Review Article

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Review on removal of heavy metals from industrial effluents by adsorption

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Abstract: Industrial activities generate significant amounts of wastewater containing toxic heavy metals, posing severe environmental and health risks. This review explores the efficient removal of heavy metals from industrial wastewater through adsorption techniques. Adsorption stands out as a promising method due to its versatility, cost-effectiveness, and high efficiency in reducing metal concentrations to permissible levels. The review systematically examines various adsorbents used in industrial effluent treatment, including activated carbon, zeolites, and biochars, highlighting their mechanisms and performance in metal ion removal. Factors influencing adsorption efficiency, such as pH, temperature, adsorbent dosage, and metal ion concentration, are critically evaluated. Recent advancements in adsorption technologies, such as hybrid materials and functionalized adsorbents, are discussed in terms of enhancing removal efficiencies and addressing specific challenges in industrial wastewater treatment. This review provides comprehensive insights into the current state of heavy metal removal by adsorption, emphasizing technological advancements, challenges, and future research directions aimed at sustainable and effective wastewater treatment practices.

Keywords: industrial effluents; heavy metals; adsorption; water pollution; environmental impact and heavy metal removal

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1 Environmental impact of industrial effluents from industries

The rapid industrialization and economic growth of recent decades have led to a significant increase in the generation of industrial effluents, which are discharged into the environment through various mediums such as air, water, and land.[1] Industrial effluents are waste materials produced by industrial processes, including manufacturing, mining, and energy production, and they can have devastating effects on the environment and human health if not managed properly.[2,3] Industrial effluents can contain a broad range of pollutants, including heavy metals, chemicals, pesticides, and other toxic substances (Figure 1).[4,5]

Noise pollution by industrial activities can generate excessive noise levels that can disrupt natural habitats and human health. Industrial effluents can also have social and economic impacts. Economic costs the clean-up and remediation of contaminated sites can be costly and burdensome for industries and governments.[7,8] Health impacts exposure to industrial pollutants can lead to increased healthcare costs and lost productivity. Social impacts industrial pollution can displace communities, disrupt traditional ways of life, and exacerbate social inequalities.[9,10] Despite these risks, many industries continue to discharge pollutants into the environment without adequate treatment or regulation.[11,12] The lack of effective monitoring and enforcement mechanisms allows industrial effluents to continue polluting the environment with impunity.[13]

1.1 Critical effects of industrial effluents on environment and health

Industrial effluents, which are waste materials generated by various industrial processes, can have devastating impacts on human health.[14] Exposure to these pollutants can lead to a range of health problems, from minor irritations to life-threatening conditions.[15,16] The significant impacts of industrial effluents on healthcare will be covered in this essay.

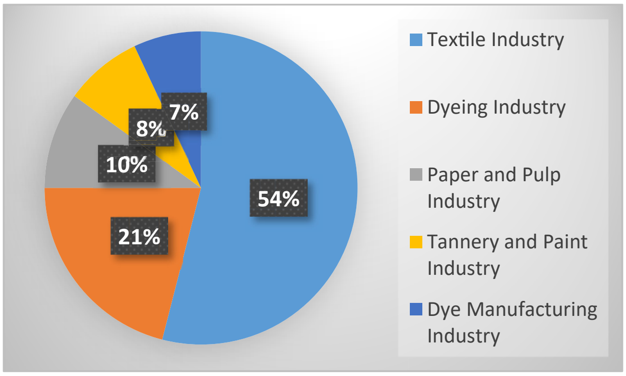


Figure 1: Effluent discharge by industries.[6]

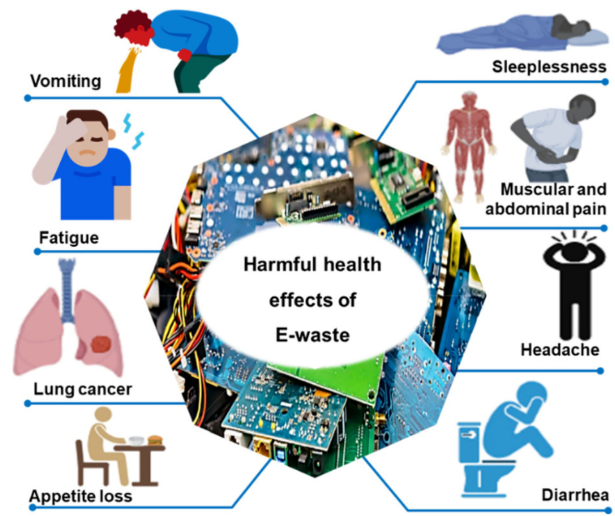


Figure 2: Harmful health effects of industrial effluents.[26]

Respiratory problems in industrial effluents can contain particulate matter, heavy metals, and volatile organic compounds (VOCs) that can irritate the respiratory system.[17,18] Exposure to these pollutants can lead to respiratory problems such as chronic obstructive pulmonary disease (COPD), asthma, and bronchitis. Inflammation and scarring, for instance, can result from particles in industrial pollutants penetrating deeply into the lungs.[19,20]

Immune system suppression in industrial effluents can contain immunosuppressant chemicals that weaken the immune system, making individuals more susceptible to infections and diseases. For example, exposure to pesticides has been linked to decreased immune function and increased risk of infections.[21] Industrial effluents have severe and far-reaching consequences on healthcare.[22,23] Exposure to these pollutants can lead to a range of health problems, from minor irritations to life-threatening conditions.[24] Through the implementation of efficient pollution control methods and sustainable practices, industries must take proactive actions to lessen their environmental footprint.[25] Furthermore, governments must establish strict regulations and monitoring systems to ensure that industries comply with environmental standards and protect public health (Figure 2).

1.2 Controlling strategies of industrial effluents from industries

Industrial effluents, which are waste materials generated by various industrial processes, can have devastating impacts on the environment and human health if not managed properly. Industries need to put in place efficient controls to limit the quantity of pollutants they discharge into the environment to lessen these consequences.[27,28] Pre-treatment involves treating industrial effluents before they are discharged into the environment.[29] To remove heavy metals, suspended particles, and other contaminants, physical, chemical, and biological methods may be used.[30,31] Wastewater treatment plants are designed to remove pollutants from industrial effluents before they are discharged into waterways.[32,33] These plants use various technologies such as sedimentation, filtration, and disinfection to remove pollutants.[34,35] Best Available Techniques (BATs) are the most effective techniques available for reducing pollution from specific industrial activities.[36,37] For example, BATs for cement manufacturing include using low-NOx burners and scrubbers to reduce emissions (Table 1).[38]

Public education and awareness campaigns can raise public awareness of the importance of environmental protection and encourage individuals to take action to reduce their environmental impact.[40,41] Regulatory frameworks provide a legal basis for controlling industrial effluents. Governments can establish laws, regulations, and standards to ensure that industries comply with environmental standards.[42] Controlling strategies for industrial effluents from

Table 1: Controlling strategies of industrial effluents.[39]

