

# Removal of Heavy Metals from Contaminated Water Using Low-Cost Adsorbents: A Comprehensive Review

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**Abstract:** Heavy metal contamination of water is a significant environmental concern because many metal ions are toxic, persistent, and capable of accumulating in living organisms. Industrial activities such as electroplating, mining, metal processing, battery manufacturing, tanning, and fertilizer production can introduce metals into aquatic environments. Conventional water-treatment technologies, including chemical precipitation, ion exchange, membrane filtration, and coagulation, can be effective, but their cost, sludge generation, operational complexity, or sensitivity to water chemistry may limit their application in certain settings. Adsorption has therefore received considerable attention as a relatively simple and potentially economical method for removing dissolved metals from contaminated water.

This review examines research published up to 31 December 2021 on the use of low-cost adsorbents for heavy metal removal. Materials considered include agricultural residues, fruit and vegetable wastes, sawdust, rice husk, tea waste, natural clays, zeolites, industrial by-products, microbial biomass, chitosan, activated carbon, and biochar. The principal adsorption mechanisms—including ion exchange, electrostatic attraction, surface complexation, physical adsorption, and precipitation—are discussed. The effects of pH, adsorbent dosage, contact time, initial metal concentration, temperature, and competing ions are also examined. Particular attention is given to adsorbent modification, regeneration, disposal of metal-loaded materials, and the challenges of translating laboratory findings into practical water-treatment systems. Studies available by 2021 demonstrate the potential of waste-derived adsorbents, while also highlighting the need for standardized testing, realistic wastewater trials, and comprehensive cost and environmental assessments.

**Keywords:** Heavy metals, contaminated water, wastewater treatment, low-cost adsorbents, adsorption, biosorption, agricultural waste, biochar, activated carbon, water purification.

## I. INTRODUCTION

Water is essential for human health, agriculture, industry, and ecosystem stability. However, rapid industrialization, urbanization, mining, and improper waste disposal have contributed to the deterioration of water quality. Among the contaminants of concern are toxic metals and metalloids, including lead (Pb), cadmium (Cd), mercury (Hg), chromium (Cr), nickel (Ni), copper (Cu), zinc (Zn), and arsenic (As).

Unlike many organic pollutants, metals cannot be destroyed through ordinary biological degradation. They may change chemical form, become immobilized, or be transferred between environmental compartments, but the element itself remains. Their mobility and toxicity depend on factors such as oxidation state, pH, dissolved organic matter, and interactions with other constituents.

For example, lead and cadmium exposure can cause serious health effects, while the toxicity and mobility of chromium depend strongly on its chemical form. Arsenic is technically a metalloid, but it is commonly included in water-

remediation studies dealing with toxic metal contaminants. These distinctions matter because a treatment that performs well for one contaminant may be ineffective for another.

A range of technologies has been developed to remove dissolved contaminants from wastewater. Chemical precipitation is widely used, but may produce metal-containing sludge. Membrane processes can achieve high removal but may require energy and produce a concentrated residual stream. Ion exchange can be selective, although competing ions and regeneration costs affect performance. Adsorption is attractive because it can use readily available materials, operate with relatively simple equipment, and be adapted to batch or continuous-flow systems. Comprehensive reviews published in 2021 also identify low-cost adsorbents and agricultural waste-derived materials as important areas of research.

The development of effective low-cost adsorbents is therefore relevant to decentralized wastewater treatment and resource-efficient pollution control. Nevertheless, a material should not be considered economically or environmentally superior solely because its raw material is inexpensive. Preparation, transport, chemical modification, regeneration, residual management, and treatment reliability must also be considered.

## **II. OBJECTIVES OF THE REVIEW**

The main objectives of this review are:

1. To describe the sources and environmental significance of heavy metal contamination in water.
2. To examine conventional treatment methods and the role of adsorption.
3. To classify low-cost adsorbents derived from agricultural, biological, mineral, and industrial sources.
4. To explain the mechanisms governing the removal of metal ions.
5. To discuss the main operational factors influencing adsorption performance.
6. To compare the benefits and limitations of different adsorbent classes.
7. To identify research gaps and future directions based on knowledge available through 2021.

