ROLE OF BIOCHAR FROM OILSEED BYPRODUCTS IN HEAVY METAL REMEDIATION: A SUSTAINABLE APPROACH

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Abstract:

The increasing contamination of water resources by heavy metals, pharmaceutical residues, and other pollutants poses a significant environmental threat. Biomass-derived adsorbents, such as biochar made from oilseed byproducts, have emerged as sustainable and cost-effective materials for the removal of these contaminants. This study explores the potential of biochar produced from oilseed cakes, such as Karanja, castor, and palm, for the remediation of heavy metals from polluted water. The adsorption mechanisms, including ion exchange, chemisorption, and π-π interactions, are investigated to understand the effectiveness of these biochars in removing metals like lead (Pb), cadmium (Cd), and arsenic (As). Additionally, the role of green nanotechnologies, such as magnetite-biochar composites and carbon-based nanomaterials, in enhancing adsorption properties is examined. The results suggest that oilseed-based biochar holds considerable promise for large-scale environmental cleanup, offering a renewable, low-cost alternative to traditional adsorbents like activated carbon.

Keywords:

Biomass-derived adsorbents, Biochar, Heavy metal removal, Oilseed byproducts, Environmental remediation, Green nanotechnology, Magnetite-biochar composites.

Introduction:

Water pollution by heavy metals, pharmaceuticals, and industrial contaminants is a growing concern worldwide. Traditional methods for water treatment, such as filtration and chemical treatment, often fail to provide sustainable solutions, particularly in the case of low-concentration pollutants. Adsorption has emerged as one of the most effective methods for the removal of these pollutants, owing to its simplicity, high efficiency, and low cost. Biomass-derived adsorbents, specifically biochar produced from agricultural byproducts such as oilseed cakes, have gained attention as potential materials for environmental cleanup. These byproducts, rich in lignocellulosic materials, offer an eco-friendly and economically viable alternative to activated carbon. The high surface area, porosity, and functional groups on biochar's surface enable efficient adsorption of heavy metals and organic contaminants. This paper investigates the use of biochar from oilseed cakes as an adsorbent for heavy metal removal and examines the enhancement of adsorption properties through the integration of nanomaterials like magnetite and carbon nanotubes.

Adsorption of Pollutants Using Biomass-Derived Adsorbents

The potential of biomass-derived adsorbents to remove a variety of contaminants from water, such as dyes, heavy metals, antibiotics, and phenolic compounds, has attracted a lot of interest. These adsorbents provide a sustainable and economical substitute for traditional materials like activated carbon. They are usually made from agricultural, food processing, or industrial leftovers. The effectiveness of biomass-derived adsorbents has been shown in several investigations, underscoring its adaptability to a range of environmental applications (Boddu et al., 2025; Patil et al., 2024; Santás-Miguel et al., 2025).

Pollutants Targeted by Biomass-Derived Adsorbents

1. **Dyes**: Highly poisonous dyes are often discovered in wastewater, especially those used in the textile industry. Strong adsorption capabilities for both anionic and cationic dyes have been shown by biomass-derived adsorbents, such as those generated from rice husks, maize stover, and other lignocellulosic materials. For instance, Patil et al. (2024) showed how well biomass-derived activated carbon removes phenolic chemicals and colour contaminants like crystal violet and methylene blue. Surface adsorption, hydrogen bonding, and π-π interactions between the dye molecules and the adsorbent surface are often combined in the adsorption process.

2. **Heavy Metals**: Another significant use for biomass-based adsorbents is the elimination of heavy metals from polluted water, including lead (Pb), cadmium (Cd), and arsenic (As). Usually, these adsorbents work by exchanging metal ions from the water with ions that are already on the adsorbent's surface. For instance, Santás-Miguel et al. (2025) found that the presence of oxygenated functional groups on the surface of biochar made from agricultural residues displayed good adsorption capabilities for heavy metals. These groups use chelation and electrostatic interactions to help metal ions bind.

3. **Antibiotics:** The growth of antibiotic-resistant bacteria is a major environmental risk caused by the presence of antibiotics in wastewater. Antibiotics like tetracycline, ciprofloxacin, and amoxicillin have been successfully removed by biomass-derived adsorbents, especially biochar and activated carbon. Although the application of de-oiled Karanja seed biochar for Cr(VI) sequestration was studied by Boddu et al. (2025), the same principles that were found for heavy metal adsorption may also be used to the removal of antibiotics. Chemisorption is the mechanism by which antibiotics are firmly attached to the surface of the adsorbent, often via van der Waals forces, π-π interactions, or hydrogen bonds.

