed a significant reduction in the intensity of the broad peak around 3000 to 3300 cm^{-1} in biochar compared to raw sewage sludge, indicating the breakdown of free and associated hydroxyl groups, as well as structural hydroxyl groups (–COOH and –COH), as pyrolysis temperatures increased (Wu et al., 2023). Table 4 shows the peak areas of specific functional groups and the influence of further pyrolysis.

XPS

XPS (X-ray photoelectron spectroscopy) dramatically aids in examining the surface of various organic and inorganic materials, providing details about the electrical characteristics of a sample's topmost layers and proving helpful for researching material surfaces. It reveals the chemical states and elemental composition of a material's surface by examining the energy levels of photoelectrons released from the material when subjected to X-rays. This knowledge is essential for customizing a material's surface qualities and comprehending how it interacts with its surroundings. Using XPS, the chemical composition of ADSBC600 (anaerobic digestion sludge biochar) was examined both before and after Pb^{2+} sorption. When ADSBC600 adsorbed Pb, additional peaks appeared in its full-range XPS spectra at binding energies of 140 eV when compared to ADSBC600 in its raw state (Ho et al., 2017). **Figure S5** shows the XPS diagram of sewage sludge biochar.

Preferential adsorption of Pb^{2+} over Zn^{2+} can be seen on biochar, caused by the lower binding energy, higher electronegativity, and lower pKH value of Pb^{2+}, according to XPS studies and binding energy computations. Hydroxyl Carboxyl and groups also played a significant role in the complexation with Pb^{2+} and Zn^{2+} (Zhao, May 2020). Wu et al. found that Cd(II) was satisfactorily adsorbed on SBC500, SBC700, and SBC900, as evidenced by a comprehensive scan of XPS spectra. XPS and FTIR research show that the characteristics of sludge biochar fluctuate with pyrolysis temperature (Wu et al., 2023). Fan et al. conducted XPS analysis on nZVI-BC before and after Cr(VI) adsorption to examine the sample surface's element composition and oxidation states. The XPS spectra of Fe 2p demonstrated the transition of elemental Fe to Fe(II) and Fe(II) to Fe(III) as Table 5 shows the XPS analysis of Sewage sludge biochar.

Table 5
XPS analysis of sewage sludge biochar.

Type of SSB	Pyrolysis Temperature (°C)	Coating	Compounds	Binding Energy (eV)	Reference
Raw	500.00	–	O-C=O	288.60	(Wu et al., 2023)
	700.00		C=O	286.40	
	900.00		C-OH	285.50	
			C–H/C=C	284.80	
Raw	600.00	–	FeOOH	723.50	(Fan et al., 2019)
			Fe (III)	717.00	
			FeOOH	711.40	
			Fe_2O_3	710.20	
			FeO	709.10	
nZVI-loaded	500.00	–	Fe-O	529.90	(Yu, 2022)
			C-O	531.00	
			C=O	532.10	
WSBC	400.00	–	C=C/C–H	284.80	(Ho et al., 2017)
			C-OH	285.30	
			C=O	286.40	
			C–C=O	288.60	

Advanced characterization techniques for heavy metal adsorption

Additional in-depth examination of the minute details of materials, chemicals, or biological beings can be accomplished using advanced characterization techniques. These methods go beyond simple analysis by providing a more complex knowledge of characteristics and behaviors. For enhanced characterization, tools like GCMS, Auger electron spectroscopy, Inductively coupled plasma, and electron spin resonance are used in materials research. These techniques provide exact access to crystallography, elemental composition, and atomic and molecular structures of materials for scientific investigation. Fig. 2 represents various advanced characterization techniques. Although advanced characterizations have been performed on different types of biochar, there has been limited exploration of sewage sludge biochar, so it is essential to explore these advanced characterizations further in the future.

Inductively coupled plasma (ICP)

ICP is an atmospheric pressure ionization technique that serves as a hard ionization process, leading to the sample's whole atomization during ionization. ICP source is made up of a sample introduction system, an ICP torch, a radio frequency coil for the production of argon

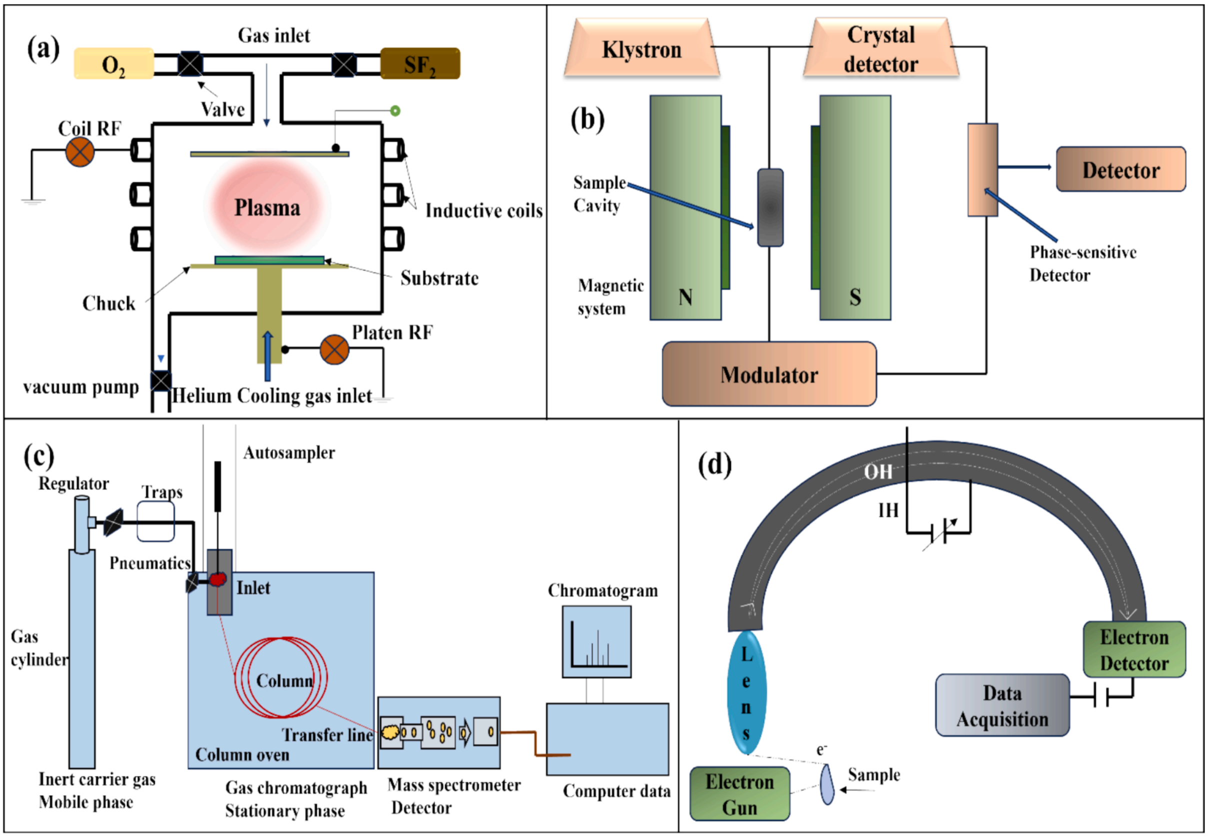

Fig. 2. Advanced characterization techniques for sewage sludge biochar (a) Inductively coupled plasma, (b)Electron spin resonance, (c) Gas chromatography- Mass spectrometry, (d) Auger electron spectroscopy.

