International Journal of Eco-Innovation in Science and Engineering (IJEISE) Vol.06 (1), 2025 (30-37)
https://ijeise.upnjatim.ac.id/ E-ISSN: 2721-8775

Article

Comparative Analysis of Biomass-Based Adsorbents for Heavy Metal Ion Removal

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Received: 11th May 2025; Revised: 19th May 2025; Accepted: 26th May 2025;
Available online: 30th May 2025; Published regularly: May and November

Abstract

This study investigates the adsorption capabilities of various biomass-based adsorbents for the removal of heavy metal ions from industrial wastewater. This research focusses on the comparative effectiveness of chemical and steam activation methods. Steam-activated adsorbents derived from wine sector waste exhibited a maximum adsorption capacity for Pb^{2+} ions of 399 mg/g. Adsorbents derived from walnut shells and chemically activated with HNO_3 ions exhibited a maximum adsorption capacity of 204.08 mg/g for Cu^{2+} ions. Steam-activated spruce sawdust adsorbents achieved optimal adsorption of Fe^{2+} ions at a capacity of 329 mg/g. The adsorption capacity for Cd^{+} ions was determined to be 116 mg/g, achieved through microwave-assisted steam activation of palm kernel shell-based adsorbents. The research emphasizes the necessity of selecting appropriate activation techniques based on specific heavy metal ions and the desired adsorption properties. Additionally, there is a necessity for further investigation into the processes of pore structure development and their impact on adsorption effectiveness. The findings suggest that developing adsorbent from biomass waste represents a sustainable and effective method for reducing heavy metal contamination in industrial wastewater, thereby advancing environmental protection and resource efficiency.

Keywords: biomass, heavy metal removal, sustainable remediation

1. Introduction

Heavy metals in industrial wastewater pose serious environmental and health risks due to their toxicity, persistence, and bioaccumulation. Nickel (Ni), Lead (Pb), Mercury (Hg), are particularly concerning, given its extensive use in electroplating, battery manufacturing, and stainless steel production [1], [2]. For example, classified as a Group 1 carcinogen by the IARC, nickel exposure is linked to respiratory issues, kidney damage, and increased cancer risks, while its environmental contamination disrupts aquatic ecosystems and biodiversity. In 2024, Indonesia's Central Statistics Agency (BPS) shows that nickel exports will increase by up to 45.85% [3]. In Sulawesi and Maluku, nickel concentrations in water exceed safe limits, and over 5,300 hectares of deforestation intensifies climate change [4], [5]. Industrial hubs like Morowali also experience high PM2.5 levels beyond WHO standards, highlighting the need for stricter regulations.

Biomass waste composed of lignocellulosic materials like lignin, cellulose, and hemicellulose, holds promise for sustainable energy and bioadsorbents with cellulose providing mechanical strength and lignin enhancing structural integrity while resisting microbial degradation [6][7][8]. In Indonesia, with a biomass energy potential of 49,810 MW, utilization remains suboptimal due to competing industrial demands [9]. Agricultural waste such as

DOI:10.4186

sugarcane sludge, palm shells, rice husks, and corn cobs offers significant bioadsorbent potential due to functional groups like phenolic, hydroxyl, and carboxyl which facilitate heavy metal adsorption [10], [11]. Heavy metal pollution from mining and electroplating industries has increased interest in adsorption as a cost-effective, eco-friendly alternative to chemical precipitation, and ion exchange. Lignocellulose-based sludge, with its porous structure and active functional groups, effectively removes hazardous metals while repurposing waste. Additionally, biomass waste management mitigates methane emissions which have 21 times the atmospheric impact of CO_2, reinforcing its role in pollution control [12] Integrating lignocellulose-based bioadsorbents into remediation efforts benefits both environmental protection and sustainable resource utilization, necessitating further research and policy support.

Adsorbents capture and retain molecules or ions on their surface through physical or chemical interactions, making them essential in wastewater treatment, air purification, and catalysis. Adsorption, a surface-based process, enables contaminant removal via materials like activated carbon, zeolites, and silica gels, each with distinct mechanisms based on porosity and surface properties [13]. Bioadsorbents derived from biomass offer a sustainable alternative for heavy metal remediation due to their abundance and eco-friendliness. Cellulose-based adsorbents, particularly poly(hydroxamic acid) and poly(amidoxime) ligands, achieve up to 90% nickel removal from electroplating wastewater [14]. Their high reusability enhances economic viability in wastewater treatment. Nanocellulose-based adsorbents further improve adsorption efficiency with a high surface area and tunable surface chemistry, especially when functionalized with carboxylate groups for metal ion removal [15]. These materials also offer superior mechanical stability for industrial applications. As renewable, modifiable, and non-toxic materials, cellulose-based adsorbents align with green chemistry principles, making them a cost-effective and sustainable solution for heavy metal contamination.

