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A COMPREHENSIVE STUDY OF HEAVY METAL REMOVAL TECHNIQUES FROM WASTEWATER: CHALLENGES AND ADVANCES

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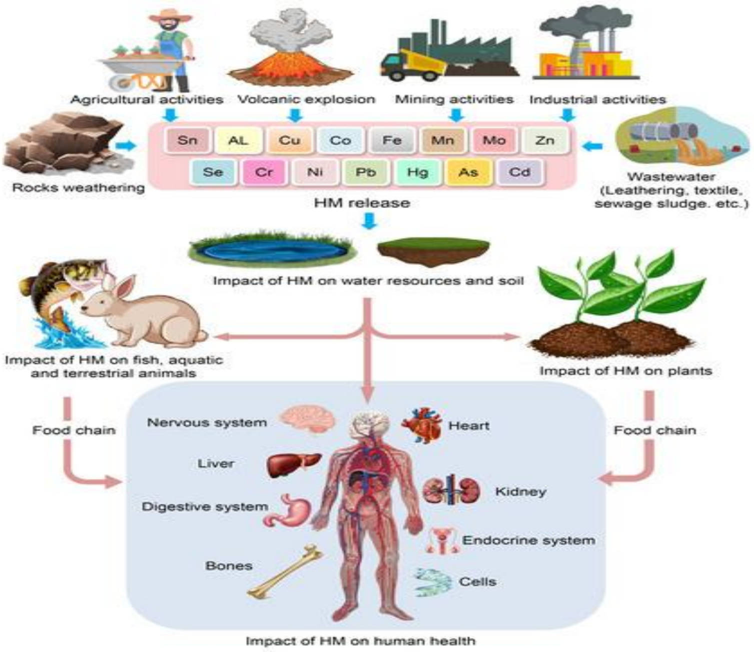
ABSTRACT

Contamination of heavy metals in wastewater is a serious both environmental and public health concern because of its toxicity, persistence, and bioaccumulative nature. This paper comprehensively reviews both conventional and advanced techniques for heavy metal removal. The primary objectives of removing heavy metals from wastewater are to protect the environment from toxic and non-biodegradable pollutants, safeguard human health from exposure to harmful and potentially carcinogenic metals such as lead, cadmium, mercury, and arsenic, and ensure compliance with regulatory limits set by the World Health Organization (WHO). The techniques include adsorption, membrane separation, chemical precipitation, electronic, chemical, reverse osmosis, coagulation-flocculation, and photocatalytic. These methods are discussed in terms of the agents or adsorbents used, the removal efficiency, the operating conditions, and the pros and cons of each method. Among these techniques, adsorption has become the most promising approach because of its high efficiency, cost-effectiveness, and operational simplicity. Although chemical and membrane-based methods are widely applied for wastewater treatment, the large-volume sludge formation and post-treatment requirements pose major issues that must be overcome for chemical techniques. Membrane separation is often hindered by fouling and scaling, and therefore, costly pre-treatment and regular cleaning are necessary. Coagulation-flocculation is a commonly used technique for removing heavy metals from wastewater, which involves destabilizing and agglomerating colloidal particles using chemical coagulants and flocculants. Despite its effectiveness in eliminating metals including Cu^{2+}, Pb^{2+}, and Ni^{2+}, this technique creates toxic, non-biodegradable sludge that poses health and environmental concerns because of the use of inorganic agents. Although Electrical-based methods have shown good efficiency they still have challenges like managing large amounts of sludge and effective separation at an industrial scale. However, Future research should aim to develop materials and methods that are not only effective but also environmentally friendly, affordable, and sustainable.

Keywords: *Heavy metal removal, Wastewater treatment, Adsorption, Coagulation-flocculation, Membrane separation.*

1. INTRODUCTION

As our industries and activities have grown, so have the levels of heavy metals in wastewater. It includes the plating and electroplating industry, batteries, pesticides, mining, rayon, metal rinses, tanning, fluidized bed bioreactors, textiles, metal smelting, petrochemicals, paper manufacturing, and electrolysis applications (Qasem et al., 2021). When wastewater with heavy metals is released into the environment, it is hazardous for both people and the environment (Gupta et al., 2021). Nature cannot break down heavy metals, and they can sometimes cause cancer. If there is too much or too little of these metals in water, it can hurt living things (Zou et al., 2016). Lead (Pb), copper (Cu), zinc (Zn), arsenic (As), cadmium (Cd), chromium (Cr), mercury (Hg), and nickel (Ni) are the most common heavy metals. The Environmental Protection Agency (EPA) has made rules about safe drinking water based on how much of certain pollutants are in it and how harmful they are to people. If you have too much of them in your body, toxic metals can be very detrimental for your health (Gabal, E., 2020). These poisonous metals can build up in the food chain over time, affecting people, animals, and other living things (Wu, H., 2020). The toxicity of hazardous materials is directly related to how much exposure there is and how long people are in contact with living things. As shown in Figure 1, these chemicals, through the food chain, enter into the human body and cause several adverse effects. Long-term exposure, whether by inhalation, contaminated food consumption, or skin contact, can cause several health problems in humans and other organisms. Moreover, heavy metal contamination of soils has become a major worldwide environmental issue that poses long-term hazards to both human health and ecosystems (Abd Elnabi et al., 2023).



