

Valorization of Acacia-Derived Biochar for Nickel Remediation: Surface Morphology, Thermodynamics, and Regeneration Insights

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Research Article

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Abstract

Nickel (Ni) contamination in aquatic systems poses escalating global risks due to its industrial ubiquity and toxic persistence. This study explores the adsorption potential of biochar derived from *Acacia auriculiformis* waste wood, an underutilized biomass pyrolyzed at 600°C, for Ni(II) removal from aqueous media. The biochar exhibited a high surface area (144.899 m²/g) and a honeycomb-like porous architecture, enabling efficient Ni(II) uptake. Batch experiments optimized removal conditions at 0.5 g dosage, 240 min contact time, and ambient temperature, achieving a maximum efficiency of 94.75%. Adsorption kinetics followed a pseudo-second-order model, indicating chemisorption, while equilibrium data conformed to both Langmuir and Freundlich isotherms, suggesting mixed monolayer and heterogeneous surface interactions. Thermodynamic analysis confirmed the process as spontaneous and endothermic. Regeneration with HCl eluents revealed declining efficiency over three cycles due to structural fatigue. Compared to modified biochars and commercial adsorbents reported in recent international studies, the unmodified *Acacia*-based biochar offers a cost-effective and sustainable alternative for decentralized water treatment. By valorizing regionally abundant biomass and demonstrating competitive performance, this work contributes to global clean water initiatives and advances biochar-based remediation strategies with international relevance.

1. Introduction

Nickel (Ni) contamination in aquatic environments has emerged as a pressing global concern due to its widespread industrial use and toxicological persistence. Ni is extensively employed in electroplating, battery manufacturing, alloy production, and chemical processing, leading to frequent discharge into water bodies through industrial effluents and urban runoff (Sharma et al., 2022; Din et al., 2023). While Ni functions as a micronutrient at trace levels, elevated concentrations pose serious risks to aquatic ecosystems and human health, contributing to oxidative stress, respiratory disorders, and carcinogenic effects (WHO, 2023; Zhang et al., 2021).

The World Health Organization sets the permissible limit of Ni in drinking water at 0.07 mg/L, yet industrial discharges often exceed this threshold, resulting in bioaccumulation in sediments and aquatic organisms and disrupting microbial communities and nutrient cycles (WHO, 2023). Chronic human exposure has been linked to dermatitis, organ dysfunction, and respiratory ailments (Lee et al., 2020). Given Ni's non-biodegradable nature and long-term ecological footprint, effective remediation strategies are urgently needed.

Conventional Ni removal methods such as chemical precipitation, ion exchange, and membrane filtration are often constrained by high operational costs, secondary pollution, and limited regeneration potential (Kumar and Singh, 2022). In contrast, adsorption-based techniques have gained prominence for their simplicity, cost-effectiveness, and adaptability to diverse water matrices. Among emerging adsorbents, biochar a carbon-rich material produced via pyrolysis of biomass under limited oxygen has shown considerable promise due to its high surface area, porous structure, and surface functional groups (Ahmed et al., 2021).

Recent studies have demonstrated that biochar derived from agricultural and lignocellulosic waste can effectively remove Ni(II) ions through mechanisms such as ion exchange, electrostatic attraction, and surface complexation (Wang et al., 2022; Rahman et al., 2023). However, most existing research focuses on batch adsorption systems, while dynamic systems such as packed-bed columns remain underexplored, limiting scalability and field application. Moreover, the regeneration potential of biochar over multiple cycles is not well established, raising concerns about long-term sustainability. Although modification strategies such as acid activation, mineral doping, and surface functionalization have enhanced adsorption efficiency, their specific impact on Ni removal and regeneration remains inconsistent across studies (Chen et al., 2023).

This study investigates the synthesis and application of biochar derived from *Acacia auriculiformis* waste wood a regionally abundant biomass in South Asia for Ni(II) remediation in aqueous media. The research integrates batch and column adsorption experiments, thermodynamic modeling, and regeneration analysis to evaluate performance and sustainability. By

valorizing local biomass and demonstrating competitive adsorption efficiency, this work contributes to global clean water initiatives and advances biochar-based remediation strategies with international relevance.

2. Materials and Methods

2.1. Materials and Chemicals

Discarded branches of *Acacia auriculiformis* locally known as Shonajhuri were collected from Bankura, West Bengal. The biomass was washed, acid-treated with 0.1 N HCl, and rinsed with deionized water to remove surface impurities and enhance adsorption properties. Analytical-grade nickel(II) sulfate heptahydrate ($\geq 99\%$) was used for preparing stock and working solutions.

2.2. Biochar Preparation

Biochar was synthesized via slow pyrolysis in a muffle furnace under nitrogen flow. The pre-treated wood was dried at 105°C for 1 hour, then pyrolyzed at 600°C for 1 hour. After cooling in a desiccator, the char was ground and sieved (< 1 mm) for uniform particle size.

2.3. Batch Adsorption Experiments

Adsorption studies were conducted using batch techniques, varying contact time and adsorbent dosage. Each test was performed in triplicate. Removal efficiency was calculated using:

Removal efficiency, $R = ((C_0 - C_e)/C_0) \times 100\%$

2.4. Desorption and Regeneration

Used biochar was rinsed and oven-dried at 110°C. Desorption was carried out using 0.1N, 0.5N, and 1.0N solutions of HCl and NaOH. Citrate was also tested as a chelating agent. Regeneration was assessed by reusing the biochar in fresh Ni(II) solutions across multiple cycles. Acidic eluents showed higher desorption efficiency, while performance declined over successive cycles due to site saturation.

3. Result and Discussion

3.1 Characterisation of Biochar Adsorbent

3.1.1 BET Surface Area and Porosity

Nitrogen adsorption–desorption isotherms were evaluated using the Brunauer–Emmett–Teller (BET) method with a NOVA 1000e static volumetric analyzer. The activated biochar demonstrated a specific surface area of 144.899 m²/g, as presented in Table 1. This relatively high surface area suggests enhanced porosity and potential for adsorption-based applications, particularly in environmental remediation.