The simplest bio adsorbent production method involves biomass carbonization through pretreatment including cleaning and drying, followed by pyrolysis at 300–700°C under low oxygen to remove volatiles and increase carbon content[16]. Activation uses chemical agents like KOH, $ZnCl_2$, or H_3PO_4, or physical methods like steam or CO_2 heating, though lignin hinders carbonization and reduces adsorption capacity [17]. To improve adsorption with NaOH or H_2O_2 before carbonization enhances pore structure but adds processing time and chemical waste management challenges.

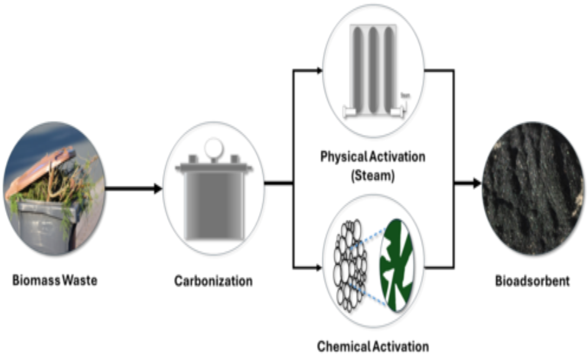

Fig 1. Biomass based adsorbent production.

This study compares two biomass based adsorbent production methods to identify the most effective technique for creating environmentally friendly bio adsorbents with superior adsorption capacity as shown on Figure 1.

The study evaluates chemical activation, physical activation, and surface modification based on adsorption efficiency, raw material availability, and environmental and economic impacts. While activated carbon has a large surface area and strong adsorption capacity, its regeneration requires high energy, increasing costs. Its adsorption ability declines at high heavy metal concentrations, and spent activated carbon poses disposal challenges. This research aims to identify a more sustainable, efficient, and cost-effective bio adsorbent production method for industrial wastewater treatment with minimal environmental impact.

2. Materials and Method

2.1. Materials

The global accessibility of biomass provides a sustainable basis for the development of novel functional materials. Biomass resources derived from plant, animal, and microbial sources offer considerable potential as renewable feedstocks in various geographical areas. These organic compounds consist of complex biopolymers, including cellulose, hemicellulose, and lignin, which provide carbon frameworks and functional groups for material applications.

Biomass presents in various specific forms amenable to valorisation: (1) forestry residues (wood chips, sawdust, and associated lignocellulosic byproducts), (2) agricultural wastes (crop residues, straw, and husks), (3) industrial processing byproducts (food waste, paper sludge), and (4) aquatic biomass (macroalgae and hydrophytes)[18], [19], [20], [21], [22], [23]. Agricultural residues like rice straw and wheat straw exhibit significant potential as biomass-based adsorbents owing to their low economic value, widespread availability, and advantageous physicochemical characteristics.

Likewise, underutilised soybean hulls demonstrate considerable capacity for heavy metal absorption, especially for Pb(II) and Cd(II) ions, due to their abundant surface functionalities, which include carbonyl, phenolic, acetamido, alcoholic, amido, amino, and sulfhydryl groups that promote metal coordination[24].

Biomass ash, a waste of agroindustrial processing, when modified with chitosan and graphene oxide composites, has improved adsorption efficiencies of 69.5% for Cu(II) and 74.7% for Cr(VI)[25]. Aquatic macrophytes represent a significant resource; Lemna minor (duckweed) accumulates metals via indirect absorption mechanisms, translocating toxic metals from roots to shoots, whereas Ceratophyllum demersum demonstrates substantial adsorption capacities for aqueous heavy metals: 6.17 mg/g (Cu(II)), 13.98 mg/g (Zn(II)), and 44.8 mg/g (Pb(II))[26], [27].

