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COMPARATIVE ADSORPTION EFFICIENCY OF AGRICULTURAL WASTE-BASED BIOADSORBENTS FOR LEAD REMOVAL FROM AQUEOUS SOLUTIONS

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Abstract

The presence of heavy metals in industrial wastewater has become a major environmental concern because of their toxic, non-biodegradable, and persistent nature. Among these pollutants, lead is especially harmful to human health and aquatic ecosystems. Conventional treatment methods such as chemical precipitation, ion exchange, and membrane filtration are effective to some extent, but they are often costly and generate secondary waste. In this context, adsorption has emerged as a simple, economical, and efficient treatment technique. The present study focuses on the comparative adsorption efficiency of agricultural waste-based bioadsorbents for the removal of lead from aqueous solutions. Agricultural wastes are gaining importance as low-cost and eco-friendly adsorbents due to their abundance, renewability, and surface functional groups. The study highlights the principles of adsorption, important operational factors affecting adsorption efficiency, and the advantages of bioadsorbents over conventional methods. It is found that agricultural waste-based adsorbents offer promising potential for sustainable wastewater treatment, particularly in developing regions where low-cost treatment options are needed. The study concludes that bioadsorption can serve as an effective and environmentally friendly approach for lead removal from contaminated water.

Keywords

Lead removal, adsorption, bioadsorbents, agricultural waste, aqueous solution, heavy metals, wastewater treatment, low-cost adsorbents

I. INTRODUCTION

Heavy metal contamination in water bodies has emerged as a serious environmental and public health problem across the world. Industrial effluents, especially from textile and related sectors, often contain hazardous metals such as lead, cadmium, chromium, copper, and nickel. These metals are non-biodegradable and tend to accumulate in living organisms, thereby causing long-term toxic effects. Lead is considered one of the most dangerous heavy metals because of its harmful effects on the nervous system, kidneys, and other vital organs. Therefore, its removal from wastewater before environmental discharge is highly necessary.

Several conventional methods have been used for heavy metal removal, including chemical precipitation, ion exchange, membrane filtration, and activated carbon adsorption. Although these methods can provide good removal efficiency, they also have important limitations such as high operational cost, sludge generation, membrane fouling, and the requirement of complex maintenance. These drawbacks create a need for more economical and sustainable alternatives. Adsorption has gained wide attention as an effective treatment technique because of its simplicity, high efficiency, and low sludge production. In recent years, agricultural waste-based bioadsorbents have emerged as promising materials for the adsorption of heavy metals from aqueous solutions. These materials are inexpensive, easily available, biodegradable, and rich in surface functional groups that can bind metal ions effectively. Thus, the comparative study of agricultural waste-based bioadsorbents is important for identifying suitable low-cost materials for wastewater treatment and for promoting environmentally sustainable solutions.

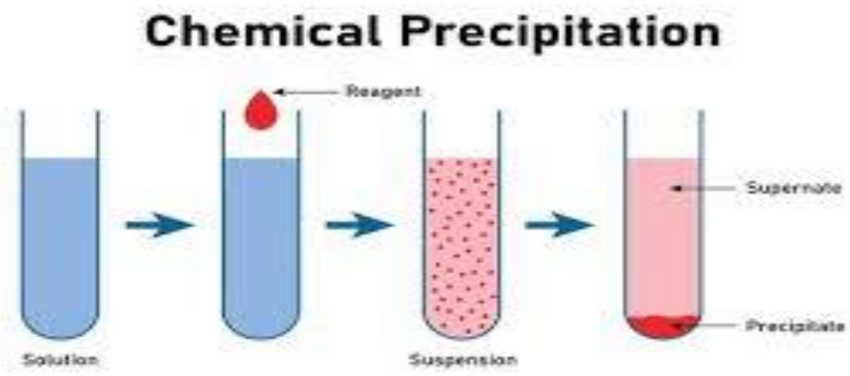
II. CONVENTIONAL METHODS FOR HEAVY METAL REMOVAL

The increasing discharge of heavy metals from textile industries into aquatic environments has necessitated the development and implementation of various treatment technologies. Textile effluents commonly contain toxic metals such as chromium (Cr), cadmium (Cd), lead (Pb), copper (Cu), and nickel (Ni), which are non-biodegradable and persistent in nature. Due to their toxicity and long-term environmental impacts, regulatory bodies such as the United States Environmental Protection Agency and the World Health Organization have established strict permissible limits for heavy metals in industrial wastewater (USEPA, 2020; WHO, 2017). Over the years, several conventional treatment methods have been developed to remove heavy metals from wastewater before discharge into the environment. Among the most widely applied conventional techniques are chemical precipitation, ion exchange, membrane filtration, and adsorption using commercial activated carbon. These methods have demonstrated varying degrees of effectiveness depending on factors such as metal concentration, pH, temperature, and the presence of competing ions. Although these technologies are effective under controlled conditions, they often involve high operational costs, complex maintenance requirements, and secondary waste generation. A critical evaluation of these conventional methods is therefore essential to understand their strengths and limitations, particularly in comparison to emerging low-cost alternatives such as agricultural waste-based adsorbents.

