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Overcoming heavy metal pollution from nickel mining wastewater in Indonesia using green chemistry activated rice husk biochar for sustainable remediation

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ABSTRACT

As the world's leading nickel producer, Indonesia faces significant environmental challenges, particularly related to mining waste containing heavy metals such as Ni^{2+}, Cu^{2+}, and Zn^{2+}. While conventional chemical methods are often used, they are expensive, hazardous, and unsustainable. Therefore, this study aims to review and synthesize the current knowledge on the utilization of rice husk biochar, activated with green chemistry principles, as an effective and sustainable remediation solution. This approach was chosen because rice husk biochar is an abundant and inexpensive biomass in Indonesia, with high porosity and functional groups efficient in heavy metal adsorption. The findings indicate that rice husk biochar activated using green chemistry methods (e.g., citric acid, $FeSO_4$, or KOH) exhibits high adsorption capacity, with some studies reporting capacities up to 384.62 mg/g for Pb(II) and removal efficiency for Cu^{2+} up to 96.02%. Furthermore, the biochar shows good stability with metal release rates of less than 1% and can be regenerated for up to 4–5 cycles, recovering 60–85% of its initial capacity. Nevertheless, this review identifies several significant limitations, such as the lack of studies on real mining waste application, long-term regeneration testing, and metal recovery from saturated biochar, all of which are crucial for circular economy implementation. This work has high originality and significance as it specifically highlights biochar from rice husks and emphasizes green chemistry principles. Practically, the use of this biochar offers an environmentally friendly and economical alternative for managing mining waste in Indonesia.

Keywords: biochar, green chemistry activation, heavy metal adsorption, nickel mining waste.

INTRODUCTION

With 256 active mining firms and an output of around 72 million tons, or 52% of the world's total nickel reserves, Indonesia is the world's largest producer of nickel. Prospecting, research, mining, processing, and marketing are all part of the mining industry (Larang et al., 2024). Open-pit mining techniques such as top soil, contour mining, overburden, and saprolite ore are used in the nickel mining process (Angelita et al., 2020). Because of the toxic acid mine drainage created by this open-pit mining, the surrounding soil becomes contaminated, which affects soil fertility, particularly on post-mining areas (Agussalim et al. 2023; Drakel et al. 2021; Mangolo et al. 2021).

The global surge in mining activities – particularly nickel extraction – has led to increasingly severe contamination of aquatic ecosystems by heavy metals such as Ni^{2+}, Cu^{2+}, and Zn^{2+}. In Indonesia, one of the world's top nickel producers, the environmental consequences of untreated or poorly managed nickel mining wastewater are becoming critical, especially in areas vulnerable to acid mine drainage (AMD). Heavy metals released through such wastewater pose long-term ecological risks due to their persistence, bioaccumulation, and toxicity. Biochar, a carbon-rich by-product of biomass pyrolysis, has emerged as a promising material for adsorbing heavy metals from contaminated water and soil because of its high surface area, porosity, and reactive surface functional groups. Numerous reviews have evaluated biochar's effectiveness for metal immobilization, including its use in soil remediation (Chandra et al., 2023), its combination with magnetite or bacteria for enhanced adsorption (Wibowo et al., 2022), and applications involving multi-source biomass (Priyanka et al., 2024). Bibliometric analyses of biochar development across various waste types have also been conducted (Syarifuddin et al., 2024). However, critical gaps remain in the literature. Few studies focus specifically on biochar derived from rice husk, a widely available agricultural waste in Indonesia with significant potential for localized, low-cost wastewater treatment. While some reviews mention chemical modification, they rarely emphasize green chemistry principles in biochar activation, and the environmental impacts of using corrosive and toxic reagents in acid/base modifications are seldom addressed. Additionally, many existing reviews are either soil-focused or broad in scope, lacking specificity on the performance of rice husk biochar in real-world mining wastewater, particularly from Indonesian nickel mining. Studies such as Mariana et al (2021) discuss Indonesian contexts but do not elaborate on integration with sustainable frameworks like circular economy or field-level mining site implementation. Furthermore, the regeneration of biochar and the potential for metal recovery both crucial for sustainable scaling are underexplored in previous reviews. Given these gaps, this article offers a novel and focused review on the use of green chemistry-activated rice husk biochar for sustainable remediation of heavy metals in Indonesian nickel mining wastewater. The objective is to consolidate current knowledge on green activation techniques, examine adsorption mechanisms, evaluate practical performance in mining contexts, and propose future research pathways aligned with environmental and economic sustainability.