2.2. Method

Referring to these problems, several discussions on heavy metal adsorption using biomass have led to the identification of two primary methods. These methods focus on enhancing the adsorption efficiency and sustainability of biomass-based adsorbents.

a. Carbonization - Activation using steam Method

Carbonization using the steam activation method involves heating carbon-rich materials in an inert atmosphere followed by exposure to steam at high temperatures (700–1000°C) to enhance porosity and surface area[28], [29], [30].

b. Carbonization - Chemical Activation Method

Carbonization using the chemical activation method involves impregnating raw biomass with

Table 1. Comparison between biomass materials and production method

No.	Materials	Method	Adsorption Capacity (mg/g)	Activation Agent	Ref.
1	Grape Industrial Waste	Carbonization → Physical Activation	75 (Cd^{2+}); 399 (Pb^{2+})	Steam	[50]
2	Spruce Sawdust	Carbonization → Physical Activation	17.2 (Zn^{2+}); 6.6 (Ni^{2+}); 4.5 (Co^{2+})	Steam	[54]
3	Date Pits	Carbonization → Physical Activation	165 (Cu^{2+}); 329 (Fe^{2+})	Steam	[55]
4	Tobacco Biomass	Carbonization → Physical Activation	62.23 (Cr(VI))	Microwave Steam	[52]
5	Palm Kernel Shell	Carbonization → Physical Activation	116 (Cd^{2+}); 59.9 (Pb^{2+})	Microwave Steam	[53]
6	Olive Stone	Carbonization → Chemical Activation	186.77 (Pb^{2+})	KOH	[56]
7	Almond Shells	Carbonization → Chemical Activation	182.69 (Pb^{2+})	KOH	[56]
8	Walnut Shells	Carbonization → Chemical Activation	204.08 (Cu^{2+})	HNO_3;KOH	[51]
9	Walnut Shells	Carbonization → Chemical Activation	210.14 (Pb^{2+})	$KMnO_4$, n-hexane, acrylic acid, acetone	[57]

chemical agents such as potassium hydroxide (KOH), phosphoric acid (H_3PO_4), or zinc chloride ($ZnCl_2$) before thermal treatment. During carbonization at moderate temperatures (400–1000°C)[36], [37], the activating agents enhance the porous structure by dehydrating and oxidizing the material, thereby improving its surface area and adsorption capacity. This method is widely used for producing activated carbon with high surface area and tunable pore structures, making it ideal for applications in adsorption, catalysis, and energy storage.

The formation of pore structures is determined by the physicochemical interactions between the activating agent and the carbon framework, which encompass the adsorption energies of both reactants and products [47], [48]. The increased adsorption energy of products correlates with enhanced pore activity. Finally, the flow rate of the activating medium influences the textural and fractal properties of the carbon, where increased flow rates result in smoother fractal structures and a decrease in the surface fractal dimension[49].

3. Results and Discussion

The difference between the two methods can be compared based on their efficiency and adsorption capacity. The phenomenon that occurs can also be explained in detail regarding the results obtained. Based on the Table 1. The adsorption process of heavy metals occurs when metal ions from a solution bind to the surface of an adsorbent material through physical and chemical mechanisms. In this study, several biomass show the highest performance in adsorbing toxic heavy metal ions such as Pb^{2+}, Hg^{2+}, and As^{3+}.

Data from table 1 indicate that numerous heavy metal ions demonstrate considerable adsorption capacities on diverse biomass-based adsorbents. Pb^{2+} ions exhibited the maximum adsorption capacity of 399 mg/g when utilising adsorbents derived from wine industry waste[50], which underwent carbonisation and steam activation at 973 K for 165 minutes, with a steam flow rate of 11.7 g/(g·hour).

Optimal adsorption of Fe^{2+} ions (329 mg/g) was attained using steam-activated spruce sawdust adsorbents [52]. Alternative physical activation methods yielded satisfactory outcomes, exemplified by the adsorption of Cd^{2+} ions (116 mg/g) utilising palm kernel shell-based adsorbents activated through microwave-assisted steam. The process duration was 45 minutes at 700°C, utilising a flow rate of 5 g/minute, thereby enhancing thermal efficiency relative to traditional methods[53].

