# Adsorption Mechanisms and Biochar Applications in the Removal of Heavy Metals from Aqueous Environments

**Aysham Mahmudova**

Baku Engineering University

**Abstract:** ***Water ecosystem contamination with heavy metals poses a continuous threat to human health due to its poisonous nature and its ability to remain unchanged in nature while accumulating in water bodies. The current approach to removing heavy metals through chemical methods and the use of ion exchange systems is not effective due to its high cost and the formation of evil sludge quantity and low removal performance at low metal concentrations. Among the other methods of wastewater treatment, adsorption is the most effective and economical, and environmentally friendly method of heavy metal removal. This paper discusses how biochar, which is produced from agricultural and livestock waste, such as cattle manure, can be utilized as an environmentally friendly adsorbent to eliminate heavy metals in water. The adsorption method works through two techniques, which are the powerful ionic or covalent bonding, and feeble Van Der Waals forces. The performance of adsorption depends on several parameters such as the area of a surface, the temperature of an environment, and the strength of adsorbent material to metal ions. Biochar prepared from agricultural and livestock wastes, especially cattle manure, can adsorb large quantities of heavy metals due to its high adsorption efficiency and surface characteristics. This property can also be reused in the future. It is a promising material that can immobilize heavy metal ions such as Pb(II), Cd(II), As(V), and Hg(II) due to its porous structure and its chemical stability. This research generally shows that biochar may be used as an eco-friendly and low-cost adsorbent in wastewater treatment. The adsorption and desorption behavior of biochar can be applied in large scale and can be useful in the development of effective remediation strategies to deal with heavy metal pollution in aquatic ecosystems.***

**Keywords:** Heavy metals, sticking, chemical bonding, physical bonding, biochar, cleaning wastewater, fixing environmental issues

## 1. Introduction

The phrase heavy metal has not been clearly defined by scientists. These contain elements that occur naturally, are heavy, and weigh 5 g/cm3 or more, which is five times heavier than the density of water. Heavy metals also include manganese, vanadium, chromium, iron, cobalt, nickel, copper, zinc, arsenic, molybdenum, silver, cadmium, lead, and mercury. These are emitted to the environment through human activities in factories and farms, water discharge, runoff, metal production, and mining operations. Heavy metals get into the body through breathing and eating of contaminated food or eating of contaminated water.

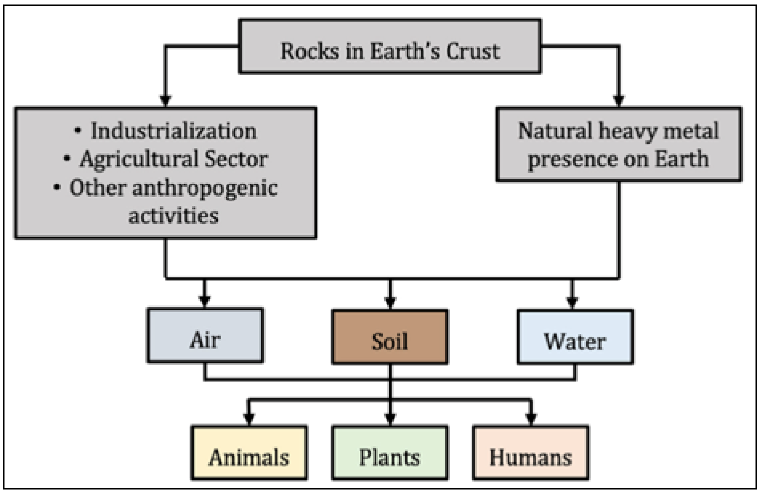



**Figure 1.** The heavy metal sources and their pathway into the environment and humans.

From the metabolic viewpoint, there are certain elements that are necessary at low concentrations to ensure metabolic processes, such as arsenic, cobalt, copper, iron, manganese, vanadium and zinc. They are vital in small quantities, yet lead, mercury, and cadmium, along with the other toxic metals, tend to be highly hazardous when consumed in large quantities.