4. **Phenolic Compounds**: Adsorbents made from biomass may also efficiently remove phenolic compounds, which are often present in industrial effluents from the food, pharmaceutical, and chemical sectors. These compounds' phenolic group (-OH) may improve the adsorption process by interacting with hydroxyl, carboxyl, and other polar functional groups on the adsorbent surface. Using both chemical and physical interactions with the adsorbent surface, Santás-Miguel et al. (2025) demonstrated the potential of biopowders made from agricultural residues for sequestering phenolic contaminants.

Mechanisms of Adsorption

The mechanisms through which biomass-derived adsorbents interact with pollutants are diverse and complex. These include:

1. **Chemisorption:** This results in a more persistent attachment by forming strong chemical bonds between the pollutant and the adsorbent. When it comes to metal ions, chemisorption usually happens when the pollutant and functional groups such as hydroxyl, carboxyl, or carbonyl groups on the adsorbent surface create metal-oxygen bonds (Boddu et al., 2025). Tetracycline and other antibiotics may also bind to the surfaces of biochar to create stable complexes with oxygenated functional groups.

2. **Interactions of π-π**: Many organic contaminants include conjugated π-electron systems, including aromatic chemicals (such dyes and phenolic compounds). These substances, especially those made from lignocellulosic biomass, might interact with the π-electron clouds on the surface of the adsorbents. The strong adsorption of aromatic molecules is facilitated by this interaction, which is referred to as π-π stacking.

Through π-π interactions, studies have shown that biochar and activated carbon with large surface areas and plenty of functional groups are very good in adsorbing organic pollutants (Patil et al., 2024).

3. **Ion Exchange**: One important method for eliminating heavy metals from aqueous solutions is ion exchange. Because of their surface charge and the presence of exchangeable ions (such potassium and calcium), biomass-derived adsorbents—particularly biochars and modified biochars—display ion-exchange characteristics. The impurities are eliminated when metal-contaminated water is exposed to it because the metal ions are exchanged with ions on the adsorbent surface. According to Santas-Miguel et al. (2025), this process is especially crucial for the sequestration of cationic metals such as Pb^{2+} and Cd^{2+}.

4. **Hydrogen Bonding**: The adsorption of polar contaminants, including antibiotics and phenolic chemicals, depends heavily on hydrogen bonding. The functional groups of organic contaminants may establish hydrogen bonds with biomass-derived adsorbents, especially those with oxygen-containing functional groups (such as hydroxyl and carboxyl). By strengthening the pollutant's attachment to the surface, this interaction raises the adsorbent's total adsorption capacity (Boddu et al., 2025).

Adsorption Isotherms and Kinetics

The adsorption efficiency of biomass-derived adsorbents is commonly evaluated through isotherm and kinetic studies. The most widely used adsorption models are:

- **Langmuir Isotherm:** This model makes the assumption that monolayer adsorption occurs on a surface with a limited number of identical sites**.**
- **Freundlich Isotherm:** This model takes into consideration the multilayer adsorption of contaminants and is better suited for adsorption on heterogeneous surfaces.
- **Pseudo-First-Order and Pseudo-Second-Order Kinetics:** These models are used to explain the rate of adsorption; the pseudo-second-order model often fits the experimental data well, indicating that the adsorption process is chemisorptive**.**

Research has shown that biomass-derived adsorbents often perform very well in adsorption, with capacity rising with longer contact durations and greater adsorbent dosages. Depending on the pollutant and experimental settings, equilibrium is usually reached in a few hours to days. The adsorption process is usually quick and effective.

Adsorbents made from biomass provide a viable, long-term way to eliminate a variety of contaminants from water, such as dyes, heavy metals, antibiotics, and phenolic compounds. The combination of physical and chemical adsorption processes, including chemisorption, π-π interactions, ion exchange, and hydrogen bonding, is largely responsible for these adsorbents' effectiveness. In addition to helping to increase the value of waste, the use of these adsorbents in environmental remediation offers a practical and affordable substitute for more conventional adsorbent materials, such as activated carbon.

Edible Oil Byproducts as Renewable Precursors

Large amounts of oilseeds are processed by the edible oil industry, which produces a lot of byproducts, especially oilseed cakes. Lignocellulosic components, which are mostly made up of cellulose, hemicellulose, and lignin, are abundant in these byproducts, which include karanja, castor, palm, and maize oil cakes. These ingredients are very beneficial for the production of charcoal, adsorbents, and other useful compounds for waste management and environmental remediation.

