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Biochar from Peanut Shell: Sustainable Adsorbent for Heavy Metal Remediation

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Abstract

The contamination of water resulting from agricultural and industrial processes needs efficient, non-toxic, and cost-effective remediation processes. Adsorption has been proven to be an effective method for removing heavy metals from water. A new sustainable alternative from agricultural waste enthusiasm the researchers because conventional adsorbents, such as activated carbon, are effective but expensive and non-renewable. The lignocellulosic composition of peanut shell waste provides great potential as an alternative adsorbent. The adsorption capacity increases with chemical and physical modifications, which elevate their porous structure and surface functional groups. Biochar formed from peanut shells successfully removes contaminants, adding acidic groups like carboxyl and sulfonate to optimize metal ion binding, such as sulfuric acid, nitric acid, and potassium hydroxide. However, there is limited research on large scale applications in complex wastewater and adsorbent regeneration where these adsorbents of wastewater treatment are only successful in the lab. It is important to perform multidisciplinary studies that combine technological, economic, and environmental factors as the advancement of sustainable water treatment is derived from peanut shells.

Keywords: Chemical modification, Peanut shell biochar, Heavy metal removal

INTRODUCTION

In this modern life, the rise in water pollution is undeniable, mostly caused by industrial and agricultural activity. here is an urgent need to develop efficient, environmentally friendly, and low-cost water treatment methods (Ahmad *et al.*, 2023; Soon *et al.*, 2022). Critical conditions were found in the Hantu River, South Sumatra, where cadmium and lead exceeded drinking water standards by 200% due to intensive use of pesticides and Palm Oil Mill Effluent (POME), with regression models showing contributions to Cd (89.6%) and Pb (92.3%) pollution (Candra *et al.*, 2024). A highly advantageous method for the removal of pollutants, such as dyes, heavy metals, and nutrients, from water-based systems was recognised: adsorption (Dutta *et al.*, 2021; Sheraz *et al.*, 2024; Singh *et al.*, 2024). Conventional adsorbents, like activated carbon and synthetic polymers, prove a remarkable potency in the removal efficiencies. Nevertheless, their high production costs and frequently nonrenewable sources have generated considerable interest in investigating sustainable options derived from agricultural waste (Karić *et al.*, 2022; Mathabatha *et al.*, 2023).

A peanut shell, which is primarily made of lignocellulosic compounds, is one of the most abundant forms of agricultural waste and is generated in significant quantities worldwide (Mathabatha *et al.*, 2023; Siqueira *et al.*, 2022). If not properly utilized, peanut shells contribute to environmental pollution; thus, converting them into value-added materials is an important step toward waste minimization. Therefore, the highest priority is converting this waste into value-added products (Blasi *et al.*, 2023). Many researchers highlighted the potential of adsorbents derived from peanut shells, especially their porous

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structure and surface functionality. Various chemical or physical modification factors will optimize the adsorption performance directly (Ahmad *et al.*, 2023).

The conversion of peanut shells into biochar is an example of a directly scientific contribution to the sustainability of resources and the remediation of pollutants.Produced biochar is utilized as a long-term adsorbent to draw out polluted water containing heavy metals (such as the Pb^{2+}, Cr^{6+}, Cd^{2+}). Instead of simply burning or landfilling peanut shells, this process transforms agricultural waste into a useful resource for cleaning up the environment, which diminishes the requirement for adsorbents that consist of fossil fuels, such as activated carbon.

The effectiveness of peanut shell-based as asorbents in eliminating of a variety of substances from industrial waste has been scientifically validated by many types of studies. The modified biochar with acid functional groups from peanut shells achieved a Pb(II) removal rate of 76.0% and an adsorption capacity of 148.6 mg/g under optimal conditions (Wu *et al.*, 2024). This performance far exceeds that of standard activated carbon, which only reached a 39.7% removal rate with an adsorption capacity of 83.1 mg/g. (Abiodun *et al.*, 2023; Ahmad *et al.*, 2023; Panchal *et al.*, 2020).

Additional functional groups as modification strategies, improve the selectivity and capacity of peanut shell adsorbents (Xu *et al.*, 2023). The efficient removal of hazardous substances, the reusability of sorbents, and the decrease of residual waste are all ways in which these novel improvements contribute to the larger trend toward green chemistry and industrial ecology (Murtaza *et al.*, 2022; Rehman *et al.*, 2023).

