CURRENT SCIENCE AND TECHNOLOGY
E-ISSN: 2785-8804
VOLUME 4, ISSUE 1, 2024, 55 – 66
DOI: https://doi.org/10.15282/cst.v4i1.11674

REVIEW ARTICLE

Modified Biochar from Waste Biomass for the Efficient Removal of Heavy Metals in Industrial Wastewater: A Review

W. N. A. A. Manan[1,2] and A. H. Zamani[1]*

[1]Faculty of Industrial Sciences and Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, Lebuh Persiaran Tun Khalil Yaakob, 26300, Kuantan, Pahang, Malaysia

[2]Faculty of Applied Sciences, Universiti Teknologi MARA Pahang, Jengka Campus, 26400 Bandar Tun Abdul Razak Jengka, Pahang, Malaysia

ABSTRACT - Due to advancements in society and industry, the problem of heavy metal contamination in water is becoming increasingly severe. Despite being a cost-effective and eco-friendly adsorbent for heavy metal ions, biochar's efficiency in adsorption and immobilisation needs further enhancement. Modified biochar, an enhanced iteration of biochar, has garnered significant interest among the scientific community. This article provides a concise overview of the latest advancements in treating heavy metal pollution in water through the utilisation of biochar. The discussion focused on the features and benefits of various biochar modification processes, including physical modification and chemical modification of biochar. A summary was made of the process by which modified biochar is used to eliminate heavy metals from water. The study revealed that biochar exhibited enhanced performance following modification, resulting in increased surface areas and a greater number of functional groups. Additionally, it demonstrated sufficient binding sites to effectively bind heavy metal ions. Biochar has great potential as a viable solution for the remediation of heavy metals in the environment. Nonetheless, the emphasis continues to be on the advancement of modified biochar that demonstrates high efficiency and cost-effectiveness, featuring a significant sorption capacity, outstanding photocatalytic performance, and environmentally acceptable characteristics that prevent secondary pollution.

ARTICLE HISTORY
Received : 06th Mar. 2024
Revised : 02nd Apr. 2024
Accepted : 06th June 2024
Published : 21st June 2024

KEYWORDS
Adsorption
Biochar
Heavy metals
Modification

1. INTRODUCTION

Heavy metal pollution is a major threat to the environment that poses a potential threat to both human health and the environment. This type of pollution is non-biodegradable and can persist in the environment for extended periods [1]. Exponential growth in population and rapid global industrialization lead to a substantial release of pollutants into the environment [2], leaving it unfit for living organisms [3]. Common heavy metals that can be found in various manufacturing include zinc (Zn), lead (Pb), chromium (Cr), copper (Cu), nickel (Ni), cadmium (Cd), arsenic (As), and mercury (Hg) [4]. These metals are widely used in various industries due to rapid industrialization such as refining metals, mining operations, metal plating, tanneries, battery manufacturing, pesticides, textiles, and fertilizers [1][5]. All living things need essential trace amounts or low concentrations of heavy metals for specific metabolic functions. High levels of these metals can cause toxicity, poisoning, and abnormal activities in various physiological systems, including the cardiovascular and immunological systems [6]. The presence of heavy metals in aquatic bodies and organisms that are used as a source of food is a matter of great concern due to its direct and indirect impact on public health. It can lead to poisoning, cancer, and even neurological disorders [1][5][6]. Consequently, it is necessary to remove and treat heavy metals in wastewater prior to their discharge into the environment. This is a critical factor that must be considered [7].

Currently, many technologies, including chemical precipitation, adsorption, ion flotation, ion exchange, coagulation/flocculation, and electrochemical methods, are employed for the treatment of wastewater contaminated with heavy metals [8]. Among these methods, the adsorption technique is the most effective approach in wastewater treatment. It is widely recognized as the best option for eliminating heavy metals due to its flexible design, reversible nature, and ability to provide high-quality wastewater treatment [7][9]. Researchers have developed various kinds of sorbent materials [10]. The selection of suitable adsorbents is determined by their adsorption capacity, reusability, cost, and, most importantly, their environmentally friendly nature [5]. Nevertheless, because of various technical constraints and the wide range of real-world applications, only a limited number of these innovative materials have successfully transitioned into practical technologies [11].

Recently, biochar from waste biomass has gained significant attention as a cost-effective solution for adsorbing pollutants. Biochar is a carbon-based porous substance that is produced by the thermal decomposition of organic matter

***CORRESPONDING AUTHOR | A. H. Zamani** | ✉ ahmadzamani@umpsa.edu.my

in the absence or partial air presence at moderate temperatures (350–700 °C) has emerged as a promising alternative due to its high surface area, porosity, and functional groups that enhance the adsorption of heavy metals [12][13]. However, typical biochar does have drawbacks, including its small particle size, poor density, and the difficulties of separating it from water [13]. Thus, modifying biochar can effectively enhance its ability to remove heavy metals. The objective of this review is to investigate the efficacy of biochar modification techniques in the removal of heavy metals and the potential for large-scale application, as well as to identify additional research opportunities. This paper discusses several biomass types and pyrolysis temperatures employed for the efficient removal of hazardous metals from water. Additionally, the prospective advancements in the incorporation of nanomagnetic elements into biochar and their significant function in the removal of heavy metals are also reviewed.

2. METHODOLOGY

The initial step in developing various modified biochar was to analyze related papers and try to connect any identified relationships between modified biochar and its impacts on the heavy metals' removal in wastewater. Within this process, relevant articles were sought from search engines including Science Direct (http://www.sciencedirect.com/), SpringerLink (https://link-springer-com), Web of Science (https://www-webofscience-com), Scopus (https://www-scopus-com/) and Taylor & Francis (https://www-tandfonline-com/). Keywords, such as 'modified biochar for heavy metals removal', 'heavy metals adsorption', 'biochar adsorption', and 'heavy metals removal from industrial wastewater' were used in this process.

In the database of Scopus, papers with the topic of "modified biochar" or "modified biochar heavy metals wastewater" were searched on January 1, 2025, and a total of 263 papers were found. The statistical analysis of the publication years of the papers reveals that the number of related papers has increased annually since 2018, with a particularly accelerated growth in the past five years (2019–present), as shown in Figure 1. Therefore, enhancing the removal ability of biochar through modification is currently a prominent research topic.