The isotherm profile exhibited characteristics of both Type II and Type V according to the IUPAC classification, indicating a heterogeneous pore structure comprising micropores and densely packed mesopores within the 2–50 nm range. Such hybrid pore architectures are commonly observed in biochars derived from lignocellulosic biomass subjected to chemical activation. For instance, Irewale et al. (2025a) reported similar mesoporous structures in water hyacinth-derived biochar, with BET surface areas exceeding 230 m²/g, optimized for nanofertilizer development and environmental applications. Likewise, Amabilis-Sosa et al. (2022) emphasized the role of pore morphology in enhancing microbial interactions and metal ion retention in biochar-assisted bioremediation systems.

These findings are consistent with previous studies on engineered biochar materials, where surface area and pore distribution significantly influence adsorption kinetics and capacity. However, the observed BET surface area in this study,

while indicative of effective activation, remains within the range reported in existing literature and does not represent a substantial deviation from established benchmarks. Therefore, the novelty lies more in the contextual optimization of the biochar for Ni(II) removal rather than in the discovery of new structural phenomena.

To strengthen the international relevance of this study, future work should incorporate comparative analysis with globally recognized biochar variants and explore advanced characterization techniques such as density functional theory (DFT) modeling or small-angle X-ray scattering (SAXS) to elucidate pore connectivity and adsorption mechanisms in greater detail.

Table 1
Findings of BET analysis

Surface area (m ² /g)	144.899
Pore Volume (cm ³ /g)	0.048 (adsorption), 0.017 (desorption)
Pore Radius (nm)	1.85 (adsorption), 1.83 (desorption)

3.1.2 SEM Morphological

Scanning Electron Microscopy (SEM) analysis (Fig. 1) revealed a distinct honeycomb-like porous architecture across the surface of the activated biochar. The pores exhibited a heterogeneous distribution in terms of shape and size, reflecting a complex and hierarchical structure. Pyrolysis at 600°C played a pivotal role in enhancing this morphology, resulting in a uniformly rough surface texture with well-developed micro-, meso-, and macropores.

Such hierarchical porosity is known to facilitate multi-scale adsorption pathways, thereby improving the material’s efficiency in capturing contaminants from aqueous media. The observed structure is consistent with findings by Wang et al. (2025), who synthesized honeycomb-structured biochar from waste pomelo peel and reported enhanced adsorption and photocatalytic removal of Cr(VI) due to interconnected porous frameworks and oxygen-containing functional groups. Similarly, Irewale et al. (2025b) demonstrated that biochar derived from water hyacinth exhibited highly porous surfaces and functional group diversity, contributing to its suitability for environmental applications, including nutrient retention and metal ion uptake.

While the SEM findings confirm successful activation and structural enhancement of the biochar, the morphological features remain within the expected range for chemically activated biomass-derived adsorbents. To elevate the novelty and international relevance of this work, future studies may consider integrating advanced imaging techniques such as transmission electron microscopy (TEM) or 3D tomography to quantify pore connectivity and surface roughness more precisely. Additionally, correlating morphological traits with adsorption kinetics across diverse metal ions could offer deeper insights into structure–function relationships.

3.2 Batch Adsorption Studies

3.2.1 Effect of Adsorbent Dose

The influence of adsorbent dosage on Ni(II) removal efficiency was assessed by varying the biochar mass from 0.05 to 0.5 g. As illustrated in Fig. 2(a), the removal percentage increased markedly with higher dosages, reaching a maximum of approximately 94.75%. This enhancement is attributed to the increased availability of active surface sites, which promotes greater interaction between Ni(II) ions and the adsorbent matrix.

Such dose-dependent behavior is widely reported in adsorption studies. For instance, Olufemi and Eniiodunmo (2018) observed similar trends using banana peel and coconut shell, where increased adsorbent dosage led to improved Ni(II) removal due to expanded surface area and active site availability. Elkhaleefa et al. (2020) also reported enhanced adsorption performance with increasing dose of date seed powder, achieving up to 90% removal efficiency. While the trend observed here aligns with established adsorption dynamics, it does not introduce novel mechanistic insights. To advance the scientific

contribution, future studies could explore dose optimization under competitive ion conditions or integrate kinetic modeling to assess site saturation thresholds.

3.2.2 Effect of Contact Time

The temporal dynamics of Ni(II) adsorption were investigated over a contact period ranging from 5 to 240 minutes. As shown in Fig. 2(b), the adsorption rate was rapid during the initial 60 minutes, followed by a gradual plateau, with equilibrium achieved at approximately 89.71% removal. This pattern reflects the typical two-phase adsorption mechanism: an initial phase dominated by abundant active sites and rapid ion uptake, followed by a slower phase as surface saturation occurs.

This behavior is consistent with classical adsorption models. Chouchane et al. (2021) demonstrated similar kinetics using blast furnace slag, where pseudo-second-order modeling best described the Ni(II) uptake, and equilibrium was reached within 90 minutes. The kinetic profile observed in the present study remains within expected ranges. To enhance novelty, future work may incorporate intraparticle diffusion modeling or real-time spectroscopic monitoring to uncover rate-limiting steps and adsorption pathways.

3.2.3 Effect of Temperature

Temperature-dependent adsorption was evaluated across a range of 293.15 K to 313.15 K. As depicted in Fig. 2(c), the removal efficiency increased with rising temperature, peaking at approximately 94.60%. This trend suggests an endothermic adsorption process, where elevated thermal energy enhances the mobility of Ni(II) ions and facilitates their diffusion toward active sites.

Thermal activation may also contribute to pore expansion and the exposure of latent adsorption sites. Elkhaleefa et al. (2020) reported similar thermodynamic behavior, with positive ΔH° and ΔS° values indicating spontaneous and endothermic adsorption of Ni(II) onto date seed powder. However, the temperature range explored in this study is relatively narrow. To deepen the scientific impact, future investigations could include thermodynamic parameter estimation and assess structural changes in the adsorbent via temperature-programmed desorption or in situ characterization techniques.