The remains substantial knowledge gaps that inhibit peanut shell biochar from being practically applied in Indonesia, nevertheless there have been promising results in the lab. First, most studies utilize synthetic wastewater under ideal batch conditions, neglecting the complex matrix effects of real industrial effluents prevalent in Indonesia, such as palm oil mill effluent (POME) and textile wastewater (Abiodun *et al.*, 2023; Bayuo *et al.*, 2023; Karić *et al.*, 2022). Secondly, there has been limited study on adsorbent regeneration and long-term stability in continuous flow systems, which makes a question whether these systems are economically feasible for small-scale businesses. Finally, there is an alarming absence of life cycle analysis and comprehensive techno-economic analyses specific to the context of agricultural waste management in Indonesia Blasi *et al.*, 2023; Fauzi *et al.*, 2019). This review addresses these gaps by critically evaluating the readiness of peanut shell biochar technology for sustainable water treatment applications in Indonesia, while identifying key research priorities for scaling up from laboratory to practical implementation.

METHODOLOGY

This study supports a literature review approach to systematically identify and evaluate the relevant scope of research papers. Literature review assists in the comprehensive analysis of relevant articles, providing a powerful theoretical foundation (Esquiaqui *et al.*, 2023). The literature review procedure complies with the methodology structure, featuring three key stages: (1) identification of recent publications, (2) the screening and critical review of information, and (3) synthesis and evaluation of research. Data were sourced from reputable international journals such as Scopus, one of the most credible resources for peer-reviewed literature (Moshood *et al.*, 2022). To preserve relevance, the selection criteria were restricted to publications from 2019 to 2025, with a focus on review articles and original research articles presenting agricultural waste applications as adsorbents.

The specific focus is "The Potential of Agricultural Wastes from Peanut Shells as a Biochar Adsorbent" to relate to the paper's main theme. At first, investigations followed 100–200 articles, which were reviewed forrelevance, methodological accuracy, and acceptance with the research objectives. After systematic sorting, 40 publications were retained for final analysis, as they provided the most significant perceptions into biochar adsorbents derived from peanut shells.

RESULTS AND DISCUSSION

The global environmental crisis demands immediate action on waste treatment. Agricultural waste, particularly peanut shells, which represent a source of lignocellulosic biomass waste, is produced at more than 10 million tons worldwide and often discarded or burned (Hashem *et al.*, 2024).

Unfortunately, their application rates remain below 20%, highlighting their unrealised potential as sustainable waste (Osman *et al.*, 2023). A promising solution involves converting agricultural residues into biochar and activated carbon, which can effectively remove pollutants. Peanut shell biochar demonstrates high adsorption potential as a cost-effective and environmentally friendly material. The principle of recycling waste into valuable materials, decreasing pollution, and developing a sustainable industry was approved for this transformation (Gama *et al.*, 2022; Mathabatha *et al.*, 2023). Pyrolysis of biomass under limited oxygen conditions produces biochar as an adsorbent, which demonstrates the ability to absorb contaminants like heavy metals, pesticides, and organic pollutants from water and soil due to a high surface area, porous structure, and functional groups such as carboxyl and hydroxyl in peanut shells (Gama *et al.*, 2022; Mathabatha *et al.*, 2023; Wu *et al.*, 2024).

Characteristics of biomass, pyrolysis temperature, and processing conditions impact to final biochar yield (Laila *et al.*, 2024), where fixed carbon denotes that peanut shell biochar has the highest fixed carbon, indicating the quality suitability as an adsorbent. A summary of the potential in agricultural waste for biochar production is suitable in Table 1.

Analysis of Peanut Shell Adsorbent

The sources of lignocellulosic biomass waste, like peanut shells, are interesting to investigate as adsorbents since their unique mesoporous structure. The characterization tests reported surface areas of 158.7 m^2/g and average pore widths of roughly 8.5 nm, similar to commercial activated carbons (Wang *et al.*, 2024; L. Zhang *et al.*, 2023).