plasma, which serves as the ion fount, and an interface that joins the mass spectrometer and the source as shown in Fig. 2 **(a)**. To ascertain if the biochar is a viable supply of soil nutrients (N, P, K, Fe, etc.), an ICP-OES analysis was conducted to confirm the metal concentration in the tobacco seed waste and the biochar. Tan et al. used ICP-OES to analyze a few elements in biochar made from municipal sludge heated to various temperatures (500–900 °C). ICP-OES analysis was performed by Rehrah et al. on biochars made from multiple agricultural wastes, including cotton waste, pecan peels, and peanut shells, and produced at varying temperatures for pyrolysis (300, 500, and 750 °C). The liberation of basic cations like Ca^{2+} and Mg^{2+} (in larger proportions for higher temperature biochars) is responsible for the observed pH rise that occurred as the pyrolysis temperature rose. At high temperatures, we also saw increased potassium in the leftover peanut peel (Onorevoli et al., 2018); (Oochit and Selvarajoo, 2019); (Rehrah, Jul. 2014). Spatial chemical analysis was performed on intact biochar fragments using laser ablation ICP. The study's results revealed significant dissimilarities in elemental composition at the micron level over the surfaces of the biochar and biochar enriched with apatite samples. The analysis revealed that the Fe/O is likely hematite or magnetite, and the Al and Si concentrations are associated, suggesting that the material is expected clay (Dang, 2019).

Auger electron spectroscopy

When analyzing the elements and chemicals of inorganic solid surfaces, Auger spectroscopy (AES) is a crucial method. Fig. 2**(d)** shows the pictorial representation of AES. For further developing the removal of As (III) for groundwater remediation, Cuong et al. (Cuong et al., 2021) make use of active MnO_2/rice husk biochar composite (MBC). The arrangement of the surface was examined using an Auger electron spectroscopy analyzer. The sample surface had some As(III) adsorbed on it, and the As(III, V) removal capacity on MBC-100 was more significant than that on BC. Zhang et al. (Zhang, 2022) created lower-cost biochar-supported Cu catalysts with no alkali added to the reaction system, assisting in achieving green catalysis and environmental sustainability. Auger electron spectroscopy was employed to identify the Cu species above the surface and to conduct more research.

Gas Chromatography-Mass spectrometry

Gas chromatography coupled with mass spectrometry is the technology most often used nowadays to examine environmental samples of volatile organic pollutants. Fig. 2 **(c)** illustrates the pictorial depiction of ESR. The well-established technology of GC–MS was utilized to ascertain the presence of PAHs (polycyclic aromatic hydrocarbons) in soil modified with biochar. To do this, several extraction and solvent techniques were investigated utilizing the 16 EPA PAHs as the targeted PAHs on biochar used in agronomic field research (Fabbri et al., 2013). Although leaching studies demonstrate that quantifiable quantities of PAHs may be liberated from biochar into water, PAHs' hydrophobic nature and chemical structure bind them tightly to the material. Experiments were conducted to determine if pre-treating biochar might eliminate PAHs and lessen the likelihood that biochar would contribute to PAH pollution in environmental systems. Gas chromatography-mass spectrometry analysis combined and condensed the eluent solutions with a stream of N_2. To minimize carryover and enhance repeatability, all subsample eluents were examined in triplicate in the GCMS, with two blank (solvent) runs conducted between each run (Khalid and Klarup, 2015).

Electron spin resonance spectroscopy

Analyzing chemical species or materials with one or more unpaired electrons can be effectively accomplished through electron paramagnetic resonance or ESR. An ESR spectrum is often generated by altering the magnetic field intensity at a constant microwave frequency, as shown in Fig. 2**(b)**. **Table S3** shows the findings of different advanced characterization techniques used in biochar. J. Liu et al. (Liu, 2020) developed an environmentally benign and energy-efficient mesoporous catalyst, BC-FeCu, where he used ESR to determine the amount of O_2, OH, and $^1O_2$ produced in the reaction system. It was discovered that BC-FeCu had better signal values for OH, O_2, and $^1O_2$, proving its superiority over BC and FeCu. By using a hydrothermal carbonization procedure, Zang et al. (Zang et al., 2020) created sludge-based biochar matter loaded with nano-Fe_3O_4 (xS@Fe-y), which they then used as a catalyst to activate peroxymonosulfate for the degradation of organic colors in the effluent. It was shown by the electron ESR detection and the free radical quenching test that SO_4, O_2, OH, and $^1O_2$ were produced throughout the catalyst activation of PMS (Zang et al., 2020). **Table S1** represents the different advanced characterisation methods.

The detailed characterization of biochar provides a wealth of information about its structural and chemical properties, such as porosity, specific surface area, and the presence of functional groups. These properties, identified through techniques like SEM, FTIR, and XPS, directly influence the adsorption efficiency of biochar. However, experimental methods alone often require extensive time and resources to optimize biochar for specific applications, such as heavy metal removal (Zhu et al., Oct. 2019); (Kaya and Erdem, 2023). To address these limitations, artificial intelligence (AI) models, such as Artificial Neural Networks (ANNs), have emerged as powerful tools to predict adsorption performance based on the properties identified through characterization. By training AI models on experimental data, researchers can establish relationships between biochar's structural features and its adsorption capacity, enabling more efficient optimization processes. Thus, integrating experimental characterization with AI modeling bridges the gap between understanding material properties and applying them to real-world environmental challenges (Fan et al., 2019); (Ke, 2021).

Empirical models for heavy metal adsorption on SSB

Classical adsorption models

The Thomas and Yoon-Nelson models are commonly employed to describe and forecast the adsorption behavior in fixed-bed column systems. The Thomas model, a mathematical approach, takes into account factors such as the influent adsorbate concentration, the adsorbent's adsorption capacity, and the influent flow rate to characterize the process. It helps determine when the concentration of adsorbate in the effluent stream or the breakthrough time begins to rise. In contrast, the Yoon-Nelson model is an empirical equation that considers the influences of mass transfer and pore diffusion on the breakthrough curve, providing valuable insights into the performance of the adsorption system. This model is beneficial for analyzing the effects of operational conditions on breakthrough times and adsorption efficiency.

To analyze the adsorption kinetics in the column, the breakthrough curves were simulated with the Thomas and Yoon-Nelson models. With R^2 values more than 0.99, both the Thomas and Yoon-Nelson models accurately characterized the column experimental findings. The two models' simulated breakthrough curves are nearly identical, demonstrating that both models may be used to evaluate the dynamic Cr(VI) uptake deportment in the fix-bed columns. The best-fit value of K_{th} in the Thomas model grows with higher flow rates. The best-fit value of K_{YN} in the Yoon-Nelson model increases as the initial Cr(VI) concentration and flow rate increase. Based on the results, the best operation flow rate and beginning concentration are 1.0 mL/min and 100 mg/L, respectively (Fan et al., 2019).

