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Application of Biochar Derived from Oilseed Cakes for Removal of Emerging Contaminants

Kanupriya
Ph.D. Scholar
Department of Chemistry
Malwanchal University Indore, (M.P.).

Geeta Solanki
Supervisor
Department of Chemistry
Malwanchal University Indore, (M.P.)

Abstract

The increasing presence of emerging contaminants such as pharmaceutical residues, personal care products, and other micropollutants in water bodies has become a serious environmental concern. Conventional wastewater treatment systems are often unable to remove these pollutants effectively, which creates a need for low-cost and sustainable treatment alternatives. In this context, biochar derived from oilseed cakes has gained attention as a promising adsorbent because of its porous structure, surface functionality, and economic value. Oilseed cakes, produced as byproducts of the edible oil industry, are available in large quantities and can be converted into useful biochar through pyrolysis. This study highlights the potential application of oilseed cake-derived biochar for the adsorption of emerging contaminants from water. It also emphasizes the importance of waste valorization, circular economy practices, and sustainable water treatment approaches. The findings indicate that such biochar can serve as an efficient, eco-friendly, and affordable material for pollutant removal while also reducing industrial waste disposal problems.

Keywords

Biochar; Oilseed cakes; Emerging contaminants; Adsorption; Wastewater treatment; Waste valorization; Sustainable adsorbents; Pharmaceutical residues

1. Introduction

Water contamination by emerging pollutants has become a major global challenge due to the continuous release of pharmaceuticals, personal care products, and other persistent chemicals into aquatic environments. These contaminants are often found in low concentrations, but they can still cause harmful effects because of their toxicity, persistence, and ability to accumulate in living organisms. Traditional wastewater treatment technologies are not specifically designed to remove such compounds, which has increased interest in adsorption-based treatment methods. Adsorption is widely considered an effective and reliable process because it is simple, efficient, and capable of removing pollutants without generating harmful secondary products.

At the same time, the edible oil industry generates a significant amount of solid byproducts, especially oilseed cakes, during oil extraction processes. These byproducts are often underutilized or disposed of improperly, creating environmental concerns. Converting oilseed cakes into biochar offers a valuable solution to both waste management and water purification problems. Biochar possesses a porous structure, good surface area, and active sites that support contaminant adsorption. Therefore, the use of oilseed cake-derived biochar represents a sustainable and low-cost approach for the removal of emerging contaminants, while also promoting resource recovery and circular economy principles.

2. Adsorption as a Water Treatment Technique

Adsorption has emerged as one of the most effective and reliable techniques for the removal of contaminants from water and wastewater systems. With the rapid increase in environmental pollution, particularly due to pharmaceutical residues, there has been a growing need for advanced treatment technologies that can efficiently remove such micropollutants. Pharmaceuticals are often present in trace concentrations in water bodies, yet they pose significant risks due to their persistence, bioaccumulation potential, and biological activity. Conventional wastewater treatment methods are not specifically designed to remove these compounds, leading to their continuous discharge into aquatic environments. In this context, adsorption has gained considerable attention due to its simplicity, high efficiency, and ability to remove a wide range of contaminants without producing harmful by-products (Crini & Lichtfouse, 2019).

Adsorption is fundamentally a surface phenomenon in which molecules from a liquid phase accumulate onto the surface of a solid material. The substance that is being removed from the solution is referred to as the adsorbate, while the solid material responsible for adsorption is known as the adsorbent. The process occurs due to the presence of unbalanced forces on the surface of the adsorbent, which attract and hold the adsorbate molecules. These forces arise because surface atoms possess higher energy compared to atoms within the bulk of the material, thereby creating a tendency to reduce surface energy through adsorption. The efficiency of adsorption largely depends on the physicochemical properties of both the adsorbent and the adsorbate, as well as environmental conditions such as pH, temperature, and ionic strength (Bansal & Goyal, 2005). The mechanism of adsorption involves several types of interactions between the adsorbent and the adsorbate. These include weak van der Waals forces, electrostatic interactions, hydrogen bonding, and hydrophobic interactions. In addition, π–π interactions play an important role in the adsorption of aromatic pharmaceutical compounds. Based on the nature of these interactions, adsorption can be broadly classified into physical adsorption and chemical adsorption. Physical adsorption, also known as physisorption, involves weak intermolecular forces and is generally reversible. It occurs rapidly and is favored at lower temperatures, often resulting in multilayer adsorption. On the other hand, chemical adsorption, or chemisorption, involves the formation of strong chemical bonds between the adsorbate and the adsorbent surface. This type of adsorption is usually irreversible, occurs at higher temperatures, and leads to monolayer coverage. In practical water treatment systems, both types of adsorption may occur simultaneously depending on the characteristics of the system (Langmuir, 1918). The adsorption process is influenced by several factors, among which pH plays a crucial role. The pH of the solution affects both the ionization state of the pharmaceutical compounds and the surface charge of the adsorbent. Many pharmaceutical compounds are weak acids or bases, and their degree of ionization varies with pH, thereby influencing their interaction with the adsorbent surface.