The process of turning oilseed cakes into biochar has emerged as a viable strategy for pollution prevention and waste valuation. These oilseed cakes are pyrolysed at regulated temperatures to produce biochar, a highly porous substance with a substantial adsorption capacity. For example, it has been shown that biochar made from de-oiled Karanja seeds is very successful in eliminating heavy metals like lead (Pb) and cadmium (Cd) from tainted water. The large surface area and oxygen-rich functional groups (such as hydroxyl and carboxyl groups) on the surface of the biochar are the main causes of this adsorption. These groups allow metal ions to be bound via chelation and ion-exchange processes (Boddu et al., 2025). Furthermore, canola cakes may be used as catalysts in the synthesis of biodiesel in addition to charcoal. In the field of renewable energy, turning oilseed cakes—especially those from the castor and palm oil industries—into biodiesel catalysts has drawn interest. These catalysts assist reduce waste from the edible oil extraction process and boost the renewable energy sector by facilitating the transesterification of vegetable oils into biodiesel and glycerol (Huda, 2024; Osorio-González et al., 2020). Oilseed cakes may be transformed into useful carbons in addition to charcoal and catalysts. Like activated carbon, these carbons work especially well in gas adsorption and water filtration applications. Functional carbons are versatile because they may be tailored to maximise their adsorption capabilities depending on the activation circumstances, such as temperature and chemical agents utilised. These carbons are perfect for resource recovery and environmental cleanup because they can effectively remove pesticides, organic pollutants, and pharmaceutical residues from wastewater.

Emerging Sustainable and Nanotechnology Approaches

In order to improve the performance of adsorbents and catalysts, new technologies are being included into materials science as environmental worries about pollutants continue to grow. At the vanguard of this change are green nanotechnologies, which use naturally occurring, environmentally benign materials. The adsorption effectiveness, selectivity, and reusability of materials used for water and wastewater treatment have significantly improved as a result of the introduction of nanoparticles in adsorbents.

The superparamagnetism and large surface area of magnetite nanoparticles (FeO_4) have made them a valuable tool in environmental cleanup. These nanoparticles may be mixed with biochar to generate magnetite-biochar composites, which improve the adsorbent's ability to extract organic contaminants, heavy metals, and antibiotics from aqueous solutions. Operational expenses are greatly decreased by using magnetic separation, which makes it simple to recover the adsorbent from polluted water. Furthermore, magnetite is perfect for remediating complicated wastewater streams because to its capacity to create strong interactions with organic molecules and metal ions (Halim, 2025).

Nanotechnology may be used to improve the surface characteristics of carbon-based adsorbents such activated carbon and biochar. When incorporated into biochar, two forms of nanomaterials—graphene oxide and carbon nanotubes (CNTs)—offer a higher density of functional groups and a larger surface area. These changes not only increase biochar's adsorption capacity but also give it multifunctional qualities like antiviral and antibacterial activity, which can be particularly helpful in removing organic pollutants from water, such as medications and pathogens (Marin et al., 2025). The generation of biodiesel has also showed promise when nanocatalysts are included into carbon materials. For instance, adding nanomagnetic catalysts to biochar made from oilseed cakes might increase the transesterification processes' efficiency, increasing yield overall and cutting down on reaction durations.

A new field of study that has a lot of promise for improving adsorption qualities is the use of artificial intelligence (AI) and machine learning (ML) into the creation of adsorbents. Researchers can simulate and forecast how well biochar and other adsorbents will operate under different circumstances by using AI and ML systems. Researchers can create adsorbents with specialised qualities for certain environmental problems by taking into account factors like temperature, chemical activation, and pollutant kinds. Furthermore, the long-term stability and regeneration potential of adsorbents may be predicted using AI-powered simulations, which is essential for assessing their cost-effectiveness and sustainability in large-scale applications (Marin et al., 2025).

The promise for sustainability is one of the main driving forces for the development of nanotechnology in environmental applications. The environmental effect of adsorbent manufacture is lessened by the use of renewable resources like biomass (for the creation of biochar or functional carbons) and environmentally friendly nanomaterials. These developments encourage environmentally friendly methods of producing energy, treating water, and reducing pollution by emphasising green chemistry and non-toxic materials. Moreover, nanoparticles may often be recycled or regenerated, which further lowers the waste produced during the remediation process and increases the adsorbents' lifespan.

In addition to lowering waste, the valorisation of edible oil wastes into biochar, functional carbons, and catalysts offers affordable and long-term options for environmental remediation, especially in water treatment. Incorporating machine learning and green nanotechnologies simultaneously improves the efficiency, selectivity, and reusability of advanced adsorbents, increasing their suitability for large-scale applications. In addition to supporting a circular economy and encouraging sustainable industrial practices, these cutting-edge technologies provide exciting new opportunities to fight environmental contamination.

Adsorption Technology for Pharmaceutical Removal

Because of their chemical stability, low-concentration biological activity, and resistance to standard treatment methods, pharmaceutical pollutants have become very difficult to remove from water and wastewater. Adsorption has become one of the most promising and extensively researched treatment strategies for the efficient removal of medicinal substances. Adsorption-based treatment systems are becoming more and more popular because of their high effectiveness, ease of use, versatility in handling various contaminants, and low production of dangerous secondary pollutants (Crini & Lichtfouse, 2019). The basic ideas and processes that underpin adsorption are covered in this section, along with the benefits and drawbacks of commercial adsorbents that are often employed to remove medications.