Heavy metals within aquatic environments have two main sources of introduction to aquatic environments namely natural processes and human activities. Metal ions are naturally released into the environment through geological and environmental activities which include volcanic eruptions and the weathering of rocks and the leaching of minerals into various bodies of water including rivers and lakes and oceans. The metals have been present on the surface of the Earth since its formation. The global environment has a serious problem of ecosystem contamination due to the combination of fast industrial growth and modern production methods which use heavy metals extensively until their levels in terrestrial and aquatic environments have reached critical levels.

## 2. Material and Method

They are naturally occurring elements of high atomic weight and density, and they have a density greater than 5 g/cm3, which is five times heavier than water. They are generally recognized as persistent, non biodegradable, and possess toxicity even at low concentrations in the absence of a universally accepted definition. Some of the most commonly encountered heavy metals in terrestrial and aquatic systems include arsenic (As), molybdenum (Mo), zinc (Zn), manganese (Mn), cadmium (Cd), cobalt (Co), and nickel (Ni).

**Table 1:** Several heavy metal ions, with its respective possible source, health hazard and WHO (World Health Organization) permissible limit for water drinking.

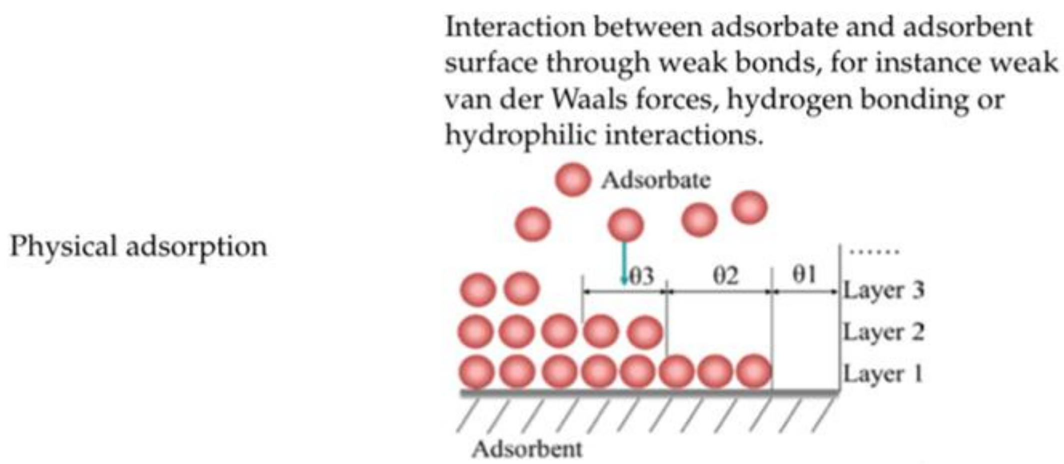
| Metal Ions | Sources | Harmful Effect | Allowed Limit (ppm) |
|---|---|---|---|
| As(V) | Volcanic activity, industries, paints, drugs, dyes and textiles, agriculture, smelting, mining | Severe arsenicosis, pigmentation problems, nausea, skin and kidney cancer | 0.01 |
| Mo (II) | Industrialization, pesticides, catalysts, alloys, non-corrosive agents | Mineral imbalance, increased serum ceruloplasmin, urinary copper excretion, gout-like symptoms | 0.07 |
| Zn (II) | Steel production plants, coal-fired stations, galvanized metal pipes | Fever, vomiting, nausea, stomach cramps, diarrhea | 3.00 |
| Mn (II) | Mining, dumping sites, agriculture, fertilizers, soil | Nervous system failure, mutagenic and hepatic encephalopathy | 0.10 |
| Cd (II) | Electroplating plants, metal smelting, paints, batteries, fertilizer and alloy industries | Renal malfunction, pulmonary issues, bone cancer, high blood pressure, Itai-Itai disease, bone abnormalities | 0.01 |
| Co (II) | Metallurgy, mining, electroplating industry, paint manufacturing, nuclear power plants | | |