## **III. SOURCES AND ENVIRONMENTAL EFFECTS OF HEAVY METAL CONTAMINATION**

Heavy metals can enter surface water, groundwater, and industrial wastewater through natural processes and human activities.

| <b>Source</b>                             | <b>Examples of contaminants</b>                          |
|-------------------------------------------|----------------------------------------------------------|
| Mining and mineral processing             | Pb, Cd, Cu, Zn, As                                       |
| Electroplating and metal finishing        | Cr, Ni, Cu, Zn                                           |
| Battery manufacturing and recycling       | Pb, Cd, Ni                                               |
| Tanneries and chemical industries         | Cr and other process-related metals                      |
| Fertilizer and pesticide-related runoff   | Cd, As and other trace elements, depending on the source |
| Landfill leachate and industrial disposal | Mixed metals                                             |
| Natural weathering of rocks               | As, Fe, Mn and other naturally occurring elements        |

The actual composition of contaminated water depends on the industrial process, local geology, waste-management practices, and treatment history.

### **3.1 Environmental and health significance**

Heavy metals can affect aquatic organisms, plants, soil quality, and human health. Their effects depend on concentration, duration of exposure, chemical speciation, and route of exposure. Some metals, such as copper and zinc, are essential micronutrients at low concentrations but may become toxic at elevated concentrations. Others, including lead and cadmium, have no established beneficial biological role in humans.

Metal contamination may also affect agricultural production when contaminated water is used for irrigation. Metals can accumulate in soils and enter food chains under suitable environmental conditions. Consequently, effective treatment

should aim not merely to reduce visible pollution but to lower dissolved and total contaminant concentrations to the required regulatory levels.

#### IV. CONVENTIONAL METHODS FOR HEAVY METAL REMOVAL

Several treatment technologies are used to control dissolved metals. The appropriate choice depends on the contaminant, concentration, wastewater composition, required discharge standard, and available resources.

| Treatment method             | Main principle                                                         | Potential limitation                                             |
|------------------------------|------------------------------------------------------------------------|------------------------------------------------------------------|
| Chemical precipitation       | Converts dissolved metals into less-soluble compounds                  | Sludge generation; performance depends on pH and metal chemistry |
| Coagulation and flocculation | Aggregates suspended or precipitated contaminants                      | Chemical consumption and residual sludge                         |
| Ion exchange                 | Exchanges dissolved ions with ions on a resin or other exchange medium | Competing ions and regeneration requirements                     |
| Membrane filtration          | Separates contaminants through selective membranes                     | Energy demand, fouling, and concentrate management               |
| Electrochemical treatment    | Uses electrical processes to remove or transform contaminants          | Electricity and equipment requirements                           |
| Adsorption                   | Transfers dissolved contaminants onto a solid surface                  | Spent adsorbent must be regenerated or safely managed            |

Adsorption is especially attractive when the adsorbent is inexpensive, locally available, effective at low concentrations, and reusable. However, it does not eliminate the contaminant: it transfers the metal from the water to a solid phase. This distinction is central to evaluating environmental safety.

#### V. CLASSIFICATION OF LOW-COST ADSORBENTS

Low-cost adsorbents can be grouped according to their origin and composition. Some materials are used directly after washing and drying, whereas others are carbonized, activated, chemically modified, or combined with other materials to improve performance.

##### 5.1 Agricultural waste-based adsorbents

Agricultural residues are among the most widely investigated low-cost materials because they are generated in large quantities and contain cellulose, hemicellulose, lignin, pectin, and other compounds bearing functional groups capable of interacting with metal ions.

Common examples include:

- Rice husk and rice straw
- Wheat straw and other crop residues
- Sawdust and wood-processing residues
- Coconut shells and nut shells
- Sugarcane bagasse
- Corn cobs and corn stalks
- Fruit peels, including banana and citrus peels
- Tea waste and other spent plant materials

The surface hydroxyl, carboxyl, and phenolic groups of these materials may bind dissolved metal ions. The relative abundance and accessibility of these groups depend on the material, pretreatment, and preparation method.

Advantages: abundant raw materials, potential waste valorization, and relatively simple preparation.

Limitations: variable composition, possible leaching of soluble organic compounds, limited mechanical strength, and potentially lower adsorption capacity than engineered materials.

Agricultural waste may be used directly or converted into biochar and activated carbon. Reviews available by 2021 identify crop residues, fruit peels, sawdust, and related by-products as important precursors for economical adsorbents.

### **5.2 Fruit and vegetable wastes**

Fruit and vegetable peels are attractive because they are readily available from households, markets, food-processing units, and restaurants. Their pectin and other plant-derived constituents may contain carboxyl and hydroxyl groups that participate in metal binding.

Banana peel, orange peel, lemon peel, and other biomass residues have been investigated for the uptake of different metal ions. Their performance depends on the metal species, solution pH, preparation method, particle size, and treatment conditions.