Category	Description
Pollution prevention	Reduce or eliminate pollutants at the source
Waste stream segregation	Separate different effluent streams for targeted treatment.
Pre-treatment	Initial treatment before final discharge or further treatment
Physico–chemical treatment	Employ physical and chemical processes to remove pollutants.
Biological treatment	Utilize microorganisms to break down organic matter.
Disinfection	Eliminate harmful pathogens before discharge.
Monitoring and regulations	Regular monitoring and adherence to discharge standards

industries involve a range of techniques that aim to reduce the amount of pollutants released into the environment.[43] By using these techniques, industries can lessen their negative effects on the environment and protect the environment and public health.[44]

1.3 Types and impact of industrial effluents from industries

Industrial effluents are waste materials generated by various industrial processes, which can have devastating impacts on the environment and human health if not managed properly.[45,46] Industrial effluents can come from a wide range of industries, including manufacturing, mining, energy production, and agriculture.[47] These effluents can take many forms, including liquid, solid, and gaseous pollutants.[48] Liquid effluents include wastewater from manufacturing processes, agricultural runoff, and contaminated groundwater.[49] Solid effluents include hazardous waste, industrial waste, and construction debris.[50,51] Gaseous effluents include air pollutants such as VOCs, particulate matter, and greenhouse gases. Industrial effluents can have significant impacts on the environment and human health.[52]

The environmental impacts, of industrial effluents can also have economic and social consequences.[53] For example, industrial accidents can result in costly clean-up efforts and damage to local businesses.[54] Moreover, communities surrounding industrial facilities may experience decreased property values and reduced quality of life due to environmental pollution.[55] Understanding the types and impacts of industrial effluents is crucial for developing effective strategies to mitigate their negative effects on the environment and human health (Figure 3).[56]

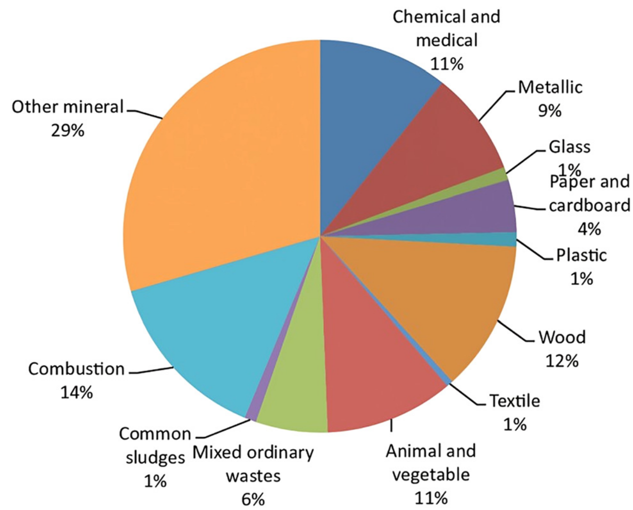


Figure 3: Types of industrial effluents from industries.

1.3.1 Solid effluents from industries

Solid effluents are a type of industrial waste that is generated by various industrial processes and activities.[57] These effluents can be in the form of hazardous or non-hazardous waste and can be generated by a wide range of industries, including manufacturing, mining, energy production, and construction.[58] Chemicals, insecticides, heavy metals, and other materials that may be hazardous to the environment and public health are included in the hazardous waste category of solid effluent.[59] Examples of hazardous waste include radioactive waste, asbestos, and chemical drums. Non-hazardous waste type of solid effluent includes materials such as paper, cardboard, glass, and metal that are not hazardous to human health or the environment.[60] Construction and Demolition (C&D) Debris type of solid effluent includes materials such as concrete, asphalt, wood, and steel that are generated during construction and demolition activities.[61] Industrial waste type of solid effluent includes materials such as machinery parts, packaging materials, and other materials that are generated during industrial processes.[62]

1.3.2 Liquid effluents from industries

Liquid effluents are a type of industrial waste that is generated by various industrial processes and activities.[63] These effluents can be in the form of wastewater, process water, or contaminated water, and can be generated by a broad range of industries, including manufacturing, mining, energy production, and agriculture.[64] Wastewater type of liquid effluent includes water that has been used in industrial processes and contains contaminants such as heavy metals, chemicals, and other pollutants.[65] Process water type of liquid effluent includes water that is used as a medium in industrial processes, such as cooling systems or chemical reactions.[66] Contaminated water type of liquid effluent includes water that has been contaminated with pollutants such as oil, chemicals, or heavy metals.[67]

1.3.3 Gaseous effluents from industries

Gaseous effluents are a type of industrial waste that is generated by various industrial processes and activities.[68] These effluents can be in the form of emissions from factories, power plants, and other industrial facilities, and can be released into the atmosphere through chimneys, stacks, or vents. Gaseous effluents can be composed of a wide range of pollutants, including VOCs, sulphur dioxide, nitrogen oxides, carbon monoxide, and particulate matter. These pollutants can have serious environmental and health impacts, including air pollution, acid rain, and climate change.[69]

2 Characterization of heavy metal from industrial effluents

The discharge of industrial effluents into the environment is a significant concern due to the potential harm they pose to both human health and ecosystems.[70] Among the various pollutants present in these effluents, heavy metals are particularly concerning due to their persistence, toxicity, and ability to bioaccumulate.[71] Heavy metals, such as lead, mercury, chromium, and arsenic, are often found in industrial effluents due to their use in various manufacturing processes, including mining, smelting, and electroplating.[72] It is essential to remove heavy metals from industrial effluent to stop them from entering the environment and harming people and animals later on (Figure 4).[73]

Similarly, studies have examined the effectiveness of adsorption using activated carbon and other materials to remove heavy metals from electroplating wastewater. Heavy metals have also been extracted from industrial effluent chemically by interacting them with acidic or alkaline materials. In addition to these conventional treatment technologies, researchers have also explored innovative approaches for removing heavy metals from industrial effluents. For instance, heavy metals have been removed from contaminated soil and water using bioremediation procedures, which involve microorganisms that may precipitate or solubilize these metals. Other innovative approaches include the use of nanoparticles and graphene-based materials for heavy metal removal.[74]

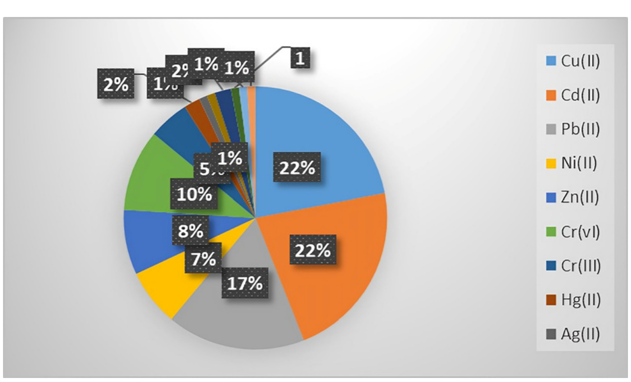


Figure 4: Common heavy metal contents.

