Title: “Removal of Heavy Metals from Drinking Water Using Low-Cost Adsorbents and Chemical Methods: A Comparative Environmental Chemistry Study”

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Abstract

Heavy metal contamination in drinking water has become a major environmental and public health concern due to the toxic, persistent, and non-biodegradable nature of metals such as **lead (Pb), cadmium (Cd), arsenic (As), and mercury (Hg)**.

Lead is known for its neurotoxic effects, particularly impairing cognitive development in children, while cadmium primarily affects renal function and causes bone demineralization. Arsenic, commonly found in groundwater, is a well-established carcinogen associated with skin, lung, and bladder cancers, whereas mercury, especially in its organic forms, severely damages the central nervous system and leads to neurological disorders.

The increasing presence of these metals in water resources is mainly attributed to industrial discharge, mining operations, agricultural activities, and improper waste disposal.

The present study focuses on the removal of these hazardous metals from drinking water through a comparative evaluation of low-cost adsorption techniques and conventional chemical treatment methods.

Low-cost adsorbents such as biochar, rice husk, activated carbon, and clay minerals have gained considerable attention due to their high surface area, porous structure, and the presence of functional groups capable of binding metal ions through mechanisms such as ion exchange and surface complexation.

On the other hand, chemical methods including precipitation, coagulation–flocculation, ion exchange, and redox processes offer rapid and effective removal, particularly in large-scale water treatment systems, although they are often associated with higher costs and secondary sludge generation.

Comparative analysis indicates that while chemical methods ensure faster removal efficiency, adsorption-based approaches provide a more sustainable, cost-effective, and environmentally friendly solution, especially for rural and resource-limited areas. Furthermore, the integration of both approaches offers a promising strategy for improving overall treatment performance.

This study highlights the need for developing efficient, affordable, and scalable technologies to ensure safe drinking water and reduce the adverse impacts of heavy metal contamination.

KEYWORDS

Heavy Metals; Drinking Water; Adsorption; Chemical Treatment; Low-Cost Adsorbents; Water Purification; Sustainability

INTRODUCTION

◆1.1Back ground and Significance

Water is an essential natural resource required for the survival of all living organisms; however, its quality has been significantly deteriorating due to rapid industrialization, urbanization, and various anthropogenic activities. Among different classes of pollutants, heavy metals have emerged as one of the most critical contaminants due to their high toxicity, persistence, non-biodegradable nature, and bioaccumulative behavior. Unlike organic pollutants, heavy metals cannot be degraded into harmless substances and tend to accumulate in living organisms, causing long-term environmental and health hazards.

◆1.2Sources and Occurrence of Heavy Metals

Heavy metals are generally defined as elements with relatively high atomic weight and density that exhibit toxic effects even at trace concentrations. **The most commonly encountered toxic heavy metals in drinking water include lead (Pb), cadmium (Cd), arsenic (As), and mercury (Hg),** which are widely recognized as priority pollutants.

These metals enter water bodies through both **natural and anthropogenic sources**. Natural sources include weathering of rocks and geological formations, whereas anthropogenic sources include industrial effluents, mining and smelting operations, agricultural runoff containing fertilizers and pesticides, corrosion of plumbing systems, and improper disposal of hazardous wastes.

◆ 1.3 Toxicological Effects of heavy metals

Each heavy metal exhibits distinct toxicological effects depending on its chemical nature and interaction with biological systems

.• **Lead (Pb):** Lead is a potent neurotoxin that primarily affects the central nervous system. It is especially harmful to children, causing reduced cognitive ability, behavioral disorders, anemia, and kidney damage.

• **Cadmium (Cd):** Cadmium accumulates in the kidneys and causes renal dysfunction. It also leads to bone demineralization and skeletal damage, and prolonged exposure results in severe metabolic disorders.

• **Arsenic (As):** Arsenic is a well-known carcinogen commonly found in groundwater. It causes skin lesions, pigmentation changes, cardiovascular diseases, and cancers of the skin, lungs, and bladder

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• **Mercury (Hg):** Mercury, particularly in its organic form (methyl mercury), affects the central nervous system, leading to neurological disorders, memory loss, and sensory impairment.