Thermogravimetric analysis identified an exceptional thermal stability with less than 5% mass loss recorded below 438°C–501°C (Bernard Himbane & Grand Ndiaye, 2024; Gama *et al.*, 2022), indicating a stable carbonaceous matrix accompanied by amorphous features and suggesting suitability for industrial wastewater applications where temperature fluctuations are common (Komala *et al.*, 2021; Shan *et al.*, 2020). Surface chemistry analysis through FTIR spectroscopy confirmed the presence of key functional groups like carboxyl (COOH) and hydroxyl (OH) that facilitate metal ion binding (Li *et al.*, 2018; Wu *et al.*, 2024). XPS data confirms a shift in the state of the oxidation and denotes a metal coordination with oxygen functional groups (Lu *et al.*, 2022; Tran *et al.*, 2019). Furthermore, the XPS analysis for Pb 4f region at the molecular level describes an inner sphere complexation. The shifting of Pb 4f binding energies in the post-adsorption proves an inner sphere complex formation during Pb (II) adsorption (Gama *et al.*, 2022). The Pb (II) adsorption capacity is 148.6 mg,

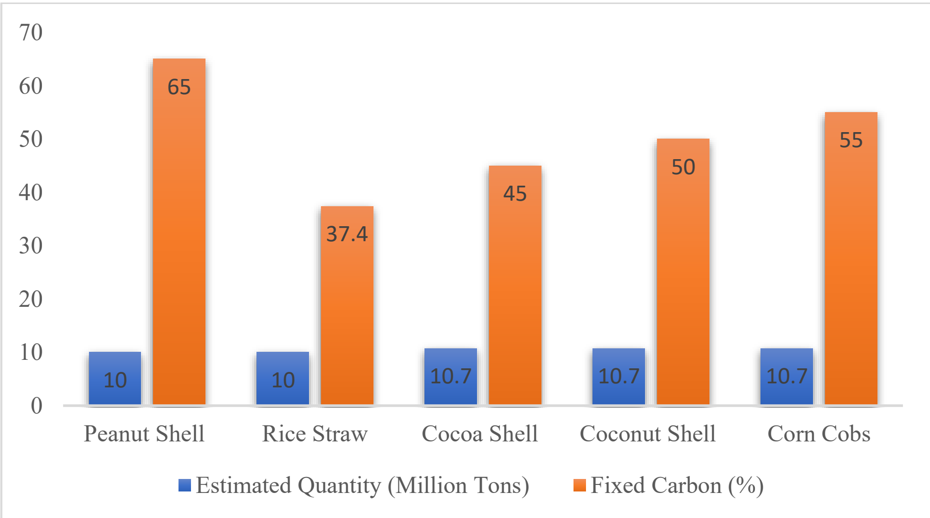

Table 1. The potential of agricultural wastes (Nurida *et al.*,2017; Mathabatha *et al.*, 2023)

surpassing most reported biochar materials, due to the synergistic combination of these physical and chemical properties (Wu *et al*., 2024). Table 2 provides a comprehensive comparison of the Pb (II) adsorption capacities of adsorbents derived from agricultural waste. The kinetic of pseudo second order were used to define the adsorption mechanism, which suggests that the rate limiting phase is chemisorption (Nwajei *et al*., 2024; Setiawan *et al*., 2023). Multilayer adsorption on energetically heterogeneous surfaces was proposed by Freundlich isotherm modeling, and adsorbent interactions were shown by Temkin analysis with an average binding energy (Kusmierek *et al*., 2017). This comprehensive multiscale understanding ranges from molecular level interactions (XPS) to bulk adsorption (isotherms), provides a solid foundation for the rational design of optimized biochar adsorbents, with special relevance for heavy metal removal from industrial wastewater streams.

Adsorption Performance of Modified Biochar for Heavy Metals

The capability of adsorption for organic substances and heavy metals, such as tetracycline, has been optimized by recent advances in biochar modification. A comprehensive investigations on chemically treated biochars are summarised in Table 2, which highlights the impact of sulfonation, acid activation, and KOH treatment on the effectiveness of contaminant removal.

Additionally, the optimal adsorption conditions are determined by comparing key operational parameters, such as pH, temperature, and contact duration. These findings provide a systematic overview of how specific biochar functionalization supports environmental restoration. Alkaline or strong acid treatments like H_2SO_4, HNO_3, and H_3PO_4 significantly transform the surface chemistry and porosity of peanut shell biochar, increasing the adsorption capacity.

The highest adsorption capacities for Pb(II) are attained by acid and sulfonation modifications, which improve the acidic functional groups up to 148.6 mg/g, such as carboxyl and sulfonate. The development of density in carboxylic and sulfonic acid groups provides more efficiency to remove Pb(II), additionally offering an evidence for metal ion binding using complexation and electrostatic interactions (Wu *et al*., 2024). Similar trends are observed by Zhang *et al*., (2023), KOH-biochars are used to remove tetracycline, which is enhanced up to 5.3 times compared to unmodified biochars due to an increase in pore volume and oxygen functionality.