2.1 Need for removal of heavy metals from industrial effluents

The removal of heavy metals from industrial effluents is a pressing concern due to the significant risks they pose to human health and ecological systems. Heavy metals, such as lead, mercury, and chromium, are naturally occurring elements that can be toxic even at low concentrations.[75] These metals can accumulate in soil, sediments, and water bodies after being discharged into the environment by industrial activities, which can have a variety of negative effects. One of the primary reasons for removing heavy metals from industrial effluents is the risk they pose to human health.[76,77] Heavy metals can bio-accumulate in the food chain, meaning they become increasingly concentrated as they move up the chain. This can lead to adverse health effects in humans who consume contaminated food or water. For example, exposure to high levels of lead has been linked to neurological disorders, kidney damage, and cancer.[78] Similarly, mercury has been shown to cause neurological damage and birth defects in children. The removal of heavy metals from industrial effluents is essential to prevent the contamination of water and food sources, thereby protecting human health. In addition to human health risks, heavy metals can also disrupt ecological systems.[79]

Another critical reason for removing heavy metals from industrial effluents is their environmental persistence. Unlike organic pollutants, which can degrade over time, heavy metals persist in the environment indefinitely. This means that the effects of their contamination can be long-lasting and widespread. For example, heavy metal contamination has been linked to the decline of entire ecosystems, including the collapse of fish populations and the degradation of wetlands. Effective regulations and treatment methods are critical to reducing heavy metal discharge into the environment. Regulatory bodies all around the globe have developed stringent criteria for reducing heavy metal emissions from industrial sources.[80] Chemical precipitation, ion exchange, adsorption, and bioremediation are some of the treatment techniques that have been developed to remove heavy metals from industrial effluents. These methods can successfully remove heavy metals from wastewater streams, avoiding their discharge into the environment and mitigating their effects on human health and natural systems.[81]

2.2 Variations in heavy metal concentrations and composition in waste

The concentrations and compositions of heavy metals in industrial effluents vary significantly depending on the specific

Table 2: Heavy metal concentrations in industrial effluents.[82]

Industry type	Dominant heavy metals (mg/L)	Other notable metals (mg/L)
Metal plating	Nickel (35) – chromium (28) – copper (12)	Zinc (5) – lead (2)
Mining	Lead (40) – arsenic (15) – manganese (30)	Cadmium (1) – mercury (trace)
Textile dyeing	Chromium (60) – zinc (25) – copper (10)	Cobalt (3) – nickel (2)
Leather tanning	Chromium (75) – arsenic (20) – aluminium (45)	Antimony (trace) – selenium (trace)
Electronics manufacturing	Lead (20) – cadmium (8) – mercury (trace)	Nickel (5) – silver (trace)
Paper & pulp processing	Mercury (trace) – copper (15) – zinc (10)	Lead (2) – chromium (1)

industry and its production processes. Various industries, including metal plating, mining and processing, chemical manufacturing, and textile dyeing, are common sources of heavy metal contamination in industrial wastewater. Metal plating industries, which involve the deposition of metals onto other materials, often use metals like chromium, nickel, and copper. These metals can be present in the wastewater generated from rinsing and cleaning processes, as well as during the actual plating process. For instance, to prevent corrosion, a thin layer of chromium is electroplated onto a metal surface in the process of chromium plating. This process can generate significant amounts of chromium-rich wastewater that requires proper treatment to prevent environmental contamination (Table 2).

Mining and processing activities also release heavy metals into the environment. Mining operations involve the extraction of minerals and metals from the earth, which can lead to the release of heavy metals like lead, arsenic, and cadmium into the environment. Processing these minerals and metals further can also result in the release of additional heavy metals. For instance, the smelting of ores to extract valuable metals can produce significant amounts of toxic emissions, including heavy metals like mercury and arsenic. Chemical manufacturing is another industry that can generate heavy metal-containing wastewater. The production of various chemicals often involves the utilize of heavy metals as catalysts or reactants. These metals can be present in the wastewater generated during these processes, posing a risk to environmental receptors if not properly treated. For example, the production of polyvinyl chloride (PVC) plastics involves the utilize of heavy metals like cadmium and lead as catalysts. The resulting wastewater can contain high levels of these metals, which require special treatment to prevent environmental contamination.[82]

2.3 Studies on removal of heavy metals from industrial effluents

El Mouden et al.[83] conducted a study that aims to synthesize NC@Co_3O_4 nanocomposites using natural clay and Co_3O_4 nanoparticles, focussing on their effectiveness, stability, and reusability in removing heavy metals (Pb(II) and Cd(II)) from wastewater. The NC@Co_3O_4 nanocomposites achieved adsorption efficiencies of 86.89 % for Pb(II) and 82.06 % for Cd(II), with maximum adsorption capacities of 55.24 mg/g and 52.91 mg/g, respectively. Kinetic and equilibrium data aligned with the PSO model and Langmuir isotherm, and Monte Carlo simulations confirmed the spontaneity of the adsorption process. Xinyue et al. conducted a study to evaluate the effectiveness of natural mineral clays extracted from the Syahkalahan mine as adsorbent matrices for the removal of lead ions (Pb) from drinking water, through detailed characterization and adsorption experiments. Characterization revealed that silica dominates the clay composition, with nanoscale particle sizes. The clays achieved >92 % lead ion removal efficiency under specific conditions. Ibrahim et al.[84] conducted a study that aims to develop an eco-friendly and cost-effective method for removing heavy metal ions from industrial wastewater by synthesizing zeolite using sulphuric acid solid residue (SASR) and kaolin through the alkaline fusion-hydrothermal method. The synthesized zeolite, characterized by XRD, FTIR, SEM, PSD, and N2 adsorption–desorption, showed high effectiveness in adsorbing Zn^{2+}, Pb^{2+}, Cu^{2+}, and Cd^{2+} ions. The maximum adsorption capacities were 12.025, 15.96, 12.247, and 16.17 $mg g^{-1}$, respectively, significantly improving the quality of wastewater for agricultural use. Chen et al.[85] conducted a study to enhance the adsorption capacity of Zr-based metal-organic frameworks (MOFs) for hexavalent chromium (Cr^{6+}) by developing a novel formic acid and amino-modified MOF, referred to as Form-UiO-66-NH_2. The modification significantly increased the specific surface area, pore size, and crystal size of the MOF, resulting in an excellent Cr^{6+} adsorption capacity of 338.98 mg/g. This is approximately 10 times higher than unmodified Zr-based MOFs and most other adsorbents, demonstrating the efficacy of the modification.

3 Heavy metal removal methods from industrial effluents

Heavy metal removal from industrial effluents is crucial due to the toxic effects these contaminants have on human

Figure 5: Heavy metal removal techniques.[87]

health and the environment. Various methods have been developed and employed to address this issue, each with its advantages and limitations.[86] Traditional methods such as chemical precipitation, ion exchange, and adsorption are widely used. Chemical precipitation involves adding reagents to form insoluble metal compounds, which are then separated from the wastewater. This method is cost-effective but can generate a significant amount of sludge that requires further treatment (Figure 5).