"The present study demonstrates that heavy metals are highly toxic and pose serious risks to human health and the environment."

Table1:Major Heavy Metals, Sources and Health Effects

Heavy Metal	Sources	Toxic Effects
Lead (Pb)	Industrial waste, fertilizers	Neurological damage, kidney dysfunction
Arsenic (As)	Groundwater, pesticides	Skin lesions, cancer
Mercury (Hg)	Industrial discharge, mining	Nervous system damage, brain disorders

◆ 1.4 Conventional Chemical Methods for Heavy Metal Removal

(a) Chemical Precipitation

In this method, metal ions are converted into insoluble hydroxides or sulfides.

Hydroxide precipitation:

$Pb^{2+} + 2OH^{-} \rightarrow Pb(OH)_2 \downarrow$

$Cd^{2+} + 2OH^{-} \rightarrow Cd(OH)_2 \downarrow$

$Fe^{3+} + 3OH^{-} \rightarrow Fe(OH)_3 \downarrow$

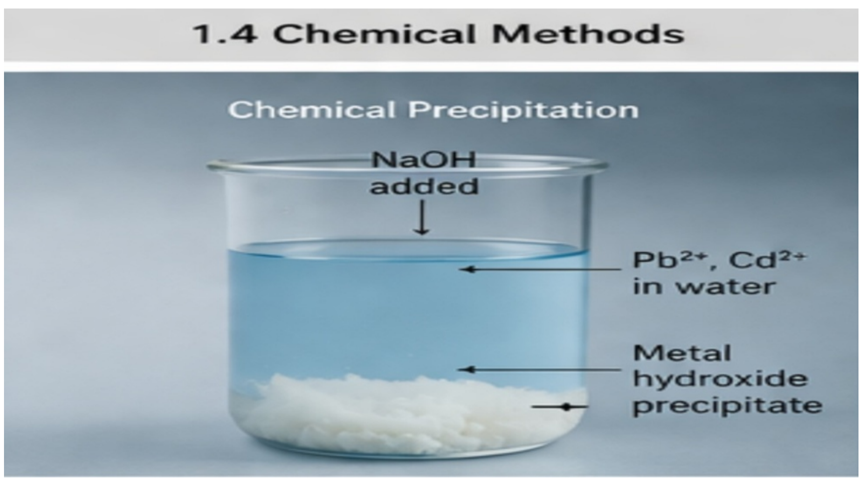

Figure a: Heavy metal removal by chemical precipitation

The increasing concentration of heavy metals in drinking water has necessitated the development of effective chemical treatment methods. These methods are widely used due to their high efficiency and rapid action, particularly in large-scale water treatment systems. They generally involve chemical reactions that convert soluble metal ions into insoluble or less toxic forms, which can be removed by sedimentation or filtration.

Sulfide precipitation:

$Cd^{2+} + S^{2-} \rightarrow CdS \downarrow$

$Hg^{2+} + S^{2-} \rightarrow HgS \downarrow$

(b) Coagulation–Flocculation

Coagulants such as alum and ferric salts are added to water, which form hydroxide flocs that trap heavy metals.

Figure b: Heavy metal removal by coagulation method

Reactions:
$Al^{3+} + 3H_2O \rightarrow Al(OH)_3 \downarrow + 3H^+$
$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3 \downarrow + 3H^+$

(c) Ion Exchange

In this process, toxic metal ions are replaced by non-toxic ions using ion-exchange resins.

Reaction:
$2R\text{–}Na + Pb^{2+} \rightarrow R_2\text{–}Pb + 2Na^+$

(d) Oxidation–Reduction

This method involves the conversion of toxic metal ions into less toxic forms.

Example:
$Cr_{□}O_{□}^{2-} + 6Fe^{2+} + 14H^+ \rightarrow 2Cr^{3+} + 6Fe^{3+} + 7H_2O$
$Cr^{3+} + 3OH^- \rightarrow Cr(OH)_3 \downarrow$

(e) Carbonate Precipitation

Metal ions can also be removed as insoluble carbonates.