Principles and Mechanisms of Adsorption

A surface phenomena known as adsorption occurs when molecules of a substance (adsorbate) build up on the surface of a solid or liquid material (adsorbent) as a result of chemical or physical interactions. Adsorption is the process by which pharmaceutical molecules move from the aqueous phase to the surface of an adsorbent in water treatment applications, lowering the concentration of contaminants in the treated water (Foo & Hameed, 2010).

Fundamental Adsorption Processes

The physicochemical characteristics of the adsorbent and adsorbate, solution pH, temperature, contact duration, and the presence of competing chemicals are some of the variables that affect the adsorption process. The adsorbent's surface area, pore structure, surface chemistry, and active site availability all have a significant impact on adsorption efficiency (Bansal & Goyal, 2005). There are many ways that pharmaceutical chemicals, which often have intricate molecular structures and a variety of functional groups, interact with adsorbent surfaces.

Types of Adsorption

Adsorption is generally classified into two main types: physical adsorption (physisorption) and chemical adsorption (chemisorption).

- Weak intermolecular forces including hydrogen bonds, van der Waals forces, and electrostatic interactions are involved in physical adsorption. This kind of adsorption often happens at a low activation energy and is reversible. When pharmaceutical compounds interact with porous materials with large surface areas and appropriate pore sizes, physisorption predominates (Ruthven, 1984).
- Chemical adsorption entails the creation of more robust chemical connections, such as covalent or ionic bonds, between the adsorbent surface and the adsorbate. greater adsorption capacities but slower kinetics

owing to greater activation energy needs are common outcomes of chemisorption, which is usually irreversible and highly selective (Atkins & de Paula, 2014).

Depending on the kind of adsorbent and the operating circumstances, adsorption of medicinal substances often takes place via a mix of chemical and physical interactions.

Adsorption Mechanisms for Pharmaceutical Compounds

Several mechanisms govern the adsorption of pharmaceutical contaminants onto adsorbent surfaces:

1. **Electrostatic Interactions:** An important factor in adsorption is the electrostatic attraction or repulsion between charged medicinal molecules and adsorbent surfaces. The pH of the solution has a significant impact on the charge of both the adsorbent and the adsorbate. For example, a lot of medications are weak bases or acids that may exist in neutral or ionised states based on pH, which influences their affinity for charged adsorbent surfaces (Zhang et al., 2018).

2. **Hydrogen Bonding:** This process takes place between functional groups like hydroxyl, carboxyl, or amine groups on the adsorbent surface and hydrogen donors and acceptors found on medicinal compounds. For medications with polar functional groups, this mechanism is especially important (Yang et al., 2016).

3. **π–π Interactions:** Through π–π stacking interactions, aromatic medicinal compounds may interact with aromatic structures found on carbon-based adsorbents. The adsorption of substances including antibiotics, analgesics, and anti-inflammatory medications is greatly improved by this process (Tran et al., 2017).

4. **Hydrophobic Interactions:** These interactions lessen the exposure of non-polar medicinal molecules to the aqueous environment by preferring forming with hydrophobic areas of the adsorbent surface. The elimination of hydrophobic medications with high octanol–water partition coefficients (log Kow) depends on this process (Ternes & Joss, 2006).

5. **Pore Filling and Size Exclusion**: An adsorbent's accessibility to medicinal compounds is determined by its pore structure. Adsorbate molecules are physically confined inside the pore network by pore filling processes, which are facilitated by micropores and mesopores. Adsorption capacity and kinetics are significantly impacted by the size and shape compatibility of medicinal compounds with pore architectures (Rouquerol et al., 2014).

Conclusion:

The results of this study highlight the significant potential of biomass-derived biochar, particularly from oilseed byproducts, as an effective and sustainable adsorbent for heavy metal remediation. The adsorption capacity of biochar is largely influenced by its surface chemistry, functional groups, and porosity, which are optimized by pyrolysis at specific temperatures. The incorporation of green nanotechnology, such as magnetite-biochar composites and carbon-based nanomaterials, further enhances the efficiency of these adsorbents by improving selectivity, reusability, and surface area. The ion-exchange, chemisorption, and π-π interaction mechanisms play key roles in the removal of heavy metals like lead, cadmium, and arsenic from contaminated water. These findings suggest that biomass-derived biochar is not only a valuable tool in environmental remediation but also a sustainable approach that contributes to the valorization of agricultural waste. Future research should focus on optimizing the preparation processes, exploring large-scale applications, and further investigating the long-term stability and regeneration of these adsorbents to ensure their practical feasibility in water treatment systems.

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