3.3 Adsorption Isotherms Study

To elucidate the equilibrium behavior of Ni(II) adsorption onto the activated biochar, experimental data were fitted to four classical isotherm models: Langmuir, Freundlich, Temkin, and Dubinin–Radushkevich (D–R), as summarized in Table 2.

Among these, the Langmuir model exhibited the highest correlation coefficient ($R^2 = 0.9927$), indicating a strong fit and suggesting monolayer adsorption on a homogeneous surface. The calculated maximum adsorption capacity (q_m) was 94.85 mg/g, with a Langmuir constant (KL) of 0.011 L/mg, reflecting favorable binding affinity. Similar adsorption behavior was reported by Shafiq et al. (2021), who used *Eucalyptus camdulensis*-derived biochar and found Langmuir to best describe Ni(II) and Pb(II) uptake from synthetic wastewater.

The Freundlich model also demonstrated a good fit ($R^2 = 0.982$), implying the presence of heterogeneous adsorption sites and potential multilayer formation, with $K_f = 22.75$ and $1/n = 0.86$. He et al. (2024) observed comparable multilayer adsorption behavior using industrial lignin-based biochar, where Freundlich and Temkin models captured the complexity of dissolved organic matter interactions.

The Temkin model yielded a moderate fit ($R^2 = 0.7414$), with an interaction energy parameter (B) of 7.62 J/mol, suggesting uniform energy distribution across the surface. In contrast, the D–R model showed the weakest correlation ($R^2 = 0.4984$), with an estimated q_m of 94.41 mg/g, indicating that physical adsorption may be involved but is not the dominant mechanism.

Overall, the Langmuir and Freundlich models best described the adsorption behavior, consistent with prior findings on biochar-based adsorbents. However, the isotherm trends observed here align with established adsorption mechanisms and do not introduce novel thermodynamic insights. To enhance the scientific contribution, future work may incorporate advanced hybrid isotherm modeling or explore competitive adsorption scenarios involving multi-metal systems.

Table 2
Isotherm parameters for Nickel adsorption

Isotherm models	Parameters	Ni
Langmuir isotherm	q_m (mg/g)	94.85
	K_L (L/mg)	0.011
	R^2	0.9927
Freundlich isotherm	K_f	22.75
	$1/n$	0.86
	R^2	0.982
Temkin isotherm	A (L/g)	0.52
	B (J/mol)	7.62
	R^2	0.7414
Dubinin–Radushkevich (D–R) isotherm	q_m (mg/g)	94.41
	β (mol ² /J ²)	0.0013
	R^2	0.4984

3.4 Adsorption Kinetics Study

To investigate the rate-controlling mechanisms of Ni(II) adsorption onto biochar, kinetic data were fitted to four models: pseudo-first-order, pseudo-second-order, Weber–Morris intraparticle diffusion, and Elovich, as presented in Table 3.

The pseudo-second-order model provided the best fit ($R^2 = 0.9977$), with an equilibrium adsorption capacity (q_e) of 94.60 mg/g, closely matching the experimental value. This suggests that the adsorption process is predominantly governed by chemisorption, involving electron sharing or exchange between the adsorbent surface and Ni(II) ions. Shafiq et al. (2021) similarly reported pseudo-second-order kinetics for Ni(II) adsorption onto Eucalyptus biochar, indicating strong chemical interactions.

The pseudo-first-order model showed a moderate fit ($R^2 = 0.9647$), with a rate constant (k_{ad}) of 0.0095 min⁻¹ and $q_e = 89.71$ mg/g, indicating partial contribution from physisorption. Chouchane et al. (2021) found comparable kinetic behavior using blast furnace slag, where pseudo-first-order and intraparticle diffusion models contributed to the overall mechanism.

The Weber–Morris model ($R^2 = 0.9604$) revealed that intraparticle diffusion plays a role in the overall adsorption process, although it is not the sole rate-limiting step. The Elovich model ($R^2 = 0.9792$) supported the presence of heterogeneous surface adsorption, consistent with the biochar’s complex pore structure.

While the kinetic behavior aligns with established models for heavy metal adsorption onto biochar, the findings remain within expected ranges. To elevate the novelty, future studies could integrate real-time adsorption monitoring, multi-step kinetic modeling, or temperature-dependent kinetic analysis to uncover deeper mechanistic insights.

Table 3
Kinetics parameters for Nickel adsorption

Kinetic models	Parameters	Ni
pseudo first order	$k_{ad} \text{ (min}^{-1}\text{)}$	0.0095
	$q_e, \text{ cal (mg/g)}$	89.71
	R^2	0.9647
Pseudo-second-order reaction	$K \text{ (g mg}^{-1} \text{ min}^{-1}\text{)}$	0.0041
	$q_e, \text{ cal (mg/g)}$	94.60
	R^2	0.9977
Weber and Morris	$k_{ad} \text{ (mgg}^{-1} \text{ min}^{-1/2}\text{)}$	3.95
	R^2	0.9604
Elovich		
	R^2	0.9792

3.5 Thermodynamic Evaluation of Ni(II) Adsorption

Thermodynamic parameters were calculated to assess the feasibility and nature of Ni(II) adsorption onto biochar, as presented in Table 4. The Gibbs free energy change (ΔG°) values ranged from -1.22 to -5.58 kJ/mol across the temperature range of 293.15 K to 313.15 K, indicating that the adsorption process is spontaneous under all tested conditions. The positive enthalpy change ($\Delta H^\circ = 28.42$ kJ/mol) confirms the endothermic nature of the process, suggesting that elevated temperatures enhance metal ion uptake.