The steam activation process facilitates the formation of oxygenated surface functional groups, including carboxyl, lactone, and phenolic hydroxyl moieties, which significantly improve heavy metal uptake via multiple interaction mechanisms [31], [32]. These surface functionalities promote metal ion adsorption through both ion exchange processes and chemisorption interactions, as evidenced by enhanced Pb(II) and Cd(II) removal efficiencies. The presence of these oxygen-containing groups has been demonstrated to be a critical determinant of adsorption performance, serving as active sites for metal ion coordination and complexation [31], [33].

The adsorption kinetics of heavy metal ions onto steam-activated carbon surfaces typically exhibit strong correlation with pseudo-second-order kinetic models, suggesting a predominance of chemisorption mechanisms. This behavior reflects rate-limiting surface reactions involving electron sharing or exchange between metal cations and oxygen-containing functional groups on the activated carbon matrix [33], [34], [35].

The properties of activated carbon are influenced by various factors, including activation temperature, duration, method and ratio, precursor material type, pretreatment techniques, activation atmosphere, physicochemical interactions, and the flow rate of the activating agent.

Higher activation temperatures encourage the formation of microporous and mesoporous structures, which enhance the surface area and total pore volume [38], [39], [40]. Prolonged activation durations enhance pore size distribution, facilitating the development of more sophisticated pore networks [39], [41], [42].

On the other side, Walnut shell-based adsorbents, chemically activated with HNO_3 and KOH, exhibited a maximum adsorption capacity of 204.08 mg/g for Cu^{2+} ions [51]. The use of KOH in chemical activation methods is notably effective for the formation of microporous structures, with pore development efficiency being significantly influenced by the precursor-to-activator ratio [41], [43], [44], [45]. Biomass-based precursors typically produce more uniform and well-developed pore structures owing to their aliphatic characteristics, in contrast to those derived from coal [46].

Pretreatment techniques, including milling, sieving, and ash elimination, improve the quality of carbon by enhancing surface area and the hierarchical structure of pores. The composition of the activation atmosphere is significant; for instance, the presence of CO_2 can enhance mesopore formation by affecting reaction kinetics [41], [42].

The comparison of steam activation and chemical activation involves not only adsorption capacity but also the characteristics of pore surfaces. Steam activation typically necessitates elevated temperatures ranging from 600 to 1000°C, whereas chemical activation functions within a temperature range of 600 to 900°C. Despite the relatively similar temperature ranges, it is essential to investigate the fundamental differences in mechanisms and their effects on pore structure for specific applications in heavy metal adsorption.

4. Conclusions

This study underscores the considerable efficacy of biomass-derived adsorbents in the extraction of heavy metal ions from industrial effluents. The comparative analysis of steam activation and chemical activation methods indicates that both procedures possess significant adsorption capacities, with steam activation often necessitating elevated temperatures and chemical activation allowing for adjustable pore shapes. The maximum adsorption capacity for Pb^{2+} ions was recorded at 399 mg/g utilising steam-activated adsorbents sourced from wine industry waste. Adsorbents derived from walnut shells and chemically activated with HNO_3 and KOH exhibited a maximum adsorption capacity of 204.08 mg/g for Cu^{2+} ions.

The results highlight the necessity of choosing suitable activation techniques according to particular heavy metal ions and targeted adsorption capabilities. The result underscores the necessity for additional research into the fundamental mechanisms of pore structure creation and their influence on adsorption efficiency. Incorporating biomass waste into sustainable remediation initiatives alleviates environmental degradation, enhances resource utilisation, and diminishes carbon footprints.

Reference

[1] P. B. Tchounwou, C. G. Yedjou, A. K. Patlolla, and D. J. Sutton, "Heavy Metals Toxicity and the Environment," EXS, vol. 101, p. 133, 2012, doi: 10.1007/978-3-7643-8340-4_6.

[2] T. E. Oladimeji, M. Oyedemi, M. E. Emetere, O. Agboola, J. B. Adeoye, and O. A. Odunlami, "Review on the impact of heavy metals from industrial wastewater effluent and removal technologies," Heliyon, vol. 10, no. 23, p. e40370, Dec. 2024, doi: 10.1016/J.HELIYON.2024.E40370.