Untreated peels may swell, release dissolved organic matter, or have limited structural stability. Washing, drying, grinding, and chemical treatment can improve consistency, although any additional processing increases cost and may generate chemical waste.

### **5.3 Sawdust, wood residues, and plant biomass**

Sawdust is generated by timber processing and woodworking activities. Its lignocellulosic structure provides potential binding sites for metal ions. Other plant materials, including bark, leaves, stems, and roots, have also been investigated. The adsorption properties of these materials vary with tree species, age, particle size, and chemical composition. Chemical modification can introduce or expose additional functional groups, but modified biomass should be tested for residual reagents and leaching before practical use.

### **5.4 Microbial and other biological adsorbents**

Biomass from bacteria, fungi, algae, and other microorganisms can bind metal ions through cell-wall functional groups. This process is commonly called biosorption and may occur with living or non-living biomass.

Non-living biomass can be useful because it does not require the maintenance of active metabolism during adsorption. Potential disadvantages include limited mechanical stability, difficulty separating fine biomass from treated water, and possible biological contamination if materials are not appropriately prepared.

Chitosan, a biopolymer derived from chitin, is another important biological adsorbent. Its amino and hydroxyl groups can interact with metal ions. Chitosan-based materials can be prepared as beads, films, composites, or coated supports, although acid sensitivity, swelling, and preparation costs can affect practical performance.

### **5.5 Natural clays and zeolites**

Natural clays and zeolites are mineral-based materials that can be used as relatively inexpensive adsorbents. Their properties may include negatively charged surfaces, exchangeable ions, and porous structures.

Metal removal can occur through ion exchange, surface complexation, and other interactions. However, natural materials differ substantially in mineral composition, purity, particle size, and exchange capacity. Some may require washing, activation, or modification before use.

A further concern is the potential presence of unwanted minerals or impurities. Therefore, the suitability of a mineral adsorbent must be established through material characterization and leaching tests rather than assumed from its natural origin.

### **5.6 Biochar**

Biochar is a carbon-rich material produced by heating biomass under oxygen-limited conditions. Agricultural residues, wood waste, and other biomass materials can serve as feedstocks.

Its properties depend on feedstock type, pyrolysis temperature, residence time, and post-treatment. Biochar may contain pores, mineral components, and surface functional groups that facilitate metal removal through several mechanisms.

A review published in 2021 discussed biochar properties, modification techniques, operating factors, and mechanisms such as ion exchange, surface complexation, electrostatic interactions, redox reactions, and precipitation.

Biochar is promising because it can valorize biomass waste. However, a high surface area does not automatically guarantee high metal removal. Feedstock-derived minerals, surface charge, pH, and the chemical form of the target contaminant can be equally important.

### **5.7 Activated carbon and industrial by-products**

Activated carbon is widely used because its pore structure and surface chemistry can be tailored. Commercial activated carbon may be relatively expensive, encouraging the development of activated carbon from agricultural residues.

Certain industrial by-products, including fly ash and other mineral-rich materials, have also been examined as adsorbents. These materials require particular care because their composition may vary and they can contain potentially hazardous constituents. Leaching tests are essential before environmental application.

Overall, the term low-cost adsorbent should be interpreted as a comparative economic category rather than a guarantee of low total treatment cost or environmental safety.

## **VI. MECHANISMS OF HEAVY METAL ADSORPTION**

The removal of metal ions by low-cost adsorbents is generally governed by several mechanisms that may occur simultaneously. Identifying the dominant mechanism helps explain why adsorption performance changes with pH, material composition, and water chemistry.

### **6.1 Surface complexation**

Surface complexation occurs when metal ions form chemical interactions with functional groups on the adsorbent. Carboxyl, hydroxyl, amino, and other oxygen- or nitrogen-containing groups may participate in these interactions.

For example, a surface group represented as  $\text{R-COOH}$  may undergo deprotonation and interact with a dissolved metal ion. The extent of binding depends on the surface chemistry and solution conditions.

### **6.2 Ion exchange**

Ion exchange occurs when metal ions in solution replace other ions associated with the adsorbent. This mechanism can be important for zeolites, clays, and biomass containing exchangeable cations.

The efficiency of ion exchange is affected by the relative concentrations and affinities of the competing ions. Consequently, results obtained with a single-metal solution may not accurately predict performance in industrial wastewater.