**Table 2:** Additional Heavy Metal Ions, Their Sources, Harmful Effects, and Allowed Limits

| Metal Ions | Sources | Harmful Effect | Allowed Limit (ppm) |
|---|---|---|---|
| Cu (II) | Battery manufacturing, plumbing corrosion | Headache, depression, reduced IQ | 1.30 |
| Pb (II) | Plumbing fixtures, cable coverings, ceramics, batteries, paints, welding, extraction of lead, glass production | Liver failure, neurological damage, gastrointestinal impairment, hypertension, infertility, arthralgia | 0.05 |
| Hg (II) | Volcanic activity, mining operations, tanning, electroplating industries | Minamata disease, cancer | 0.002 |

Heavy metal content in the environment is being increased by natural processes and human activities. Heavy metals can result in serious health issues such as irreversible harm to organs when people are highly exposed to them. The concentration of heavy metals may exceed the recommended limits and these metals may become toxic and carcinogenic but they are not dangerous in smaller quantities which are not dangerous to humans and animals and plants.

Environmental researchers have researched new environmental technologies and developed new technologies to reduce the impact of heavy metal pollution over the past decades. Heavy metal pollution continues to be a significant concern that has led to scientists to research about metal concentrations in various ecosystems to discover their impacts and remove them, and develop protective measures. Water pollution environmental assessments that are tabulated in Table 2 are a reference point that experts utilize to develop sustainable remediation strategies.



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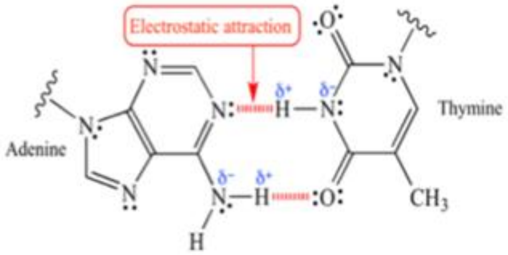
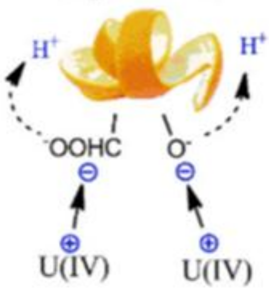
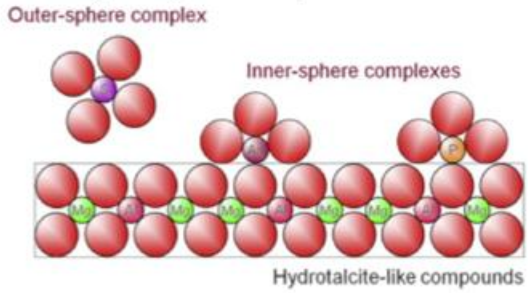
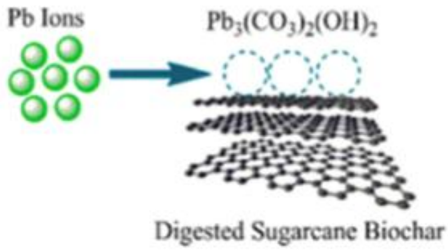
<tr><td>Electrostatic interaction</td><td>Attraction between the ion and the surface of the opposite charge, e.g., positive charged ions with a negative surface of an adsorbent.<br><br></td></tr>
<tr><td>Ion exchange</td><td>A process involving the interchange of adsorbent and adsorbate with the matching ions charge.<br><br></td></tr>
<tr><td>Surface complexation</td><td>A process where direct bond between adsorbate and adsorbent surface occurs at the inner sphere complex, while the outer sphere complex interacts with adsorbent via electrostatic interaction while retaining the hydration sphere.<br><br></td></tr>
<tr><td>Precipitation</td><td>Solid formation in solution or on a surface when the adsorbate ions interact on the adsorbent surface with a surface functional group due to a pH change.<br><br></td></tr>
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Zhu and coworkers carried out experiments which involved testing the biochar produced from cattle manure (CM) in its ability to absorb heavy metals. The results of their study revealed that cattle manure had better adsorption properties than rice husks and thus it could be used in contaminant removal. The Cattle manure biochar (CMB) has been shown to be a very effective heavy metal treatment material and it is a new way of using livestock waste resources. There is a wide range of adsorption mechanisms that are involved in the application of biochar and these have been summarized in Table 3. To understand the differences between these mechanisms, Figure 2 depicts the working of each adsorption process with biochar in the removal of Methylene Blue (MB).