[3] "BPS Catat Nilai Ekspor Nikel Naik 45,85 Persen pada April 2024 | tempo.co." Accessed: May 06, 2025. [Online]. Available: https://www.tempo.co/ekonomi/bps-catat-nilai-ekspor-nikel-naik-45-85-persen-pada-april-2024-58863

[4] "Penelitian Sebut Industri Nikel Merusak Hutan dan Lingkungan Indonesia | tempo.co." Accessed: May 06, 2025. [Online]. Available: https://www.tempo.co/ekonomi/penelitian-sebut-industri-nikel-merusak-hutan-dan-lingkungan-indonesia-94498

[5] "Nikel Indonesia: Limbah tambang mengancam lingkungan di Sulawesi Tenggara - 'Yang kamu rusak adalah masa depannya' - BBC News Indonesia." Accessed: May 06, 2025. [Online]. Available: https://www.bbc.com/indonesia/articles/c870n03351xo

[6] E. Ahmad and K. K. Pant, "Lignin Conversion: A Key to the Concept of Lignocellulosic Biomass-Based Integrated Biorefinery," Waste Biorefinery: Potential and Perspectives, pp. 409–444, Jan. 2018, doi: 10.1016/B978-0-444-63992-9.00014-8.

[7] C. G. Yoo, X. Meng, Y. Pu, and A. J. Ragauskas, "The critical role of lignin in lignocellulosic biomass conversion and recent pretreatment strategies: A comprehensive review," Bioresour Technol, vol. 301, p. 122784, Apr. 2020, doi: 10.1016/J.BIORTECH.2020.122784.

[8] B. C. Pertiwi, J. Juliananda, N. M. I. P. Suari, W. Widiyastuti, T. Nurtono, and H. Setyawan, "Solar-Driven Water Purification for Sustainable Clean Water Supply," AIP Conf Proc, vol. 3073, no. 1, Mar. 2024, doi: 10.1063/5.0193793/3269538.

[9] S. Yana, M. Nizar, Irhamni, and D. Mulyati, "Biomass waste as a renewable energy in developing bio-based economies in Indonesia: A review," Renewable and Sustainable Energy Reviews, vol. 160, p. 112268, May 2022, doi: 10.1016/J.RSER.2022.112268.

[10] S. S. Santi, B. C. Pertiwi, M. P. N. Matovanni, I. S. Cakradetha, and Suriyanto, "Study on Indonesian corn cob particle size in fast pyrolisis bio-oil," IOP Conf Ser Earth Environ Sci, vol. 1454, no. 1, p. 012011, Feb. 2025, doi: 10.1088/1755-1315/1454/1/012011.

[11] N. Karić et al., "Bio-waste valorisation: Agricultural wastes as biosorbents for removal of (in)organic pollutants in wastewater treatment," Chemical Engineering Journal Advances, vol. 9, p. 100239, Mar. 2022, doi: 10.1016/J.CEJA.2021.100239.

[12] A. Arif Setiawan, S. Eddy, K. Risky Midia, P. Studi Sains Lingkungan, and F. Sains dan Teknologi, "Potensi Limbah Biomassa Sebagai Bioadsorben Dalam Menanggulangi Pencemaran Logam Berat," Environmental Science Journal (esjo) : Jurnal Ilmu Lingkungan , pp. 29–38, Dec. 2022, doi: 10.31851/ESJO.V1I1.11126.

[13] K. Y. Foo and B. H. Hameed, "Insights into the modeling of adsorption isotherm systems," Chemical Engineering Journal, vol. 156, no. 1, pp. 2–10, Jan. 2010, doi: 10.1016/J.CEJ.2009.09.013.

[14] M. L. Rahman et al., "Poly(hydroxamic acid) ligand from cornstalk cellulose for heavy metal recovery from electroplating wastewater," Sustain Chem Pharm, vol. 43, p. 101871, Feb. 2025, doi: 10.1016/J.SCP.2024.101871.

[15] V. Nagendran, L. C. Goveas, R. Vinayagam, T. Varadavenkatesan, and R. Selvaraj, "Challenges and advances in nanocellulose-based adsorbents for dye removal: mechanisms and future directions," Discover Applied Sciences 2024 7:1, vol. 7, no. 1, pp. 1–23, Dec. 2024, doi: 10.1007/S42452-024-06413-Z.

[16] F. Amalina, A. S. A. Razak, S. Krishnan, H. Sulaiman, A. W. Zularisam, and M. Nasrullah, "Biochar production techniques utilizing biomass waste-derived materials and environmental applications – A review," Journal of Hazardous Materials Advances, vol. 7, p. 100134, Aug. 2022, doi: 10.1016/J.HAZADV.2022.100134.