### **6.3 Electrostatic attraction**

Electrostatic interactions depend on the electrical charge of the adsorbent surface and the charge of the dissolved species. Surface charge changes with pH, so adsorption may increase or decrease as the solution becomes more acidic or alkaline.

Electrostatic attraction is only one contributor to metal removal; it should not be assumed to explain every adsorption result.

### **6.4 Physical adsorption**

Physical adsorption involves interactions such as weak intermolecular forces and retention within accessible pores. Porosity can improve access to adsorption sites, but the pore-size distribution and surface chemistry determine whether metal species can reach and interact with those sites.

### **6.5 Precipitation and co-precipitation**

Metal removal can also occur when dissolved metal species form insoluble compounds or become incorporated into precipitates associated with the adsorbent. This may occur at higher pH or in the presence of particular mineral constituents.

An apparent reduction in dissolved metal concentration does not necessarily demonstrate adsorption alone. Precipitation, filtration, and retention of suspended particles may contribute to the measured removal. Appropriate controls are therefore required.

### **6.6 Redox reactions**

Some adsorbents can alter the oxidation state of particular contaminants. This is particularly relevant to chromium, where hexavalent chromium, Cr(VI), and trivalent chromium, Cr(III), have different chemical behaviour and toxicity. A study that measures only total chromium may not reveal whether the oxidation state changed during treatment. Where relevant, both total concentration and chemical speciation should be evaluated. Biochar research available by 2021 identifies multiple interacting mechanisms rather than a single universal explanation for metal removal.

## **VII. FACTORS AFFECTING ADSORPTION EFFICIENCY**

### **7.1 pH of the solution**

Solution pH is often one of the most influential operating parameters because it affects both the adsorbent surface and the chemical form of the metal.

At low pH, protons may compete with metal ions for binding sites, reducing uptake. At higher pH, surface groups may become more negatively charged, potentially increasing binding of positively charged metal ions. However, increasing pH may also cause some metals to precipitate.

Therefore, the optimum pH must be determined separately for each metal–adsorbent system, with controls to distinguish adsorption from precipitation.

### **7.2 Adsorbent dosage**

Increasing the amount of adsorbent generally provides more potential binding sites and may increase the percentage of metal removed. However, the adsorption capacity per unit mass may decline when a larger dose is used, because the available metal is distributed over more adsorbent.

An appropriate dose balances treatment efficiency, material consumption, and the cost of separating the adsorbent from the treated water.

### **7.3 Contact time**

Adsorption commonly proceeds through an initial rapid stage, followed by a slower approach to equilibrium. The initial stage may involve readily accessible surface sites, whereas later uptake may be limited by diffusion or fewer remaining sites.

The equilibrium time should be determined experimentally rather than assumed from results obtained using a different material or metal.

### **7.4 Initial metal concentration**

Initial concentration affects the driving force for mass transfer and the amount of metal available relative to the number of adsorption sites. At a fixed adsorbent dose, higher concentrations may increase uptake per unit mass while decreasing the percentage removed.

Both percentage removal and adsorption capacity should therefore be reported.

### **7.5 Temperature**

Temperature may influence diffusion, surface interactions, and the equilibrium of adsorption. Its effect depends on the particular system and cannot be generalized as always positive or negative.

### **7.6 Competing ions and real wastewater**

Industrial wastewater often contains several metals, dissolved salts, organic compounds, and suspended matter. These constituents can compete for binding sites, alter surface charge, block pores, or change metal speciation.

Single-metal laboratory experiments are useful for understanding basic behaviour, but they should be followed by experiments using multi-metal mixtures and representative real wastewater.

### **7.7 Particle size and surface modification**

Reducing particle size may improve access to binding sites but can complicate solid–liquid separation. Chemical activation and surface modification may improve adsorption, although the additional cost, chemical consumption, and possibility of leaching must be assessed.

### VIII. COMPARATIVE EVALUATION OF LOW-COST ADSORBENTS

The following table provides a qualitative comparison. It is not a ranking based on experimentally verified adsorption capacities, because those capacities depend on the individual study conditions.