The time required for the sorption process to reach equilibrium is determined by adsorption kinetics models, which provide detailed data on diffusion and reaction rates. Predicting adsorbate transmission via perforated media and fixed bed sorption efficiency relies heavily on adsorption kinetics factors inferred from studies. To fully comprehend the adsorption process, it is crucial to fit experimental data from batch kinetic studies into various kinetic models. This complements other methods, such as analyzing adsorption isotherms, characterizing surface properties, and studying thermodynamics, which collectively help elucidate the underlying mechanisms of adsorption (Tong et al., 2019). Adsorption isotherms are quantitative methodologies for characterizing adsorbate equilibria associated with solid and liquid phases at constant ambient temperatures. The information obtained using adsorption isotherms is used to get information about the maximum adsorption capacity of sorbents and sorption phenomena, which is vital in assessing the efficacy of adsorbents while optimizing adsorption mechanisms and establishing economical and effective treatment plans (Mayilswamy et al., 2023).

Artificial Neural network models

Artificial Neural Networks (ANN) are one of the computational techniques used in data mining. In reality, ANN is a model of the functioning of the human brain. Researchers and scientists started considering using the brain's anatomy to create patterns. As a result, many ANN models were created by mimicking the structure of the human brain. Like the human brain, neural networks are computer programs composed of an indefinite number of cells, nodes, units, or neurons that link sets of inputs to outputs. These interconnected sets are used in network learning. Therefore, the neural network aims to estimate an output pattern or patterns using the input variables. Numerous advantages make the ANN a potent statistical tool, including its ability to learn patterns with only minor modifications, approximate nonlinear systems accurately even without knowledge about the relationships between variables, ease of use, and independence from traditional experimental designs (O. Bozorg-Haddad and B. Zolghadr-Asli, Computational Intelligence for Water and Environmental Sciences., 2022). Artificial neural networks are widely utilized as versatile tools across various domains, including data mining, manufacturing systems, waste management, structural health monitoring, the automotive industry, and renewable and sustainable energy applications (Nighojkar, 2023) (Kalla et al., 2024); (Podstawczyk et al., Oct. 2015); (Uddin, 2020).

In terms of predicted accuracy and adaptability, artificial intelligence (AI) models like ANN and SVM perform better than conventional techniques (such as empirical isotherms like Langmuir and Freundlich). AI can handle complicated, nonlinear interactions and massive datasets, providing accurate predictions under a variety of scenarios, whereas traditional methods rely on simplified equations and limited parameters. Traditional models, on the other hand, are more accessible for fundamental research since they are simpler to understand and demand less computing power. Although AI models are excellent at optimization and large-scale applications, their successful implementation necessitates strong datasets and specialized knowledge (Ke, Aug. 2021); (Jaffari, 2024).

Zhu et al. (Zhu et al., Oct. 2019)created models based on quantifiable biochar properties, including CHON, pH, and CEC (cation exchange capacity), that could be used to forecast the target metal's adsorption efficacy in water and wastewater. Furthermore, understanding the relative importance of each variable influencing adsorption efficiency provided valuable insights into the removal of heavy metals using biochars. This knowledge offers practical guidelines for treating real wastewater and contaminated groundwater containing heavy metals (Zhu et al., Oct. 2019). Kaya et al. (Kaya and Erdem, 2023) used an ANN model created with experimental adsorption data to analyze the removal efficiency of Pb^{2+} ions from an aqueous solution. In the experimental section, the ANN system was fed with the subsequent adsorption parameters: pH, temperature, starting Pb^{2+} concentration, amount of adsorbent, and mixing speed. For biochars, the R^2 values were determined to be 98 % and 97 %. It has been demonstrated that the ANN modeling tool helps estimate the percentage removal value of Pb^{2+} from an aqueous solution. A range of artificial intelligence models, including SVM, ANN, RF, M5Tree, GP, BA-SVM, BA-RF, BA-M5Tree, BA-GP, BA-ANN, SVM-RF, SVM-M5Tree, SVM-GP, SVM-ANN, RF-GP, RF-ANN, M5Tree-ANN, RF-M5Tree, and GP-ANN, were developed by Ke et al. (Ke, Aug. 2021) to estimate the sorption efficacy of the heavy metal in the biochar system with a high degree of reliability. By analyzing all the models, the adsorption efficiency of biochar was predicted. The most reliable and accurate prediction model among them was the SVM-ANN model, which was presented.

Growth of AI models

The field of artificial intelligence (AI) presents many promising applications, one of which is the adsorption of heavy metals. Empirical models like Freundlich and Langmuir have been used to characterize adsorption equilibrium for decades, but their prediction power is limited. Additionally, the link between adsorption outcomes and operating circumstances remains unknown. Machine learning can be utilized to develop hybrid isotherm and kinetic models, enhancing accuracy and efficiency in modeling multicomponent systems for the cost-effective removal of heavy metals. Applying machine learning and artificial intelligence principles will contribute to a deeper comprehension of biochar's effectiveness, ultimately reducing energy, time, and costs. This emerging research area holds significant promise for future exploration

Table 6
Advantages and disadvantages of AI models used in wastewater treatment.

Sl No.	AI Models	Advantages	Disadvantages	Reference
1	SVM	• Simple to comprehend, interpret, and categorize • Preprocessing is not n ecessary.	• Poor training effectiveness • Not suitable for imbalanced data sets	(Guo, 2020)
2	DT	• Classifying, interpreting, and comprehending easy • No need for preprocessing	• Training efficiency is low • Cannot be used for unbalanced data sets.	(Rodríguez-Rángel et al., 2500)
3	RF	• Can be used for high-dimensional datasets • High generalization	• Computationally expensive • Need of dense decision trees for high accuracy	
4	BRT	• High prediction accuracy • Robust to overfitting	• Computationally intensive • Reduced interpretability	(Elith et al., Jul. 2008)
5	PSO	• Computational efficiency is high	• Cannot be used for discrete problems	(Qi et al., Sep. 2020)
6	ANN	• Handles complex linear relationships • Adaptable and versatile	• Large dataset is required	(Zhu et al., Oct. 2019)
7	GA	• Flexible and efficient • Encourage multi-objective optimization	• Training is difficult • Local search ability is poor	(Qi et al., Sep. 2020)
8	KNN	• Can be used for non-linear classification • Easy to use	• Memory consumption is high • Computationally expensive	(Rodríguez-Rángel et al., 2500)
9	PCA	• Reduce dimensionality	• Sensitive to noise data	(Lee et al., Oct. 2008)
10	SOM	• Can be used for high-dimensional datasets	• High computational complexity	(Martín de la Vega and Jaramillo-Morán, May 2018)

and emphasis as Table 6 shows the advantages and disadvantages of AI models used in wastewater treatment.