[17] I. Neme, G. Gonfa, and C. Masi, "Activated carbon from biomass precursors using phosphoric acid: A review," Heliyon, vol. 8, no. 12, p. e11940, Dec. 2022, doi: 10.1016/J.HELIYON.2022.E11940.

[18] M. A. Alfasane, A. Akhtar, N. S. Lopa, and M. M. Rahman, "Introduction to biomass," in Biomass-Based Supercapacitors: Design, Fabrication and Sustainability, wiley, 2023, pp. 3–21. doi: 10.1002/9781119866435.ch1.

[19] E. Christoforou and P. A. Fokaides, "Biomass raw material," in Green Energy and Technology, vol. PartF1, Springer Verlag, 2019, pp. 5–24. doi: 10.1007/978-3-030-00862-8_2.

[20] A. Ephraim, P. Arlabosse, A. Nzihou, D. P. Minh, and P. Sharrock, "Biomass categories," in Handbook on Characterization of Biomass, Biowaste and Related By-products, Springer International Publishing, 2020, pp. 1–29. doi: 10.1007/978-3-030-35020-8_1.

[21] M. F. Demirbas, M. Balat, and H. Balat, "Potential contribution of biomass to the sustainable energy development," Energy Convers Manag, vol. 50, no. 7, pp. 1746–1760, Jul. 2009, doi: 10.1016/j.enconman.2009.03.013.

[22] R. Blanchard, "Biomass heating," in Domestic Microgeneration: Renewable and Distributed Energy Technologies, Policies and Economics, Taylor and Francis, 2015, pp. 77–101. doi: 10.4324/9781315697109-12.

[23] N. A. S. Amin, J. Akhtar, and S. Karagoz, "Hydrothermal liquefaction of biomass," in Sustainable Bioenergy Production, CRC Press, 2014, pp. 383–400. doi: 10.1201/b16764.

[24] D.-I. Ferţu et al., "Circular Approach of Using Soybean Biomass for the Removal of Toxic Metal Ions from Wastewater," Water (Switzerland), vol. 16, no. 24, p. 3663, Dec. 2024, doi: 10.3390/w16243663.

[25] S. Omer, A. Singh, and S. Upadhyay, "Synthesis of chitosan-g-biomass ash/graphene oxide nanocomposite for the removal of copper and chromium from industrial waste water," Clay Research, vol. 38, no. 1, pp. 19–28, Jan. 2019, Accessed: May 10, 2025. [Online]. Available: https://www.scopus.com/record/display.uri?eid=2-s2.0-85076893947&origin=scopusAI

[26] O. Keskinkan, M. Z. L. Goksu, M. Basibuyuk, and C. F. Forster, "Heavy metal adsorption properties of a submerged aquatic plant (Ceratophyllum demersum)," Bioresour

Technol, vol. 92, no. 2, pp. 197–200, Apr. 2004, doi: 10.1016/j.biortech.2003.07.011.

[27] G. Y. Töre and Ö. B. Özkoç, "Recent developments in aquatic macrophytes for environmental pollution control: A case study on heavy metal removal from lake water and agricultural return wastewater with the use of duckweed (Lemnacea)," in Phytoremediation Technology for the Removal of Heavy Metals and Other Contaminants from Soil and Water, Elsevier, 2022, pp. 75–127. doi: 10.1016/B978-0-323-85763-5.00005-2.

[28] L. Zhang and S. Zuo, "The Significance of Lignocellulosic Raw Materials on the Pore Structure of Activated Carbons Prepared by Steam Activation," Molecules, vol. 29, no. 13, p. 3197, Jul. 2024, doi: 10.3390/molecules29133197.

[29] C. I. D. C. Bueno and W. A. Carvalho, "Lead(II) removal in discontinous systems by carbon activated by phosphoric acid and vapor[Remoção de chumbo(II) em sistemas descontínuos por carvões ativados com ácido fosfórico e com vapor]," Quim Nova, vol. 30, no. 8, pp. 1911–1918, Jan. 2007, doi: 10.1590/s0100-40422007000800022.

[30] S. Tuomikoski, H. Runtti, H. Romar, U. Lassi, and T. Kangas, "Multiple heavy metal removal simultaneously by a biomass-based porous carbon," Water Environment Research, vol. 93, no. 8, pp. 1303–1314, Aug. 2021, doi: 10.1002/wer.1514.