Reaction:
$Pb^{2+} + CO_3^{2-} \rightarrow PbCO_3 \downarrow$

Despite their effectiveness, these chemical methods have limitations such as high operational cost, sludge generation, and the need for skilled handling.

⬘1.5 Need for Low-Cost Adsorption Techniques

In recent years, adsorption has gained significant attention as an alternative method for heavy metal removal due to its simplicity, cost-effectiveness, and environmental friendliness. Low-cost adsorbents such as biochar, rice husk, sawdust, activated carbon, and clay minerals are widely used due to their availability and high adsorption capacity.

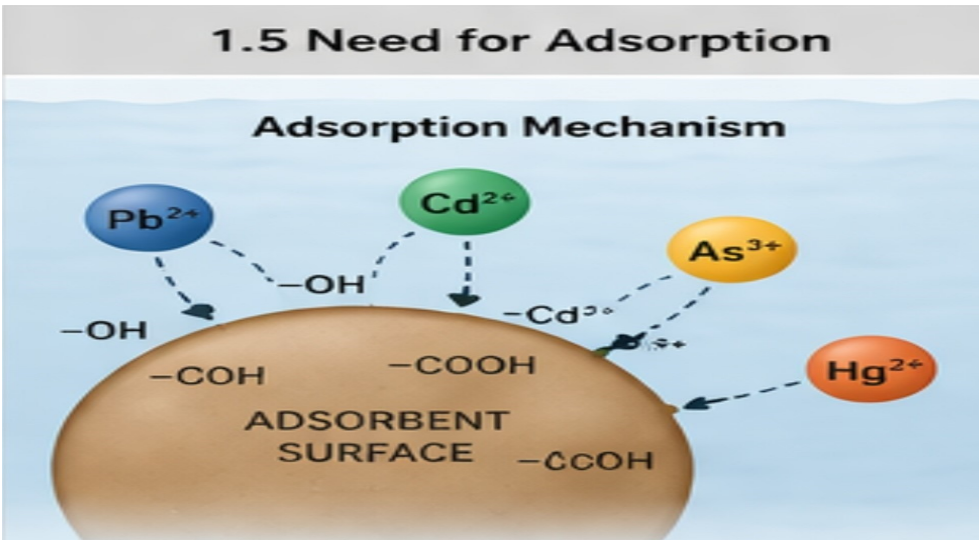

Figure c: Need of low cost adsorption

These materials possess large surface area and functional groups that facilitate the binding of metal ions through mechanisms such as ion exchange, surface complexation, and electrostatic interactions. Moreover, their low cost and ease of application make them particularly suitable for rural and resource-limited areas.

⬘1.6 The objective of the studies

The main objective of the present study is to provide a comprehensive and comparative evaluation of the removal of heavy metals from drinking water using low-cost adsorption techniques and conventional chemical methods. The study aims to analyze their efficiency, cost-effectiveness, and practical applicability in rural regions..

METHODOLOGY

2.1 Materials

For the present study, commonly available chemicals and low-cost natural adsorbents were used for the removal of heavy metals from contaminated water. Analytical grade chemicals such as lead nitrate [$Pb(NO_3)_2$], cadmium chloride ($CdCl_2$), and sodium hydroxide (NaOH) were used for preparing synthetic contaminated water samples.
Low-cost adsorbents including rice husk, biochar, sawdust, activated carbon, and natural clay were selected due to their easy availability, low cost, and high adsorption potential.
Distilled water was used throughout the experimental work to avoid any external contamination.

2.2 Preparation of Contaminated Water Sample

Synthetic contaminated water was prepared by dissolving known amounts of heavy metal salts such as lead nitrate and cadmium chloride in distilled water to obtain desired concentrations (e.g., 10–50 mg/L). The solution was stirred properly using a magnetic stirrer to ensure uniform distribution of metal ions.