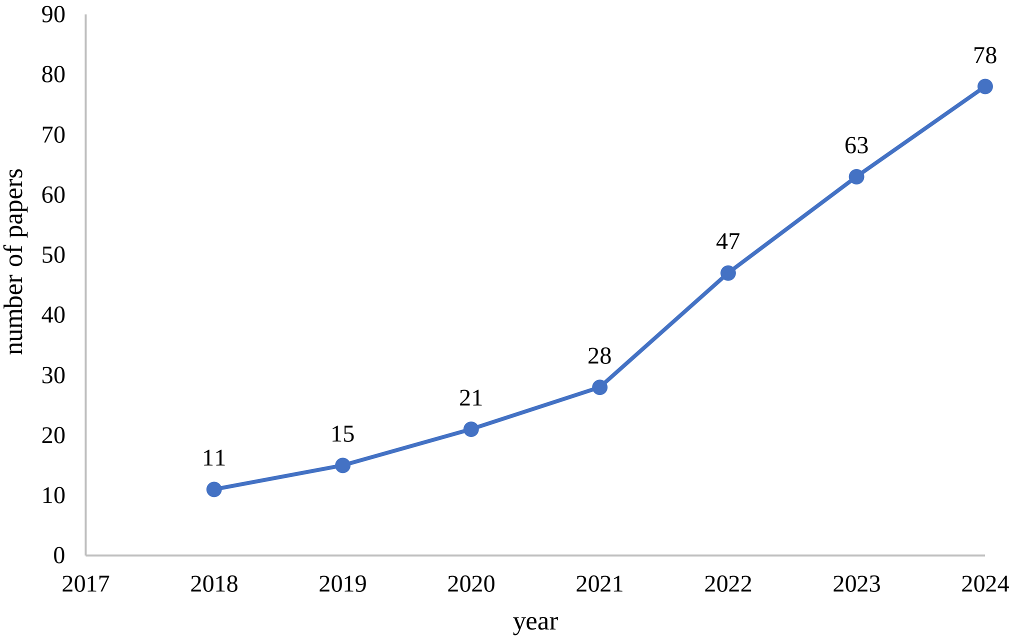


Figure 1. The number of papers with the topic of "modified biochar" or "modified biochar heavy metals wastewater" in 2018–2024

3. BIOCHAR

In the past decade, biochar has been experimented widely in numerous agronomic and environmental problems, due to its strong effect on immobilization of pollutants, enhancement in soil health, and carbon sequestration in relation to climate change and an excellent capability to eliminate heavy metals, organic pollutants, and other pollutants from wastewater [14]. Biochar is a black, carbon-rich, and porous solid material (like charcoal) that can be produced through thermochemical conversion or pyrolysis of biomass with presence of little or no oxygen [15] and at temperatures above 250 °C [16].

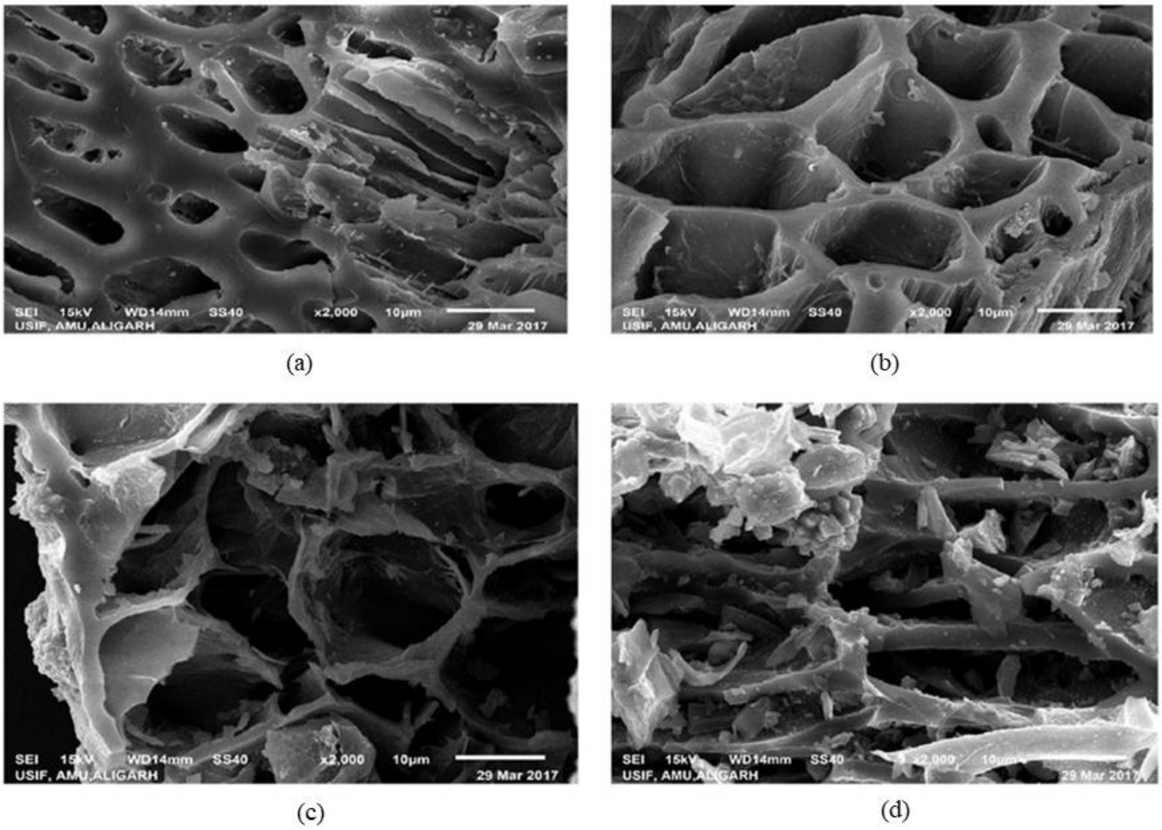
3.1 Properties and Structure of Biochar

Biochar is widely acknowledged as an environmentally efficient adsorbent for the removal of heavy metals in wastewater [8]. Biochar-based adsorption is a highly efficient, practical, and diverse method for eliminating heavy metals from the environment [1]. Biochar has been increasingly popular in recent years because of its unique physicochemical properties, including its porosity and surface functioning. Biochar and activated carbon exhibit greater porosity and amorphous carbon content, however they differ in terms of structural characteristics [12]. Table 1 shows the properties of biochar derived from various biomass sources.

Table 1. Properties of biochar derived from various biomass sources

Biomass	Carbon composition (wt %)	Surface area (m^2/g)	Pore size (nm)	Pore volume (cm^3/g)	References
Rice husk	58.00	415.00	-	0.22	[17]
	-	46.80	-	0.033	[18]
	-	117.80	-	0.073	
Rice straw	37.18	3.61	23.81	0.0059	[19]
	-	64.90	2.68	0.040	[20]
Palm shell	64.00	570.80	3.60	0.0260	[21]
Sawdust	-	36.60	-	0.015	[22]
Woody waste	44.60	201.30	2-50	0.600	[23]
cotton straw	-	24.82	9.6122	0.0684	[24]

The production of biochar was influenced by the kind of feedstock, the temperature at which pyrolysis occurred, and the rate at which heating took place [25]. Various raw materials, such as crop residues, wood biomass, animal litter, and solid waste, have produced biochar using slow to intermediate pyrolysis methods. The temperature used for pyrolysis in these tests ranged from 100 to 900 ℃, with heating rates varying from 2.5 to 20 ℃ per minute [25]. The characteristics of biochar are significantly influenced by the pyrolysis temperature. As the pyrolysis temperature increased to 650 °C, a flake-structured pore wall with deformed and irregular characteristics was observed in Figure 2 (d) [26].