Artificial neural networks (ANNs), Support Vector Machines (SVM), Random Forests (RF), Boosted Regression Trees (BRT), K-Nearest Neighbor (KNN), Genetic Algorithms (GA), Principal Component Analysis (PCA), Particle Swarm Optimization (PSO), Self-Organizing Map (SOM), Simulated Annealing (SA), and Decision tree (DT), are the main categories of AI tools. To improve the precision of optimal solution prediction, AI technologies have also been integrated with experimental design (e.g., response surface approach and uniform design) (Fan et al., Jun. 2018). Machine learning (ML) may simulate and learn heavy metal adsorption behavior on biochars, potentially resolving the problem. The first stage is creating and training a high-quality model that reliably predicts adsorption efficiency. Jaffari et al. examined three tree-based models and three deep learning models like ANN, Tab-Transformer, and FT-Transformer—to forecast the adsorption capabilities of biochar materials towards different heavy metal ions (Jaffari, 2024). Researchers are now investigating the application of AI to predict the efficacy of biochar-enhanced heavy metal removal in diverse environmental settings and optimize biochar production and adsorption qualities. In heavy metal-contaminated areas, combining AI with biochar has enormous potential for sustainable practices and future environmental restoration.

Recent research on AI modeling of sewage sludge biochar for heavy metal ion removal emphasizes the application of advanced machine learning techniques such as Support Vector Machines (SVMs) and Artificial Neural Networks (ANNs). These methods are employed to enhance predictive accuracy and optimize the adsorption process for improved environmental remediation outcomes.These models utilize biochar properties such as pore size, functional groups, and pyrolysis conditions to predict adsorption efficiency for metals like lead and cadmium. AI enables faster optimization of biochar characteristics, reducing experimental trials and enhancing its applicability in wastewater treatment systems. These approaches streamline environmental remediation strategies through data-driven predictions (Huang, Feb. 2023).

Modification and in-depth study of adsorption of sewage sludge biochar for wastewater treatment

Unmodified biochars suffer from reduced surface area, pore characteristics, and insufficient active functional moieties, which reduce their adsorption capacity toward a wide range of pollutants. Modified biochars showed improved porousness, a larger density of functional moieties and surface area, effective physicochemical stability, and were favorable for use and environmental remediation. The major methods of biochar modification include chemical modification and physical modification. Acid-alkali modification, modification via oxidizing agents, modification using nanomaterials, etc. come under chemical modification (Racek et al., Jul. 2020) as Table 7 shows Different types of modifications done for sewage sludge biochar and its adsorption parameters.

The chemical modification of biochar is seen as an affordable method because it does not require any heat for the whole process. When biochar is treated with KOH, its surface hydroxyl groups increase and its basicity dissolves ash and condenses organic materials (such as lignin and cellulose) in the biochar (Fan, Aug. 2016); (Li et al., Sep. 2014). When biochar was modified with H_2O_2, it was discovered that the surfaces of the biochar had more O-containing functional groups, especially carboxyl groups (Rajapaksha, Apr. 2016). Biochar is often batch-washed without raising any issues regarding the release of organic or inorganic chemicals (such as PO_4^{3-} and CO_3^{2-}). This can affect the way biochar absorbs metals, so it's important to think about ways to effectively get rid of these liberated chemicals. When it comes to physical modification techniques include activating precursors with carbon dioxide (CO_2) or steam after carbonizing them at temperatures lower than 800 °C. In order to create a microporous biochar framework and carbon monoxide (CO) gas, carbonaceous components of biochar must interact with CO_2 gas. This process is known as CO_2 activation. Steam activation includes the removal of the contained substances, the fixed C transition to CO_2 and CO, and the reaction of carbonaceous biochar with steam to produce evanescent substances. By reducing its polarity and aromaticity, this activation method seeks to improve the biochar's pore volume, surface area, and shape.

Conclusion

Significant amounts of heavy metals, recognized for their harmful and non-biodegradable nature, are discharged into surface water from industrial or agricultural sources, resulting in groundwater pollution, a persistent cause of concern. Therefore, heavy metals in wastewater can be removed using an adsorption approach employing sewage sludge biochar. The scientific community has recently given biochar, an emerging carbon material derived mainly from inexpensive biomass remaining, a great deal of attention because of its promising potential in various environmental applications, comprising water treatment, environmental remediation, soil improvement, and carbon sequestration. This review explores multiple characterization techniques for sewage sludge biochar, including SEM, FTIR, XRD, XPS, AES, ICP, ESR, and GC–MS. ANN models are also used to predict the adsorption capacity of sewage sludge biochar to adsorb heavy metals. The SVM-ANN model was the most precise and dependable prediction model from the ANN models. During the characterization of SBC, it was found that surface functional groups of SBCs were modified by pyrolysis. With these characterization approaches, it is possible to assess pyrolysis's significant contribution to the adsorption capacity of biochar produced from sewage sludge.

Ethical Responsibilities of Authors: All authors have read, understood, and complied with the journal's "Ethical Responsibilities of Authors" guidelines.

Authors' Contribution: The manuscript was written with the contributions of all authors. All authors have approved the final version of the manuscript. Bhavana Shanmughan prepared the data and wrote the original draft. Amrita Nighojkar and Balasubramanian Kandasubramanian conceptualized the research work and reviewed and edited the manuscript.

CRediT authorship contribution statement

Bhavana Shanmughan: Writing – original draft. **Amrita Nighojkar:** Writing – review & editing, Methodology. **Balasubramanian**

Table 7

Different types of modifications done for sewage sludge biochar and its adsorption parameters.

Modification	Heavy metal adsorbed	Adsorption capacity	Adsorption isotherm	Kinetic model	Reference
Co-precipitation with HAP	Cu(II) Cd(II)	89.98 114.68	Langmuir	Pseudo second order	(Chen, Feb. 2021)
Chemical modification with HNO3	–	–	–	Pseudo first order	(Hung, Jan. 2022)
Pre-treatment withK_2CO_3 andH_3PO_4	Cr(III) As(V)	–	Langmuir Freundlich	Pseudo first order	(Tomczyk et al., 2020)
Chemical modification with HNO_3	–	70.60	–	Pseudo first order	(Hung, Jan. 2022)

Kandsubramanian: Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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References

Albroomi, H.I., Elsayed, M.A., Baraka, A., Abdelmaged, M.A., Jul. 2017. Batch and fixed-bed adsorption of tartrazine azo-dye onto activated carbon prepared from apricot stones. *Appl. Water Sci.* 7 (4), 2063–2074. https://doi.org/10.1007/s13201-016-0387-2.

Brodowski, S., Amelung, W., Haumaier, L., Abetz, C., Zech, W., Sep. 2005. Morphological and chemical properties of black carbon in physical soil fractions as revealed by scanning electron microscopy and energy-dispersive X-ray spectroscopy. *Geoderma* 128 (1–2), 116–129. https://doi.org/10.1016/j.geoderma.2004.12.019.

Bryukhov, M., Ulrikh, D., 2022. "Wastewater treatment: Methods and prospects," in *IOP Conference Series: Earth and Environmental Science*. Institute of Physics. https://doi.org/10.1088/1755-1315/1061/1/012049.