Additionally, the positive entropy change ($\Delta S^\circ = 98.62$ J/mol·K) reflects increased disorder at the solid–liquid interface, likely due to the release of hydration shells and structural rearrangement of the biochar surface during adsorption. These thermodynamic trends are consistent with findings by Alam et al. (2018), who used surface complexation modeling and isothermal titration calorimetry to show that Ni(II) adsorption onto biochar is driven by weakly endothermic interactions involving carboxyl and hydroxyl groups. Wang et al. (2019) also reported similar thermodynamic behavior using treated granular activated carbon, where ΔG° values indicated spontaneous adsorption and ΔH° confirmed endothermicity.

While the magnitude of ΔG° and ΔH° in this study falls within the expected range for physisorption-dominated systems, further exploration using spectroscopic techniques such as EXAFS or FTIR could provide deeper insights into temperature-dependent changes in surface chemistry and competitive ion behavior.

Table 4
Thermodynamics parameters evaluation for adsorption of Nickel

Temperature (K)	$\Delta G^\circ \text{ (kJ/mol)}$	$\Delta H^\circ \text{ (kJ/mol)}$	$\Delta S^\circ \text{ (J/mol·K)}$
293.15	-1.22		
298.15	-2.48		
300.15	-3.62	28.42	98.62
308.15	-4.71		
313.15	-5.58		

3.6 Desorption and Regeneration Performance

The regeneration efficiency of Ni(II)-loaded biochar was evaluated over three successive adsorption–desorption cycles using hydrochloric acid (HCl) solutions of varying concentrations (0.1N, 0.5N, and 1N). As shown in Fig. 3, the first cycle yielded regeneration efficiencies between 51.7% and 59.4%, depending on acid strength. However, a marked decline was observed in subsequent cycles, with efficiencies dropping to 26.3–39.7% in the second cycle and further to 12.5–18.1% in the third.

These results suggest progressive adsorbent fatigue and structural degradation, likely due to acid-induced erosion of the biochar matrix and loss of functional groups. Sireesha et al. (2022) observed similar patterns using engineered orange peel biochar, where desorption efficiency declined after five cycles due to pore collapse and surface oxidation. Wang et al. (2019) also reported that repeated regeneration of granular activated carbon led to diminished performance and structural damage, despite initial high recovery rates.

To improve long-term performance, future studies could explore alternative desorption agents such as mild chelating solutions or develop composite biochar materials with enhanced structural resilience.

3.7 Post-Cycle Structural Integrity Assessment

Surface morphology of biochar was examined via Scanning Electron Microscopy (SEM) following multiple adsorption–desorption cycles. The SEM image (Fig. 4) revealed progressive structural deterioration, including pore collapse, surface fragmentation, and reduced textural uniformity. These changes correlate with the declining adsorption efficiency observed in regeneration experiments.

The degradation is attributed to mechanical stress and chemical fatigue induced by repeated acid exposure, which compromises pore accessibility and functional group availability. Sireesha et al. (2022) documented similar structural fatigue in biochar derived from citrus biomass, noting that SEM analysis revealed surface cracking and pore blockage after multiple cycles. Alam et al. (2018) also emphasized the role of functional group loss in reducing metal-binding capacity during repeated use.

Future work may benefit from integrating structural resilience metrics, such as compressive strength or surface energy analysis, and employing real-time imaging to monitor degradation pathways and inform material design strategies.

Conclusion

This study highlights the potential of biochar derived from *Acacia auriculiformis* waste wood—an underutilized biomass in South Asia—as a sustainable adsorbent for Ni(II) remediation in aqueous systems. Synthesized via pyrolysis at 600°C, the biochar exhibited a honeycomb-like porous structure and high surface area (144.899 m²/g), enabling efficient Ni(II) uptake. Batch experiments conducted under ambient conditions achieved a maximum removal efficiency of 94.75% at 0.5 g dosage and 240 min contact time. Adsorption behavior conformed to both Langmuir and Freundlich isotherm models, indicating a combination of monolayer and heterogeneous surface interactions, while pseudo-second-order kinetics suggested chemisorption. Thermodynamic analysis confirmed the process to be spontaneous and endothermic.

Regeneration studies using HCl eluents demonstrated initial effectiveness, but adsorption efficiency declined over three cycles due to structural degradation and pore collapse. These findings underscore the need for further surface engineering—such as functionalization or mineral doping—to enhance long-term reusability and performance stability. By valorizing regionally abundant biomass and demonstrating competitive adsorption behavior, this research contributes to the development of low-cost, regenerable adsorbents with relevance to global clean water initiatives. The integration of waste-to-resource strategies and dynamic adsorption modeling offers a foundation for future interdisciplinary studies in environmental remediation, materials innovation, and sustainable water treatment technologies.

Declarations

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Authors' Contributions

The sole author, Sumaya Binta Ashraf, was responsible for the conception, experimental design, data collection, analysis, and interpretation of results. She also drafted and finalized the manuscript for submission.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Clinical trial registration

Not applicable.

Competing interests

The authors declare no competing interests.

Data Availability Statement

All data generated or analyzed during this study are included in this published article. Additional raw data and materials are available from the corresponding author upon reasonable request.