(a) (b) (c) (d)

Figure 2. SEM images of biochar at different pyrolysis temperatures (a) PPB/350, (b) PPB/450, (c) PPB/550, and (d) PPB/650 [26]

It appears that pyrolysis is the most advantageous process for turning biomass into charcoal and bio-oil. Furthermore, a higher production of biochar is achieved by lowering the pyrolysis temperatures and extending the residence times. [27]. Gasification, slow pyrolysis, and fast pyrolysis are the thermochemical processes employed in the production of biochar [28]. Table 2 shows the difference types of pyrolysis processes and their product distribution.

Table 2. Pyrolysis processes and product distribution

Process	Temperature (°C)	Residence time	Product (%)	References
Fast pyrolysis	300 - 1000	Short (< 2 s)	75% bio-oil	[25]
	425 - 550		12% biochar	[28]
			13% syngas	
Slow pyrolysis	100 - 1000	Long (5 – 30 min)	30% bio-oil	[25]
			35% biochar	
			35% syngas	
	350 - 800	Long (minutes to days)	30% bio-oil	[28]
			30% biochar	
			35% syngas	
Gasification	> 800	Moderate (10 – 20 s)	5% bio-oil	[25]
			10% biochar	
			85% syngas	
		Second to hours	5% tar	[28]
			10% biochar	
			85% syngas	

4. MODIFICATION TECHNIQUES FOR BIOCHAR

The objective of biochar modification is to enhance the quality of raw biochar to optimize its effectiveness in eliminating pollutants at higher concentrations [29]. Modifying biochar is essential for enhancing its adsorption capacity, activation capacity, and overall physical and chemical properties [10]. Typically, biochar can be modified by two methods. The first method involves impregnating the prepared biochar with chemicals or co-precipitating it with metals. The second method involves mixing biomass raw materials with modification reagents and then preparing them through high-temperature pyrolysis [30]. The modification methods of biochar include physical, chemical and integration of nanomagnetic materials with biochar.

4.1 Physical Modifications

Physical activation of biochar involves placing it to elevated temperatures in an oxygen-free environment [31]. Physical activation typically consists of two key processes: carbonization and activation. Carbonization takes place at a comparatively low temperature range of 427 to 877 °C, while the subsequent step, activation, occurs at elevated temperatures between 627 and 927 °C [32]. The activation of biochar is achieved using steam or gas purging, typically utilized to enhance the properties of pre-carbonized biochar. Generally, physical activation or modification techniques tend to be more straightforward and cost-effective, however they are less effective compared to chemical activation approaches. Physical activation enhances the physicochemical features of biochar by eliminating by-products of incomplete combustion and oxidizing the carbon surface to increase the surface area of the biochar [32]-[34].

4.2 Chemical Modifications

The chemical activation of biochar involves the treatment of biochar with activating chemicals, such acids, bases, or salts. This procedure changes the surface chemistry of biochar, enhancing its porosity and increasing its adsorption capacity [31][35]. Acids that are commonly used involve hydrochloric acid (HCl), sulfuric acid (H_2SO_4), nitric acid (HNO_3), phosphoric acid (H_3PO_4), oxalic acid ($C_2H_2O_4$), and citric acid ($C_6H_8O_7$) [36]. Potassium hydroxide (KOH) and sodium hydroxide (NaOH) are frequently used reagents for alkali-modified biochar [37]. Activating agents interact with biochar, resulting in the formation of functional groups and the expansion of additional pores. Chemical activation methods enhance the surface area, pore volume, and reactivity of biochar, making it suitable for applications including water treatment, soil amendment, and energy storage [35].

4.3 Integration of Nanomagnetic Materials with Biochar

The recovery of biochar from aqueous solutions poses a challenge due to its smaller particle size. Therefore, biochar modification involves processing biochar to enhance its qualities [37]. Physical modifications enhance biochar surface area, porosity, and shape, whereas chemical modifications enhance adsorptive ability by adding functional groups. Selection of modification method depends on desired qualities and application. Many strategies have been explored to improve the adsorption efficiency of biochar by adding various modifiers [1]. According to the research study by Zubair et al. (2022), biochar that has been modified with steel dust composite showed a remarkable phosphate removal percentage of about 87.8 % [16]. The results of this study suggest that the synthesized magnetic biochar-steel dust composites have significant potential for efficiently treating phosphate in real wastewater samples.

There is a need for new technologies or adsorbents that have greater abatement efficiency, lower costs, and simple recovery processes [38]. The pyrolysis temperature significantly affected the adsorption capacity of biochar. In addition to pyrolysis temperature, other variables such as pyrolysis time can change the physicochemical properties of biochar, which in turn affects its adsorption capacity [27]. Thus, one of the primary research interests in the use of biochar-based nanocomposites for wastewater decontamination has been the removal of heavy metals. The benefits of biochar and the qualities of functional nanoparticles can also be combined by impregnating raw biochar with functional nanoparticles after pyrolysis to create biochar-based composites [39]. Magnetic biochar is a composite material that incorporates transition metals (such as Fe, Co, and Ni) or their oxides into biochar matrices. Both biochar and magnetic biochar have shown excellent efficiency in environmental remediation applications [38]. Table 3 shows the finding from other researchers that used the magnetic biochar to remove metal pollutions.

Table 3. Magnetic biochar study to remove metal pollutions

Feedstock material	Preparation method	Target pollutant	Removal efficiency (%) or adsorption capacity (mg/g)	References
Commercial wood-activated carbon	chemical co-precipitation method	Cr (VI)	88.8%	[40]
Iron-enriched sewage sludge (SS)	pyrolyzing sewage sludge (300, 500, 700, and 900 °C)	Cr (VI)	43.7%	[41]
Fir wood	chemical precipitation	Pb (II)	308 mg/g	[42]
Acacia wood	Slow pyrolysis method	As (III)/ As (V)	294.1176 mg/g	[43]
Rape straw powder	pyrolyzing at different temperatures, then magnetizing activated carbon by hydrothermal method	Pb (II) and Cd (II)	Pb (II) (253.2 mg/g) and Cd (II) (73.3 mg/g)	[44]
Corn straw	one-step synthesis at different ferric nitrate ratios and different calcination temperatures	Cd (II)	46.90 mg/g	[45]
Macadamia nutshell	solvent-free pyrolysis and pretreated with $FeCl_3$-assisted mechanochemical activation	Cu (II) and Pb (II)	Cu (II) (339.78 mg/g) and Pb (II) (200.44 mg/g)	[46]
Lychee peels	Wet impregnation method	NO^{3-} and PO_4^{3-}	NO^{3-} (60.3 mg/g) and PO_4^3 (57.4 mg/g)	[47]
Tea wastes	modifications via thermal and chemical treatments	As	714 mg/g	[48]
Prosopis farcta	Co-precipitation method with incorporating chitosan (CS)	Pb (II)	89.54 %	[49]

An external magnetic field can be used to easily separate the magnetic biochar particles from the aqueous solution. Furthermore, the unique properties of magnetic biochar materials offer many opportunities to overcome the current obstacles in the adsorption process [50]. According to Rajendran et al. (2022), the adsorption of magnetite was enhanced when using commercial iron oxide nanoparticles (Fe_3O_4 MNPs) [4]. These nanoparticles effectively removed Cu, Pb, Mn, and Zn particulate matter. The highest removal efficiency was detected for Mn (II) using Fe_3O_4 nanoparticles. The synthesis and derivatives of magnetic modified biochar and the mechanism for removing heavy metals are presented in Figure 3 [4].