| Adsorbent class             | Potential advantages                                    | Important limitations                                       |
|-----------------------------|---------------------------------------------------------|-------------------------------------------------------------|
| Fruit and vegetable peels   | Abundant, inexpensive, biodegradable feedstock          | Variable composition, possible leaching and swelling        |
| Rice husk and crop residues | Widely available agricultural by-products               | May require pretreatment or carbonization                   |
| Sawdust and bark            | Readily available lignocellulosic materials             | Variable performance and mechanical stability               |
| Tea waste                   | Waste valorization and accessible surface groups        | Composition varies; separation and leaching require testing |
| Microbial biomass and algae | Functional groups capable of binding metals             | Biomass stability, recovery, and biological safety          |
| Chitosan                    | Amino and hydroxyl groups; adaptable forms              | Preparation cost and pH-dependent stability                 |
| Clay and zeolite            | Mineral stability and ion-exchange potential            | Variable composition and possible impurities                |
| Biochar                     | Adjustable surface chemistry; can use waste biomass     | Properties vary with feedstock and production conditions    |
| Activated carbon from waste | Potentially high porosity and tunable surface chemistry | Activation cost, energy use, and regeneration requirements  |
| Industrial by-products      | Potentially inexpensive and locally available           | Composition variability and leaching risks                  |

Reviews published through 2021 emphasize that modified agricultural wastes and biochars can perform well under selected conditions, but comparison across studies remains difficult when test conditions differ.

### IX. EVALUATION OF ADSORPTION PERFORMANCE

Two commonly reported parameters are percentage removal and equilibrium adsorption capacity.

#### 9.1 Percentage removal

$$\text{Removal (\%)} = \frac{C_0 - C_t}{C_0} \times 100$$

Where:

- $C_0$  = initial dissolved metal concentration
- $C_t$  = dissolved metal concentration after treatment time  $t$

#### 9.2 Adsorption capacity

$$q_t = \frac{(C_0 - C_t)V}{m}$$

Where:

- $q_t$  = adsorption capacity at time  $t$ , usually expressed in mg/g
- $V$  = volume of solution in litres
- $m$  = mass of adsorbent in grams

At equilibrium,  $C_t$  and  $q_t$  may be replaced with  $C_e$  and  $q_e$ , respectively.

### 9.3 Illustrative calculation

Suppose a laboratory experiment treats 1 L of water containing 50 mg/L of a metal using 2 g of adsorbent. If the measured final concentration is 10 mg/L:

$$\text{Removal} = \frac{50 - 10}{50} \times 100 = 80\%$$

$$q_e = \frac{(50 - 10) \times 1}{2} = 20 \text{ mg/g}$$

These values are illustrative and are not experimental findings attributed to a published study.

A complete evaluation should report both metrics alongside pH, temperature, dosage, contact time, initial concentration, analytical method, and uncertainty. A high removal percentage at a high initial concentration does not necessarily mean the final concentration meets a drinking-water or discharge standard.

## X. ADSORPTION ISOTHERMS AND KINETIC MODELS

Adsorption models help describe experimental data and estimate how metal uptake changes with concentration and time.

### 10.1 Langmuir isotherm

The Langmuir model assumes adsorption on a finite set of sites with a defined maximum capacity under its idealized assumptions:

$$q_e = \frac{q_{\max} K_L C_e}{1 + K_L C_e}$$

Here,  $q_{\max}$  is the estimated maximum adsorption capacity and  $K_L$  is the Langmuir constant.

### 10.2 Freundlich isotherm

The Freundlich model is an empirical expression often used for heterogeneous adsorption surfaces:

$$q_e = K_F C_e^{1/n}$$

Here,  $(K_F)$  and  $(n)$  are empirical constants.

Neither model should be treated as proof of a particular molecular mechanism. Model selection should be based on fit quality, residual analysis, experimental design, and physical plausibility.

### 10.3 Pseudo-first-order and pseudo-second-order kinetics

Kinetic models are frequently used to describe the rate at which adsorption approaches equilibrium. The pseudo-second-order model is commonly fitted in adsorption studies, but a good fit alone does not establish that chemisorption is the rate-controlling mechanism.

Researchers should compare alternative models, evaluate residuals, and, where possible, investigate mass-transfer limitations and diffusion directly.

## XI. REGENERATION, REUSE, AND MANAGEMENT OF SPENT ADSORBENTS

Regeneration can reduce the quantity of fresh adsorbent required and may improve the economic feasibility of a treatment system. Common approaches include acid or alkaline washing, salt solutions, and other suitable desorption procedures.

However, regeneration can reduce adsorption capacity, damage the material, or create a concentrated metal-bearing solution. This secondary stream requires treatment or metal recovery. A material that works well in its first adsorption cycle may perform differently after repeated regeneration.

Spent adsorbents should be characterized to determine whether their metal content or leaching behaviour creates a hazardous-waste concern. Disposal in soil, ordinary landfill, or open environments should not be assumed safe. Depending on local regulations and the waste's properties, stabilization, recovery, or disposal through an authorized facility may be required.