Acid or alkali modified biochar consistently outperforms response to their unmodified counterparts, as expressed by higher kinetic and equilibrium constants, which correlate with improved surface area, porosity, and functional group density (Zhang *et al*., 2023).

The adsorption capability of raw peanut shell biochar for Cr (VI) from Table 3, has 14.56 mg/g within pH 2 and adsorbent dose of 4 g/L. In similar experimental conditions, modification with CTAB on peanut shell biochar approximately doubled adsorption capacity to 27.05 mg/g, suggesting more stable adsorption and higher capacity compared to raw biochar. However, a restricted increase in the adsorption capacity is 15.58 mg/g using KOH activation (Murad *et al*., 2022). The capacity of chemical activation with ZnCl was not explicitly announced. However, these peanut shells can enhance the surface area and pore volume (Fletcher *et al*., 2024).

The Effects of pH and Temperature on Pb (II) and Cr (VI) Adsorption

Adsorption efficiency is significantly influenced by pH, due to the adsorbent's surface charge and the formation of metal ions. The most effective conditions for Cr(VI) adsorption is an acidic environment (pH 2), due to negatively charged species, particularly $HCrO_4$, facilitating electrostatic attraction. However , Pb(II) ion removal works optimally at slightly acidic to neutral pH ranges of 5-6. This occurs due to lower pH values induce electrostatic repulsion between the adsorbent surface and positively charged Pb^{2+} ions, and higher pH levels lower the adsorption capacity because of hydroxide precipitation.

Adsorption of Cr(VI) and Pb(II) into adsorbents derived from peanut shells is endothermic, indicating that the process requires energy. Adsorption performance is improved at temperatures between 298 to 318 K as these temperatures increase ion mobility and strengthen interactions with functional groups like COOH and OH.

Table 2. Comparative of Pb (II) Adsorption Capacity from Agricultural Waste-Based Adsorbents

Agricultural Waste Type	Pb (II) Adsorption Capacity (mg/g)	Optimal Conditions / Notes	Reference
Peanut Shell	148.6	pH 5, 0.5 g/L adsorbent dosage, 120 min contact time	(Wu *et al.*, 2024)
Walnut Shell	20 - 65	Processed into activated carbon, capacity varies with treatment	(Timalsina *et al.*, 2024)
Rice Husk	80 - 98.2	pH around 7-8, optimized adsorbent dose and contact time	(Suhendrayatna *et al.*, 2018)
Sugarcane Bagasse	50 - 70	Used as bioadsorbent, adsorption conditions vary	(Li *et al.*, 2020)

Table 3. The adsorption performance of various modified biochars

Modification Type	Contaminant	Max Adsorption (mg/g)	Optimal pH	Temperature (°C)	Contact Time (minutes)	Adsorbent Dose	Reference
H_2SO4 + H_3PO_4 + Sulfonation	Pb (II)	148.6	5	25–45	180	0.5	(Wu *et al.*, 2024)
Sulfuric Acid	Pb (II)	NA	3–6	25–45	200	0.2	(Wu *et al.*, 2024)
KOH	Tetracycline	272.2	6–7	25	1440	0.5	(Zhang *et al.*, 2023)
Raw peanut shell biochar	Cr (VI)	14.56	2	50	4	300	(Murad *et al.*, 2022)

Practical Limitations in Adsorbent

The investigation consistently underlines a limitation in biochar regeneration and reusability, where the capacity declines after repeated cycles due to pore blockage and irreversible adsorption (Mutabazi *et al.*, 2024). The impact of competing ions and complex liquid waste matrices, demanding a long-term performance assessment to allow application in real world (Agani *et al.*, 2020).

CONCLUSION

In conclusion, peanut shell-derived biochar demonstrates significant potential as a sustainable and effective adsorbent for heavy metal removal, particularly for Pb (II) and Cr (VI), with its efficacy significantly enhanced through chemical modifications such as acid treatment and sulfonation, which increase surface functional groups and porosity. However, its main advantages of being low-cost and derived from abundant agricultural waste are counterbalanced by limitations including predominantly lab-scale validation, reduced reusability due to pore fouling, and unproven performance in complex real wastewater matrices, thus indicating that future research should prioritize pilot-scale studies using authentic industrial effluents, develop efficient regeneration protocols, and conduct comprehensive lifecycle and techno-economic assessments to evaluate practical feasibility and environmental impacts, thereby bridging the gap between laboratory promise and field-scale application through multidisciplinary approaches.

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