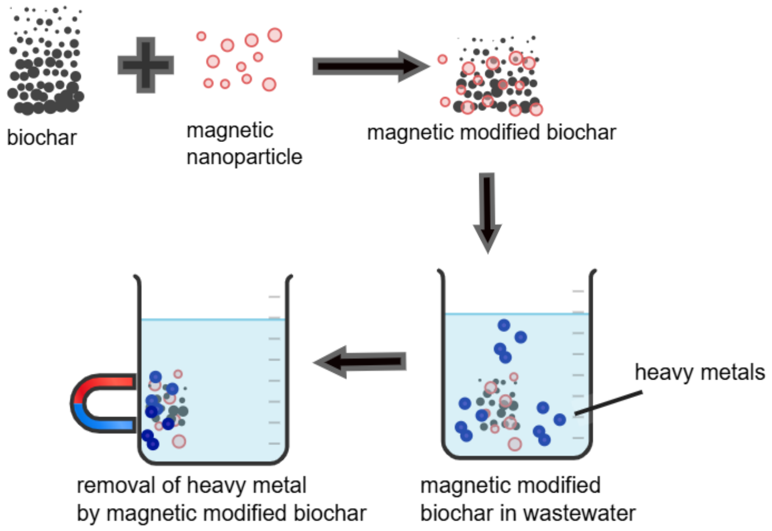


Figure 3. Removal of heavy metals using magnetic modified biochar [4]

The co-precipitation method for biochar preparation incorporates the suspension of biochar powder in transition metal solutions [9]. For example, ammonium hydroxide and sodium hydroxide are added at a precise temperature, continuously stirring up for a certain period at a pH of 9–11. In this process, the residue is washed, which synthesizes magnetic biochar. Although the co-precipitation method is more complicated than the impregnation pyrolysis approach for biochar synthesis, it is more appropriate and controllable [51]. The adsorption capacity for synthesized magnetic biochar by co-precipitation had seven-fold greater strength than impregnation pyrolysis [52]. The superior magnetic properties of Fe-based materials can be attributed to their significant role in the fabrication of metal-modified biochar adsorbents. This indicates the excellent effect of Fe-based modifiers on modifying biochar [53]. The preparation of biochar-magnetite composites via the precipitation method can be illustrated through the formation mechanism of magnetite as described in Equation (1) [54].

$$Fe^{2+} + 2Fe^{3+} + 8OH^{-} \rightarrow Fe_3O_4 + 4H_2O \tag{1}$$

5. ENHANCED ADSORPTION MECHANISMS

To enhance the utilization of biochar, further modifications are required to effectively improve its remediation capabilities [55]. Adsorption is an economical method for the removal of heavy metals from industrial or mining wastewater. Adsorption is defined as the accumulation of an ion or molecule on the surface of another solid or liquid. The adsorbate refers to the substance that is adsorbed onto the adsorbent, which is the material facilitating the adsorption process [7]. Biochar modification may enhance the adsorption capacity of biochar for heavy metals by increasing the number of functional groups on its surface, as well as increasing the specific surface area and pore capacity of the biochar [30].

5.1 Influence of Surface Area, Pore Structure and functional groups

Specific surface area (SSA) is an important characteristic of biochar, as it offers an active surface for interaction with target chemical species. Consequently, SSA significantly affects the sorption and catalytic capabilities of biochar, along with the kinetics of reactions [56]. Surface structure modification focuses on altering the pore structure of biochar to enhance its specific surface area, thus improving its adsorption capacity [30]. KOH activation is frequently used to produce activated biochar characterized by significant porosity and a large BET specific surface area of up to 2000 m^2/g (Equation (2)); however, this preparation method results in higher chemical consumption, increased costs, and raised environmental concerns [57].

$$6KOH + 2C \rightarrow 2K + 3H_2 + 2K_2CO_3 \tag{2}$$

The activated biochar modified by H_3PO_4 exhibited microporous properties [58] and the activation of biochar using HNO_3 can improve the presence of carbon and oxygen-containing surface groups through oxidation, while preserving its physical morphology [59]. Surface chemical modification involves altering the functional groups present on the surface of biochar to enhance the amount of adsorption sites and improve the overall adsorption efficiency [30].

Despite the extensive research on the adsorption of heavy metals from water using various adsorbents, limited attention has been given to remove heavy metals from water using activated biochar combined with nanomagnetic materials derived from agricultural waste. In a recent study conducted by Sharma et al [60], rice straw biomass was successfully converted into biochar and activated magnetic biochar, which has a significant potential for wastewater treatment because activation and magnetization are carried out simultaneously. The results showed that adsorption capacity using activated nanomagnetic biochar was 130 µg/g compared to raw nanobiochar which is 38.67 µg/g, respectively. The chemical activation of biochar primarily results in modifications to its oxygen-related functional groups, particularly carbonyl (C=O), hydroxyl (–OH), and carboxyl (–COOH). Functional groups significantly enhance the catalytic and adsorption properties of biochar [60]. The incorporation of oxygen-containing functional groups onto the surface of biochar increases its water affinity and enhances its efficacy in liquid-phase applications.

The above finding is consistent with the study by Yin et al. [20]. According to Yin et al. [20], they synthesized rice straw into activated magnetic biochar (AMBCs) via a one-step synthetic method in which $ZnCl_2$ and $FeCl_3$ were used as double modifiers [20]. AMBCs had larger surface area, higher pore volume and more contained-oxygen functional groups (such as -COOH, C-OH, C=O) compared to pristine biochar. Additionally, it was found that the adsorption capacity for Cu (II) was higher in a single-solute system. In this system, Cu (II) primarily underwent adsorption through chemical complexation between the oxygen functional groups present and Cu (II). The results demonstrate the positive impact of Fe-based modifiers on the adsorption efficiency of heavy metals. Figure 4 shows the FTIR results of AMBCs compare with raw biochar (RBC) and magnetized biochar (MBC).

Furthermore, Tan et al. [62] also reports that the addition of magnetic compartments (Fe^{2+}/Fe^{3+}) to rice straw before pyrolysis produced hematite (γ-Fe_2O_3), but the biochar's original OH, COOH, C = O, C = C, and C–O–C functional groups were retained, which improved cadmium adsorption [62]. The formation of γ-Fe_2O_3 during the pyrolysis process can also play a role in the adsorption of heavy metals. The magnetic biochar demonstrated a significant level of efficacy in removing Cd (II), with removal rates reaching as high as 91 %. This rate is much higher than that of the pristine biochar [63]. The novelty of this research is due to the biomass is converted into activated nanomagnetic biochar through a simultaneous process of activation and magnetization. This approach provides notable benefits such as increased porosity, a large specific surface area, and the presence of various functional groups. These advantages not only enhance the adsorption capabilities but also result in reduced production costs and a simplified production process [60].

