A Review on the Role of Bamboo Biochar in Removing Heavy Metals from Wastewater

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Abstract:
Heavy metal contamination of wastewater is a significant environmental issue due to the toxicity, persistence, and bioaccumulation potential of metals such as lead (Pb), cadmium (Cd), chromium (Cr), arsenic (As), mercury (Hg), copper (Cu), nickel (Ni), and zinc (Zn). Conventional treatment methods are often costly and generate secondary pollutants. Biochar derived from bamboo has emerged as a sustainable, low-cost, and environmentally friendly adsorbent for heavy metal remediation. Bamboo biochar possesses a highly porous structure, large specific surface area, abundant functional groups, and excellent adsorption capacity. This review summarizes the production, physicochemical properties, adsorption mechanisms, factors affecting adsorption, modification strategies, and recent applications of bamboo biochar for heavy metal removal from wastewater.

Key words: Bamboo biochar, Heavy metals, Wastewater treatment, Adsorption, Surface modification, Environmental remediation

1. Introduction

Industrialization, mining, electroplating, textile manufacturing, battery production, and agricultural activities release substantial quantities of heavy metals into aquatic environments. Unlike organic pollutants, heavy metals are non-biodegradable and accumulate in living organisms, causing severe ecological and human health problems.

Adsorption has gained considerable attention as an effective treatment technology because of its simplicity, low operational cost, and high efficiency. Biochar, a carbon-rich material produced by the pyrolysis of biomass under oxygen-limited conditions, has emerged as an excellent adsorbent. Bamboo is particularly attractive as a biochar feedstock due to its rapid growth rate, high lignocellulosic content, abundance, and renewability (Lehmann & Joseph, 2015).

Bamboo biochar exhibits favorable physicochemical properties that facilitate the adsorption of heavy metal ions from wastewater, making it a promising material for sustainable environmental remediation.

2. Bamboo as a Feedstock for Biochar Production

Bamboo is one of the fastest-growing plants globally and is widely distributed in Asia, Africa, and South America. Its biomass consists primarily of:

- Cellulose (40–50%)
- Hemicellulose (20–30%)
- Lignin (20–30%)

The high carbon content and porous structure developed during pyrolysis make bamboo an ideal precursor for biochar production.

Advantages of Bamboo Feedstock

- Rapid renewability
- Low production cost
- High carbon yield
- Wide availability
- Environmentally sustainable

3. Production of Bamboo Biochar

Biochar is produced through pyrolysis under limited oxygen conditions.

Pyrolysis Process

Temperature (°C)	Characteristics
300–400	High oxygen-containing functional groups
400–600	Balanced porosity and surface functionality
600–900	High surface area and aromatic carbon content

The physicochemical properties of bamboo biochar depend on:
- Pyrolysis temperature
- Heating rate
- Residence time
- Particle size
- Feedstock characteristics

Higher temperatures generally increase surface area and pore volume while decreasing surface functional groups.

4. Physicochemical Properties of Bamboo Biochar
The effectiveness of bamboo biochar as an adsorbent is attributed to several properties:

4.1 Large Surface Area
Pyrolysis creates micro- and mesoporous structures that provide abundant adsorption sites.

4.2 Porous Structure
Well-developed pore networks facilitate diffusion and entrapment of metal ions.

4.3 Surface Functional Groups
Bamboo biochar contains:
- Hydroxyl (-OH)
- Carboxyl (-COOH)
- Carbonyl (C=O)
- Phenolic groups

These groups interact with metal ions through complexation and ion exchange.

4.4 Alkaline Nature
The alkaline pH of bamboo biochar promotes precipitation of certain heavy metals and reduces metal mobility.

5. Mechanisms of Heavy Metal Removal
Heavy metal adsorption onto bamboo biochar occurs through multiple mechanisms.

5.1 Ion Exchange
Metal ions replace naturally occurring ions such as:
- K^+
- Ca^{2+}
- Mg^{2+}

Example:
Pb^{2+} + Biochar–Ca → Biochar–Pb + Ca^{2+}

5.2 Surface Complexation
Functional groups on biochar surfaces bind metal ions.
Example:
-COOH + Pb^{2+} → COO–Pb
This mechanism is particularly important for Cd, Cu, and Pb adsorption.