. Figure 1: Origins and impacts of Heavy Metal Ions on humans through the food chain (Abd Elnabi et al., 2023).

Researchers are currently focused on identifying effective approaches to eliminate various pollutants from natural water systems, encompassing heavy metals, synthetic dyes, sediments, chemicals, radioactive materials, pharmaceuticals, and other wastes (Reddy & Lee, 2013). Heavy metals are the most common of these pollutants. They are well-defined as rudiments with a density more than 5 grams per cubic centimetre (Jaishankar et al., 2014). Harmful heavy metals are metallic elements with a higher density that can be harmful even in small amounts (Tahoon et al., 2020). These poisonous metals can build up in living things, which can lead to many different diseases and ailments. Some ways are making hazardous gases, making batteries, mining minerals, making leather, making alloys, and using non-renewable energy sources (Beauvais & Alexandratos, 1998). Because toxic metal pollution is increasing, scientists are working on different ways to clean it up, such as adsorption (Srivastava et al., 2011), membrane filtration (Naghdali et al., 2019), and chemical precipitation

(Wang et al., 2005). flocculation, and coagulation (Agudosi et al., 2018), photocatalysis (Rahimi et al., 2014), ion exchange (Al-Enezi et al., 2004), and reverse osmosis (Qasem et al., 2021). Due to a variety of economic and technological factors, only a few wastewater treatment procedures are used by many industries to extract their wastes. Even though these processes can get rid of different pollutants in wastewaters, they have some problems (high expense, complicated processes, low efficiency, etc.) (Türkmen et al., 2022). The adsorption technique was considered the most effective method for the removal of heavy metals from wastewater, as it is regarded as harmless, fresh, well-organized, and technically feasible (Türkmen et al., 2022). Commercial and polymeric adsorbents were very good at getting rid of heavy metal ions in wastewater (Tahoon et al., 2022). Absorbent materials have a large surface area and lots of holes, which makes them very effective at removing toxic substances and easy to use. This is why they are the most popular way to get rid of heavy metals from wastewater around the world (Song et al., 2016). Using semi-permeable membranes, membrane separation is a good way to get rid of heavy metals in water. Ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) are all methods that use size exclusion, charge effects, and sometimes adsorption. These methods work well, don't use many chemicals, and can be used to treat water on a small or large scale in industry (Abdullah et al., 2019).

The main object of this review is to provide a comprehensive summary of both conventional and advanced procedures for removing heavy metals from wastewater. It discusses the benefits and drawbacks of several techniques, which includes chemical precipitation, membrane separation, adsorption, and photocatalysis. This study also purposes to enlighten the hazards that heavy metal contamination poses to the environment and public health, including poisonousness, bioaccumulation, and carcinogenic potential. Moreover, it also enlightened the need for affordable, environmentally friendly, and long-term solutions to heavy metal contamination that nevertheless adhere to World Health Organization (WHO) regulations.

2. METHODOLOGY

There are several techniques available for removing toxic metals from wastewater, such as adsorption (Srivastava et al., 2011), membrane filtration (Naghdali et al., 2019), chemical precipitation (Wang et al., 2005), flocculation and coagulation (Agudosi et al., 2018), photocatalysis (Rahimi et al., 2014), ion exchange (Al-Enezi et al., 2004), and reverse osmosis (Qasem et al., 2021) as shown in Figure 2. However, these techniques are not employed very often in many fields because they are expensive and hard to understand. The review was conducted through a systematic search of academic databases, focusing on peer-reviewed articles published in the recent years. Studies were selected based on their relevance to wastewater treatment techniques, specifically those that provided empirical data on effectiveness, cost, environmental impact, and feasibility. Each conventional method has its own pros and cons, which are shown in Table 1 and Table 2 lists the main sources of these metals, their health effects, and the amounts that are safe to use.

Figure 2: Conventional methods for the removal of heavy metal ions (Srivastava et al., 2011), (Naghdali et al., 2019), (Wang et al., 2005), (Agudosi et al., 2018), (Rahimi et al., 2014), (Al-Enezi et al., 2004), and (Qasem et al., 2021).

Table 1: The pros and cons of each traditional method.

Methods	**Advantages**	**Disadvantages**	**References**
Adsorption	High efficiency, easy operation, effective for heavy metal removal.	High cost (activated carbon) and slow process.	(Qasem et al., 2021)
Membrane Filtration	Low chemical use, minimal sludge, continuous operation.	Membrane fouling, high maintenance and operating cost, pre-treatment required.	(Qasem et al., 2021)
Chemical Precipitation	Easy to use, removes most metals.	High chemical demand, excessive sludge, disposal issues, and pre-treatment required.	(Ku & Jung, (2001)
Flocculation and Coagulation	Suitable for large-scale wastewater treatment.	Expensive, high sludge production, and disposal difficulties.	(Qasem et al., 2021)
Photocatalysis	Eco-friendly, No sludge formation, High removal efficiency	Technological Maturity, Limited Throughput, Inefficiency with Mixed Contaminants	(Qasem et al., 2021)
Ion Exchange	High efficiency, metal selective, Regeneratable	High initial cost, Limited lifespan, cannot be used on large scale	(Dabrowski et al., 2004)
Reverse Osmosis	Effective removal, Produces high quality water	High chemical cost, high energy consumption	(Chakraborty et al., 2022)