Cao, J., et al., Oct. 2024. Sludge-based biochar preparation: pyrolysis and co-pyrolysis methods, improvements, and environmental applications. *Fuel* 373, 132265. https://doi.org/10.1016/j.fuel.2024.132265.

Chavan, D., Mayilswamy, N., Chame, S., Kandasubramanian, B., Dec. 2024. Biochar Adsorption: A Green Approach to PFAS Contaminant Removal. *CleanMat* 1 (1), 52–77. https://doi.org/10.1002/clem.16.

Chen, Y., et al., Feb. 2021. Hydroxyapatite modified sludge-based biochar for the adsorption of Cu2+ and Cd2+: Adsorption behavior and mechanisms. *Bioresour. Technol.* 321, 124413. https://doi.org/10.1016/j.biortech.2020.124413.

Cheng, S., Jang, J.-H., Dempsey, B.A., Logan, B.E., Jan. 2011. Efficient recovery of nano-sized iron oxide particles from synthetic acid-mine drainage (AMD) water using fuel cell technologies. *Water Res.* 45 (1), 303–307. https://doi.org/10.1016/j.watres.2010.07.054.

Cuong, D.V., Wu, P.C., Chen, L.I., Hou, C.H., 2021. Active MnO2/biochar composite for efficient As(III) removal: Insight into the mechanisms of redox transformation and adsorption. *Water Res.* 188, 116495. https://doi.org/10.1016/j.watres.2020.116495.

Damahe, D., Mayilswamy, N., Kandasubramanian, B., Aug. 2024. Biochar/metal nanoparticles-based composites for Dye remediation: A review. *Hybrid Adv.* 6, 100254. https://doi.org/10.1016/j.hybadv.2024.100254.

Dang, V.M., et al., 2019. Immobilization of heavy metals in contaminated soil after mining activity by using biochar and other industrial by-products: the significant role of minerals on the biochar surfaces. *Environ. Technol. (united Kingdom)* 40 (24), 3200–3215. https://doi.org/10.1080/09593330.2018.1468487.

Domínguez, A., Menéndez, J.A., Inguanzo, M., Pís, J.J., Jul. 2006. Production of bio-fuels by high temperature pyrolysis of sewage sludge using conventional and microwave heating. *Bioresour. Technol.* 97 (10), 1185–1193. https://doi.org/10.1016/j.biortech.2005.05.011.

El Hanandeh, A., Mahdi, Z., Imtiaz, M.S., Jan. 2021. Modelling of the adsorption of Pb, Cu and Ni ions from single and multi-component aqueous solutions by date seed derived biochar: Comparison of six machine learning approaches. *Environ. Res.* 192, 110338. https://doi.org/10.1016/j.envres.2020.110338.

Elith, J., Leathwick, J.R., Hastie, T., Jul. 2008. A working guide to boosted regression trees. *J. Anim. Ecol.* 77 (4), 802–813. https://doi.org/10.1111/j.1365-2656.2008.01390.x.

A. S. Erses Yay, B. Birinci, S. Açıkalın, and K. Yay, "Hydrothermal carbonization of olive pomace and determining the environmental impacts of post-process products," *J. Clean. Prod.*, vol. 315, p. 128087, Sep. 2021, doi: 10.1016/j.jclepro.2021.128087.

Fabbri, D., Rombolà, A.G., Torri, C., Spokas, K.A., 2013. Determination of polycyclic aromatic hydrocarbons in biochar and biochar amended soil. *J. Anal. Appl. Pyrolysis* 103, 60–67. https://doi.org/10.1016/j.jaap.2012.10.003.

Fan, S., et al., Aug. 2016. Biochar prepared from co-pyrolysis of municipal sewage sludge and tea waste for the adsorption of methylene blue from aqueous solutions: Kinetics, isotherm, thermodynamic and mechanism. *J. Mol. Liq.* 220, 432–441. https://doi.org/10.1016/j.molliq.2016.04.107.

Fan, M., Hu, J., Cao, R., Ruan, W., Wei, X., Jun. 2018. A review on experimental design for pollutants removal in water treatment with the aid of artificial intelligence. *Chemosphere* 200, 330–343. https://doi.org/10.1016/j.chemosphere.2018.02.111.

Fan, Z., Zhang, Q., Gao, B., Li, M., Liu, C., Qiu, Y., 2019. Removal of hexavalent chromium by biochar supported nZVI composite: Batch and fixed-bed column evaluations, mechanisms, and secondary contamination prevention. *Chemosphere* 217, 85–94. https://doi.org/10.1016/j.chemosphere.2018.11.009.

Francis, J.C., Nighojkar, A., Kandasubramanian, B., Aug. 2023. Relevance of wood biochar on CO2 adsorption: A review. *Hybrid Adv.* 3, 100056. https://doi.org/10.1016/j.hybadv.2023.100056.

Gao, L.Y., et al., 2019. Relative distribution of Cd2+ adsorption mechanisms on biochars derived from rice straw and sewage sludge. *Bioresour. Technol.* 272, 114–122. https://doi.org/10.1016/j.biortech.2018.09.138.

Ghorbani, M., et al., Oct. 2022. Feasibility of Biochar Derived from Sewage Sludge to Promote Sustainable Agriculture and Mitigate GHG Emissions—A Review. *Int. J. Environ. Res. Public Health* 19 (19), 12983. https://doi.org/10.3390/ijerph191912983.

Gole, P., Raut, K., Kandasubramanian, B., Aug. 2024. Polymer-based biochar materials for environmental remediation: A review. *Hybrid Adv.* 6, 100267. https://doi.org/10.1016/j.hybadv.2024.100267.

Guo, Z., et al., 2020. Data-driven prediction and control of wastewater treatment process through the combination of convolutional neural network and recurrent neural network. *RSC Adv.* 10 (23), 13410–13419. https://doi.org/10.1039/D0RA00736F.

V. K. Gupta and Suhas, "Application of low-cost adsorbents for dye removal – A review," *J. Environ. Manage.*, vol. 90, no. 8, pp. 2313–2342, Jun. 2009, doi: 10.1016/j.jenvman.2008.11.017.

S. H. Ho, Y. di Chen, Z. kai Yang, D. Nagarajan, J. S. Chang, and N. qi Ren, "High-efficiency removal of lead from wastewater by biochar derived from anaerobic digestion sludge," *Bioresour. Technol.*, vol. 246, pp. 142–149, 2017, doi: 10.1016/j.biortech.2017.08.025.

M. K. Hossain, V. Strezov, K. Yin Chan, and P. F. Nelson, "Agronomic properties of wastewater sludge biochar and bioavailability of metals in production of cherry tomato (Lycopersicon esculentum)," *Chemosphere*, vol. 78, no. 9, pp. 1167–1171, Feb. 2010, doi: 10.1016/j.chemosphere.2010.01.009.

Huang, Y., et al., Feb. 2023. A global synthesis of biochar's sustainability in climate-smart agriculture - Evidence from field and laboratory experiments. *Renew. Sustain. Energy Rev.* 172, 113042. https://doi.org/10.1016/j.rser.2022.113042.