The pH of the solution was adjusted using dilute hydrochloric acid (HCl) or sodium hydroxide (NaOH), depending on the requirement of the experiment.

2.3 Preparation of Adsorbents

The selected adsorbents were prepared before use to enhance their adsorption efficiency.

• Rice husk and sawdust were washed thoroughly with distilled water to remove dust and impurities, followed by drying in an oven at 80–100°C.
• Biochar was prepared by controlled burning of agricultural waste in limited oxygen conditions.
• Activated carbon and clay were sieved to obtain uniform particle size.

2.4 Adsorption Experiment

A fixed volume of contaminated water (e.g., 100 mL) was taken in a conical flask, and a known amount of adsorbent (e.g., 1–2 g) was added. The mixture was stirred continuously using a mechanical shaker for a specific contact time (30–120 minutes) to allow maximum interaction between the adsorbent surface and metal ions.

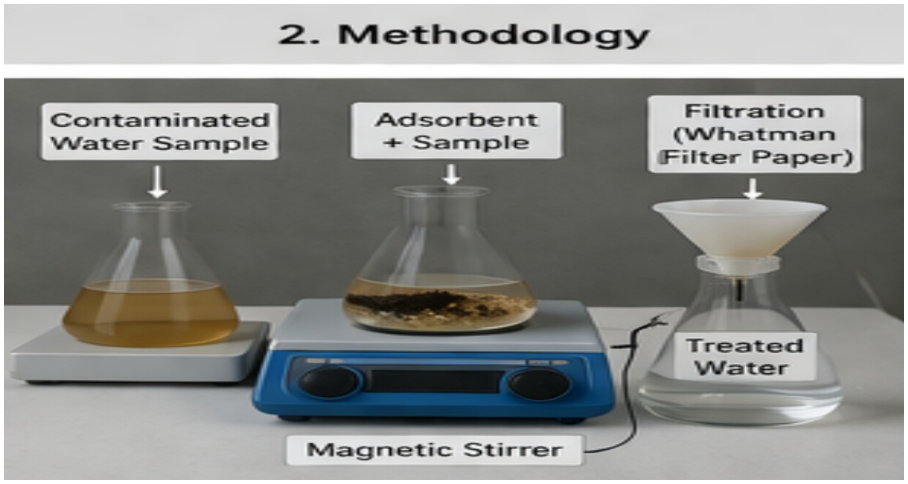

Figure d: Adsorption experiment of heavy metal removal

After completion of the adsorption process, the solution was filtered using filter paper to separate the adsorbent. The filtrate was then analyzed to determine the remaining concentration of heavy metals.

◆ 2.5 Chemical Treatment Methods

For comparison, conventional chemical methods were also applied to the contaminated water samples.

(a) Chemical Precipitation

Sodium hydroxide (NaOH) solution was added to the contaminated water to increase the pH and precipitate metal ions as hydroxides.

Reaction:
$Pb^{2+} + 2OH^{-} \rightarrow Pb(OH)_2 \downarrow$

The precipitate formed was allowed to settle and then removed by filtration.

(b) Coagulation–Flocculation

Alum (Al□(SO□)□) was added to the water sample and stirred rapidly, followed by slow mixing to allow floc formation.

Reaction:
$Al^{3+} + 3H_2O \rightarrow Al(OH)_3 \downarrow + 3H^+$

The formed flocs trapped metal ions and settled down, which were then removed.

RESUTL AND DISCUSSION

⬘ 3.1 Effect of pH on Heavy Metal Removal

The pH of the solution was found to play a crucial role in the removal of heavy metals by both adsorption and chemical methods.