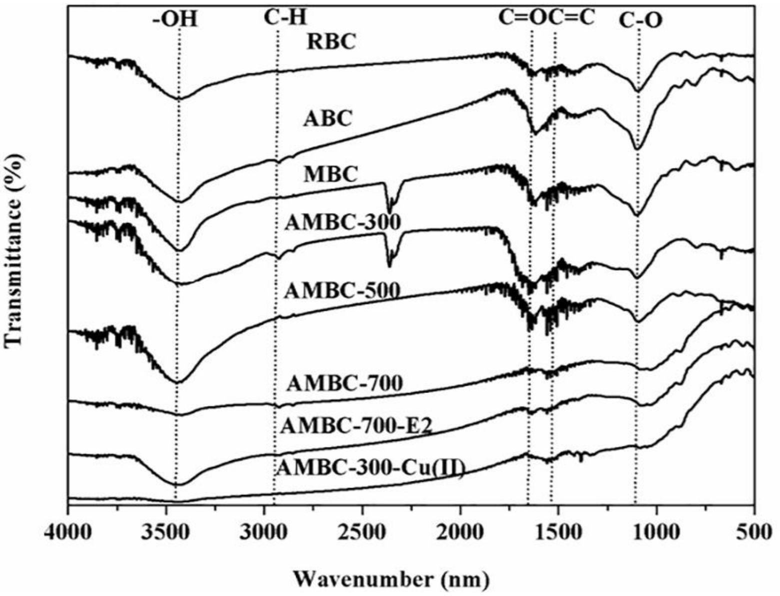


Figure 4. FTIR spectra between RBC, MBC and AMBC [20]

5.2 Adsorption Isotherms and Kinetics Models

Adsorption isotherms can describe the mechanisms of interaction between the adsorbent surface and heavy metal ions [7]. The interaction between contaminants and adsorbents is investigated using adsorption isotherms. The phenomenon of influencing the distribution, retention, or mobility of the adsorbate from the liquid or gaseous medium to the adsorbent under constant pH and temperature conditions is described by the adsorption isotherms [64]. The analysis of isotherms is a crucial adsorption model used to assess the interaction between an adsorbate and an adsorbent. It allows for the analysis of the sorption process and the determination of the adsorption capacity of the adsorbent [65]. Table 4 shows the isotherm models' equations that will be related in adsorption study which is either linear or non-linear models.

Table 4. Isotherm model equations

Isotherm model	Equation	Parameter	Reference
Non-liner models			
Langmuir	$q_e = \frac{Q^0_{max}K_LC_e}{1+C_e}$	Q^0_{max}: Langmuir maximum adsorption capacity (mg/g)	[9][47][66][67]
		C_e: equilibrium solution concentration (mg/L) of the adsorbate	
	$R_L = \frac{1}{1+K_LC_1}$	q_e: amount of adsorbate removed at equilibrium (mg/g)	
Freundlich	$q_e = K_FC_e^{1/n}$	K_L: constant related to the affinity between the adsorbates and biochar (L/mg)	
		R_L: shows isotherm that is unfavorable ($R_L > 1$), favorable ($0 < R_L < 1$), linear ($R_L = 1$), or irreversible ($R_L = 0$)	
		K_F: Freundlich constant (mg/g)/(mg/L)n	
		n: the Freundlich constant	
Linear models			
Langmuir	$\frac{1}{q_e} = \frac{1}{Q^0_{max}K_L}\frac{1}{C_e} + \frac{1}{Q^0_{max}}$	Q^0_{max}: Langmuir maximum adsorption capacity (mg/g)	[9][66][67]
		K_F: Freundlich constant (mg/g)/(mg/L)n	
Freundlich	$\log q_e = \log K_F + \frac{1}{n}\log C_e$	n: the Freundlich constant	
Temkin	$q_e = \frac{RT}{b_T}(K_TC_e)$	K_T: Temkin isotherm equilibrium binding constant (J/mol)	
		b_T: Temkin isotherm constant	
		R: universal gas constant (J/mol.K)	
		T: Temperature (K)	

The kinetics of adsorption is essential for assessing the efficiency of an adsorbent [7]. The efficiency of the adsorbent cycle is determined by the kinetics of adsorption [68]. The kinetic analysis of the sorption experiment is critical and deserving of attention to categorize the sorption rate, reaction pathway, effectiveness of the sorbent, and reaction rate of the system [65]. Table 5 shows the kinetic models' equations that were related in adsorption study.

Table 5. Kinetic models equations

Kinetic model	Equation	Parameter	Reference
Pseudo 1st order	$q_t = q_e(1 - e^{-k_1 t})$	q_t = adsorption capacities of the adsorbent at equilibrium (mg/g)	[47][48][66][67]
Pseudo 2nd order	$q_t = \frac{k_2 q_e^2 t}{1 + k_2 q_e^2 t}$	q_e = adsorption capacities of the adsorbent at a certain time (mg/g)	
		k_1 = pseudo-first order adsorption rate constant (1/min)	
		k_2 = pseudo-second order adsorption rate constant (g/mg.min)	

6. FUTURE DIRECTIONS AND RESEARCH OPPORTUNITIES

Toxic heavy metals frequently occur in industrial wastewater; however, the adsorption process demonstrates potential for effectively removing these metals from water supplies at a low cost, utilizing readily available adsorbents. Heavy metal pollution resulting from various industrial processes is a significant contemporary issue. Abundant and efficient adsorbents are available in nature, as waste materials, or as by-products. The adsorbents exhibit favorable properties, including a high removal efficiency, increased adsorbent capacity, and excellent regeneration characteristics [7]. The utilization of biochar presents both economic and environmental advantages [31].

Future research may explore dimensions such as the high-efficiency preparation methods of composites. Recent research has demonstrated the viability of producing biochar and iron composites with outstanding characteristics. The current challenge involves advancing technological innovation to improve preparation efficiency and decrease costs to satisfy the requirements of large-scale applications [69]. Future research may lower preparation costs by integrating strategies for the resource utilization of mine waste, agricultural waste, and forestry solid waste, while also designing a large-scale and stable production process.

Biochar generated through pyrolysis exhibits inadequate surface functional groups and porosity; thus, a functionalization process is essential prior to its application as a robust functional solid in practical scenarios [12]. Biochar is a significant material for the development of various functional substances due to its ability to modify surface functionality and porosity. The porosity and surface area of biochar can be enhanced through various physicochemical methods that influence pore size distribution, thereby expanding the range of potential applications, including catalysis, bio composites, energy storage devices, nanotubes, supercapacitors, and environmental protection [31][69].