Hung, C.-M., et al., Jan. 2022. Efficacy and cytotoxicity of engineered ferromanganese-bearing sludge-derived biochar for percarbonate-induced phthalate ester degradation. *J. Hazard. Mater.* 422, 126922. https://doi.org/10.1016/j.jhazmat.2021.126922.

Hwang, I.H., Ouchi, Y., Matsuto, T., Aug. 2007. Characteristics of leachate from pyrolysis residue of sewage sludge. *Chemosphere* 68 (10), 1913–1919. https://doi.org/10.1016/j.chemosphere.2007.02.060.

Ifthikar, J., et al., Aug. 2018. Facile One-Pot Synthesis of Sustainable Carboxymethyl Chitosan – Sewage Sludge Biochar for Effective Heavy Metal Chelation and Regeneration. *Bioresour. Technol.* 262, 22–31. https://doi.org/10.1016/j.biortech.2018.04.053.

Inyang, M., Gao, B., Pullammanappallil, P., Ding, W., Zimmerman, A.R., Nov. 2010. Biochar from anaerobically digested sugarcane bagasse. *Bioresour. Technol.* 101 (22), 8868–8872. https://doi.org/10.1016/j.biortech.2010.06.088.

Z. H. Jaffari *et al.*, "Transformer-based deep learning models for adsorption capacity prediction of heavy metal ions toward biochar-based adsorbents," *J. Hazard. Mater.*, vol. 462, no. October 2023, p. 132773, 2024, doi: 10.1016/j.jhazmat.2023.132773.

Janyasuthiwong, S., Rene, E.R., Esposito, G., Lens, P.N.L., 2016. Effect of pH on the Performance of Sulfate and Thiosulfate-Fed Sulfate Reducing Inverse Fluidized Bed Reactors. *J. Environ. Eng.* 142 (9), Sep. https://doi.org/10.1061/(ASCE)EE.1943-7870.0001004.

A. Kalla, N. Mayilswamy, B. Kandasubramanian, and P. Mahajan- Tatpate, "Biochar: a sustainable and an eco-friendly material for energy storage applications," *Int. J. Green Energy*, vol. 21, no. 7, pp. 1695–1709, May 2024, doi: 10.1080/15435075.2023.2259973.

Kang, X., Xiao, F., Zhou, S., Zhang, Q., Qiu, L., Wang, L., Oct. 2022. Study on the performance of sewage sludge biochar modified by nZVI to remove Cu(II) and Cr(VI) in water. *Water Sci. Technol.* 86 (7), 1821–1834. https://doi.org/10.2166/wst.2022.302.

Kang, X., Xiao, F., Zhou, S., Zhang, Q., Qiu, L., Wang, L., 2022. Study on the performance of sewage sludge biochar modified by nZVI to remove Cu(II) and Cr(VI) in water. *Water Sci. Technol.* 86 (7), 1821–1834. https://doi.org/10.2166/wst.2022.302.

Kaya, N., Erdem, F., 2023. Artificial neural network approach for lead removal from aqueous solution by agricultural waste derived biochars. *Sigma J. Eng. Nat. Sci.* 41 (1), 64–73. https://doi.org/10.14744/sigma.2023.00008.

Ke, B., et al., Aug. 2021. Predicting the sorption efficiency of heavy metal based on the biochar characteristics, metal sources, and environmental conditions using various novel hybrid machine learning models. *Chemosphere* 276, 130204. https://doi.org/10.1016/j.chemosphere.2021.130204.

Ke, B., et al., 2021. Predicting the sorption efficiency of heavy metal based on the biochar characteristics, metal sources, and environmental conditions using various novel hybrid machine learning models. *Chemosphere* 276, 130204. https://doi.org/10.1016/j.chemosphere.2021.130204.

Keiluweit, M., Nico, P.S., Johnson, M.G., Kleber, M., Feb. 2010. Dynamic Molecular Structure of Plant Biomass-Derived Black Carbon (Biochar). *Environ. Sci. Technol.* 44 (4), 1247–1253. https://doi.org/10.1021/es9031419.

Khalid, F.N.M., Klarup, D., 2015. The influence of sunlight and oxidative treatment on measured PAH concentrations in biochar. *Environ. Sci. Pollut. Res.* 22 (17), 12975–12981. https://doi.org/10.1007/s11356-015-4469-8.

B. Khiari, M. Jeguirim, L. Limousy, and S. Bennici, "Biomass derived chars for energy applications," *Renew. Sustain. Energy Rev.*, vol. 108, no. November 2018, pp. 253–273, 2019, doi: 10.1016/j.rser.2019.03.057.

Kılıç, M., Kırbıyık, Ç., Çepelioğullar, Ö., Pütün, A.E., Oct. 2013. Adsorption of heavy metal ions from aqueous solutions by bio-char, a by-product of pyrolysis. *Appl. Surf. Sci.* 283, 856–862. https://doi.org/10.1016/j.apsusc.2013.07.033.

Kulkarni, S.S., Mayilswamy, N., Sidharth, S., 2023. *Sustainable Wastewater Management via Biochar Derived from Industrial Sewage Sludge* no. 0123456789. https://doi.org/10.1007/s43615-023-00273-2.

Kulkarni, S.R., Nighojkar, A., Kandasubramanian, B., Nov. 2023. Aqueous Adsorption of Pharmaceutical Pollutants on Biochar: a Review on Physicochemical Characteristics, Classical Sorption Models, and Advancements in Machine Learning Techniques. *Water, Air, Soil Pollut.* 234 (11), 684. https://doi.org/10.1007/s11270-023-06696-9.

Lee, M.W., Hong, S.H., Choi, H., Kim, J.-H., Lee, D.S., Park, J.M., Oct. 2008. Real-time remote monitoring of small-scaled biological wastewater treatment plants by a multivariate statistical process control and neural network-based software sensors. *Process Biochem.* 43 (10), 1107–1113. https://doi.org/10.1016/j.procbio.2008.06.002.

Li, J., Li, Y., Wu, Y., Zheng, M., Sep. 2014. A comparison of biochars from lignin, cellulose and wood as the sorbent to an aromatic pollutant. *J. Hazard. Mater.* 280, 450–457. https://doi.org/10.1016/j.jhazmat.2014.08.033.

Liu, J., et al., 2020. *The Biochar-Supported Iron-Copper Bimetallic Composite Activating Oxygen System for Simultaneous Adsorption and Degradation of Tetracycline* vol. 402. https://doi.org/10.1016/j.cej.2020.126039.

Lu, H., Zhang, W., Yang, Y., Huang, X., Wang, S., Qiu, R., 2012. Relative distribution of Pb2+ sorption mechanisms by sludge-derived biochar. *Water Res.* 46 (3), 854–862. https://doi.org/10.1016/j.watres.2011.11.058.

Martín de la Vega, P.T., Jaramillo-Morán, M.A., May 2018. Obtaining Key Parameters and Working Conditions of Wastewater Biological Nutrient Removal by Means of Artificial Intelligence Tools. *Water* 10 (6), 685. https://doi.org/10.3390/w10060685.