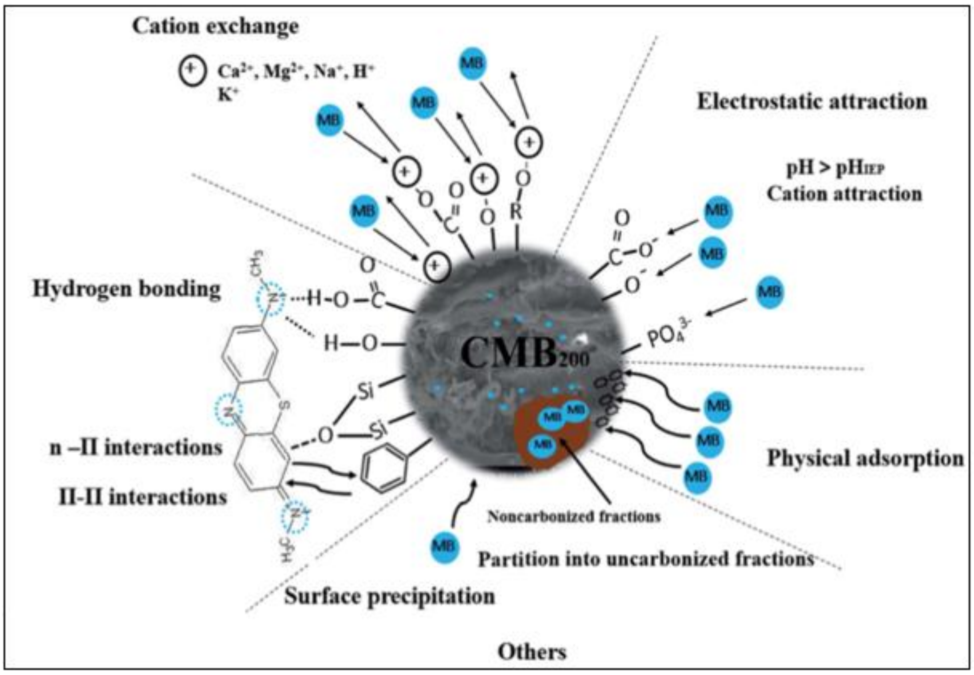


**Figure 2:** Interaction mechanisms involving adsorption in the biochar-MB system

The term adsorption was first introduced in 1881 by the German physicist Heinrich Kayser, and it remains widely used today. Adsorption refers to a surface phenomenon or separation process in which certain substances are removed from a fluid phase- either gas or liquid- by adhering to the surface of a solid material. In simpler terms, ions or molecules from an aqueous solution attach to the surface of solid particles, known as the adsorbent, through the process of adsorption. It is important to distinguish adsorption from absorption: while adsorption occurs on the surface of materials, absorption involves the penetration of substances into the bulk of another medium.

Adsorption is generally a reversible process; its reverse reaction is called desorption, wherein the adsorbed substance, or adsorbate, is released from the surface. Desorption is essential in catalytic reactions, as it allows the surface to be regenerated for subsequent adsorption cycles. This regeneration enables continuous adsorption by freeing the active sites for new molecules to attach. The variation in the amount of adsorbate can also be expressed as the difference between adsorption and desorption rates. The overall mechanism and related terminology of the adsorption–desorption process are depicted in Figure 3.