RESULTS

Acid mining water formation

Sulfuric acid (H_2SO_4) in AMD has the ability to dissolve metals into their ionic forms, thereby contaminating soil and groundwater (Kanda et al., 2017). This process increases the mobility of toxic elements and contributes to ecological risks (Rose, 2019). Moreover, studies in Indonesian mining areas reported similar impacts on soil and water quality, emphasizing the role of sulfide oxidation in AMD formation (Prasad, 2018; Punia and Singh, 2021; Sulistiyohadi et al., 2020) The presence of FeS and FeS_2 sulfide minerals, which are oxidized by the oxidizers H_2O, O_2 and CO_2 with the aid of a bacterial catalyst called *Thiobacillus ferroxidans*, results in acid mine drainage, (Suryadi, 2020). The chemical reaction that leads to the development of acid mine drainage is illustrated in Figure 1.

Because of the heavy metals and acidic pH generated by acid mine drainage, ecosystems in mining areas are significantly degraded (Datta et al., 2024; Mukherjee et al., 2024). This condition also reduces groundwater quality (Ganvir and Guhey, 2020) and decreases soil productivity due to toxic element accumulation (Pan et al., 2022; Zheng et al., 2024). Moreover, several studies confirm that heavy metal contamination from mining continues to cause long-term environmental risks (Dashdondog et al., 2022; Donald et al., 2022; Li et al., 2022)

Acid mine water's effect on nickel mining lands

Due to the presence of acid mine drainage, which dissolves metals in the form of ions, nickel mining activities commonly release heavy metals such as Cr, As, Cd, Cu, Pb, Hg, Fe, Ni, Zn, Ag, and Co (Godirilwe et al., 2024). The acidic conditions of these effluents, typically with a pH range of 5.2–6.8, differ from the normal pH of 6–9 (Saidy et al., 2024). Several studies have also reported variations in heavy metal concentrations and pH in nickel mining environments (Capilitan et al., 2023; Sugiono et al., 2024). The breakdown of organic materials into nutrients is inhibited in mining areas due to the high mortality of soil microorganisms. This condition is reflected in the low biological content and the limited availability of essential nutrients such as Ca, Na, and Mg, along with macronutrients

$$
\begin{aligned}
2FeS_2 + 7O_2 + 2H_2O &\longrightarrow 2Fe^{2+} + 4SO_4^{2-} + 4H^+ \\
4Fe^{2+} + O_2 + 2H^+ &\longrightarrow 4Fe^{3+} + 2H_2O \\
2FeS_2 + 14Fe^{3+} + 8H_2O &\longrightarrow 16Fe^{2+} + 2SO_4^{2-} + 16H^+ \\
Fe^{3+} + 2H_2O &\longrightarrow Fe(OH)_3S + 3H^+ \\
\hline
4FeS_2 + 15O_2 + 14H_2O &\longrightarrow 4Fe^{2+}(OH) + 8H_2SO_4
\end{aligned}
$$

Figure 1. Acid mine drainage response

including C, N, P, and K, which in turn reduces soil fertility (Bathrobas, 2023; Kertesz and Frossard, 2024; Muhilan et al., 2024). Similar findings were also reported by Fazliddinovna et al. (2024), who emphasized that the decline in microbial activity directly disrupts nutrient cycling processes in post-mining soils.

Acid mine water – chemical management approach

Until now, chemical techniques have been used to regulate acid mine drainage. Table 1 presents an example of how chemical treatments are applied to address acid mine drainage effectively.