Bioremediation, involving the use of microorganisms or plants to remove heavy metals, has gained attention due to its environmental friendliness and sustainability. Techniques such as biosorption, where biological materials bind and concentrate heavy metals and phytoremediation, where plants absorb and accumulate metals, are effective but often slow and dependent on specific conditions. Advanced oxidation processes (AOPs) have also been explored, utilizing oxidizing agents like ozone, hydrogen peroxide, and UV light to degrade and remove heavy metals. These methods can achieve high efficiency but are energy-intensive and require careful control of reaction conditions.[88]

3.1 Conventional techniques for heavy metal removal from industrial effluents

Conventional techniques for heavy metal removal from industrial effluents have been extensively studied and implemented due to their effectiveness in mitigating environmental pollution. These techniques include ion exchange, membrane filtration, adsorption, chemical precipitation, and electrochemical methods. Chemical precipitation is one of the most widely used methods. It involves adding chemicals to the effluent, which reacts with the heavy metals to form insoluble precipitates that can be easily removed by sedimentation or filtration. Common precipitating agents include lime, sulphide, and hydroxide. Large volumes of sludge may be produced by this process, though, and it will need to be treated and disposed of.[89]

3.1.1 Precipitation method

The precipitation method is a conventional technique extensively utilized for the removal of heavy metals from wastewater. This process involves converting dissolved heavy metal ions into insoluble solid particles by adding chemical precipitants, such as lime, sulphides, or hydroxides. These precipitants combine with the heavy metal ions to create insoluble compounds that are easily filtered or sedimented out of the water. One popular technique is lime precipitation, which raises the pH of the water by adding calcium hydroxide, resulting in the precipitation of heavy metals as metal hydroxides.

3.1.2 Ion exchange method

The ion exchange method is a widely used conventional technique for the removal of heavy metals from wastewater. This process involves exchanging ions between a solid medium, typically a resin, and the aqueous solution containing the heavy metals. The resins used in ion exchange are usually synthetic polymers that are functionalized with specific ion exchange groups. These groups have a high affinity for certain metal ions, allowing them to effectively capture and remove metals such as lead, cadmium, copper, and zinc from the water.

Table 3 summarizes the efficiency of heavy metal removal using precipitation and ion exchange methods. Precipitation involves the formation of insoluble metal hydroxides or sulfides, achieving high removal efficiencies depending on pH and chemical dosage. Ion exchange, meanwhile, utilizes resins or zeolites to selectively remove metals through exchange with ions in solution, offering efficient removal depending on resin type and regeneration capability. Both methods are effective in treating heavy metal-contaminated water, with precipitation suitable for large-scale applications and ion exchange offering versatility in treating low-concentration effluents and recovering metals for reuse.

Table 3: Precipitation and ion exchange method HM removal efficiency.[90]

Removal efficiency (%) – precipitation	Removal efficiency (%) – ion exchange	Precipitant chemical	Ion exchange resin
90–98	95–99	Sodium sulphide (Na_2S)	Strong cation exchange resin
85–95	92–98	Sodium hydroxide (NaOH) or iron sulphide (FeS)	Chelating ion exchange resin
80–90	98–99	Mercaptans	Selective mercury removal resin
75–88 (Cr(VI))	85–95 (Cr(VI))	Sodium hydroxide (NaOH) for Cr(VI), sodium dithionite ($Na_2S_2O_4$) for Cr(III)	Anionic exchange resin for Cr(VI), cation exchange resin for Cr(III)
88–95	90–97	Sodium hydroxide (NaOH) or sulphide precipitation	Strong cation exchange resin
80–92	88–96	Sodium hydroxide (NaOH) or sulphide precipitation	Iminodiacetic acid (IDA) chelating resin
82–90	85–94	Sodium hydroxide (NaOH) or sulphide precipitation	Weak cation exchange resin

3.2 Emerging technologies for heavy metal removal from industrial effluents

Emerging technologies for heavy metal removal from industrial effluents have gained significant attention due to the pressing need for effective and sustainable water treatment solutions. Traditional methods like chemical precipitation, ion exchange, and adsorption have been widely used, but they often come with limitations such as high operational costs, generation of secondary pollutants, and inefficiency in removing low concentrations of heavy metals. In response to these challenges, several innovative technologies have been developed and are being researched for their potential to offer more efficient and environmentally friendly solutions. One promising technology is the use of nanomaterials, which have unique properties such as high surface area-to-volume ratio and tunable surface chemistry, making them highly effective for adsorbing heavy metals. Nanoparticles of materials like zero-valent iron, titanium dioxide, and carbon nanotubes have shown remarkable efficiency in removing heavy metals from wastewater.[91]

3.2.1 Adsorption method for heavy metal removal

Adsorption is a widely employed method for removing heavy metals from aqueous solutions due to its effectiveness and versatility. This process involves the attachment of metal ions onto a solid surface, known as an adsorbent, through various mechanisms such as ion exchange, electrostatic interactions, and complexation. Common adsorbents include activated carbon, zeolites, clays, and various biomaterials like agricultural wastes or algae biomass. The effectiveness of adsorption depends on factors like pH, temperature, concentration of metals, and surface area of the adsorbent. Adsorption offers several advantages such as high efficiency, ease of operation, and the potential for regeneration and reuse of the adsorbent material.

Figure 6 illustrates the process of heavy metal removal through adsorption, a pivotal environmental remediation technique. It visually represents the sequential stages involved: initial metal ion adsorption onto the adsorbent surface, followed by saturation and equilibrium phases. The graph showcases key parameters such as adsorption capacity over time or concentration levels, providing insights into the efficiency and dynamics of the adsorption process. This figure serves as a crucial visual aid for understanding the effectiveness of adsorption in mitigating heavy metal contamination in various environmental contexts.

3.2.2 Bioremediation method for heavy metal removal

Bioremediation offers a sustainable approach to removing heavy metals from contaminated environments, leveraging the metabolic capabilities of microorganisms and plants to detoxify polluted sites. This method involves various strategies, including bioaccumulation, bio sorption, and biotransformation. Bioaccumulation involves the uptake and concentration of heavy metals within microbial cells or plant tissues, effectively reducing their concentration in the surrounding environment. Bio sorption utilizes the binding capacity of microbial biomass or plant tissues to adsorb heavy metals onto their surfaces, making them less bioavailable and thereby reducing toxicity. Biotransformation involves enzymatic processes where microorganisms convert toxic heavy metals into less harmful forms through oxidation, reduction, or methylation reactions. These mechanisms not only mitigate environmental contamination but also offer cost-effective alternatives to traditional remediation methods.[85]