5.3 Electrostatic Attraction
Negatively charged biochar surfaces attract positively charged metal ions.

5.4 Physical Adsorption
Metal ions become trapped within porous structures through van der Waals forces.

5.5 Surface Precipitation

At alkaline pH, metals precipitate as:

- Metal hydroxides
- Carbonates
- Phosphates

Examples:

- $Pb(OH)_2$
- $Cu(OH)_2$
- $ZnCO_3$

6. Modification of Bamboo Biochar

Raw bamboo biochar often exhibits limited adsorption capacity. Various modification methods significantly improve performance.

6.1 Acid Modification

Common acids:

- HCl
- HNO_3
- H_2SO_4

Benefits:

- Increased surface area
- Enhanced porosity
- More oxygen-containing functional groups

6.2 Alkali Modification

Using:

- $NaOH$
- KOH

Benefits:

Improved pore development
Increased surface charge

6.3 Metal Oxide Modification

Common metal oxides:

- Fe_3O_4
- MnO_2
- MgO

Advantages:

- Enhanced adsorption
- Magnetic separation capability
- Increased active sites

6.4 Nanocomposite Modification

Incorporation of:

- Graphene oxide
- Carbon nanotubes
- Nanoparticles

Results in significantly higher adsorption capacities.

7. Removal of Specific Heavy Metals

Lead (Pb^{2+})

Lead is highly toxic and affects neurological development.
Reported adsorption capacities of modified bamboo biochar range from 80–250 mg/g.

Major mechanisms:

- Complexation
- Precipitation
- Ion exchange

Cadmium (Cd^{2+})

Cadmium causes kidney damage and skeletal disorders.

Adsorption capacities:

- 40–180 mg/g

Main mechanisms:

- Surface complexation
- Electrostatic attraction

Chromium (Cr(VI))
Cr(VI) is highly carcinogenic.
Bamboo biochar removes chromium through:

- Adsorption
- Reduction of Cr(VI) to Cr(III)
- Precipitation

Copper (Cu^{2+})
Copper removal efficiencies often exceed 90%.
Mechanisms include:

- Ion exchange
- Surface complexation
  Q3R

Arsenic (As)
Iron-modified bamboo biochar exhibits excellent arsenic adsorption due to the affinity between iron oxides and arsenic species.

8. Factors Affecting Heavy Metal Adsorption
pH
Most adsorption processes are favored at pH 5–7.

Contact Time
Rapid adsorption occurs initially due to abundant active sites.

Initial Metal Concentration
Higher concentrations increase adsorption until saturation.

Temperature
Adsorption may increase with temperature in endothermic systems.

Biochar Dosage
Increasing dosage generally enhances removal efficiency.

9. Environmental and Economic Benefits
Environmental Benefits

- Waste biomass utilization
- Carbon sequestration
- Reduced landfill disposal
- Sustainable wastewater treatment

Economic Benefits

- Low-cost raw materials
- Simple production process
- Regeneration potential
- Reduced treatment expenses

10. Challenges and Future Perspectives
Despite its potential, several challenges remain:

1. Scale-up limitations.
2. Variability in biochar properties.
3. Regeneration efficiency concerns.
4. Disposal of metal-loaded biochar.
5. Limited field-scale studies.

Future research should focus on:

- Advanced modification techniques.
- Pilot-scale applications.
- Multi-metal adsorption systems.
- Long-term environmental safety.
- Circular economy approaches.

11. Conclusion

Bamboo biochar is a promising, sustainable, and cost-effective adsorbent for removing heavy metals from wastewater. Its high surface area, porous structure, and abundant functional groups facilitate efficient adsorption through ion exchange, complexation, electrostatic attraction, and precipitation mechanisms. Modified bamboo biochars, particularly those enhanced with acids, alkalis, and metal oxides, exhibit superior adsorption capacities for Pb, Cd, Cr, Cu, and As. Continued research on large-scale implementation, regeneration, and environmental safety will further establish bamboo biochar as a viable technology for wastewater remediation.

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