Furthermore, modified biochar has demonstrated a clear potential for the removal of pollutants from industrial wastewater. Recent studies by Xiao et al. [24] utilized alkaline-pretreated H_3PO_4-modified cotton straw biochar (PCS) to assess its effects on actual water samples and industrial wastewater, thereby validating the influence of the water matrices. Experiments were conducted using tap water, river water from the Liangxi River, lake water from Taihu Lake, and industrial wastewater from a steel plant. The findings indicated that the adsorption capacity for Cr (VI) in industrial wastewater attained 59.52 mg/g. The results indicate that the PCS maintained consistent Cr (VI) remediation efficacy across various environmental media, suggesting its potential for practical application [24].

7. CONCLUSION

In summary, the modification of biochar presents potential as effective materials for environmental remediation. Physical and chemical modifications of biochar result in enhanced properties, including improved surface functional groups and increased surface area. Furthermore, chemically activated biochar exhibits increased porosity and heightened chemical activity. The magnetic separation method has been shown in several studies to be a viable technique for solid-liquid phase separation. Consequently, extensive research is required to develop magnetic biochar with superior adsorption capacity. Heavy metal ions frequently coexist in wastewater, leading to competition for adsorption sites. Research on the competitive adsorption of heavy metal ions from contaminated water utilizing modified biochar is limited. Additional competitive sorption studies are required to precisely assess the metal sorption capacity of biochar in natural environments. The comprehensive implementation of biochar-based adsorbents as economical materials is recommended to enhance understanding of critical factors related to their reuse, large-scale production, pollutant/resource recycling, and the management of spent biochar.

ACKNOWLEDGEMENTS

The authors would like to acknowledge with gratitude the financial support from Ministry of Higher Education, Malaysia, under the Skim Latihan Akademik Bumiputera (SLAB).

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHORS CONTRIBUTION

W. N. A. A Manan (Conceptualization; Formal analysis; Visualisation; Writing - original draft; Resources)

A. H. Zamani (Writing – review and editing)

REFERENCES

[1] K. H. H. Aziz and R. Kareem, “Recent advances in water remediation from toxic heavy metals using biochar as a green and efficient adsorbent: A review,” *Case Studies in Chemical and Environmental Engineering*, vol. 8, pp. 100495, 2023.

[2] N. Asghar, A. Hussain, D. A. Nguyen, S. Ali, I. Hussain, A. Junejo, et al., “Advancement in nanomaterials for environmental pollutants remediation: a systematic review on bibliometrics analysis, material types, synthesis pathways, and related mechanisms,” *Journal of Nanobiotechnology*, vol. 22, no. 26, pp. 1-28, 2024.

[3] P. Sharma, S. Sharma, S. K. Sharma, A. Jain and K. Shrivastava, “Review on recent advancement of adsorption potential of sugarcane bagasse biochar in wastewater treatment,” *Chemical Engineering Research and Design*, vol. 206, pp. 428–439, 2024.

[4] S. Rajendran, A.K. Priya, P.S. Kumar, T. K. A. Hoang, K. Sekar, K. Y. Chong, et al., “A critical and recent developments on adsorption technique for removal of heavy metals from wastewater-A review,” *Chemosphere*, vol. 303, p. 135146, 2022.

[5] A. K. Thakur, R. Singh, R. T. Pullela and V. Pundir, “Green adsorbents for the removal of heavy metals from wastewater: a review,” *Materials Today: Proceedings*, vol. 57, pp. 1468–1472, 2022.

[6] S. A. Razzak, M. O. Faruque, Z. Alsheikh, et al., “A comprehensive review on conventional and biological-driven heavy metals removal from industrial wastewater,” *Environmental Advances*, vol. 7, p. 100168, 2022.

[7] N. S. Topare and V. S. Wadgaonkar, “A review on application of low-cost adsorbents for heavy metals removal from wastewater,” *Materials Today: Proceedings*, vol. 77, pp. 8–18, 2023.

[8] D. Xu, X. Ni, J. Kang, B. He, Y. Zuo, A. A. Mosa, et al., “Mechanisms of cadmium adsorption by ramie nano-biochar with different aged treatments,” *Applied Soil Energy*, vol. 193, p. 105175, 2024.

[9] R. Sinha, R. Kumar, K. Abhishek, J. Shang, S. Bhattacharya, S. Sengupta, et al., “Single-step synthesis of activated magnetic biochar derived from rice husk for hexavalent chromium adsorption: Equilibrium mechanism, kinetics, and thermodynamics analysis,” *Groundwater for Sustainable Development*, vol. 18, p. 100796, 2022.

[10] B. Qiu, Q. Shao, J. Shi, C. Yang and H. Chu, “Application of biochar for the adsorption of organic pollutants from wastewater: modification strategies, mechanisms and challenges,” *Separation and Purification Technology*, vol. 300, p. 121925, 2022.

[11] G. Kwon, A. Bhatnagar, H. Wang, E. E. Kwon and H. Song, “A review of recent advancements in utilization of biomass and industrial wastes into engineered biochar,” *Journal of Hazardous Materials*, vol. 400, p. 123242, 2020.

[12] R. K. Mishra and K. Mohanty, “A review of the next-generation biochar production from waste biomass for material applications,” *Science of the Total Environment*, vol. 904, p. 167171, 2023.

[13] A. Zhang, X. Li, J. Xing and G. Xu, “Adsorption of potentially toxic elements in water by modified biochar: A review,” Journal of Environmental Chemical Engineering, vol. 8, p. 104196, 2020.

[14] M. Vithanage, I. Herath, S. Joseph, J. Bundschuh, N. Bolan, Y. S. Ok, et al., “Interaction of arsenic with biochar in soil and water: A critical review,” *Carbon*, vol. 113, pp. 219 – 230, 2017.

[15] Y. Xie, L. Wang, H. Li, L. J. Westholm, L. Carvalho, E. Thorin, et al., “A critical review on production, modification and utilization of biochar,” *Journal of Analytical and Applied Pyrolysis*, vol. 161, p. 105405, 2022.

[16] M. Zubair, M. S. Manzar, M. A. Suleiman, M. A. Suleiman, D. P. Fernandes, L. Meili, et al. “Production of magnetic biochar-steel dust composites for enhanced phosphate adsorption,” *Journal of Water Process Engineering*, vol. 47, p. 102793, 2022.

[17] D. Dias, M. Bernardo, I. Matos, I. Fonseca, F. Pinto and N. Lapa “Activation of co-pyrolysis chars from rice wastes to improve the removal of Cr^{3+} from simulated and real industrial wastewaters,” *Journal of Cleaner Production*, vol. 267, p. 121993, 2020.

[18] A. Gopinath, G. Divyapriya, V. Srivastava, A. R. Laiju, P. V. Nidheesh and M. S. Kumar, “Conversion of sewage sludge into biochar: A potential resource in water and wastewater treatment,” *Environmental Research*, vol. 194, p. 110656, 2021.

[19] A. K. Sakhiya, P. Baghel, A. Anand, V. K. Vijay and P. Kaushal, “A comparative study of physical and chemical activation of rice straw derived biochar to enhance Zn^{2+} adsorption,” *Bioresource Technology Reports*, vol. 15, p. 100774, 2021.