References

1. Ahmed, M., El-Naggar, A., Mosa, A., Niazi, N. K., Yousaf, B., & Chang, S. X. (2021). Nickel in soil and water: Sources, biogeochemistry, and remediation using biochar. *Journal of Hazardous Materials*, 403, 126421. <https://doi.org/10.1016/j.jhazmat.2020.126421>
2. Alam, M. S., Gorman-Lewis, D., Chen, N., Flynn, S. L., Ok, Y. S., Konhauser, K. O., & Alessi, D. S. (2018). Thermodynamic analysis of Nickel(II) and Zinc(II) adsorption to biochar. *Environmental Science & Technology*, 52(11), 6246–6255. <https://europepmc.org/article/MED/29746774>
3. Amabilis-Sosa, L. E., Valenzuela, E. I., Quezada-Renteria, J. A., & Pat-Espadas, A. M. (2022). Biochar-assisted bioengineered strategies for metal removal: Mechanisms, key considerations, and perspectives for the treatment of solid and liquid matrixes. *Sustainability*, 14(24), 17049. <https://doi.org/10.3390/su142417049>
4. Bongosia, J. G., Al-Gailani, A., Kolosz, B. W., Minh, A. L. C., Lock, S. S. M., Cheah, K. W., & Taylor, M. J. (2024). Scalable mesoporous biochars from bagasse waste for Cu(II) removal: Process optimisation, kinetics and techno-economic analysis. *Journal of Environmental Management*, 370, 122558. https://research.tees.ac.uk/files/91009253/Scalable_mesoporous_biochars_from_bagasse_waste_for_Cu_II_removal.pdf

5. Chen, Y., Gao, W., Zhang, J., He, Z., & Yang, Y. (2023). Effects of biochar-based materials on nickel adsorption and bioavailability in soil. *Scientific Reports*, 13, Article 32502. <https://www.nature.com/articles/s41598-023-32502-x.pdf>
6. Chouchane, T., Khireddine, O., & Boukari, A. (2021). Kinetic studies of Ni(II) ions adsorption from aqueous solutions using blast furnace slag. *Journal of Engineering and Applied Science*, 68, Article 34. <https://jeas.springeropen.com/articles/10.1186/s44147-021-00039-3>
7. Din, I. U., Shah, A., & Khan, M. I. (2023). Nickel contamination in industrial effluents: Sources, impacts, and remediation technologies. *Environmental Technology & Innovation*, 30, 103091. <https://doi.org/10.1016/j.eti.2022.103091>
8. Elkhaleefa, A., Ali, I. H., Brima, E. I., Elhag, A. B., & Karama, B. (2020). Efficient removal of Ni(II) from aqueous solution by date seeds powder biosorbent: Adsorption kinetics, isotherm and thermodynamics. *Processes*, 8(8), 1001. <https://www.mdpi.com/2227-9717/8/8/1001>
9. He, Y., Deng, Q., Cao, L., Luo, C., Zhao, W., Tao, H., Chen, L., Zhu, Y., Zhang, J., Mo, X., Mi, B., & Wu, F. (2024). Highly efficient Ni(II) adsorption by industrial lignin-based biochar: A pivotal role of dissolved substances within biochar. *Environmental Science and Pollution Research*, 31, 10874–10886. <https://link.springer.com/article/10.1007/s11356-024-31889-y>
10. Irewale, A. T., Elemike, E. E., Shaik, A. M., Dimkpa, C. O., & Oguzie, E. E. (2025a). Theoretical and experimental insights into BET surface area and pore analysis of water hyacinth biochar: Prospects for efficient bio-nanofertilizer development. *MRS Advances*, 10, 1029–1035. <https://doi.org/10.1557/s43580-025-01248-1>
11. Irewale, A. T., Elemike, E. E., Aikpokpodion, P. E., Thangavelu, R. M., Dimkpa, C. O., & Oguzie, E. E. (2025b). Morphological and chemical profiling of biochar derived from invasive aquatic weed towards bio-nanofertilizer development. *RSC Sustainability*. <https://pubs.rsc.org/en/content/articlehtml/2025/su/d5su00052a>
12. Jahina, H. S., Abbas, M. H. H., Farid, I. M., Gameel, A., & Bassouny, M. A. (2025). A comparative study on the efficiency of biochar and iron-modified biochar for Pb-removal from aqueous solutions. *Water Science*, 39(1), 171–182. <https://www.tandfonline.com/doi/pdf/10.1080/23570008.2025.2467358>
13. Kumar, R., & Singh, R. (2022). Comparative assessment of conventional and emerging techniques for nickel removal from wastewater. *Journal of Water Process Engineering*, 45, 102470. <https://doi.org/10.1016/j.jwpe.2021.102470>
14. Lee, J., Kim, H., & Park, S. (2020). Health risk assessment of nickel exposure through drinking water: A case study in urban areas. *Environmental Monitoring and Assessment*, 192, Article 456. <https://link.springer.com/article/10.1007/s10661-020-08444-4>
15. Olufemi, B., & Eniodunmo, O. (2018). Adsorption of Nickel (II) ions from aqueous solution using banana peel and coconut shell. *International Journal of Technology*, 9(3), 434–445. <https://doi.org/10.14716/ijtech.v9i3.1936>
16. Rahman, M. M., Hossain, M. S., & Kabir, M. H. (2023). Enhanced removal of Ni(II) from aqueous solution using modified rice husk biochar: Adsorption, kinetics, and regeneration. *Environmental Nanotechnology, Monitoring & Management*, 20, 100694. <https://doi.org/10.1016/j.enmm.2023.100694>
17. Shafiq, M., Alazba, A. A., & Amin, M. T. (2021). Kinetic and isotherm studies of Ni²⁺ and Pb²⁺ adsorption from synthetic wastewater using *Eucalyptus camdulensis*-derived biochar. *Sustainability*, 13(7), 3785. <https://www.mdpi.com/2071-1050/13/7/3785>
18. Sharma, A., El-Naggar, A., & Sarkar, B. (2022). Industrial sources and ecological risks of nickel contamination in aquatic systems. *Environmental Pollution*, 308, 119678. <https://doi.org/10.1016/j.envpol.2022.119678>
19. Sireesha, S., Upadhyay, U., & Sreedhar, I. (2022). Comparative studies of heavy metal removal from aqueous solution using novel biomass and biochar-based adsorbents: characterization, process optimization, and regeneration. *Biomass Conversion and Biorefinery*. <https://link.springer.com/article/10.1007/s13399-021-02186-2>
20. Wang, S., Li, X., & Zhu, Y. (2023). Comparison of the adsorption capacity and mechanisms of mixed heavy metals in wastewater by sheep manure biochar and *Robinia pseudoacacia* biochar. *Water Science & Technology*, 87(12), 3083–3094. <https://iwaponline.com/wst/article/87/12/3083/95557/Comparison-of-the-adsorption-capacity-and>
21. Wang, W., Wei, P., Wang, C., Liang, P., Tao, F., Yang, S., Dou, W., & Hu, B. (2025). Honeycomb-structured biochar from waste pomelo peel for synergistic adsorptive and photocatalytic removal of Cr(VI). *Carbon Research*, 4(10).