Matlock, M.M., Howerton, B.S., Atwood, D.A., Nov. 2002. Chemical precipitation of heavy metals from acid mine drainage. *Water Res.* 36 (19), 4757–4764. https://doi.org/10.1016/S0043-1354(02)00149-5.

Mayilswamy, N., Kandasubramanian, B., 2024. Various Biomasses from Wastewater and Possibilities of Conversion to Energy Resources. In: In *Sewage and Biomass from Wastewater to Energy*, pp. 259–281. https://doi.org/10.1002/9781394204502.ch10.

Mayilswamy, N., Nighojkar, A., Edirisinghe, M., Sundaram, S., Kandasubramanian, B., 2023. Sludge-derived biochar: Physicochemical characteristics for environmental remediation. *Appl. Phys. Rev.* 10 (3), Sep. https://doi.org/10.1063/5.0137651.

R. Mourgela and P. Regkouzas, "Ni (II) Adsorption on Biochars Produced from Different Types of Biomass," 2020.

Mourgela, R.N., Regkouzas, P., Pellera, F.M., Diamadopoulos, E., 2020. Ni(II) Adsorption on Biochars Produced from Different Types of Biomass. *Water. Air. Soil Pollut.* 231 (5), 1–16. https://doi.org/10.1007/s11270-020-04591-1.

Nighojkar, A., et al., 2023. Using machine learning to predict the efficiency of biochar in pesticide remediation. *Npj Sustain. Agric.* 1 (1), Oct. https://doi.org/10.1038/s44264-023-00001-1.

O. Bozorg-Haddad and B. Zolghadr-Asli, *Computational Intelligence for Water and Environmental Sciences*. 2022. [Online]. Available: https://books.google.com/books?id=jDx6EAAAQBAJ.

Onorevoli, A.B., Pereira, G., Jacques, A., Jacques, A., "sc",, 2018. *Biochem. Pharmacol.* https://doi.org/10.1016/j.jece.2018.01.039.

D. Oochit and A. Selvarajoo, "Pyrolysis of Biomass Pyrolysis of Biomass," no. November, 2019, doi: 10.1007/978-3-319-49595-8.

Podstawczyk, D., Witek-Krowiak, A., Dawiec, A., Bhatnagar, A., Oct. 2015. Biosorption of copper(II) ions by flax meal: Empirical modeling and process optimization by response surface methodology (RSM) and artificial neural network (ANN) simulation. *Ecol. Eng.* 83, 364–379. https://doi.org/10.1016/j.ecoleng.2015.07.004.

Qi, J., Hou, Y., Hu, J., Ruan, W., Xiang, Y., Wei, X., Sep. 2020. Decontamination of methylene Blue from simulated wastewater by the mesoporous rGO/Fe/Co nanohybrids: Artificial intelligence modeling and optimization. *Mater. Today Commun.* 24, 100709. https://doi.org/10.1016/j.mtcomm.2019.100709.

Racek, J., Sevcik, J., Chorazy, T., Kucerik, J., Hlavinek, P., Jul. 2020. Biochar – Recovery Material from Pyrolysis of Sewage Sludge: A Review. *Waste and Biomass Valorization* 11 (7), 3677–3709. https://doi.org/10.1007/s12649-019-00679-w.

Rajapaksha, A.U., et al., Apr. 2016. Engineered/designer biochar for contaminant removal/immobilization from soil and water: Potential and implication of biochar modification. *Chemosphere* 148, 276–291. https://doi.org/10.1016/j.chemosphere.2016.01.043.

Regkouzas, P., Diamadopoulos, E., Jun. 2019. Adsorption of selected organic micro-pollutants on sewage sludge biochar. *Chemosphere* 224, 840–851. https://doi.org/10.1016/j.chemosphere.2019.02.165.

Rehrah, D., et al., Jul. 2014. Production and characterization of biochars from agricultural by-products for use in soil quality enhancement. *J. Anal. Appl. Pyrolysis* 108, 301–309. https://doi.org/10.1016/j.jaap.2014.03.008.

H. Rodríguez-Rángel, D. M. Arias, L. A. Morales-Rosales, V. Gonzalez-Huitron, M. Valenzuela Partida, and J. García, "Machine Learning Methods Modeling Carbohydrate-Enriched Cyanobacteria Biomass Production in Wastewater Treatment Systems," *Energies*, vol. 15, no. 7, p. 2500, Mar. 2022, doi: 10.3390/en15072500.

Shen, T., Tang, Y., Lu, X.Y., Meng, Z., 2018. Mechanisms of copper stabilization by mineral constituents in sewage sludge biochar. *J. Clean. Prod.* 193, 185–193. https://doi.org/10.1016/j.jclepro.2018.05.071.

Skubiszewska-zi, J., 2015. "biochar Characteristic,. https://doi.org/10.1016/j.jaap.2015.01.025.

Smith, K.M., Fowler, G.D., Pullket, S., Graham, N.J.D., Jun. 2009. Sewage sludge-based adsorbents: A review of their production, properties and use in water treatment applications. *Water Res.* 43 (10), 2569–2594. https://doi.org/10.1016/j.watres.2009.02.038.

Sobol, Ł., Dyjakon, A., Soukup, K., Aug. 2023. Dioxins and furans in biochars, hydrochars and torreficates produced by thermochemical conversion of biomass: a review. *Environ. Chem. Lett.* 21 (4), 2225–2249. https://doi.org/10.1007/s10311-023-01600-7.

Subash, A., Naebe, M., Wang, X., Sahoo, S.K., Kandasubramanian, B., Dec. 2023. Electrospinning of polylactic acid fibers reinforced with Ti3C2 for the removal of nickel ions from wastewater. *Hybrid Adv.* 4, 100109. https://doi.org/10.1016/j.hybadv.2023.100109.

Sylwan, I., Runtti, H., Westholm, L.J., Romar, H., Thorin, E., 2020. Heavy metal sorption by sludge-derived biochar with focus on Pb2+ sorption capacity at µg/L concentrations. *Processes* 8 (12), 1–23. https://doi.org/10.3390/pr8121559.

Tezer, Ö., Karabağ, N., Öngen, A., Ayol, A., Mar. 2023. Syngas production from municipal sewage sludge by gasification Process: Effects of fixed bed reactor types and gasification agents on syngas quality. *Sustain. Energy Technol. Assessments* 56, 103042. https://doi.org/10.1016/j.seta.2023.103042.

Tian, J., et al., Dec. 2022. Solvent-Free Synthesis of Magnetic Sewage Sludge-Derived Biochar for Heavy Metal Removal from Wastewater. *Int. J. Environ. Res. Public Health* 20 (1), 155. https://doi.org/10.3390/ijerph20010155.

J. Tian *et al.*, "Solvent-Free Synthesis of Magnetic Sewage Sludge-Derived Biochar for Heavy Metal Removal from Wastewater," *Int. J. Environ. Res. Public Health*, vol. 20, no. 1, 2023, doi: 10.3390/ijerph20010155.