Several studies have explored the use of chemical methods to treat acid mine drainage, particularly through neutralization techniques (Nguegang and Ambushe, 2024; Zhao et al., 2024). This method involves adding bases such as NaOH, $Ca(OH)_2$, or $CaCO_3$ to neutralize pH and precipitate heavy metals including Ni, Cu, Zn, Fe, Pb, and Al (Castro Huaman et al., 2023; Mothetha et al., 2023; Tong et al., 2021).

Figure 2 illustrates the general shortcoming of chemical procedures, which is the easy degradation of salts that precipitate because of the presence of water. In addition, the expenses associated with employing chemical treatments to remediate acid mine drainage are high, which leads to the method's abandonment. Table 2 shows the heavy metal deposition process utilizing bases.

In an effort to mitigate heavy metal pollution in acid mine drainage (AMD) systems, biomaterial-based approaches are receiving increasing attention. One prominent material is biochar, a pyrolysis product of biomass such as rice husks, which offers an efficient and sustainable solution for heavy metal adsorption. Biochar has a high specific surface area, micro-macro porosity, and contains various active functional groups such as carboxylate (-COOH) and hydroxyl (-OH) that play an important role in the complexation, precipitation, and ion exchange processes of heavy metal ions such as Ni^{2+}, Cu^{2+}, and Zn^{2+} (Katiyar et al., 2023; Zhang, 2021). In contrast to conventional chemical methods that generally produce hazardous sludge residues, the use of biochar in AMD remediation can reduce the production of secondary wastes and improve the efficiency of environmental restoration. This makes biochar a more environmentally friendly and economical technology in the long run (Labianca et al., 2023; Zhang et al., 2023). Furthermore, biochar activation processes, either through physical (e.g. increasing pyrolysis temperature) or chemical (e.g. impregnation with acids or bases) treatments, have been shown to significantly increase the adsorption capacity (Chatterjee et al., 2020; C. Zhao et al., 2023).

Overall, the application of biochar in the context of AMD not only simplifies the remediation process, but also opens up opportunities for integration with other ecological approaches to form a more holistic and sustainable environmental restoration strategy (Chandola & Rana, 2023; Masud et al., 2023).

Utilization of rice husk biochar – green chemistry approach

Introduction of biochar from rice husk

Indonesia as one of the largest rice producers in the world, faces major challenges in agricultural waste management, particularly rice husks (Matin et al., 2023; Swastika et al., 2024). Each year, rice production generates millions of tons of husks that are often burned or left to accumulate, creating air and environmental pollution problems (Cardoso et al., 2024; Kordi et al., 2024). However, behind this challenge lies great potential. Rice husk is an abundant, cheap and readily available lignocellulosic biomass throughout Indonesia (Chavan et al. 2024; Salim et al. 2017; Singh et al. 2024). Its utilization as a feedstock has significant added value, not only reducing waste stockpiles but also converting it into valuable materials that can contribute to environmental solutions (Kalak, 2023).

Table 1. Acid mine drainage treated chemically

No.	Method	Material	Chemical composition	Capacity	Reference
1.	Neutralization	Lime and alum	$CaCO_3$	pH stability, reduction of BOD, COD, TSS and Fe metal	(Nadya Irawan et al. 2016)
2.	Neutralization	Lime	$CaCO_3$	pH stability	(E. I. Sari, Tono, and Guskarnali 2018)
3.	Neutralization	Lime	$CaCO_3$	pH stability	(Sumarjono 2020)
4.	Neutralization	Base	$Ca(OH)_2$	pH stability, decrease in TSS and Cu metal	(Arifin, Jadid, and Widiono 2023)
5.	Neutralization	*Fly Ash*	CaO	pH Stability and Reduction of Fe and Mn metals	(Yunita, Widayati, and Usman 2023)