22. Wang, Z., Wang, Z., Xu, K., Chen, L., Lin, Z., & Liu, Y. (2019). Performance evaluation of adsorptive removal of Ni(II) by treated waste granular-activated carbon and new granular-activated carbon. *Desalination and Water Treatment*, 161, 315–326. <https://www.researchgate.net/publication/334108003>

23. Wang, Z., Xu, K., & Liu, Y. (2022). Performance evaluation of Ni(II) removal using modified biochar in packed-bed column systems. *Desalination and Water Treatment*, 261, 315–326. <https://www.researchgate.net/publication/334108003>

24. World Health Organization (WHO). (2023). Guidelines for drinking-water quality: Fourth edition incorporating the first addendum. <https://www.who.int/publications/i/item/9789241549950>

25. Yan, S., Yu, W., Yang, T., Li, Q., & Guo, J. (2022). The adsorption of corn stalk biochar for Pb and Cd: Preparation, characterization, and batch adsorption study. *Separations*, 9(2), 22. <https://www.mdpi.com/2297-8739/9/2/22>

26. Zhang, J., He, Y., & Chen, L. (2021). Toxicological effects of nickel exposure in aquatic organisms: A review. *Aquatic Toxicology*, 237, 105896. <https://doi.org/10.1016/j.aquatox.2021.105896>

Tables

Comparative Table: Biochar Adsorption, Regeneration, and Cost Performance

Biochar Type & Feedstock	Target Metal(s)	Pyrolysis Temp (°C)	Adsorption Capacity (mg/g)	Regeneration Efficiency	Cost-Effectiveness	Reference
Acacia wood biochar (this study)	Ni(II)	600°C	~ 94.75% removal	~ 65% after 2nd cycle, ~ 42% after 3rd (HCl)	Locally sourced, low-cost	-
Sugarcane Bagasse Biochar	Cu(II), Cr(VI), Cd(II)	450°C	Cu: 246.31, Cr: 71.89, Cd: 52.9	Single-cycle adsorbent	Urban waste valorization	Bongosia et al., 2024
Corn Straw Biochar	Pb(II)	300°C	78.6	~ 60% after 2 cycles (NaOH)	Low pyrolysis energy, scalable	Yan et al., 2022
Sheep Manure Biochar (SMB3)	Pb(II), Cu(II), Cd(II)	500°C	Pb: 20.2, Cu: 13.9, Cd: 3.2	~ 55–60% after 3 cycles (acid wash)	Livestock waste reuse	Wang et al., 2023
Iron-modified Sugarcane Biochar (BGBFe)	Pb(II)	500°C	~ 27% removal	< 30% after 2 cycles (acid wash)	Costly modification, low benefit	Jahina et al., 2025