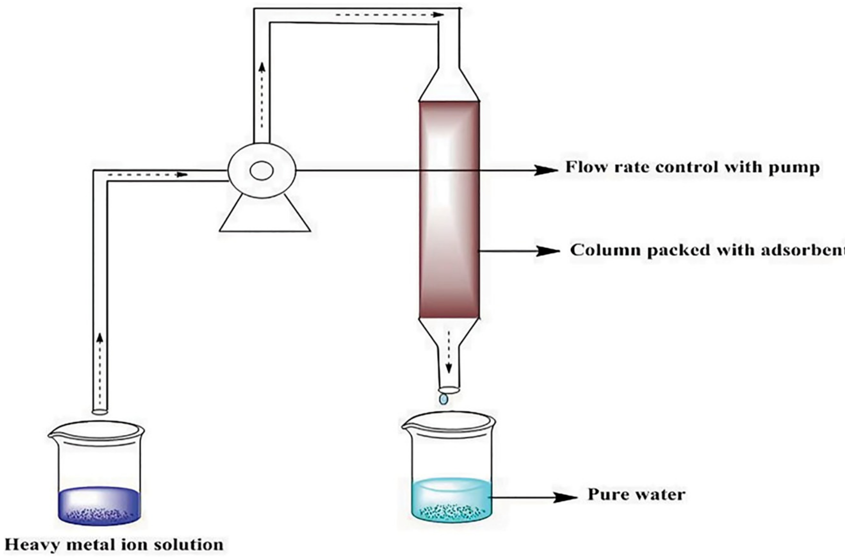


Figure 6: Heavy metal removal by adsorption process.[92]

3.2.3 Membrane filtration method for heavy metal removal

Membrane filtration methods for heavy metal removal are pivotal in contemporary water treatment strategies due to their efficiency and versatility. This technique relies on semi-permeable membranes that selectively separate heavy metals from aqueous solutions based on size, charge, and chemical properties. By leveraging membranes with specific pore sizes and surface chemistries, contaminants such as lead, mercury, cadmium, and arsenic can be effectively removed from water sources. The process involves pressuring the contaminated water through the membrane, where heavy metal ions are either physically obstructed or chemically adsorbed onto the membrane surface or within its matrix. Reverse osmosis (RO), nanofiltration (NF), and ultrafiltration (UF) are three popular membrane filtration techniques that are used by water quality regulations and the required level of purification.

3.2.4 Electrochemical method for heavy metal removal

Electrochemical methods for heavy metal removal offer a promising approach to tackling environmental contamination. By leveraging electrochemical principles, these techniques utilize electrodes to facilitate oxidation or reduction reactions, effectively converting dissolved heavy metals into less harmful forms or solid precipitates. This process typically involves applying a voltage across electrodes immersed in contaminated water, inducing electrolysis and driving the migration of ions towards oppositely charged electrodes. During electrolysis, heavy metal ions are either attracted to the cathode for reduction or repelled towards the anode for oxidation, depending on their chemical properties. Reduction processes often involve the deposition of metals onto the cathode, where they can be later recovered, while oxidation reactions lead to the formation of less soluble metal hydroxides or oxides that precipitate out of the solution.[55]

3.3 Unveiling the effectiveness of adsorption method in heavy metal removal

The adsorption method stands as a pivotal technique in the realm of environmental remediation, particularly in the removal of heavy metals from contaminated water sources.[93] This process involves the adherence of heavy metal ions onto a solid surface, typically an adsorbent material, through a range of physical and chemical interactions. Its effectiveness lies in its versatility and efficiency across various contaminants, offering a reliable solution amidst increasing concerns over water pollution. Key to the method's efficacy is the selection of appropriate adsorbents, which can be natural materials like activated carbon, zeolites, and clay minerals, or synthetic polymers engineered for specific metal ion affinities (Table 4).[62]

Moreover, adsorption offers advantages such as ease of operation, scalability, and the potential for regeneration and reuse of adsorbents, making it economically viable for large-scale applications. It is particularly valuable in treating low-concentration effluents and complex wastewater streams from industries like mining, metallurgy, and electronics manufacturing, where heavy metals pose significant environmental and health risks. The challenges such as adsorbent stability, saturation limits, and the influence of competing

Table 4: Comparison of heavy metal removal methods.[94]

Heavy metal	Adsorption (%)	Bioremediation (%)	Membrane filtration (%)	Electrochemical (%)
Lead (pb)	95	60	92	75
Mercury (hg)	92	70	95	80
Cadmium (Cd)	90	55	88	68
Arsenic (as)	87	65	90	72

ions in real-world applications necessitate ongoing research to optimize materials and processes. Future advancements may focus on hybrid materials, nanotechnology-driven adsorbents, and novel regeneration strategies to enhance efficiency and sustainability further.[95]

4 Exploration of adsorption method in heavy metal removal

The exploration of adsorption methods in heavy metal removal represents a pivotal area of environmental research and engineering. Adsorption, a process where molecules adhere to the surface of a solid material, offers a promising avenue for mitigating the detrimental effects of heavy metals on ecosystems and human health. This method involves the use of adsorbents such as activated carbon, zeolites, and various modified materials that attract heavy metal ions from aqueous solutions, effectively trapping them on their surfaces.[67] Researchers have extensively studied the adsorption capacity, kinetics, and mechanisms of various adsorbents to optimize their efficiency in heavy metal removal. The process is influenced by factors such as pH, temperature, the concentration of heavy metals, and the surface properties of the adsorbents. Understanding these parameters is crucial for designing effective adsorption systems that can be applied in both industrial wastewater treatment and environmental remediation efforts.[96]

Moreover, the exploration of novel adsorbents and the enhancement of existing materials through modification or functionalization are ongoing areas of interest. Advances in nanotechnology have also contributed to the development of nanostructured adsorbents with increased surface area and reactivity, further improving their effectiveness in heavy metal ion removal (Figure 7).

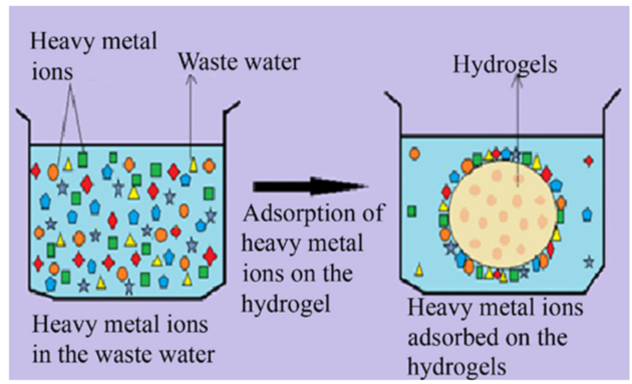


Figure 7: Adsorption of heavy metal ions on the hydrogel.[97]

4.1 Mechanisms and principles of adsorption method

Adsorption is a fundamental process in chemistry and engineering where molecules or ions from a fluid adhere to a surface. This method relies on several key mechanisms and principles to achieve effective separation and purification. Fundamentally, attractive forces between the material being adsorbed, known as the adsorbate, and the surface it adheres to, known as the adsorbent, cause adsorption to occur. These forces might be chemical, including particular interactions like hydrogen bonding or ion exchange, or physical, like van der Waals forces.[69]