$$H_2SO_{4(l)} + 2NaOH_{(s)} \rightleftharpoons Na_2SO_{4(s)} + 2H_2O_{(l)}$$
$$H_2SO_{4(l)} + Ca(OH)_{2(s)} \rightleftharpoons CaSO_{4(s)} + 2H_2O_{(l)}$$
$$H_2SO_{4(l)} + CaCO_{3(s)} \rightleftharpoons CaSO_{4(s)} + 2H_2CO_{3(s)}$$
$$NiSO_{4(l)} + 2NaOH_{(s)} \rightleftharpoons Na_2SO_{4(s)} + Ni(OH)_{(2)(s)}$$
$$NiSO_{4(l)} + Ca(OH)_{2(s)} \rightleftharpoons CaSO_{4(s)} + Ni(OH)_{(2)(s)}$$
$$NiSO_{4(l)} + CaCO_{3(s)} \rightleftharpoons CaSO_{4(s)} + NiCO_{3(s)}$$
$$\longrightarrow \text{pH of Stability}$$

Figure 2. Basic idea behind chemical approaches to acid mine drainage management

Table 2. Chemical approaches for acid mine drainage heavy metal removal

No.	NaOH reagent		$Ca(OH)_2$ reagent		$CaCO_3$ reagent	
	Substrate	Results	Substrate	Results	Substrate	Results
1.	$Fe_2(SO_4)_3$	$Fe_2(OH)_3$	$Fe_2(SO_4)_3$	$Fe_2(OH)_3$	$Fe_2(SO_4)_3$	$Fe_2(CO_3)_3$
2.	$Fe(SO_4)_2$	$Fe(OH)_2$	$Fe(SO_4)_2$	$Fe(OH)_2$	$Fe(SO_4)_2$	$Fe(CO_3)_2$
3.	$CuSO_4$	$Cu(OH)_2$	$CuSO_4$	$Cu(OH)_2$	$CuSO_4$	$CuCO_3$
4.	$ZnSO_4$	$Zn(OH)_2$	$ZnSO_4$	$Zn(OH)_2$	$ZnSO_4$	$ZnCO_3$
5.	$PbSO_4$	$Pb(OH)_2$	$PbSO_4$	$Pb(OH)_2$	$PbSO_4$	$PbCO_3$
6.	$AlSO_4$	$Al(OH)_2$	$AlSO_4$	$Al(OH)_2$	$AlSO_4$	$AlCO_3$

Biochar is a renewable and carbon-rich material made from organic waste such as rice husk, and it offers a sustainable approach to environmental challenges (Jha et al., 2022; Keerthi, 2024). Its high carbon content and stable structure provide long-term benefits, including carbon sequestration (Voruganti, 2023; Woo, 2013). Biochar also has a high cation exchange capacity and a large surface area, which make it an effective adsorbent for water and wastewater treatment (Jagadeesh and Sundaram, 2023; Mohit et al., 2024). The transformation of such biomass into biochar is primarily achieved through a thermochemical process known as pyrolysis. Pyrolysis is a precisely controlled thermochemical process involving the thermal decomposition of organic biomass at elevated temperatures (typically 300–1000 °C) in an oxygen-limited or inert atmosphere. This method selectively converts diverse organic feedstocks into the stable, carbon-rich solid known as biochar, making it fundamental to biochar production (Handa and Rajamani, 2023; Rezapoor and Rahimpour, 2024; Varjani et al., 2022. The following are some environmental applications of biochar that support its potential as a sustainable and multifunctional material in environmental remediation. Table 3 summarizes various uses of biochar in the environmental field.