Chemical Precipitation

Chemical precipitation is one of the most commonly used methods for removing heavy metals from industrial wastewater. This process involves the addition of chemical reagents that react with dissolved metal ions to form insoluble compounds, which can then be separated through sedimentation or filtration. The most widely used precipitation method is hydroxide precipitation, where alkaline agents such as lime ($Ca(OH)_2$) or sodium hydroxide ($NaOH$) are added to increase the pH and convert dissolved metals into metal hydroxides (Fu & Wang, 2011). The effectiveness of chemical precipitation largely depends on the solubility of metal hydroxides at specific pH levels. For example, metals such as chromium, copper, and nickel precipitate efficiently within certain optimal pH ranges. Sulfide precipitation is another variation, where sulfide compounds are added to form metal sulfides, which are generally less soluble than hydroxides. Studies have shown that chemical precipitation can achieve high removal efficiencies for metals present at moderate to high concentrations (Tchounwou et al., 2012).

Despite its widespread application, chemical precipitation has several limitations. The process generates large volumes of sludge containing concentrated heavy metals, which require further treatment and safe disposal. Sludge handling and disposal significantly increase operational costs and pose environmental risks if not properly managed. Additionally, chemical precipitation is less effective at removing metals present at low concentrations and may require precise pH control and continuous chemical dosing. These challenges limit its applicability in small-scale textile industries, particularly in developing regions.



Source : https://www.shutterstock.com/search/chemical-precipitation?image_type=illustration

Figure 1.1 Chemical Precipitation

Ion Exchange

Ion exchange is another widely used technique for heavy metal removal from wastewater. This process involves the reversible exchange of ions between a solid ion-exchange resin and the surrounding aqueous solution. Synthetic resins containing functional groups such as sulfonic acid, carboxylic acid, or amine groups are commonly used to selectively remove metal ions from wastewater streams. In ion exchange systems, metal cations in wastewater are exchanged with less harmful ions (e.g., sodium or hydrogen ions) attached to the resin surface. Once the resin becomes saturated with metal ions, it can be regenerated using chemical solutions such as acids or bases, allowing repeated use of the material. Ion exchange is particularly effective for removing low concentrations of heavy metals and can achieve high selectivity for specific metals (Fu & Wang, 2011).

However, ion exchange systems require careful pre-treatment of wastewater to remove suspended solids and organic matter that may foul the resin. The regeneration process also produces secondary waste streams containing concentrated metal solutions, which must be treated before disposal. Furthermore, the cost of synthetic resins and regeneration chemicals can be relatively high, limiting their economic feasibility for large-scale textile wastewater treatment (Tchounwou et al., 2012).

Membrane Filtration

Membrane filtration technologies, including ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO), have gained attention for their ability to remove heavy metals and other contaminants from wastewater. These processes use semi-permeable membranes to separate dissolved substances based on size exclusion or charge interactions. Reverse osmosis, in particular, is highly effective in removing dissolved metal ions and achieving high-quality treated water suitable for reuse. Nanofiltration membranes can selectively remove divalent and multivalent metal ions, making them suitable for textile effluent treatment. Membrane processes offer several advantages, including high removal efficiency, compact design, and minimal chemical usage. According to Fu and Wang (2011), reverse osmosis systems can achieve metal removal efficiencies exceeding 95% under optimized conditions.

Despite these advantages, membrane filtration systems are associated with high capital and operational costs. Membrane fouling, caused by the accumulation of suspended solids and organic matter on membrane surfaces, reduces efficiency and increases maintenance requirements. Frequent cleaning and membrane replacement add to operational expenses. Additionally, membrane processes generate concentrated reject streams that require further treatment or safe disposal. These limitations restrict the widespread application of membrane technologies in cost-sensitive textile industries.

Adsorption Using Commercial Activated Carbon

Adsorption is widely regarded as one of the most effective methods for heavy metal removal, particularly when using commercial activated carbon. Activated carbon is a highly porous material with a large surface area and abundant surface functional groups capable of binding metal ions. It can be produced from coal, wood, coconut shells, or other carbon-rich materials through physical or chemical activation processes. The mechanism of metal adsorption onto activated carbon involves physical adsorption, ion exchange, and surface complexation. Numerous studies have demonstrated that activated carbon exhibits high adsorption capacities for metals such as lead, cadmium, and chromium (Fu & Wang, 2011). The process is relatively simple to operate and does not require complex equipment.