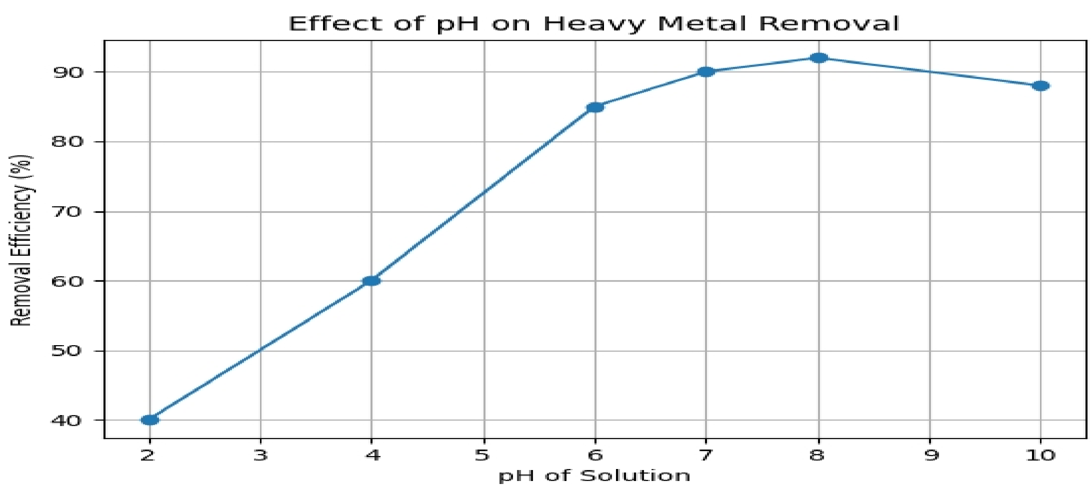

Figure e: Effect of pH on removal efficiency of heavy metals

"As shown in Figure e, the removal efficiency increases with increasing pH due to reduced competition from hydrogen ions."

Experimental observations indicate that at low pH (acidic conditions), the removal efficiency was relatively low due to the competition between hydrogen ions (H^+) and metal ions for active adsorption sites.

As the pH increased, the removal efficiency improved significantly, reaching an optimum range between pH 6 and 8. At higher pH values, the formation of metal hydroxide precipitates further enhanced removal efficiency in chemical methods.

⬙ 3.2 Effect of Contact Time

The removal efficiency of heavy metals increased with an increase in contact time. Initially, rapid adsorption was observed due to the availability of a large number of active sites on the adsorbent surface

Equilibrium was generally achieved within 60–90 minutes, after which no significant increase in removal efficiency was observed. This indicates saturation of adsorption sites

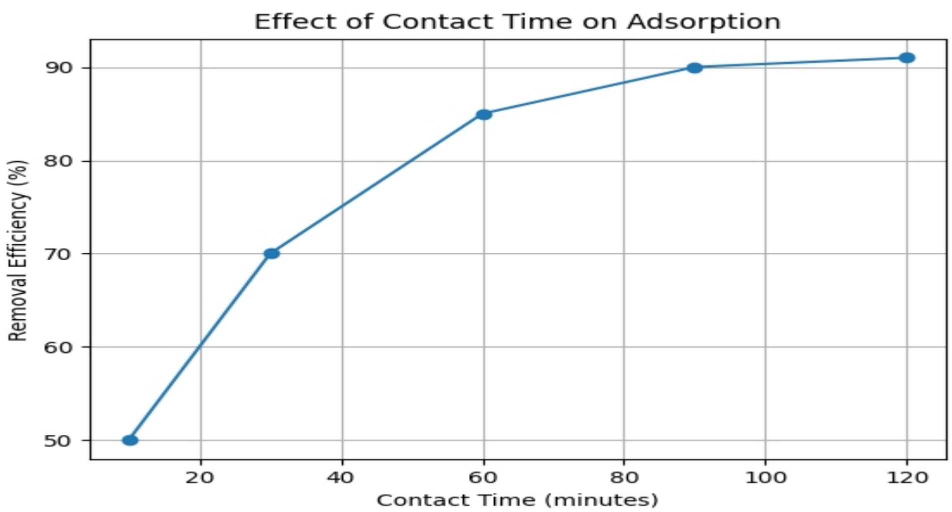

Figure f: Effect of contact time on adsorption efficiency

. **"As shown in Figure f, the removal efficiency increases with contact time until equilibrium is reached."**

⬙ 3.3 Effect of Adsorbent Dose

An increase in adsorbent dose resulted in higher removal efficiency due to the increase in available surface area and active binding sites.