Green chemistry activation of rice husk biochar

Figure 3 illustrates the step-by-step flow of rice husk biochar production, starting from raw biomass collection to thermal conversion and post-treatment processes. Although biochar produced from pyrolysis already has adsorption capability, further activation is often required to enhance surface area, pore volume, and the number of active functional groups (Panwar

Table 3. Biochar use in the environmental field

No.	Raw materials	Type of pollutant	Main application	Reference
1.	Banana peel	Heavy metals	Adsorption of As, Pb, Hg, Cd	(Zainudin and Kesumaningwati, 2022)
2.	Poplar wood powder	Nutrients, organic pollutants	Removal of BOD, COD, TDS, nitrate, nitrite, ammonium	(Varshini and Gayathri, 2023)
3.	Siwalan fiber	Heavy metals, soils	Heavy metal adsorption; soil fertility; river remediation	(Zultaqawa et al., 2023)
4.	Sorghum stem	Heavy metals, organic pollutants (dyes)	Cu^{2+} adsorption; removal of methylene blue	(Annisa et al., 2024; Hou et al., 2020)
5.	Corn cob	Heavy metals, organic pollutants	Cr^{6+} adsorption; removal of BOD, COD	(Shakya and Agarwal, 2023)
6	Pine sawdust	Heavy metals, pharmaceuticals	Cu^{2+} adsorption; adsorption of antibiotics (tetracycline)	(Lou et al., 2016; Wang et al., 2020)
7.	Tangerine peel	Heavy metals, organic pollutants (dyes)	Cd, Co, Cr, Cu, Mn, Ni, Pb, Zn adsorption; removal of methylene blue	(Abdić et al., 2018; Batista et al., 2025)
8.	Coconut husk	Heavy metals, greywater	Adsorption of As, Hg; adsorption of toxic metals (Pb, Cd, Cr, Ni, etc.)	(Duwiejuah et al., 2024; Joseph Ellis et al., 2024)
9.	Gossypium hirsutum	Heavy metals	Adsorption of Pb^{2+}, Cu^{2+}, Zn^{2+}, Ni^{2}	(Ali et al., 2023)
10.	Sunflower	Heavy metals, soil	Adsorption of Pb^{2+} and Cu^{2+}; improve soil properties	(Lipi et al., 2023; Radenković et al., 2024)
11.	Olive stones and almond shells	Heavy metals	Adsorption of Pb^{2+} and Cu^{2+}	(Rahimi et al., 2024)
12.	Myrica esculenta biomass	Heavy metals	Pb^{2+}, Cu^{2+} adsorption	(Kumar et al., 2023)
13.	Pine cone	Heavy metals, organic pollutants, inorganic non-metal (fluoride)	Pb^{2+} adsorption; removal of methylene blue; removal of F^{+} from water	(Biswas et al., 2020; Dawood et al., 2017; Khan et al., 2022)
14.	Apple tree root	Heavy metals and organics; advanced application	Wastewater treatment (adsorption of toxic metals/organics); microwave absorption	(Mahmoodi et al., 2025)

and Pawar, 2022; Wen et al., 2023). These improvements significantly increase its adsorption capacity (Joshi et al., 2023; Xue et al., 2024). In the context of green chemistry, the focus is on activation methods that minimize hazardous substances and reduce environmental impact (Karadia, 2023). Recent studies have introduced environmentally friendly activation strategies, including biological and low-chemical approaches (Amalina et al., 2024; Rashidi and Yusup, 2020). Other works highlight alternative sustainable techniques that align with green chemistry principles, as summarized in Table 4.

DISCUSSION

Adsorption capacity and efficiency for nickel and other heavy metals

Rice husk biochar activated through green chemistry approaches has demonstrated promising adsorption performance against various heavy metals, including Ni^{2+}, Cu^{2+}, Zn^{2+}, Cd^{2+}, and Pb^{2+}. Activation using eco-friendly agents such as KOH, $FeSO_4$, and organic acids significantly increases surface area (> 600 m²/g) and introduces oxygen-containing functional groups (–COOH, –OH), enhancing metal complexation and ion-exchange capacity. Recent innovations in biochar functionalization, including doping with deep eutectic solvents and nanoparticles (Hinsene et al., 2024) or hydroxyapatite-functionalized magnetic biochar (Zou et al., 2024), have further improved adsorption capacities, with reported maxima of 66.23 mg/g for Cr(VI), 384.62 mg/g for Pb(II), and 81.59 mg/g for Cu^{2+}. These studies highlight that adsorption is primarily governed by chemisorption and often fits Langmuir isotherm models, with optimal removal achieved under controlled laboratory conditions (pH 5–6, moderate temperature, and defined adsorbent dosage). Comparative analyses indicate that activated biochar generally outperforms raw biochar and, in some cases, approaches the efficiency of conventional adsorbents such as activated carbon or zeolite (Remmani et al., 2024; Sadegh et al., 2024). However, adsorption