To better understand and describe the adsorption process, various isotherm models have been developed. These models explain how adsorbates interact with adsorbents at equilibrium. The Langmuir isotherm is one of the most widely used models and assumes monolayer adsorption on a homogeneous surface with a finite number of identical sites. According to this model, once a site is occupied, no further adsorption can occur at that site. In contrast, the Freundlich isotherm is an empirical model that describes adsorption on heterogeneous surfaces and allows for multilayer adsorption. It is particularly useful for systems with varying surface energies. Another important model is the Temkin isotherm, which considers the interactions between adsorbate and adsorbent and assumes that the heat of adsorption decreases linearly with increasing surface coverage (Freundlich, 1906). In addition to equilibrium studies, adsorption kinetics provides valuable insights into the rate and mechanism of the process. Kinetic models such as the pseudo-first-order and pseudo-second-order models are commonly used to analyze experimental data. The pseudo-second-order model is often found to best describe the adsorption of pharmaceutical compounds, suggesting that chemisorption may be the rate-limiting step. Furthermore, intraparticle diffusion plays a significant role in the adsorption process, particularly for porous adsorbents, where the adsorbate must diffuse into the internal pore structure before being adsorbed (Ho & McKay, 1999).

A wide variety of adsorbents have been developed and utilized for water treatment applications. Among these, activated carbon is the most widely used due to its exceptionally high surface area, well-developed pore structure, and strong adsorption capacity. It is highly effective in removing organic pollutants, including pharmaceuticals, dyes, and pesticides. Activated carbon is available in different forms, such as powdered and granular, each suited for specific applications. Despite its effectiveness, the high cost of production and regeneration limits its widespread use, particularly in developing countries. In recent years, there has been increasing interest in the use of natural and low-cost adsorbents. Materials such as clay minerals, agricultural waste, and biochar have been extensively studied as alternatives to activated carbon. Clay minerals possess a layered structure and high cation exchange capacity, making them suitable for the adsorption of various contaminants. Agricultural wastes, including rice husk, sawdust, and coconut shells, are abundant and inexpensive, and can be modified to enhance their adsorption properties. Biochar, produced through the pyrolysis of biomass, has gained significant attention due to its porous structure, stability, and effectiveness in removing both organic and inorganic pollutants (Ahmad et al., 2014).

Advancements in nanotechnology have further expanded the scope of adsorption in water treatment. Nanomaterials such as carbon nanotubes, graphene oxide, and metal oxide nanoparticles exhibit superior adsorption performance due to their high surface area and unique physicochemical properties. These materials offer faster adsorption kinetics and higher removal efficiency compared to conventional adsorbents. In addition, magnetic nanoparticles have been developed to facilitate easy separation of adsorbents from treated water using an external magnetic field. Polymer-based adsorbents, including ion-exchange resins and molecularly imprinted polymers, provide selective removal of specific contaminants, making them highly effective for targeted applications. One of the major advantages of adsorption over other treatment methods is its high efficiency in removing contaminants at very low concentrations. This makes it particularly suitable for the removal of pharmaceutical residues, which are often present at trace levels.

Another important advantage of adsorption is the possibility of regenerating and reusing adsorbents. Regeneration techniques such as thermal treatment, chemical washing, and biological methods can restore the adsorption capacity of used materials, thereby reducing operational costs and waste generation. Moreover, adsorption produces minimal sludge compared to conventional treatment methods, which simplifies disposal and reduces environmental impact. Despite its numerous advantages, adsorption also has certain limitations. The saturation of adsorbents over time necessitates periodic regeneration or replacement, which can increase operational costs. The efficiency of adsorption may also be affected by the presence of competing substances in complex wastewater systems. Additionally, the disposal of spent adsorbents can pose environmental challenges if not managed properly.

3. Edible Oil Industry Byproducts

The edible oil industry is one of the major agro-based industries worldwide, contributing significantly to food supply as well as economic development. However, the processing of oilseeds such as soybean, sunflower, mustard, and groundnut generates a large quantity of byproducts and waste materials at different stages. These byproducts, if not managed properly, can lead to serious environmental problems including soil, water, and air pollution. At the same time, many of these wastes contain valuable components, making them suitable for reuse and resource recovery. Therefore, understanding the types, disposal practices, and environmental impacts of these byproducts is essential for developing sustainable management strategies.