[31] M. Song, Y. Wei, S. Cai, L. Yu, Z. Zhong, and B. Jin, "Study on adsorption properties and mechanism of Pb2 + with different carbon based adsorbents," Science of the Total Environment, vol. 618, pp. 1416–1422, Mar. 2018, doi: 10.1016/j.scitotenv.2017.09.268.

[32] E. R. Tarigan, E. Frida, S. Humaidi, and Susilawati, "Adsorption Mechanism of Heavy Metals Using Activated Carbon Derived from Hydrilla Verticillata," Trends in Sciences, vol. 22, no. 1, p. 8732, Jan. 2025, doi: 10.48048/tis.2025.8732.

[33] S. H. Kong et al., "Removal of heavy metals using activated carbon from microwave steam activation of palm kernel shell," Environmental Advances, vol. 9, p. 100272, Oct. 2022, doi: 10.1016/j.envadv.2022.100272.

[34] J. Yan and R. Li, "Simple and low-cost production of magnetite/graphene nanocomposites for heavy metal ions adsorption," Science of the Total Environment, vol. 813, p. 152604, Mar. 2022, doi: 10.1016/j.scitotenv.2021.152604.

[35] C. K. Ahn, D. Park, S. H. Woo, and J. M. Park, "Removal of cationic heavy metal from aqueous solution by activated carbon impregnated with anionic surfactants," J Hazard Mater, vol. 164, no. 2–3, pp. 1130–1136, May 2009, doi: 10.1016/j.jhazmat.2008.09.036.

[36] D. Bergna et al., "Activated carbon from renewable sources: Thermochemical conversion and activation of biomass and carbon residues from biomass gasification," in Waste Biomass Management - A Holistic Approach, Springer International Publishing, 2017, pp. 187–213. doi: 10.1007/978-3-319-49595-8_9.

[37] D. Bergna et al., "Activated carbon from renewable sources: Thermochemical conversion and activation of biomass and carbon residues from biomass gasification," in Waste Biomass Management - A Holistic Approach, Springer International Publishing, 2017, pp. 187–213. doi: 10.1007/978-3-319-49595-8_9.

[38] H. Zhang, J. Chen, and S. Guo, "Preparation of natural gas adsorbents from high-sulfur petroleum coke," Fuel, vol. 87, no. 3, pp. 304–311, Mar. 2008, doi: 10.1016/j.fuel.2007.05.002.

[39] J. Zhang et al., "Preparation of carbonaceous adsorbent used for separation of methane/nitrogen in coal bed methane[煤层气中甲烷/氮气分离用椰壳活性炭的制备]," Meitan Xuebao/Journal of the China Coal Society, vol. 44, no. 4, pp. 1129–1137, Apr. 2019, doi: 10.13225/j.cnki.jccs.2018.0622.

[40] Y. J. Kim, I. Hong, J. Shim, and J. C. An, "Preparation and characterization of black liquor-derived activated carbon by self-chemical activation," Carbon Letters, vol. 30, no. 2, pp. 115–121, Apr. 2020, doi: 10.1007/s42823-020-00132-2.

[41] D. V. Cuong, N. L. Liu, V. A. Nguyen, and C. H. Hou, "Meso/micropore-controlled hierarchical porous carbon derived from activated biochar as a high-performance adsorbent for copper removal," Science of the Total Environment, vol. 692, pp. 844–853, Nov. 2019, doi: 10.1016/j.scitotenv.2019.07.125.

[42] Z. Qie et al., "Effect of pretreatment and activation conditions on pore development of coal-based activated carbon," Journal of Industrial and Engineering Chemistry, vol. 139, pp. 611–619, Nov. 2024, doi: 10.1016/j.jiec.2024.05.037.

[43] Q. Li et al., "Preparation of biomass-derived porous carbons by a facile method and application to CO2 adsorption," J Taiwan Inst Chem Eng, vol. 116, pp. 128–136, Nov. 2020, doi: 10.1016/j.jtice.2020.11.001.

[44] L. an Xing et al., "Ultra-microporous cotton fiber-derived activated carbon by a facile one-step chemical activation strategy for efficient CO2 adsorption," Sep Purif Technol, vol. 324, p. 124470, Nov. 2023, doi: 10.1016/j.seppur.2023.124470.