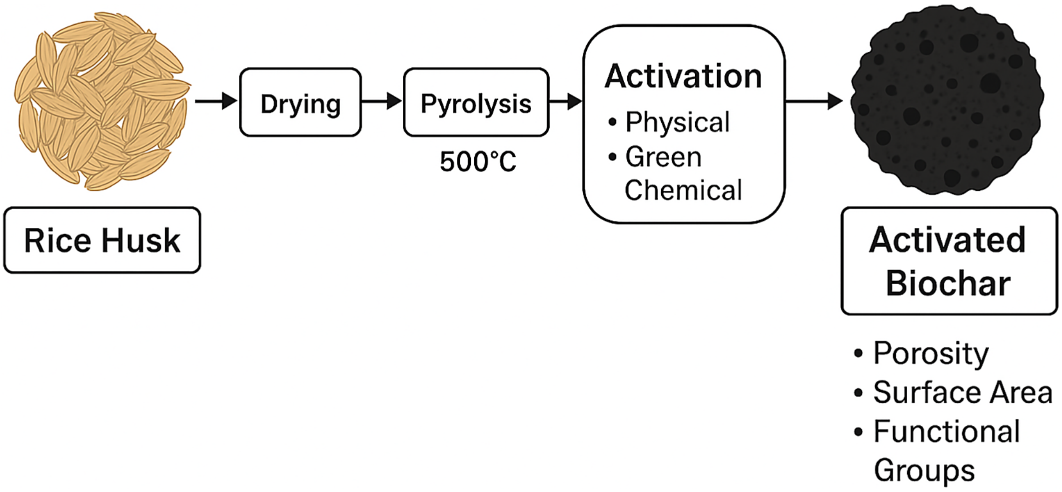

Figure 3. Rice husk biochar production flow

Table 4. Green chemical activation

Activation categories	Activation agent	Principles of green chemistry	Key advantages	References
Acid activation	Citric acid	Organic, biodegradable, non-corrosive	Expands pores, increases surface area	(Huang et al., 2022; Lee and Kang, 2024; Zhang et al., 2024)
	Phosphoric acid	Reusable, low concentration	Effectively forms highly porous biochar	(Jiang et al., 2024; Wang and Liu, 2023; Xu et al., 2024)
Alkali activation	Potassium hydroxide (KOH)	Reagents can be optimized, energy efficiency principle	Biochar with well-structured pores and high functionality	(Monteagudo et al., 2025; Wang et al., 2024; Wei et al., 2024)
	Sodium carbonate (Na_2CO_3)	Mild base, low environmental impact	Chemical stability and increased surface area	(Luo et al., 2025; Tesfaye Gari et al., 2023; Wang et al., 2024)
Green solvent	Deep eutectic solvents (DESs)	Biodegradable, non-toxic, flexible in design	Formation of new functional groups, surface selectivity	(Barman and Banjare, 2024; Negi et al., 2024; Wang et al., 2025)
Mechanochemical activation	Ball milling	No chemical additives, energy saving	Structural defects, increased surface area	(Li et al., 2025; Pattanayak et al., 2025; Vugrin et al., 2023)
Redox activation	Ferrous sulfat ($FeSO_4$)	Non-toxic, easy to obtain, effective redox reaction	Formation of Fe-oxide nanoparticles, enhanced heavy metal adsorption capacity	(Dong et al., 2023; Lu et al., 2021)
Green pre-treatment	Hydrothermal Carbonization (HTC)	Water-based reaction medium, medium temperature and pressure	Better early biochar, minimize the need for advanced chemical activation	(Lilian et al., 2024; Petrović et al., 2024; Yu et al., 2024)

efficiency is highly sensitive to operational parameters, including solution pH, contact time, and initial metal concentration. In acidic conditions typical of acid mine drainage (AMD, pH < 4), proton competition reduces metal uptake, as observed for Ni^{2+} (Banerjee et al., 2024). This underscores the need for surface modifications or hybridization to maintain performance under realistic AMD conditions.