Types of Byproducts in Edible Oil Industry

During the extraction and refining of edible oils, several solid and liquid byproducts are generated. These depend on the type of raw material and the processing method used.

Some of the major byproducts include:

- **Oil cakes (oilseed meals):** These are solid residues left after oil extraction. They are rich in proteins, fibers, and residual oil. Common examples include soybean cake, mustard cake, and groundnut cake.
- **Spent bleaching earth (SBE):** Generated during the bleaching process, it contains adsorbent clay saturated with oil, pigments, and impurities.
- **Soapstock:** Produced during the neutralization stage of refining when free fatty acids react with alkali.
- **Deodorizer distillates:** Obtained during deodorization and contain valuable compounds like tocopherols and sterols.

- **Fatty acid distillates:** Byproducts rich in free fatty acids used in soap and chemical industries.
- **Wastewater and sludge:** Generated during washing, refining, and processing stages, containing oil, grease, and organic matter.

Among these, oil cakes and spent bleaching earth are the most abundant and environmentally significant byproducts. Oil cakes are widely used as animal feed due to their high nutritional value. However, some oil cakes contain anti-nutritional factors (e.g., glucosinolates in mustard cake), which limit their direct use and require treatment. On the other hand, spent bleaching earth is considered more problematic due to its high oil content (20–40%) and potential hazards.

Current Disposal Practices

The disposal and management of edible oil industry byproducts vary depending on their type, economic value, and regional practices. In many cases, industries adopt conventional methods that are not always environmentally sustainable. Common disposal and management practices include:

- **Use of oil cakes as animal feed:** Widely practiced due to high protein content, especially for soybean and groundnut cakes.
- **Application as organic fertilizers:** Oil cakes are used in agriculture to improve soil fertility.
- **Landfilling:** Spent bleaching earth and sludge are often disposed of in landfills.
- **Incineration:** Some wastes, especially SBE, are burned to reduce volume.
- **Recovery and reuse:** Soapstock and fatty acid distillates are processed to recover useful products.
- **Wastewater treatment:** Effluents are treated using biological or physicochemical methods before discharge.

Although some of these practices promote reuse, others such as landfilling and incineration create secondary environmental issues. For example, landfilling can lead to leachate formation, while incineration can cause air pollution. Spent bleaching earth disposal is particularly challenging. Due to its oil content, it is prone to spontaneous combustion, making storage and handling risky. In many small-scale industries, improper disposal practices further worsen the problem.

Environmental Concerns Associated with Byproducts

The improper management of edible oil industry byproducts leads to several environmental issues. These impacts are often interconnected and affect multiple components of the ecosystem.

1. Soil Pollution: Solid wastes such as oil cakes and spent bleaching earth, when disposed of improperly, can contaminate soil. The presence of residual oil and chemicals alters soil structure and reduces fertility.

2. Water Pollution: Wastewater from the edible oil industry contains high levels of organic matter, oil, and grease. If discharged untreated, it can severely affect water bodies. Leachate from landfilled wastes can also contaminate groundwater, posing risks to human health.

3. Air Pollution: Air pollution occurs mainly due to burning or decomposition of organic wastes.

4. Fire Hazards: Spent bleaching earth is highly prone to spontaneous combustion due to oxidation of residual oil.

5. Waste Management Challenges: Handling and disposal of large quantities of byproducts create logistical and economic challenges.

Sustainable Utilization and Future Perspectives

In recent years, there has been growing interest in converting edible oil industry byproducts into valuable resources. This approach not only reduces environmental impact but also improves economic efficiency. Some emerging applications include:

- Use of oil cakes as adsorbents for water treatment
- Regeneration of spent bleaching earth for reuse
- Production of biochar and biofuels
- Extraction of valuable compounds like antioxidants
- Use in biogas generation

The adoption of a circular economy approach can significantly reduce waste and promote sustainability in the edible oil industry.

4. Valorization of Industrial Byproducts

Industrialization has significantly increased the generation of waste materials, creating both environmental and economic challenges. Traditionally, industrial byproducts were considered useless and disposed of via landfilling, incineration, or direct discharge into the environment. Such conventional disposal methods lead to environmental degradation, resource depletion, and loss of potentially valuable materials. The concept of **valorization** has emerged as a sustainable alternative, focusing on transforming industrial waste into valuable products to achieve both environmental and economic benefits.