The efficiency of adsorption processes depends on several factors, including the surface area and porosity of the adsorbent material, the concentration and nature of the adsorbate, temperature, and pressure conditions. Mechanisms like physisorption and chemisorption dictate how strongly molecules adhere to the surface, influencing adsorption capacity and selectivity. Adsorption has wide applications in various industries, from environmental remediation and water purification to gas separation and pharmaceutical manufacturing. Understanding these mechanisms is crucial for optimizing adsorption processes, ensuring they are both economically viable and environmentally sustainable.[98]

4.2 Diverse technologies employed in adsorption method

Adsorption methods encompass a diverse array of technologies leveraging various principles to separate or purify substances from gases or liquids. One prominent

Table 5: Technologies employed in adsorption Method.[100]

Technology	Typical applications	Advantages	Disadvantages
Fixed-bed adsorption	Water purification, gas separation, air pollution control	Simple design, high capacity	High-pressure drop requires regeneration
Fluidized-bed adsorption	Gas chromatography, protein purification	Efficient mass transfer, continuous operation	More complex design, potential for particle attrition
Pressure swing adsorption (PSA)	Oxygen production from air, hydrogen purification	High-purity product, energy efficient	Requires multiple columns, cycling operation
Temperature swing adsorption (TSA)	Air separation (nitrogen production), VOC removal	High selectivity, good for heat-sensitive materials	Higher energy consumption compared to PSA
Membrane adsorption	Biomolecule purification, wastewater treatment	High selectivity, continuous operation	Developing technology at, a higher cost compared to traditional methods
Chromatography	Drug discovery, protein analysis	High-resolution, versatile technique	A time-consuming process, with limited capacity for large-scale applications
Molecular sieving	Desiccant drying, natural gas processing	High selectivity, excellent for size-based separation	Limited capacity for some applications

technique involves activated carbon, where porous carbon materials attract and retain molecules on their surfaces through Van der Waals forces or chemical interactions. This method finds wide application in water purification, air filtration, and even medical treatments due to its high surface area and versatile adsorptive properties. Zeolites, crystalline alum inosilicates with well-defined pore structures, offer another effective adsorption technology. These minerals selectively trap molecules based on size and shape, making them valuable in catalysis, gas separation, and detergent formulations. Similarly, molecular sieves exploit intricate pore networks to sieve out unwanted substances from liquids or gases, crucial in industries ranging from petrochemicals to pharmaceuticals. Polymeric adsorbents, synthesized for specific molecular affinities, contribute significantly to environmental remediation and chemical processing (Table 5).[99]

These materials are tailored to adsorb pollutants like heavy metals or dyes from wastewater, showcasing their utility in sustainable practices. Additionally, advancements in nanotechnology have introduced engineered nanoparticles that enhance adsorption capacities and selectivity, revolutionizing fields such as drug delivery and environmental monitoring. Overall, the diverse technologies employed in adsorption underscore its broad applicability across industries, continually evolving through innovations in material science, chemistry, and engineering. As demands for cleaner processes and resource efficiency grow, ongoing research promises further advancements in adsorption methodologies, driving sustainable solutions and technological breakthroughs.[101]

4.3 Impact of operational parameters in adsorption method

The effectiveness of adsorption methods heavily depends on several operational parameters that influence the efficiency and performance of the process. Parameters such as temperature, pressure, contact time, and the concentration of the adsorbate in the feed stream play critical roles in determining the adsorption capacity and kinetics. Temperature affects adsorption by altering the affinity between the adsorbent and adsorbate, typically increasing adsorption capacity at lower temperatures for physical adsorption but potentially impacting chemical adsorption differently.[102] Pressure influences gas adsorption by changing the gas density and the distribution of molecules on the adsorbent surface. Contact time, or residence time, dictates how long the adsorbate remains in contact with the adsorbent, crucial for achieving equilibrium adsorption. Furthermore, the adsorption process's efficiency and the adsorbent's saturation capacity are affected by the ad sorbate's initial concentration in the feed stream. Optimizing these operational parameters is essential for maximizing adsorption efficiency, reducing energy consumption, and ensuring the economic viability of adsorption-based technologies across various applications.[103,104]

Table 6 summarizes key operational parameters and their impacts on the efficiency of the adsorption method using activated carbon to remove lead ions from water. Initial metal concentration affects efficiency negatively as it increases, due to reduced availability of adsorbent per metal ion. The optimal pH for lead removal is around 6.5, where surface charge interactions are most favourable. Increasing

Table 6: Operational parameters and impacts in adsorption method.[106]

Parameter	Units	Impact on removal efficiency	Value
Initial metal concentration	mg/L	Decreases with increasing concentration. Less adsorbent is available per metal ion at higher concentrations.	20 mg/L
pH	–	Varies depending on the metal and adsorbent. Generally, optimal removal occurs at a specific pH range due to surface charge interactions.	pH 6.5 (for this example)
Adsorbent dosage	g/L	Increases with increasing dosage. More adsorbent provides more surface area for metal ion attachment.	2 g
Contact time	min	Increases up to a point, then plateaus. More time allows for greater metal ion diffusion and interaction with the adsorbent.	45 min
Temperature	°C	Varies depending on the metal and adsorbent. Generally, the increased temperature can increase removal efficiency, but may also be energetically unfavourable.	25 °C (room temperature, efficient for this example)
Presence of other contaminants	–	May decrease removal efficiency. Other ions can compete for adsorption sites on the adsorbent.	Not present (ideal scenario for this test)
Metal ion type	–	Different metals have varying affinities for the adsorbent.	Lead (Pb)
Adsorbent type	–	Different adsorbents have different properties affecting removal efficiency (e.g., surface area, pore size).	Activated carbon

adsorbent dosage enhances efficiency by providing more attachment surface, with 2 g per litre being effective here. Contact time up to 45 min improves removal efficiency by allowing sufficient interaction between metal ions and the adsorbent. Temperature impacts efficiency variably but is generally efficient at 25 °C. The absence of other contaminants optimizes efficiency by preventing competition for adsorption sites. Lead ions specifically exhibit varying affinities for different adsorbents, where activated carbon shows effective removal due to its surface area and pore size characteristics.[105]

5 Effective removal of heavy metals by advanced adsorbents

The presence of heavy metals in water and soil has become a significant concern in recent years, as they can pose serious threats to human health and the environment. Heavy metals such as lead, mercury, chromium, and arsenic are highly toxic and can cause a range of adverse health effects, including neurological damage, kidney damage, and even cancer. Furthermore, these metals can also contaminate soil and water bodies, affecting ecosystems and disrupting the food chain. Traditional methods for removing heavy metals from contaminated media have limitations, including high costs, low efficiency, and generation of secondary pollutants. For example, chemical precipitation and coagulation can be effective but often require large amounts of chemicals and generate sludge that requires further treatment. Ion exchange resins can be effective but may not be suitable for large-scale applications due to their limited capacity and regeneration requirements (Table 7).[100]