Emerging trends involve multifunctional biochar systems, such as magnetic biochar for easy separation and biochar–geopolymer or biochar–magnetite composites that enhance adsorption capacity and stability in acidic environments (John et al., 2023; Navarathna et al., 2020). Despite these advances, several critical gaps remain. Most studies utilize synthetic single-metal solutions rather than multi-ion AMD systems typical of nickel or copper mining, limiting the understanding of competitive adsorption. Field-scale performance, long-term regeneration, and reusability beyond five cycles are rarely reported, restricting insight into operational feasibility. Additionally, metal recovery from saturated biochar, which is crucial for circular economy applications, is largely unexplored.

Rice husk biochar demonstrates high potential for heavy metal adsorption under laboratory conditions. Nevertheless, further research is required to evaluate its performance in real-world AMD from Indonesian nickel mining, optimize operational parameters, and integrate sustainable activation strategies. Addressing these challenges through field-scale trials, regeneration studies, and hybrid system development will be essential for translating laboratory success into practical, environmentally viable solutions. The proposed mechanisms of heavy metal interactions with rice husk biochar – including complexation, ion exchange, and adsorption onto functional groups – are illustrated in Figure 4.

Stability and regeneration of biochar

The stability of biochar in retaining adsorbed heavy metals is a crucial factor for evaluating its long-term effectiveness. Wang et al. (2022) reported that biochar derived from rice husk maintained over 90% of adsorbed metals under neutral pH conditions. Similarly, Qi et al (2023) demonstrated that activated biochar exhibited minimal heavy metal leaching during repeated adsorption–desorption cycles. A number of studies have shown that biochar activated using green chemistry approaches exhibits excellent durability, particularly in media with neutral to acidic pH. For example, a study by (Gusiatin and Rouhani, 2023) found that the modified rice husk-based biochar only experienced a metal release rate of less than 1% after seven days of testing using the TCLP (Toxicity Characteristic Leaching Procedure) method, indicating a very stable metal retention capacity. In terms of regeneration, simple methods such as washing with weak acid solutions (e.g. 0.1 M HCl) and mild thermal treatment have been shown to recover between 60 to 85% of the initial adsorption capacity. This allows reuse of the biochar for 4 to 5 cycles without significant performance degradation, making it an economical and sustainable solution in the long term. Furthermore, studies from laboratory to pilot scale show promising results in real applications of nickel mine effluent treatment. For example, (Ungureanu et al., 2023) tested biochar on nickel mine wastewater in Eastern Europe, and successfully reduced the Ni^{2+} concentration from 10 mg/L to below 0.1 mg/L using a 500-liter continuous flow column reactor. Meanwhile, (Gado et al., 2025) demonstrated the application of residual biomass-based biochar at field scale, recording heavy metal removal efficiencies above 80%, while successfully recovering valuable metals such as nickel (Ni) and cobalt (Co) from saturated biochar using an acid elution technique.

The advancement of green chemically-activated rice husk biochar continues to offer considerable potential, particularly in improving its long-term effectiveness and integration with broader sustainable remediation technologies. Future research should explore the development of next-generation green activation methods, including the use of microorganisms and enzymes as biological alternatives to conventional chemical activators. These approaches not only reduce environmental impact but may also introduce novel surface functionalities. Additionally, deep eutectic solvents (DESs) and other natural solvents are emerging as promising candidates for producing highly functionalized biochar with minimal toxicity and high biodegradability Integration of biochar with other green remediation technologies, such as phytoremediation and constructed wetlands, presents another promising direction. In phytoremediation, biochar can enhance metal uptake by hyperaccumulator plants, improving the efficiency of metal removal from soils and waters. In constructed wetland systems, biochar can function as an effective filter medium, enhancing the retention and stabilization of heavy metals in flowing water environments. These hybrid systems offer scalable, low-energy solutions aligned with ecological engineering principles.