A. Tomczyk, Z. Sokołowska, and P. Boguta, "Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects," Mar. 2020, *Springer*. doi: 10.1007/s11157-020-09523-3.

Tong, Y., McNamara, P.J., Mayer, B.K., 2019. Adsorption of organic micropollutants onto biochar: a review of relevant kinetics, mechanisms and equilibrium. *Environ. Sci. Water Res. Technol.* 5 (5), 821–838. https://doi.org/10.1039/C8EW00938D.

Tripathi, M., Sahu, J.N., Ganesan, P., Mar. 2016. Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review. *Renew. Sustain. Energy Rev.* 55, 467–481. https://doi.org/10.1016/j.rser.2015.10.122.

Uddin, G.M., et al., 2020. Artificial Intelligence-Based Emission Reduction Strategy for Limestone Forced Oxidation Flue Gas Desulfurization System. *J. Energy Resour. Technol.* 142 (9), Sep. https://doi.org/10.1115/1.4046468.

Van Zwieten, L., et al., Feb. 2010. Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. *Plant Soil* 327 (1–2), 235–246. https://doi.org/10.1007/s11104-009-0050-x.

vom Eyser, C., Schmidt, T.C., Tuerk, J., Jun. 2016. Fate and behaviour of diclofenac during hydrothermal carbonization. *Chemosphere* 153, 280–286. https://doi.org/10.1016/j.chemosphere.2016.03.051.

Wang, Z., et al., Feb. 2015. Investigating the mechanisms of biochar's removal of lead from solution. *Bioresour. Technol.* 177, 308–317. https://doi.org/10.1016/j.biortech.2014.11.077.

Wang, X., et al., Nov. 2023. Synergizing redox of zerovalent iron and singlet oxygen to remove aniline, chromium and antimony in printing and dyeing wastewater synchronously: Multifunctional effect of sludge derived biochar. *Chem. Eng. J.* 476, 146927. https://doi.org/10.1016/j.cej.2023.146927.

Wang, H., Feng, M., Zhou, F., Huang, X., Tsang, D.C.W., Zhang, W., 2017. Effects of atmospheric ageing under different temperatures on surface properties of sludge-derived biochar and metal/metalloid stabilization. *Chemosphere* 184, 176–184. https://doi.org/10.1016/j.chemosphere.2017.05.175.

Wei, D., et al., 2018. Biosorption performance evaluation of heavy metal onto aerobic granular sludge-derived biochar in the presence of effluent organic matter via batch and fluorescence approaches. *Bioresour. Technol.* 249, 410–416. https://doi.org/10.1016/j.biortech.2017.10.015.

Wu, M., Liu, B., Li, J., Su, X., Liu, W., Li, X., 2023. Influence of pyrolysis temperature on sludge biochar: the ecological risk assessment of heavy metals and the adsorption of Cd(II). *Environ. Sci. Pollut. Res.* 30 (5), 12608–12617. https://doi.org/10.1007/s11356-022-22827-x.

Xu, L., Wang, J., Jun. 2017. The application of graphene-based materials for the removal of heavy metals and radionuclides from water and wastewater. *Crit. Rev. Environ. Sci. Technol.* 47 (12), 1042–1105. https://doi.org/10.1080/10643389.2017.1342514.

Y. Wang, H. Li, and S. Lin, "Advances in the Study of Heavy Metal Adsorption from Water and Soil by Modified Biochar," 2022.

Yalasangi, V., Mayilswamy, N., Kandasubramanian, B., Dec. 2024. Biochar-derived adsorbents for removal of Rhodamine B from wastewater. *Bioresour. Technol. Reports* 28, 101987. https://doi.org/10.1016/j.biteb.2024.101987.

L. Yang *et al.*, "Highly efficient nickel (II) removal by sewage sludge biochar supported α-Fe2O3 and α-FeOOH: Sorption characteristics and mechanisms," *PLoS One*, vol. 14, no. 6, p. e0218114, Jun. 2019, doi: 10.1371/journal.pone.0218114.

Yao, Y., et al., Mar. 2012. Adsorption of sulfamethoxazole on biochar and its impact on reclaimed water irrigation. *J. Hazard. Mater.* 209–210, 408–413. https://doi.org/10.1016/j.jhazmat.2012.01.046.

Yavari, S., Malakahmad, A., Sapari, N.B., Yavari, S., Jul. 2017. Sorption properties optimization of agricultural wastes-derived biochars using response surface methodology. *Process Saf. Environ. Prot.* 109, 509–519. https://doi.org/10.1016/j.psep.2017.05.002.

Yu, C., 2022. Removal of Cr(VI) from aqueous solutions by nZVI-loaded sludge-derived biochar: performance and mechanism. *Water Sci. Technol.* 86 (9), 2089–2105. https://doi.org/10.2166/wst.2022.333.

Zang, T., Wang, H., Liu, Y., Dai, L., Zhou, S., Ai, S., 2020. Fe-doped biochar derived from waste sludge for degradation of rhodamine B via enhancing activation of peroxymonosulfate. *Chemosphere* 261, 127616. https://doi.org/10.1016/j.chemosphere.2020.127616.

Zhang, Q., et al., 2022. Sustainable production of gluconic acid and glucuronic acid via microwave-assisted glucose oxidation over low-cost Cu-biochar catalysts. *Green Chem.* 24 (17), 6657–6670. https://doi.org/10.1039/d2gc02568j.

H. Zhang, K. Lu, J. Zhang, C. Ma, Z. Wang, and X. Tian, "Removal and Adsorption Mechanisms of Phosphorus, Cd and Pb from Wastewater Conferred by Landfill Leachate Sludge-Derived Biochar," *Sustain.*, vol. 15, no. 13, 2023, doi: 10.3390/su151310045.

Zhang, W., Zheng, J., Zheng, P., Qiu, R., 2015. Atrazine immobilization on sludge derived biochar and the interactive influence of coexisting Pb(II) or Cr(VI) ions. *Chemosphere* 134, 438–445. https://doi.org/10.1016/j.chemosphere.2015.05.011.

Zhao, M., et al., 2020. Mechanisms of Pb and/or Zn adsorption by different biochars: Biochar characteristics, stability, and binding energies. *Sci. Total Environ.* 717, 136894. https://doi.org/10.1016/j.scitotenv.2020.136894.

Zhao, M., et al., May 2020. Mechanisms of Pb and/or Zn adsorption by different biochars: Biochar characteristics, stability, and binding energies. *Sci. Total Environ.* 717, 136894. https://doi.org/10.1016/j.scitotenv.2020.136894.

Zhou, Y., et al., Jun. 2024. Recent Progress in Sludge-Derived Biochar and Its Role in Wastewater Purification. *Sustainability* 16 (12), 5012. https://doi.org/10.3390/su16125012.

Zhu, X., Wang, X., Ok, Y.S., Oct. 2019. The application of machine learning methods for prediction of metal sorption onto biochars. *J. Hazard. Mater.* 378, 120727. https://doi.org/10.1016/j.jhazmat.2019.06.004.