Several types of advanced adsorbents have been developed for heavy metal removal, including activated carbons, zeolites, silica-based materials, and polymer-based

Table 7: Advanced adsorbents for removal of heavy metals.[107]

Adsorbent	Maximum removal efficiency (%)	Advantages	Disadvantages
Functionalized metal-organic frameworks (MOFs)	>95	Highly selective, large surface area, tunable properties	Can be expensive to synthesize, and regeneration methods are still under development
Magnetic ion-impregnated biochar	80–90	Easy separation after treatment due to magnetism, eco-friendly, reusable	Lower removal efficiency compared to some MOFs
Chitosan-based nanomaterials	70–80	Abundant natural resource, good biocompatibility	May require complex preparation methods
Layered double hydroxides (LDHs)	60–85	High anion exchange capacity, good stability	Lower surface area compared to some MOFs
Plasma-treated graphene oxide	>90	Excellent adsorption capacity, fast adsorption kinetics	Can be challenging to disperse uniformly in water

materials. These materials have shown excellent removal efficiency and selectivity for various heavy metals in different matrices. For example, activated carbon has been shown to remove lead and mercury from water with high efficiency, while zeolites have been used to remove chromium and arsenic from soil.[102] Advanced adsorbents also face challenges in terms of scalability, regeneration requirements, and cost-effectiveness. Further research is needed to develop cost-effective and sustainable adsorbent materials that can be used for large-scale applications. Additionally, there is a need to understand the mechanisms of heavy metal removal by advanced adsorbents and to develop methods for optimizing their performance.[103,104]

5.1 Conventional adsorbents for heavy metal removal

Conventional adsorbents have been widely used for heavy metal removal from contaminated media, including water, soil, and wastewater. These materials are typically low-cost, abundant, and well-established, making them a popular choice for heavy metal remediation. For the removal of heavy metals, one of the most often employed traditional adsorbents is activated carbon. It is created by heating carbon-rich materials, like bamboo or coconut shells, to high temperatures to enhance their porosity and surface area. Through a process known as physisorption, activated carbon has been proven to successfully remove a wide spectrum of heavy metals, including lead, mercury, and chromium. This process involves weak physical interactions between the heavy metal ions and the activated carbon surface. Zeolites are another type of conventional adsorbent that has been utilized for heavy metal removal. Zeolites are natural or synthetic minerals with a crystalline structure that contains cavities and channels. These structures allow zeolites to selectively bind to heavy metal ions through ion exchange reactions. Zeolites are effective in removing heavy metals such as chromium, arsenic, and lead from contaminated water and soil.[106]

5.2 Low-cost adsorbents for heavy metal removal

Low-cost adsorbents have gained significant attention in recent years as a potential solution for heavy metal removal from polluted media. These materials are designed to be inexpensive, abundant, and easy to produce, making them an attractive alternative to traditional adsorbents. Agricultural waste products, such as rice husk, coconut shell, and banana peel, have been explored as low-cost adsorbents for heavy metal removal. Bamboo-based materials are another type of low-cost adsorbent that have been explored for heavy metal removal. Bamboo is an abundant and renewable resource that can be easily converted into activated carbon or other forms of adsorbent materials. Bamboo-based adsorbents are effective at removing heavy metals such as arsenic, chromium, and lead from polluted water and soil.[108]

5.3 Emerging adsorbent materials for heavy metal removal

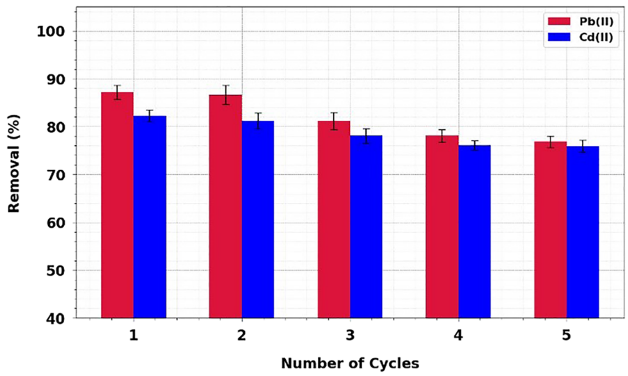
Emerging adsorbent materials are being developed and explored for heavy metal removal due to their potential to overcome the limitations of traditional adsorbents. These materials are often designed with specific functional groups, surface modifications, and structural arrangements that enhance their adsorption capacity, selectivity, and reusability. One such emerging class of adsorbent materials is graphene-based materials. Graphene, a 2D material composed of carbon atoms, has been shown to exhibit exceptional adsorption properties due to its high surface area, porosity, and electrical conductivity. Graphene-based adsorbents are effective at removing heavy metals such as lead, mercury, and chromium from polluted water and soil. Another emerging class of adsorbent materials is MOFs. Metal ions or clusters connected by organic molecules provide the basis of MOFs, which are porous materials. They offer a high surface area, tunable pore size, and adjustable chemical functionality, making them highly effective at adsorbing heavy metals. MOFs have demonstrated a high degree of efficiency and selectivity in the removal of heavy metals, including copper, zinc, and cadmium, from contaminated soil and water.[109] Bio sorbents are another type of emerging adsorbent material that has gained attention in recent years. Bio sorbents are derived from biological sources such as bacteria, fungi, or plants and are often modified to enhance their adsorption properties. For example, bio sorbents derived from Sargassum seaweed are effective at removing heavy metals such as lead and cadmium from contaminated water.[110]

6 State of art of survey

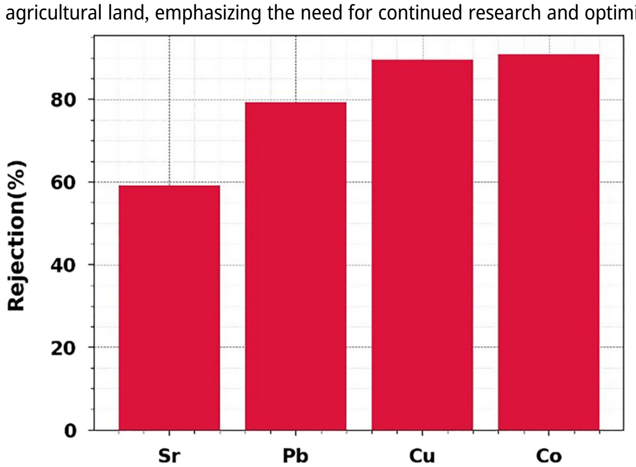
The state-of-the-art survey explores current methodologies for removing heavy metals from various matrices. Techniques ranging from chemical precipitation and ion exchange to adsorption and membrane filtration are critically analysed for their efficiency, cost-effectiveness, and environmental impact. Emphasis is placed on recent advancements in materials science and engineering, including

Table 8: Comparative analysis of heavy metal removal techniques.