Another key area of future research is the valorization of spent biochar through metal recovery and circular resource utilization. Biochar saturated with heavy metals can serve as a secondary source of critical elements like nickel, cobalt, zinc, and copper, recoverable through green desorption or leaching methods. Moreover, such biochar can potentially be transformed into catalytic materials for advanced applications in photocatalysis or electrocatalysis after appropriate post-treatments such as re-carbonization or doping with transition metals. Long-term field studies are also needed to better understand the environmental fate and

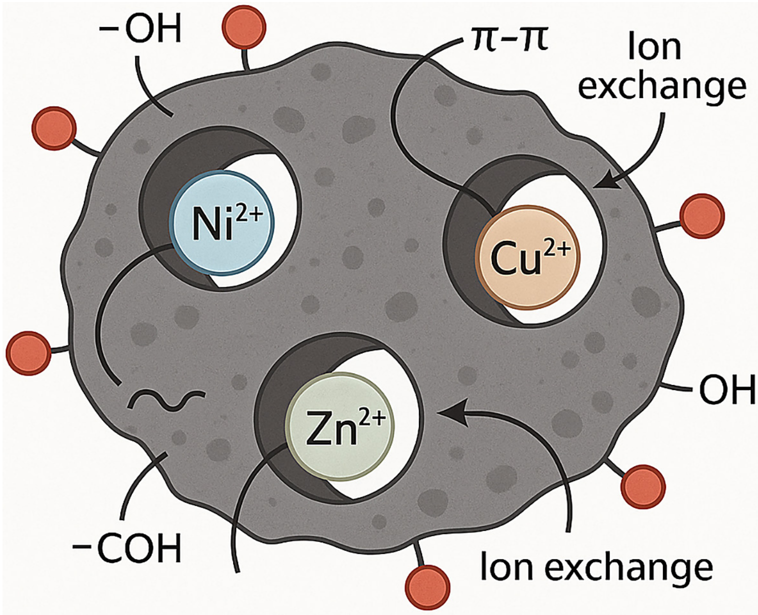

Figure 4. Heavy metal adsorption by biochar

stability of activated biochar in real-world conditions. This includes assessing its potential for metal leaching over time, as well as its indirect ecological impacts on soil and aquatic microbiomes, nutrient cycles, and local biodiversity. Understanding these dynamics is critical to ensuring safe and effective large-scale deployment.

Finally, ongoing efforts should focus on optimizing biochar for selective adsorption of specific metals. Tailoring the surface chemistry through targeted modifications or composite formulations can significantly improve selectivity and adsorption efficiency. In parallel, the development of machine learning-based predictive models could accelerate material design by linking structural features of biochar with performance under varying environmental conditions, thereby enabling data-driven optimization of treatment systems. Together, these research directions not only point toward more effective and sustainable uses of rice husk biochar but also align with broader environmental and circular economy goals. Advancing this field requires interdisciplinary collaboration that bridges materials science, environmental engineering, microbiology, and data science.

CONCLUSION

This study demonstrates that green chemistry-activated rice husk biochar is highly effective in adsorbing heavy metals such as Ni^{2+}, Cu^{2+}, and Zn^{2+}, with reported capacities up to 384.62 mg/g and stability with less than 1% metal release. The novelty of this work lies in highlighting rice husk biochar from Indonesia as a locally abundant, low-cost, and sustainable adsorbent while emphasizing eco-friendly activation strategies. This study explicitly identifies unaddressed issues such as the lack of real mining wastewater application, limited regeneration studies, and unexplored metal recovery from saturated biochar. By filling these gaps, this work provides a new perspective on sustainable remediation and opens prospects for integrating biochar into circular economy practices.

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