A complete assessment should include:

- Adsorption capacity after each regeneration cycle.
- Amount of metal released during desorption.
- Chemical and energy consumption.
- Changes in adsorbent structure and stability.
- Leaching of metals and preparation chemicals.
- Final management of concentrated residues.

## **XII. ENVIRONMENTAL AND ECONOMIC ASSESSMENT**

Low-cost adsorbents are attractive because they can use locally available residues and reduce dependence on expensive commercial materials. Their environmental value, however, depends on the full treatment pathway.

A meaningful economic assessment should include raw-material collection, transport, washing, drying, grinding, carbonization or activation, chemical modification, storage, reactor operation, separation, regeneration, and waste disposal.

Likewise, an environmental assessment should consider energy consumption, greenhouse-gas emissions, water use, chemical inputs, and the risks associated with metal-loaded residues. Local availability can make a simple biomass adsorbent economical in one region but impractical in another.

An appropriate comparison should therefore be based on cost per volume of water treated to the required final quality, rather than raw adsorbent price alone.

## **XIII. RESEARCH GAPS AND FUTURE PERSPECTIVES UP TO 2021**

Despite extensive research on low-cost adsorbents, several challenges remained unresolved by the end of 2021.

### **13.1 Limited standardization between studies**

Different studies use different pH values, initial concentrations, contact times, particle sizes, adsorbent dosages, and analytical methods. Consequently, comparing reported adsorption capacities directly can be misleading. Standardized experimental protocols and consistent reporting are required.

### **13.2 Insufficient testing with real wastewater**

Many laboratory studies use synthetic solutions containing a single metal. Real industrial wastewater contains competing ions, dissolved organic matter, suspended solids, and other contaminants. More experiments using real wastewater are necessary to assess practical treatment performance.

### **13.3 Need for long-term performance data**

Short-duration batch experiments do not establish how an adsorbent performs during continuous operation. Fixed-bed column studies should evaluate breakthrough behaviour, pressure drop, hydraulic performance, capacity utilization, and service life.

### **13.4 Selectivity in multi-metal systems**

A low-cost adsorbent may bind one metal more strongly than another. Future research should examine competitive adsorption, selective recovery, and the influence of coexisting ions.

### **13.5 Safe regeneration and disposal**

Research should assess repeated reuse, metal recovery, leaching, and the stability of spent adsorbents. The environmental benefit of a low-cost material may be reduced if regeneration requires substantial chemicals or produces difficult-to-manage residues.

### **13.6 Development of modified biochars and composites**

Surface modification, mineral impregnation, and composite formation offer opportunities to improve selectivity and adsorption capacity. The advantages must be balanced against production cost, material stability, and the possibility of releasing nanoparticles or chemical additives into water.

### **13.7 Scale-up and economic feasibility**

Laboratory adsorption capacity does not automatically translate into cost-effective treatment at a larger scale. Pilot-scale studies should combine treatment efficiency, operating costs, material availability, regeneration, and waste management.

These challenges are consistent with review literature available in 2021, which highlights the potential of bio-waste-based adsorbents while emphasizing the need for better performance comparisons, regeneration assessment, and realistic application studies.

## **XIV. CONCLUSION**

Low-cost adsorbents offer a promising approach for reducing heavy metal contamination in water and wastewater. Agricultural residues, fruit peels, sawdust, tea waste, microbial biomass, chitosan, clays, zeolites, biochar, and waste-derived activated carbon have all attracted research interest because of their potential availability and useful surface properties.

Their removal performance depends on the chemical characteristics of the adsorbent, the identity and concentration of the contaminant, solution pH, contact time, dosage, temperature, and the presence of competing substances. Adsorption may involve surface complexation, ion exchange, electrostatic interactions, pore retention, precipitation, and redox reactions. No single mechanism or adsorbent is optimal for every metal and water composition.

The literature available up to 31 December 2021 supports further development of waste-derived adsorbents, especially where local residues can be converted into effective treatment materials. Nevertheless, the practical value of these materials must be demonstrated through standardized experiments, real-wastewater testing, continuous-flow studies, regeneration trials, and complete economic and environmental assessments.

Ultimately, successful heavy metal remediation requires more than achieving a high laboratory removal percentage. The treatment process must consistently meet the required final water-quality standards while managing the concentrated contaminants safely. Low-cost adsorbents should therefore be considered potential components of an integrated water-treatment strategy rather than universal replacements for all conventional treatment technologies.

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