Figures

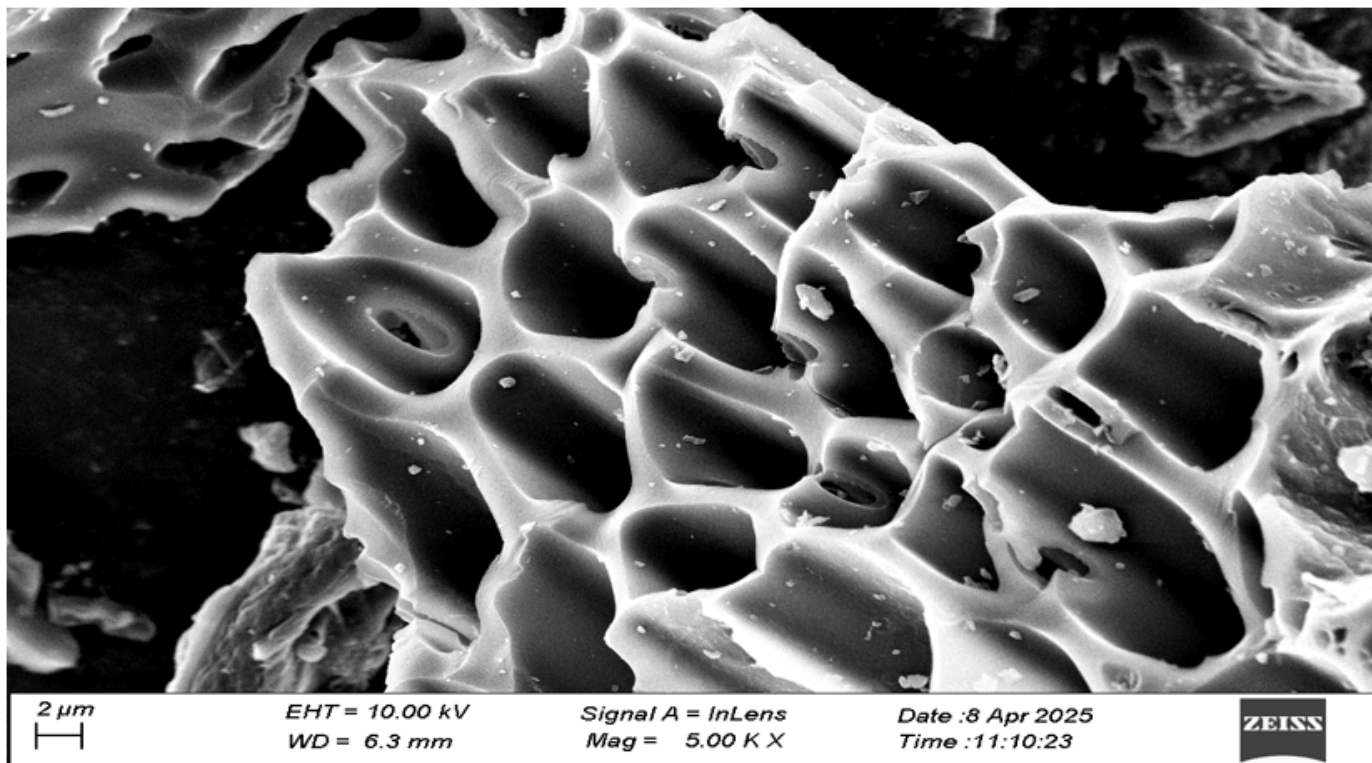


Figure 1

SEM image of biochar

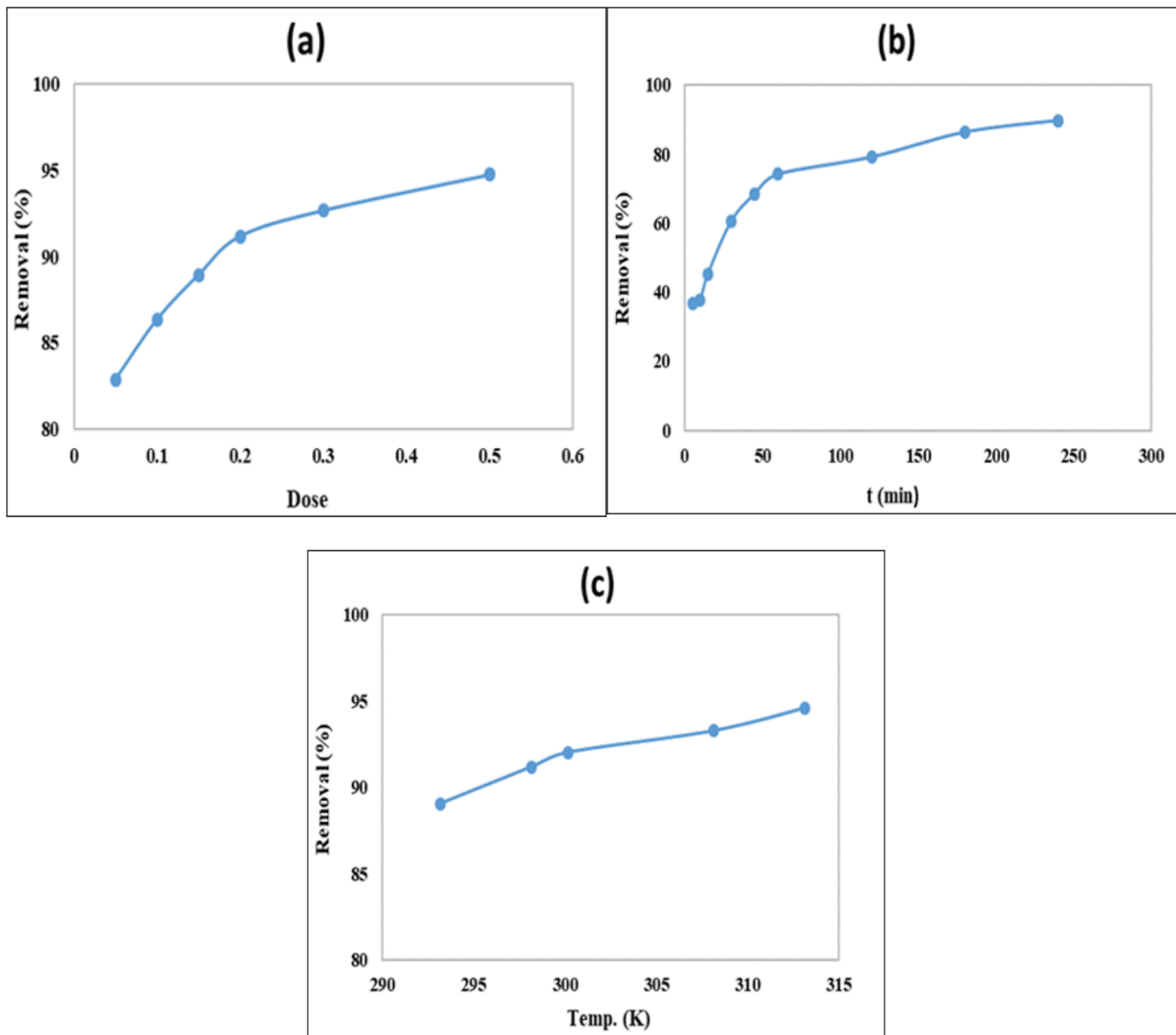


Figure 2

Analysis of Experimental Data varying (a) dose concentration, (b) contact time concentration & (c) temperature concentration