[20] Z. Yin, Y. Liu, S. Liu, L. Jiang, X. Tan, G. Zeng, et al. “Activated magnetic biochar by one-step synthesis: enhanced adsorption and coadsorption for 17β-estradiol and copper,” Science of the Total Environment, vol. 639, pp. 1530–1542, 2018.

[21] P. N. Y. Yek, R. K. Liew, M. S. Osman, C. L. Lee, J. H. Chuah, Y. K. Park, et al., “Microwave steam activation, an innovative pyrolysis approach to convert waste palm shell into highly microporous activated carbon,” *Journal of Environmental Management*, vol. 236, pp. 245–253, 2019.

[22] D. Lee, J. Lu and J. Chang, “Pyrolysis synergy of municipal solid waste (MSW): A review,” *Bioresource Technology*, vol. 318, p. 123912, 2020.

[23] M. He, Z. Xu, Y. Sun, P. S. Chan, I. Lui, D. C. W. Tsang, “Critical impacts of pyrolysis conditions and activation methods on application-oriented production of wood waste-derived biochar,” *Bioresource Technology*, vol. 341, p. 125811, 2021.

[24] X. Xiao, F. Zhou, C. Yang, L. Lu, Y. Zhao, B. Tu, et al. “Adsorption and reduction of Cr (VI) by C-P-O groups in biochar: Performance and mechanisms,” *Solid State Sciences*, vol. 160, p. 107815, 2025.

[25] M. Ahmad, A. U. Rajapaksha, J. U. Lim, M. Zhang, N. Bolan, D. Mohan, et al., “Biochar as a sorbent for contaminant management in soil and water: A review,” *Chemosphere*, vol. 99, pp. 19–33, 2014.

[26] A. Shakya and T. Agarwal, “Removal of Cr (VI) from water using pineapple peel derived biochars: adsorption potential and re-usability assessment,” *Journal of Molecular Liquids*, vol. 293, p. 111497, 2019.

[27] F. Amalina, A. S. A. Razak, S. Krishnan, A. W. Zularisam and M. Nasrullah, “A comprehensive assessment of the method for producing biochar, its characterization, stability, and potential applications in regenerative economic sustainability – a review,” *Cleaner Materials*, vol. 3, p. 100045, 2022.

[28] M. Inyang and E. Dickenson, “The potential role of biochar in the removal of organic and microbial contaminants from potable and reuse water: A review,” *Chemosphere*, vol. 134, pp. 232–240, 2015.

[29] M. Gupta, N. Savla, C. Pandit, S. Pandit, P. K. Gupta, M. Pant, et al. “Use of biomass-derived biochar in wastewater treatment and power production: a promising solution for a sustainable environment,” *Science of the Total Environment*, vol. 825, p. 153892, 2022.

[30] Y. Wang, H. Li and S. Lin, “Advances in the study of heavy metal adsorption from water and soil by modified biochar,” *Water*, vol. 14, pp. 1-11, 2022.

[31] O. S. Olubenga, P. G. Adeleye, S. B. Oladipupo, A. T. Adeleye and K. I. John, “Biomass-derived biochar in wastewater treatment – a circular economy approach,” *Waste Management Bulletin*, vol. 1, pp. 1-14, 2024.

[32] D. C. C. da Silva Medeiros, C. Nzediegwu, C. Benally, S. A. Messele, J. H. Kwak, M. A. Naeth, et al. “Pristine and engineered biochar for the removal of contaminants co-existing in several types of industrial wastewaters: A critical review,” *Science of the Total Environment*, vol. 809, p. 151120, 2022.

[33] M. B. Ahmed, J. L. Zhou, H. N. Ngo, W. Guo and M. Chen, “Progress in the preparation and application of modified biochar for improved contaminant removal from water and wastewater,” *Bioresource Technology*, vol. 214, pp. 836-851, 2016.

[34] J. S. Cha, S. H. Park, S. Jung, C. Ryu, J. K. Jeon, M. C. Shin, et al. “Production and utilization of biochar: A review,” *Journal of Industrial and Engineering Chemistry*, vol. 40, pp. 1-5, 2016.

[35] B. Sajjadi, T. Zubatiuk, D. Leszczynska, J. Leszczynski, and W. Y. Chen, “Chemical activation of biochar for energy and environmental applications: a comprehensive review,” *Reviews in Chemical Engineering*, vol. 35, no. 7, pp. 777-815, 2019.

[36] N. Zhang, “White tea waste derived magnetic biochar: green synthesis, characterization and mechanistic studies of heavy metal removal in aqueous solution,” Ph.D. dissertation, Civil and Environmental Engineering, University of Auckland, 2023.

[37] K. Zhang, Y. Li and Z. Fang, “Remediation of cadmium or arsenic contaminated water and soil by modified biochar: A review,” *Chemosphere*, vol. 311, p. 136914, 2023.

[38] Y. t. Sun, J. d. Chen, Z. h. Wei, Y. k. Chen, C. l. Shao and J. f. Zhou, "Copper ion removal from aqueous media using banana peel biochar/ Fe_3O_4/ branched polyethyleneimine," *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 658, p. 130736, 2023.

[39] X. Tan, Y. Liu, Y. Gu, Y. Xu, G. Zeng, X. Hu, et al. "Biochar-based nanocomposites for the decontamination of wastewater: a review," *Bioresource Technology*, vol. 212, pp. 318-333, 2016.

[40] Z. Wu, H. Zhang, E. Ali, A. Shahab, H. Huang, H. Ullah, et al. "Synthesis of novel magnetic activated carbon for effective Cr (VI) removal via synergistic adsorption and chemical reduction," *Environmental Technology & Innovation*, vol. 30, p. 103092, 2023.

[41] D. Fu, T. A. Kurniawan, Y. Wang, Z. Zhou, Q. Wei, Y. Hu, et al. "Applicability of magnetic biochar derived from Fe-enriched sewage sludge for chromate removal from aqueous solution," *Chemical Engineering Science*, vol. 281, p. 119145, 2023.

[42] J. Dong, P. Jiang, H. Wang, R. Lu, Y. Liu, Y. Li, et al. "Influence of biomass feedstock on magnetic biochar preparation for efficient Pb (II) removal," *Environmental Technology & Innovation*, vol. 32, p. 103363, 2023.

[43] S. Das and S. Mondal, "Synthesis of magnetic biochar derived from waste wood of *acacia Auriculiformis* for the removal of arsenic," *Environmental Nanotechnology, Monitoring & Management*, vol. 20, p. 100893, 2023.

[44] Z. Zhang, T. Wang, H. Zhang, Y. Liu and B. Xing, "Adsorption of Pb (II) and Cd (II) by magnetic activated carbon and its mechanism," *Science of the Total Environment*, vol. 757, p. 143910, 2021.

[45] Z. H. Khan, M. Gao, W. Qiu, M. S. Islam and Z. Song, "Mechanism for cadmium adsorption by magnetic biochar composites in an aqueous solution," *Chemosphere*, vol. 246, p. 125701, 2020.