[45] D. Luxembourg, X. Py, A. Didion, R. Gadiou, C. Vix-Guterl, and G. Flamant, "Chemical activations of herringbone-type nanofibers," Microporous and Mesoporous Materials, vol. 98, no. 1–3, pp. 123–131, Jan. 2007, doi: 10.1016/j.micromeso.2006.08.024.

[46] C. Li et al., "Activation of poplar sawdust and anthracite coal: Distinct involvement of aliphatic and aromatic structures in pore development," Biomass Bioenergy, vol. 190, p. 107392, Nov. 2024, doi: 10.1016/j.biombioe.2024.107392.

[47] E. E. Santiso, "Understanding the effect of adsorption on activated processes using molecular theory and simulation," Mol Simul, vol. 40, no. 7, pp. 664–677, Aug. 2014, doi: 10.1080/08927022.2013.840903.

[48] S. Furmaniak, P. A. Gauden, P. Kowalczyk, and A. Patrykiejew, "Monte Carlo study of chemical reaction equilibria in pores of activated carbons," RSC Adv, vol. 7, no. 85, pp. 53667–53679, Jan. 2017, doi: 10.1039/c7ra08992a.

[49] M. M. Mahamud, "Textural changes during CO 2 activation of chars: A fractal approach," Appl Surf Sci, vol. 253, no. 14, pp. 6019–6031, May 2007, doi: 10.1016/j.apsusc.2006.12.109.

[50] F. Sardella, M. Gimenez, C. Navas, C. Morandi, C. Deiana, and K. Sapag, "Conversion of viticultural industry wastes into activated carbons for removal of lead and cadmium," J Environ Chem Eng, vol. 3, no. 1, pp. 253–260, Mar. 2015, doi: 10.1016/J.JECE.2014.06.026.

[51] S. Tuomikoski, H. Runtti, H. Romar, U. Lassi, and T. Kangas, "Multiple heavy metal removal simultaneously by a biomass-based porous carbon," Water Environment Research, vol. 93, no. 8, pp. 1303–1314, Aug. 2021, doi: 10.1002/wer.1514.

[52] C. Bouchelta, M. S. Medjram, M. Zoubida, F. A. Chekkat, N. Ramdane, and J. P. Bellat, "Effects of pyrolysis conditions on the porous structure development of date pits activated carbon," J Anal Appl Pyrolysis, vol. 94, pp. 215–222, Mar. 2012, doi: 10.1016/J.JAAP.2011.12.014.

[53] L. Gonsalvesh, J. Yperman, R. Carleer, M. Mench, R. Herzig, and J. Vangronsveld, "Valorisation of heavy metals enriched tobacco biomass through slow pyrolysis and steam activation," Journal of Chemical Technology and Biotechnology, vol. 91, no. 6, pp. 1585–1595, Jun. 2016, doi: 10.1002/JCTB.4889;REQUESTEDJOURNAL:JOURNAL:10974660;JOURNAL:JOURNAL:10974660;WGROUP:STRING:PUBLICATION.

[54] S. H. Kong et al., "Removal of heavy metals using activated carbon from microwave steam activation of palm kernel shell," Environmental Advances, vol. 9, p. 100272, Oct. 2022, doi: 10.1016/J.ENVADV.2022.100272.

[55] V. Rahimi, C. H. Pimentel, D. Gómez-Díaz, M. S. Freire, M. Lazzari, and J. González-Álvarez, "Development and Characterization of Biomass-Derived Carbons for the Removal of Cu2+ and Pb2+ from Aqueous Solutions," C-Journal of Carbon Research, vol. 11, no. 1, p. 2, Mar. 2025, doi: 10.3390/c11010002.

[56] R. Xie, H. Wang, Y. Chen, and W. Jiang, "Walnut shell-based activated carbon with excellent copper (II) adsorption and lower chromium (VI) removal prepared by acid-base modification," Environ Prog Sustain Energy, vol. 32, no. 3, pp. 688–696, Oct. 2013, doi: 10.1002/EP.11686;WGROUP:STRING:PUBLICATION.

[57] L. Cheng, L. Sun, W. Xue, Z. Zeng, and S. Li, "Adsorption equilibrium and kinetics of Pb(II) from aqueous solution by modified walnut shell," Environ Prog Sustain Energy, vol. 35, no. 6, pp. 1724–1731, Nov. 2016, doi: 10.1002/EP.12424.