However, the high cost of commercial activated carbon limits its practical use in large-scale textile wastewater treatment. The regeneration process can also reduce adsorption efficiency over time and may require chemical treatments that generate secondary pollutants. Additionally, the disposal of spent activated carbon loaded with heavy metals poses environmental challenges. These economic and environmental constraints have encouraged researchers to explore low-cost alternative adsorbents derived from agricultural waste materials.

Limitations of Conventional Treatment Methods

Although conventional methods such as chemical precipitation, ion exchange, membrane filtration, and activated carbon adsorption have proven effective, they suffer from several significant limitations. One major drawback is the high operational and maintenance cost associated with chemical reagents, energy consumption, and specialized equipment. Small and medium-scale textile industries often lack the financial resources and technical expertise required to implement these advanced treatment systems effectively.

Another critical limitation is the generation of secondary waste products. Chemical precipitation produces large quantities of toxic sludge, ion exchange generates regeneration brine solutions, and membrane filtration produces concentrated reject streams. These by-products require further treatment and safe disposal, increasing overall environmental and economic burdens. According to the United Nations Environment Programme, inadequate management of industrial sludge remains a persistent environmental issue in many developing countries (UNEP, 2019). Moreover, conventional methods may exhibit reduced efficiency at low metal concentrations and can be sensitive to variations in wastewater composition. The presence of competing ions, fluctuating pH, and high salinity in textile effluents can negatively affect treatment performance. These challenges highlight the need for alternative treatment approaches that are cost-effective, environmentally friendly, and capable of operating efficiently under varying conditions.

In recent years, attention has shifted toward sustainable materials such as agricultural waste for heavy metal removal. These materials are abundant, renewable, and inexpensive, making them attractive alternatives to commercial adsorbents. By converting agricultural residues into effective adsorbents, it is possible to address both waste management and wastewater treatment challenges simultaneously.

III. ADSORPTION AS AN EFFECTIVE TREATMENT TECHNIQUE

Adsorption has emerged as one of the most efficient, economical, and environmentally friendly techniques for the removal of heavy metals from textile wastewater. Unlike conventional methods such as chemical precipitation or membrane filtration, adsorption is simple to operate, highly effective even at low metal concentrations, and capable of minimizing secondary waste generation. Due to these advantages, adsorption has gained considerable attention in wastewater treatment research and industrial applications (Fu & Wang, 2011).

Textile effluents typically contain complex mixtures of toxic metals such as chromium (Cr), cadmium (Cd), lead (Pb), copper (Cu), and nickel (Ni). These metals are non-biodegradable and tend to accumulate in the environment, making their removal essential before wastewater discharge. According to the United States Environmental Protection Agency, heavy metals must be reduced to permissible levels to prevent ecological and human health risks (USEPA, 2020). Adsorption is particularly suitable because it can effectively remove metals even at trace concentrations, where other conventional methods may be less efficient. In recent years, adsorption has been widely studied using various adsorbents such as activated carbon, zeolites, biosorbents, and agricultural wastes. Its effectiveness is attributed to its ability to bind metal ions onto the surface of solid materials through physical or chemical interactions. The process is influenced by several operational parameters, and its advantages over conventional techniques make it a promising solution for sustainable wastewater treatment (Tchounwou et al., 2012).

Principles of Adsorption

The fundamental principles of adsorption involve the accumulation of substances (adsorbates) from a liquid phase onto the surface of a solid material (adsorbent). The following key principles explain the adsorption process:

- **Surface Phenomenon**
  - Adsorption occurs at the interface between the solid adsorbent and the liquid solution.
  - The efficiency depends largely on the surface area and porosity of the adsorbent.
  - Materials with high surface area provide more active binding sites for metal ions (Fu & Wang, 2011).
- **Types of Adsorption**
  - **Physical Adsorption (Physisorption)**
    - Involves weak van der Waals forces.
    - Generally reversible.
    - Occurs at lower temperatures.
  - **Chemical Adsorption (Chemisorption)**
    - Involves formation of chemical bonds between metal ions and functional groups on the adsorbent surface.
    - Stronger and often irreversible.
    - More specific and selective for certain metals (Tchounwou et al., 2012).
- **Adsorption Isotherms**
  - Describe the relationship between the amount of metal adsorbed and its equilibrium concentration in solution.
  - **Langmuir Isotherm**
    - Assumes monolayer adsorption on a homogeneous surface.
  - **Freundlich Isotherm**
    - Assumes heterogeneous surface adsorption with multilayer formation.
  - These models help predict adsorption capacity and optimize treatment systems (Fu & Wang, 2011).
- **Adsorption Kinetics**
  - Determines the rate at which metal ions are removed from solution.
  - Common kinetic models include:
    - Pseudo-first-order model
    - Pseudo-second-order model
  - Kinetic studies are essential for designing industrial adsorption systems.
- **Thermodynamic Considerations**
  - Adsorption may be endothermic or exothermic.
  - Thermodynamic parameters such as Gibbs free energy (ΔG), enthalpy (ΔH), and entropy (ΔS) help determine spontaneity and feasibility.