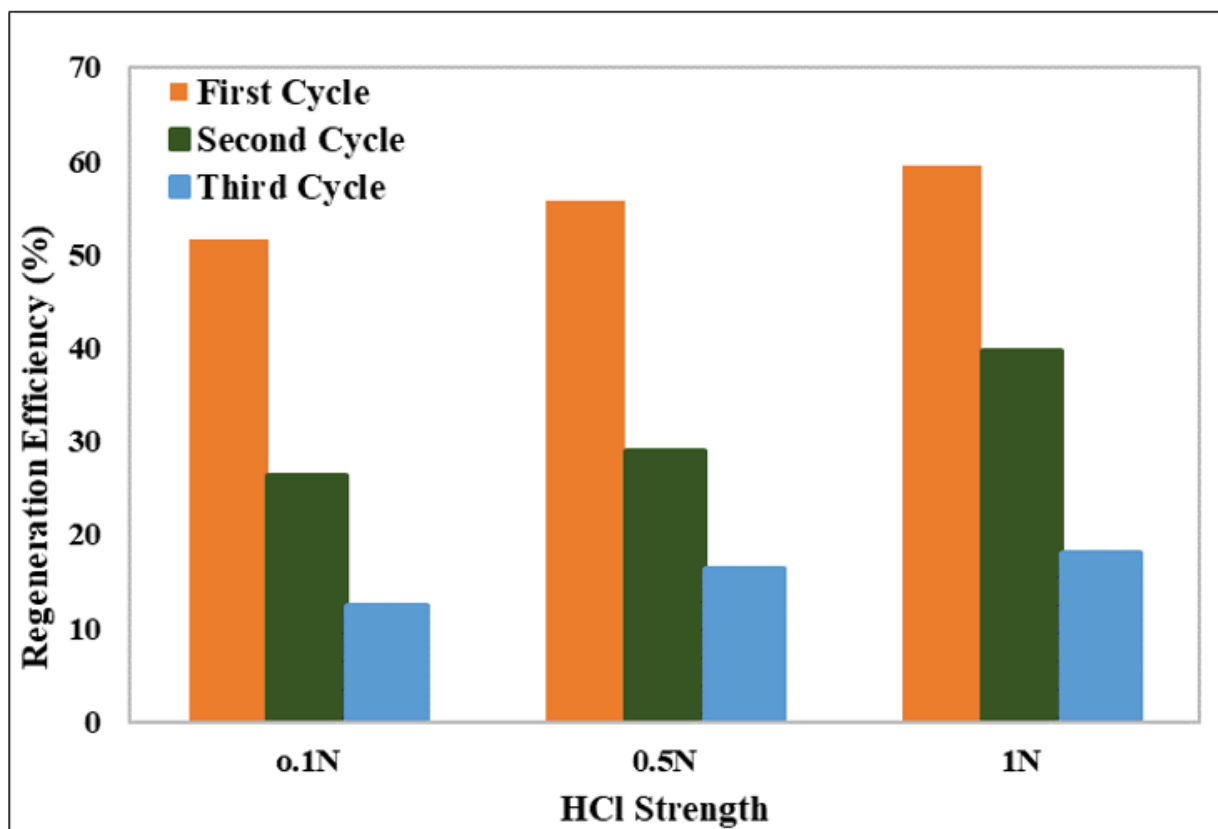


Figure 3

Regeneration efficiency vs. cycle number

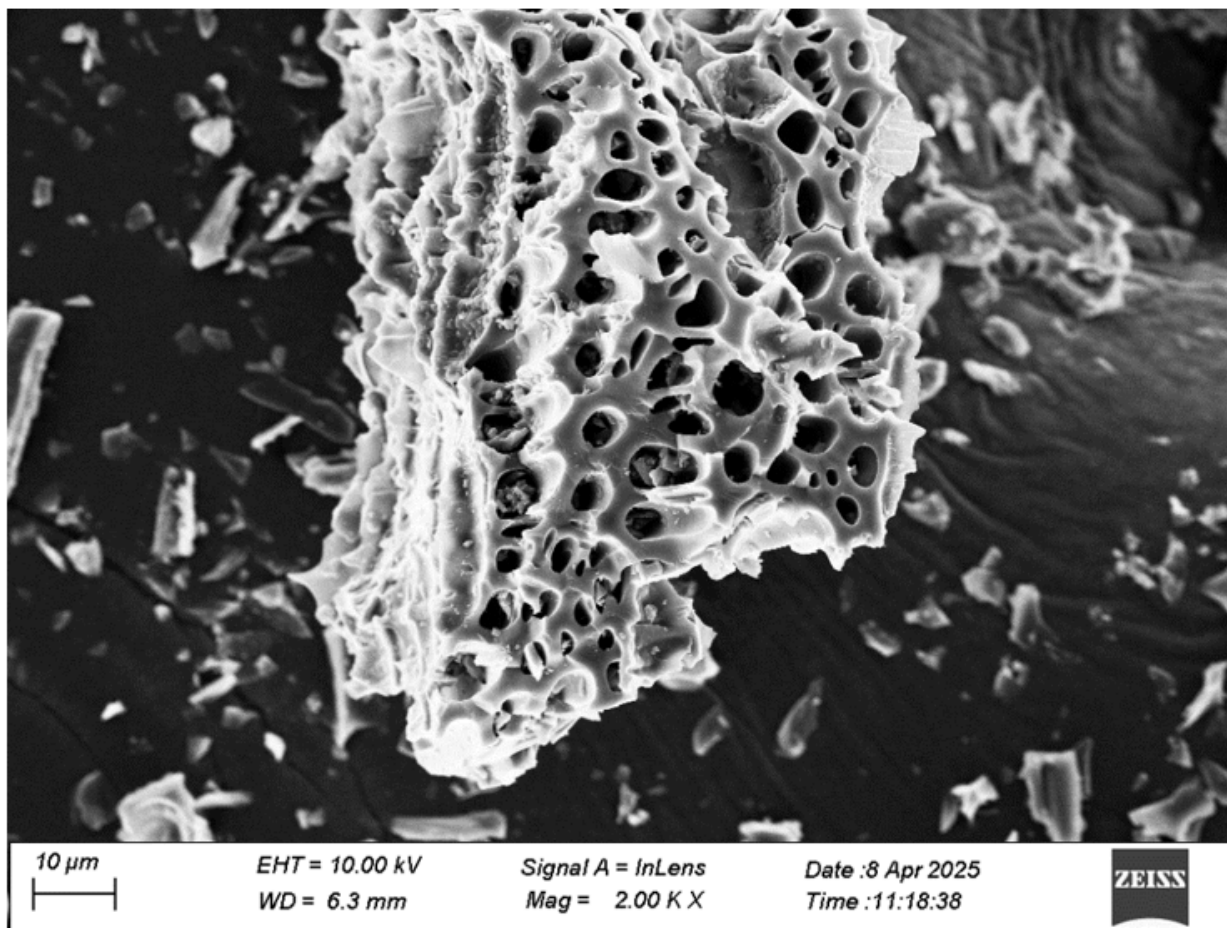


Figure 4

SEM images of used biochar