[46] J. Zhou, Y. He, L. Huang, A. Xu, Y. Zhao, J. Wang, et al., "Preparation of magnetic biochar from macadamia nutshell pretreated by FeCl3-assisted mechanochemical activation for adsorption of heavy metals," *Journal of Environmental Chemical Engineering*, vol. 12, p. 113122, 2024.

[47] M. T. Le, X. H. Nguyen, T. P. Nguyen and D. X. Cuong, "Lychee peels-derived biochar-supported CaFe2O2 magnetic nanocomposite as an excellent for effective removal of nitrate and phosphate from wastewater," *Journal of Environmental Chemical Engineering*, vol. 11, p. 110991, 2023.

[48] M. McGeogh, H. Annath and C. Manwandi, "Turning teawaste particles into magnetic bio-sorbents particles for arsenic removal from wastewater: isotherm and kinetic studies," *Particuology*, vol. 87, pp. 179-193, 2024.

[49] N. Karami, A. Mohammadpour, M. R. Samaei, A. M. Amani, M. Dehghani, R. S. Varma et al. "Green synthesis of sustainable magnetic nanoparticles Fe_3O_4 and Fe_3O_4-chitosan derived from *Prosopis farcta* biomass extract and their performance in the sorption of lead (II)," *International Journal of Biological Macromolecules*, vol. 254, p. 127663, 2024.

[50] D. H. K. Reddy and S. M. Lee, "Magnetic biochar composite: Facile synthesis, characterization, and application for heavy metal removal," *Colloid and surfaces: A Physicochemical and Engineering Aspects*, vol. 454, pp. 96-103, 2014.

[51] Y. Yi, Z. Huang, B. Lu, J. Xian, E. P. Tsang, W. Cheng, et al. "Magnetic biochar for environmental remediation: A review," *Bioresource Technology*, vol. 298, p. 122468, 2020.

[52] S. Wang, B. Gao, A. R. Zimmerman, Y. Li, L. Ma, W. G. Harris, et al. "Removal of arsenic by magnetic biochar prepared from pinewood and natural hematite," *Bioresource Technology*, vol. 175, pp. 391-395, 2015.

[53] C. Liu and H. X. Zhang, "Modified-biochar adsorbents (MBAs) for heavy metal ions adsorption: a critical review," *Journal of Environmental Chemical Engineering*, vol. 10, p. 107939, 2022.

[54] A. G. Niculescu, C. Chircov and A. M. Grumezescu, "Magnetite nanoparticles: Synthesis methods – a comparative review," *Methods*, vol. 199, pp. 16-27, 2022.

[55] H. Su, Z. Fang, P. E. Tsang, J. Fang and D. Zhao, "Stabilisation of nanoscale zero-valent iron with biochar for enhanced transport and in-situ remediation of hexavalent chromium in soil," *Environmental Pollution*, vol. 214, pp. 94-100, 2016.

[56] X. Yang, Y. Wan, Y. Zheng, F. He, Z. Yu, J. Huang, et al. "Surface functional groups of carbon-based adsorbents and their roles in the removal of heavy metals from aqueous solutions: A critical review," *Chemical Engineering Journal*, vol. 366, pp. 608-621, 2019.

[57] C. Wen, T. Liu, D. Wang, Y. Wang, H. Chen, G. Luo, et al. "Biochar as the effective adsorbent to combustion gaseous pollutants: preparation, activation, functionalization and the adsorption mechanisms," *Progress in Energy and Combustion Science*, vol. 99, p. 101098, 2023.

[58] X. Zhang, B. Gao, J. Fang, W. Zou, L. Dong, C. Cao, et al. "Chemically activated hydrochar as an effective adsorbent for volatile organic compounds (VOC)," *Chemosphere*, vol. 218, pp. 680-686, 2019.

[59] S. A. Opatokun, A. Prabhu, A. A. Shoaibi, C. Srivasakannan and V. Strezov, "Food wastes derived adsorbents for carbon dioxide and benzene gas sorption," *Chemosphere*, vol. 168, pp. 326-332, 2017.

[60] P. K. Sharma, R. K. Singh and R. Kumar, “Adsorptive behavior of Fe/Zn- modified nanobiochar for arsenic removal from naturally contaminated groundwater,” *Groundwater for Sustainable Development*, vol. 23, p. 101011, 2023.

[61] M. Z. Yameen, S. R. Naqvi, D. Juchelková and M. N. A. Khan, “Harnessing the power of functionalized biochar: progress, challenges, and future perspectives in energy, water treatment, and environmental sustainability,” *Biochar*, vol. 6:25, pp. 1-80, 2024.

[62] Z. Tan, Y. Wang, A. Kasiuliene, C. Huang and P. Ai, “Cadmium removal potential by rice straw-derived magnetic biochar,” *Clean Technologies and Environmental Policy*, vol. 19, pp. 761-774, 2017.

[63] M. Kamali, L. Appels, E. E. Kwon, T. M. Aminabhavi and R. Dewil, “Biochar in water and wastewater treatment – a sustainable assessment,” *Chemical Engineering Journal*, vol. 420, p. 129946, 2021.

[64] T. A. Saleh, M. Mustaqeem and M. Khaled, “Water treatment technologies in removing heavy metal ions from wastewater: a review,” *Environmental Nanotechnology, Monitoring & Management*, vol. 17, p. 100617, 2022.

[65] V. S. Munagapati, H. Y. Wen, A. R. K. Gollakota, J. C. Wen, K. Y. A. Lin, C. M. Shu, et al. “Magnetic Fe3O4 nanoparticles loaded guava leaves powder impregnated into calcium alginate hydrogel beads (Fe3O4-GLP@CAB) for efficient removal of methylene blue dye from aqueous environment: synthesis, characterization, and its adsorption performance,” *International Journal of Biological Macromolecules*, vol. 246, p. 125675, 2023.

[66] B. Biswas, T. Rahman, M. Sakhakarmy, H. Jahromi, M. Eisa, J. Baltrusaitis, et al. “Phosphorus adsorption using chemical and metal chloride activated biochars: isotherms, kinetics and mechanism study,” *Heliyon*, vol. 9, p. 19830, 2023.

[67] A. S. El-Shafie, E. Rahman, Y. Gadelhak, R. Mahmoud and M. El-Azazy, “Techno-economic assessment of waste mandarin biochar as a green adsorbent for binary dye wastewater effluents of methylene blue and basic fuchsin: lab and large-scale investigations,” *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, vol. 306, p. 123621, 2024.

[68] A. Anderson, A. Anbarasu, R. R. Pasupuleti, S. Manigandan, T. R. Praveenkumar, J. A. Kumar, “Treatment of heavy metals containing wastewater using biodegradable adsorbents: a review of mechanism and future trends,” *Chemosphere*, vol. 295, p. 133724, 2022.

[69] H. Zhong, Z. Feng, Y. Luo, Y. Zheng, Z. Luo, T. Peng, et al. “When biochar meets iron mineral: an opportunity to achieve enhanced performance in treating toxic metal(loid)s and refractory organics,” *Separation and Purification Technology*, vol. 350, p. 128022, 2024.