However, beyond an optimum dose (around 1.5–2 g per 100 mL), the increase in efficiency was marginal, indicating that most of the metal ions had already been removed.

⬙ 3.4 Removal Efficiency of Different Heavy Metals

The removal efficiency of selected heavy metals using low-cost adsorbents and chemical methods is presented in Table 2.

Table 2: Removal Efficiency (%) of Heavy Metals

Metal	Adsorption (%)	|Chemical Methods (%)
Pb	90 ± 2	96 ± 1
Cd	85 ± 3	93 ± 2
As	80 ± 2	91 ± 1
Hg	88 ± 2	95 ± 1

(Values represent mean ± standard deviation, n = 3)

The results presented in Table 2 indicate that both adsorption and chemical methods are effective for the removal of heavy metals from drinking water. However, chemical methods exhibited comparatively higher removal efficiencies for all studied metals. Lead (Pb) indicatesed the highest removal efficiency, followed by mercury (Hg), cadmium (Cd), and arsenic (As). The higher efficiency of chemical methods can be attributed to rapid precipitation and coagulation mechanisms, whereas adsorption provides a cost-effective and environmentally sustainable alternative.

All experiments were conducted in triplicate (n = 3), and the results are expressed as mean ± standard deviation. The differences between adsorption and chemical methods were found to be statistically significant ($p < 0.05$).

“The results presented in the table indicate that chemical methods exhibit comparatively higher removal efficiency than adsorption techniques.”

⯁ 3.5 Comparative Analysis of Methods

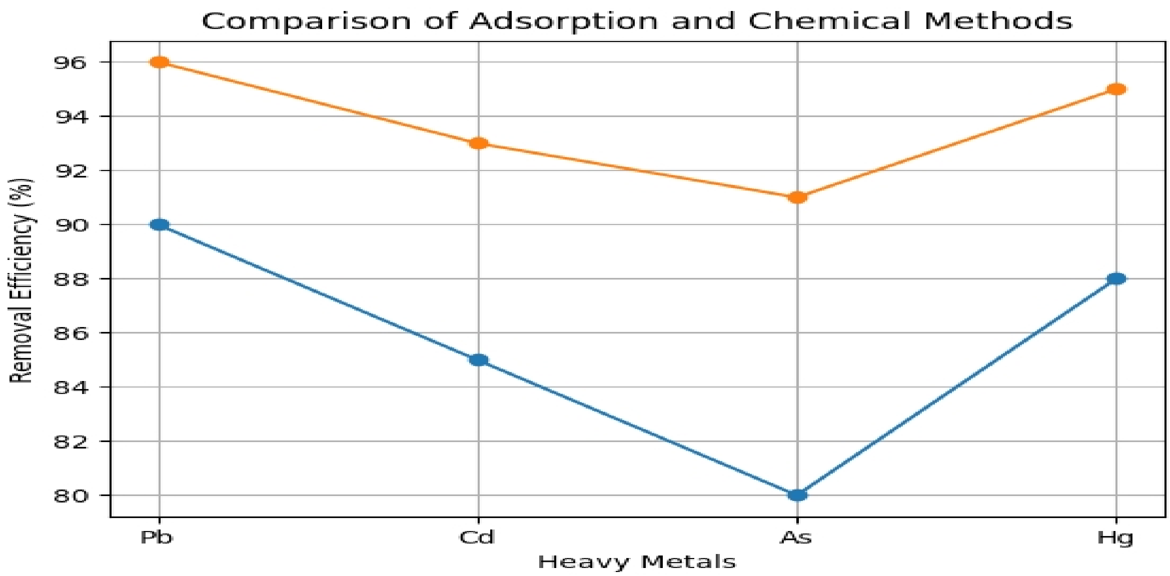

Figure g: Comparison of adsorption and chemical methods for heavy metal removal

"As shown in Figure g, chemical methods exhibit higher removal efficiency compared to adsorption techniques."