Factors Affecting Adsorption Efficiency

The efficiency of adsorption in removing heavy metals from textile wastewater depends on several operational and environmental factors:

- **pH of the Solution**
  - One of the most critical factors influencing adsorption.
  - Affects metal speciation and surface charge of the adsorbent.
  - Low pH may cause competition between hydrogen ions and metal ions.
  - Optimal pH varies depending on the type of metal (Fu & Wang, 2011).
- **Initial Metal Concentration**
  - Higher concentrations increase the driving force for mass transfer.
  - However, adsorption sites may become saturated at very high concentrations.
- **Adsorbent Dose**
  - Increasing adsorbent dosage generally improves removal efficiency.
  - Excess dosage may lead to particle aggregation, reducing effective surface area.

- **Contact Time**
    - Determines equilibrium attainment.
    - Rapid adsorption often occurs initially due to abundant active sites.
    - Equilibrium is reached when no further significant adsorption occurs.
- **Temperature**
    - Influences adsorption capacity and reaction kinetics.
    - Endothermic adsorption increases with temperature.
    - Exothermic adsorption decreases with temperature.
- **Presence of Competing Ions**
    - Textile wastewater contains multiple dissolved salts and metals.
    - Competing ions may reduce adsorption efficiency due to site competition (Tchounwou et al., 2012).
- **Surface Characteristics of Adsorbent**
    - Surface area
    - Pore size distribution
    - Functional groups (–OH, –COOH, $–NH_2$)
    - Greater porosity enhances adsorption performance.
- **Agitation Speed**
    - Enhances contact between adsorbent and adsorbate.
    - Improves mass transfer rate.

According to the World Health Organization, optimizing these parameters is essential to ensure safe discharge levels of heavy metals into the environment (WHO, 2017).

IV. Advantages of Adsorption over Other Techniques

Adsorption offers several advantages compared to conventional heavy metal removal techniques:

- **High Removal Efficiency**
    - Effective even at low metal concentrations.
    - Suitable for polishing treatment stages (Fu & Wang, 2011).
- **Cost-Effectiveness**
    - Especially when low-cost adsorbents such as agricultural waste are used.
    - Lower operational cost compared to membrane filtration and ion exchange.
- **Simplicity of Design and Operation**
    - Easy to operate.
    - Does not require highly skilled labor.
    - Suitable for small-scale textile industries.
- **Minimal Sludge Production**
    - Produces less secondary waste compared to chemical precipitation.
    - Reduces sludge disposal costs.
- **Regeneration and Reusability**
    - Many adsorbents can be regenerated and reused.
    - Enhances sustainability.
- **Environmental Friendliness**
    - Can utilize renewable and biodegradable materials.
    - Supports circular economy principles.
- **Flexibility**
    - Can be applied in batch or continuous systems.

  - Compatible with other treatment methods in hybrid systems.
- **Selectivity**
  - Modified adsorbents can selectively remove specific metals.
- **Energy Efficiency**
  - Generally requires less energy compared to advanced membrane systems.
- **Adaptability to Variable Conditions**
  - Can perform under varying pH and concentration ranges with proper optimization.

Due to these advantages, adsorption is increasingly considered a sustainable alternative for treating textile wastewater contaminated with heavy metals. Research efforts are now focused on developing low-cost, eco-friendly adsorbents derived from agricultural waste materials to further improve treatment efficiency while reducing operational costs.

V. Conclusion

The study emphasizes that adsorption is one of the most suitable techniques for the removal of lead from aqueous solutions, particularly when low-cost agricultural waste-based bioadsorbents are used. Compared with conventional treatment methods, bioadsorption offers important advantages such as lower cost, operational simplicity, minimal secondary waste generation, and environmental sustainability. Agricultural wastes provide a valuable alternative to commercial adsorbents because they are abundant, renewable, and effective in binding heavy metal ions. Overall, the comparative evaluation shows that agricultural waste-based bioadsorbents have strong potential for wastewater treatment applications and can contribute significantly to sustainable management of industrial effluents. Further research on optimization and large-scale application can strengthen their practical use in real wastewater treatment systems.

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