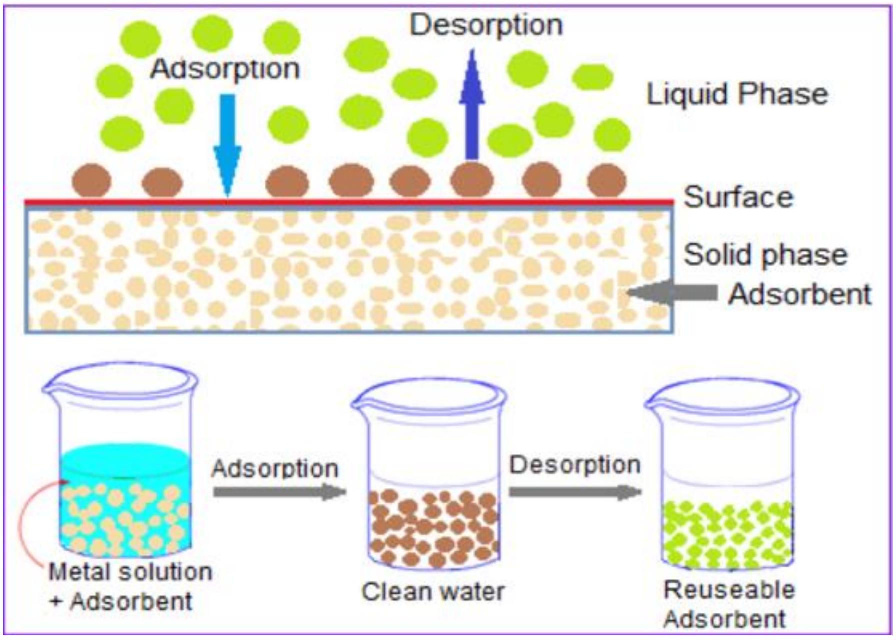


**Figure 3:** The mechanism of metal ions adsorption desorption process in water

The adsorption process can be categorized into two main types: chemical adsorption (chemisorption) and physical adsorption (physisorption). In some instances, both types of adsorptions may occur simultaneously. Chemisorption takes place in regions where chemical bonds form between the adsorbent and the adsorbate, typically involving ionic or covalent interactions. This process is highly specific and occurs only when chemical bonding is possible. The formation of these chemical bonds results in an enthalpy change ranging between 200 and 400 kJ/mol. Chemisorption efficiency is significantly influenced by the surface area and temperature, as these parameters directly affect the strength and extent of adsorption.

In contrast, physisorption involves weak interactions such as van der Waals forces. It is an exothermic process with lower enthalpy values, typically between 20 and 40 kJ/mol. Unlike chemisorption, physisorption is non-specific and can occur on the surface of nearly all solids to a comparable degree. Its effectiveness is influenced by surface area and temperature-favoring materials with a larger surface area and lower temperature.

## 3. Conclusion

Environmental pollution caused due to heavy metal contamination has become a global crisis since such elements do not degrade naturally but accumulate in our bodies and cause toxic effects. The natural processes and the human activities (mining and industrialization and farming) are responsible for the continuous introduction of such metals as arsenic and cadmium and mercury and lead and nickel into our water and soil and air. These minerals are hazardous even in negligible quantities as they cause nervous and kidney and heart diseases. Scientists need to develop sustainable-cleaning technologies immediately due to the urgent-cleaning of the contamination. Of the different ways to adsorb is one of the highly efficient and cheap and environmentally friendly treatment processes to remove heavy metals from the environment. This is a process in which the adsorbent is in contact with the surface of the adsorbate, and it can be chemisorption with strong ionic or covalent bonds or physisorption with weak Van der Waals forces. Each mechanism is dependent on factors that include surface area, temperature and bonding energy, which dictate the adsorption efficiency. Biochar adsorbents can be used to eliminate heavy metals according to the recent studies. The common biochar is easily affordable and is capable of absorbing more toxic metals compared to the common cattle manure-based biochar. The adsorption and desorption mechanism of these biochar molecules has to be known to researchers. This data will assist them in removing toxic metals in a more efficient manner and also in reusing the biochar numerous times.

In summary, adsorption technology provides a practical and environmentally friendly method to reduce heavy metal pollution, especially when using sustainable materials like biochar. Researchers need to focus on developing more selective adsorbents that can be regenerated efficiently, and that can be used on a large scale to protect the environment and human health over the long term.

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