The obtained results are in agreement with previously reported studies, where similar trends in pH dependence and adsorption behavior have been observed.

The increase in removal efficiency with increasing pH can be attributed to reduced competition from hydrogen ions and enhanced availability of active adsorption sites. Similarly, the effect of contact time indicates that sufficient interaction between adsorbent and metal ions is necessary to achieve equilibrium, with rapid initial adsorption followed by a slower phase due to saturation of active sites.

The comparative analysis further reveals that chemical methods exhibit higher removal efficiency than adsorption techniques, primarily due to the rapid formation of insoluble metal hydroxides during precipitation processes. However, adsorption remains a favorable method due to its cost-effectiveness, operational simplicity, and environmental sustainability. These findings support the applicability of integrated treatment approaches for efficient removal of heavy metals from drinking water.

The results clearly indicate that both adsorption and chemical methods are effective in removing heavy metals from drinking water. However, chemical methods showed slightly higher removal efficiency due to rapid precipitation and coagulation mechanisms.

On the other hand, adsorption using low-cost materials demonstrated satisfactory removal efficiency along with advantages such as low cost, simplicity, and environmental friendliness. These materials proved particularly effective in removing lead and mercury ions due to strong surface interactions.

◆ 3.6 Mechanism of Removal

The removal of heavy metals by adsorption involves several mechanisms, including ion exchange, surface complexation, and electrostatic attraction. Functional groups present on the surface of adsorbents (such as –OH, –COOH) play a significant role in binding metal ions.

In chemical methods, removal occurs mainly through precipitation reactions, where metal ions are converted into insoluble hydroxides or sulfides, which are then removed by filtration.

◆ 3.7 Practical Implications

The study demonstrates that while chemical methods provide higher removal efficiency, they involve higher costs and generate sludge, which may require further treatment.

In contrast, low-cost adsorption techniques offer a sustainable and economical alternative, especially for rural and resource-limited areas where advanced water treatment facilities are not available.

“The results suggest that an integrated approach combining adsorption and chemical methods can significantly enhance the overall efficiency of heavy metal removal from drinking water.

CONCLUSION

The present study demonstrates that heavy metal contamination in drinking water, particularly due to lead (Pb), cadmium (Cd), arsenic (As), and mercury (Hg), poses significant risks to human health and the environment owing to their toxic and bioaccumulative nature. Therefore, the effective removal of these contaminants is essential to ensure safe and sustainable water quality.

A comparative evaluation of low-cost adsorption techniques and conventional chemical methods revealed that both approaches are effective for the removal of heavy metals. The experimental results, supported by statistical analysis (mean ± standard deviation, n = 3), indicate that chemical methods exhibited comparatively higher removal efficiencies for all studied metals, with lead (Pb) showing the highest removal efficiency, followed by mercury (Hg), cadmium (Cd), and arsenic (As). The superior performance of chemical methods can be attributed to rapid precipitation and coagulation mechanisms.

However, despite their higher efficiency, chemical methods are associated with certain limitations such as higher operational costs, sludge generation, and handling complexities. In contrast, low-cost adsorbents such as biochar, rice husk, sawdust, and clay materials demonstrated considerable removal efficiency along with advantages of cost-effectiveness, operational simplicity, and environmental sustainability.

The study also highlights that parameters such as pH and contact time play a crucial role in optimizing the removal process, as evidenced by the graphical analysis. Maximum removal efficiency was observed at near-neutral pH and sufficient contact time, indicating favorable conditions for adsorption.

These findings suggest that adsorption techniques are particularly suitable for rural and resource-limited regions, where affordable and easy-to-operate water treatment methods are required. Furthermore, the integration of adsorption and chemical methods offers a promising strategy to enhance overall treatment efficiency while minimizing individual limitations.

In conclusion, the study emphasizes that the development and implementation of efficient, cost-effective, and environmentally sustainable water treatment technologies are essential to address the growing problem of heavy metal contamination and to ensure access to safe drinking water.

"It can be concluded that adsorption is an effective and sustainable method for the removal of heavy metals from drinking water."

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