83



Addressing soil heavy metal contamination and its hazardous effects is crucial, particularly without impacting food security. Phytoremediation offers a promising solution, utilizing metal-binding proteins and plant-microbe interactions to enhance metal accumulation and removal efficiency. This method leverages the natural abilities of certain plants to absorb and concentrate metals from the soil, aided by microbial partners that facilitate metal uptake and stabilization. Despite its potential, challenges remain in effectively removing heavy metals while ensuring the safety and productivity of agricultural land, emphasizing the need for continued research and optimization of phytoremediation techniques.



Identifying alternative water sources involves employing sustainable treatment processes, such as nano filtration membrane technology integrated with nanoparticles. This approach offers enhanced selectivity, resistance to fouling, and improved overall efficiency in water purification systems. However, its effectiveness depends significantly on operational variables such as pH levels and temperature conditions. By harnessing nanotechnology within membrane filtration, water treatment processes can achieve greater reliability and environmental sustainability, crucial for meeting future water supply challenges.

111

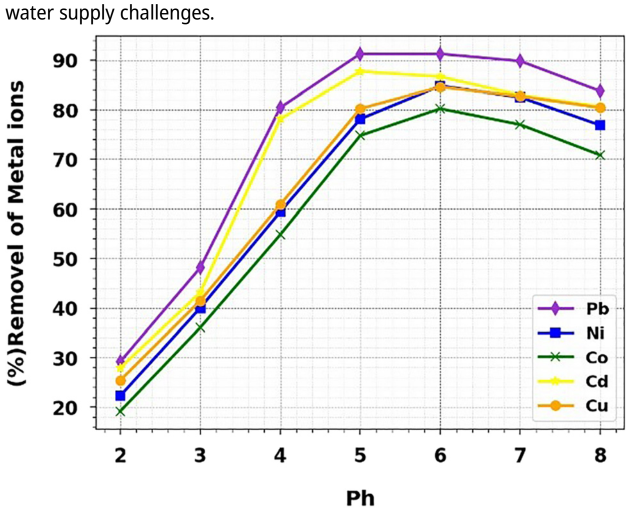
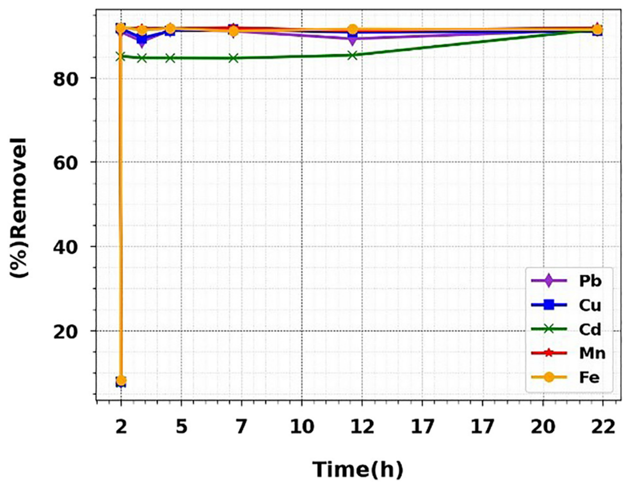


Table 8: (continued)

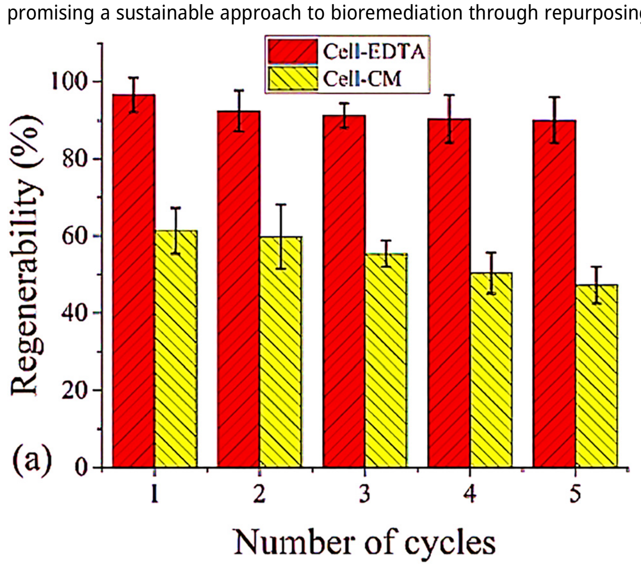
Silica-supported iron oxide nanocomposites, synthesized through a green approach, are employed for removing heavy metal ions from water. The process involves thorough characterization using XRD, SEM, FTIR, and evaluation of zeta potential. Batch adsorption experiments demonstrate significant effectiveness in adsorbing Pb^{2+}, Cd^{2+}, Ni^{2+}, Cu^{2+}, and Zn^{2+} ions, with adsorption behaviour conforming to the Langmuir isotherm and pseudo second-order kinetics. Optimal adsorption requires specific pH conditions, ensuring efficient removal of contaminants from water. This method showcases a promising approach for environmental remediation, highlighting the potential of biosynthesized nanocomposites in sustainable water purification technologies.

26



Jackfruit seed waste (JSW) biochar, thermally activated, demonstrates efficient batch adsorption capability for heavy metal ions from water at pH 7. Notably, it exhibits substantial uptake capacities: Fe(III) at 76.4 mg/g, Pb(II) at 79.4 mg/g, Cu(II) at 97.9 mg/g, Cd(II) at 79.9 mg/g, and Mn(VII) at 79.8 mg/g. Further optimization of the process is crucial to enhance the removal efficiency of these heavy metals under neutral pH conditions, promising a sustainable approach to bioremediation through repurposing agricultural waste.

112



Pineapple leaves, often discarded post-harvest, present an opportunity for value-added products like cellulose fibre. This study focused on extracting and modifying cellulose from these leaves into Cell-EDTA and Cell-CM variants, enhanced with EDTA and carboxymethyl groups. Adsorption kinetics varied with Cell-CM following a pseudo-first-order model and Cell-EDTA a pseudo-second-order model, both conforming to the Langmuir adsorption isotherm. Regenerability tests with 1 M HCl favoured Cell-EDTA's performance over Cell-CM, highlighting their potential in metal ion removal from wastewater.

nanotechnology and bioremediation strategies. This survey aims to provide a comprehensive overview of existing technologies and their applicability in addressing contemporary challenges in heavy metal remediation (Table 8).

7 Summary

The review comprehensively explores the application of adsorption techniques for removing heavy metals from industrial wastewater. Highlighting the significance of this method in environmental remediation, it discusses various adsorbents and their effectiveness in capturing metals like lead, cadmium, and chromium. The study emphasizes factors influencing adsorption efficiency, including pH, temperature, and adsorbent dosage. It reviews recent advancements in adsorption technology, such as modified adsorbents and hybrid materials, which enhance metal ion removal rates. Furthermore, the review underscores the importance of optimizing operational parameters to achieve higher adsorption capacities and cost-effectiveness in wastewater treatment processes. Overall, it provides a valuable overview of current trends and challenges in the field, offering insights into improving the efficacy of heavy metal removal from industrial effluents through adsorption methods.

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