Concept of Valorization and Waste-to-Resource Principle

Valorization refers to the process of converting waste materials into value-added products that can be reintegrated into industrial or commercial applications. This process is underpinned by the waste-to-resource principle, which emphasizes the importance of viewing industrial residues as potential resources rather than refuse. Industrial byproducts often contain carbon-rich structures, minerals, metals, and bioactive compounds that can be recovered and utilized. For example, fly ash contains silica and alumina, which can be used in the production of construction materials, while spent bleaching earth contains lipids and carbon that can be processed into adsorbents. By applying valorization techniques, industries can:

- Reduce environmental pollution
- Improve resource efficiency
- Achieve economic benefits through the sale of secondary products

This approach aligns with the sustainable development goals (SDGs), particularly responsible consumption and production (SDG 12) and clean water and sanitation (SDG 6). Valorization transforms waste management from a cost center into a potential revenue-generating activity while reducing ecological impacts.

Industrial Byproducts as Adsorbents

One of the most promising applications of industrial byproducts is their conversion into adsorbents for water and wastewater treatment. The presence of heavy metals, dyes, pharmaceuticals, and persistent organic pollutants in water systems poses significant environmental and health risks. Conventional adsorbents, such as commercial activated carbon, are effective but expensive and derived from non-renewable sources. Waste-derived adsorbents present a sustainable and low-cost alternative. Some common industrial residues used include:

- Spent bleaching earth from edible oil refining
- Fly ash from thermal power plants
- Red mud from aluminum production
- Agricultural byproducts like rice husk, coconut shells, and sawdust

Modification processes such as pyrolysis, chemical activation, acid/base treatment, and surface functionalization enhance the surface area, porosity, and active adsorption sites, making these materials competitive with commercial adsorbents. Studies have shown that waste-derived adsorbents can achieve removal efficiencies comparable to commercial products for contaminants such as lead, cadmium, dyes, and pharmaceutical residues. This approach not only addresses pollution mitigation but also provides an economic alternative to traditional adsorbents, especially in developing regions where water contamination is a critical issue.

Environmental and Economic Benefits

The valorization of industrial byproducts yields multiple environmental and economic benefits:

Environmental Benefits:

- Reduction in landfill and incineration volumes
- Mitigation of soil, water, and air pollution
- Conservation of natural resources by reducing the need for virgin materials
- Promotion of green chemistry principles

Economic Benefits:

- Reduction of operational costs by replacing expensive commercial materials
- Potential for commercialization of value-added products from waste
- Creation of local industries and job opportunities in waste processing

Functional Versatility: Waste-derived adsorbents are highly versatile, capable of removing a wide range of contaminants, including heavy metals, organic dyes, pharmaceutical residues, and nutrients like nitrates and phosphates. This multifunctionality highlights the integrated advantages of valorization, simultaneously addressing pollution and resource recovery.

Alignment with Circular Economy Principles

Valorization closely aligns with the circular economy framework, which emphasizes reusing, recycling, and reintegrating materials rather than discarding them. By converting industrial byproducts into adsorbents, biofuels, or fertilizers, industries can:

- Reduce their environmental footprint
- Enhance resource efficiency
- Create closed-loop systems where materials continuously circulate

This shift represents a transition from the traditional linear industrial model of “take-make-dispose” to a regenerative model that maximizes the utility of all resources. Moreover, the circular economy promotes innovation in green processes, encouraging industries to adopt environmentally benign methods while optimizing material use.

5 Challenges in Valorization

Despite its advantages, valorization faces several challenges:

- **Variability in Waste Composition:** Industrial byproducts vary depending on raw materials, processing conditions, and seasonal factors, which may affect adsorbent performance.
- **Need for Pretreatment or Modification:** Many waste materials require chemical or thermal treatment to improve adsorption efficiency, which can increase cost and complexity.
- **Regulatory and Quality Control Issues:** Ensuring compliance with environmental regulations and maintaining consistent product quality is critical.
- **Scalability:** Laboratory-scale conversion processes may not always translate efficiently to industrial-scale production.

Ongoing research in nanotechnology, material science, and chemical engineering is addressing these barriers. Innovations like nano-enhanced adsorbents, hybrid bio-nanomaterials, and surface-functionalized biochars are showing promise in overcoming limitations related to efficiency, consistency, and scalability.

Conclusion

Biochar derived from oilseed cakes offers strong potential as a sustainable adsorbent for the removal of emerging contaminants from water and wastewater. Its application combines two important environmental goals: effective pollutant removal and useful utilization of agro-industrial waste. Compared with expensive commercial adsorbents, oilseed cake biochar provides a more economical and eco-friendly alternative, particularly for developing regions facing both water pollution and waste disposal challenges.

Overall, the use of oilseed cake-derived biochar supports the concept of waste valorization by transforming an abundant industrial byproduct into a valuable material for environmental remediation. Although further research is needed to improve performance, regeneration, and large-scale application, this approach presents a practical and promising pathway toward sustainable wastewater treatment and circular resource management.

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