Table 2: Heavy metal ions, major sources, health haxards, and theis permissible limits

Heavy Metals	**Sources**	**Health Hazards**	**Permissible Limits** mg/L	**References**
Lead (Pb)	Manufacturing of battery, ammunition, bronze products, pipes, ceramic and glass industries.	Lead poisoning causes brain damage, anorexia, vomiting, anemia, and disorders of the circulatory and nervous systems.	0.05	(Low et al., 2000)
Manganese (Mn)	Mining, Industrial, Environment	Memory loss resembling Parkinson's disease, motor dysfunction	0.5	(Mve et al., 2016)
Arsenic (As)	Coal combustion, phosphate fertilizers, mining, herbicides, and insecticides.	Arsenicosis, kidney cancer, lung, skin, bladder, and, neurological disorders	0.01	(Mandal & Suzuki, 2002).
Chromium (Cr)	Textile industries, wood treatment units, steel fabrication, chemical and paints and pigments.	Headache, lung tumors, vomiting, hemorrhage, nausea, diarrhea, and cancer in the digestive tract.	0.1 for Cr(VI). 5 for Cr(III)	(Chakraborty et al., 2022)
Copper (Cu)	Fertilizer industry, plating baths, municipal and stormwater run-offs, paints and pigments.	Lung cancer, Wilson's disease, vomiting, insomnia, liver damage, diarrhea, and renal damage.	1.3	(Ahmad et al., 2009)
Cadmium (Cd)	Mining, alloy industries, batteries, pigments, phosphate fertilizers, metal plating, and stabilizers.	Renal disorders, emphysema, carcinogenic, kidney damage, and Itai-itai disease.	0.005	(Bamgbose et al., 2010)

Heavy Metals	**Sources**	**Health Hazards**	**Permissible Limits** mg/L	**References**
Zinc (Zn)	Industrial activities such as mining, metal plating, paint and pigment, and fertilizer.	Increased thirst, lethargy, anemia, neurological signs, depression, and dehydration.	5	(Shobana et al., 2014)
Mercury (Hg)	Mining, agriculture, industrial activities, and dental amalgams.	Kidney toxicity, tremors, insomnia, gastrointestinal tract, and motor dysfunction.	0.006	(Jeon & Park, 2005)
Nickel (Ni)	Electroplating, mining, chemical industries, and paints.	Chronic asthma, dermatitis, nausea, coughing, and cancer.	0.015	(Hannachi et al., 2010)
Cobalt (Co)	Mining operations, tanneries, petrochemical industries, electroplating, and textile mill products.	Carcinogenic, asthma-like allergies, and damage to the heart, thyroid, and liver.	0.1	(Demirbaş, 2003)

2.1 Adsorption

Atoms or ions from a gas, liquid, or solid adhere to a solid's surface via a process known as adsorption. This method is often used to get rid of heavy metal ions because it works well and does not cost much. Adsorption is better than other common methods because it is cost effective, does not make toxic sludge, does not use too many chemicals, and does not use too much energy (Chakraborty et al., 2022). There are some problems with adsorption, though. For example, it requires chemical regeneration, it costs a lot to make adsorbents (like activated carbon), and each time it is regenerated, it can hold less adsorbent (Bilal et al., 2013). The adsorption processes are seen to be environmentally beneficial, as the adsorbents may be recycled and used again. The presence of a functional moiety, pore size distribution, large surface area, cost-effectiveness, and polarity are the primary considerations when choosing adsorbents. Adsorption is the attachment of solutes to an adsorbent surface, driven by physical and chemical forces. Physical adsorption involves weak forces (Van der Waals, dispersion, hydrogen bonding), allowing random attachment, while chemical adsorption creates strong, specific bonds (e.g., covalent, electrostatic). The process is influenced by various factors including weaker forces, such as dispersion, hydrogen bonds, and Van der Waals. (Demirbas, 2008) (Gupta et al., 2021).

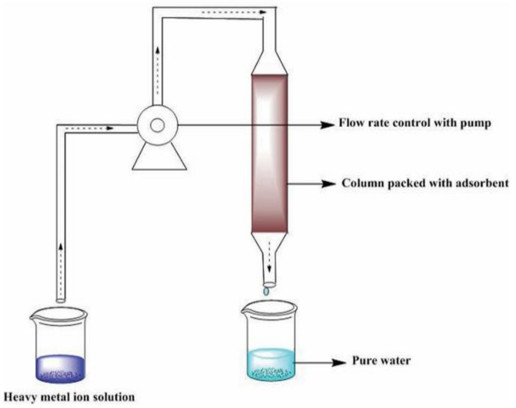


Figure 3. Adsorption process by continuous column for heavy metal removal (Chakraborty et al., 2022).

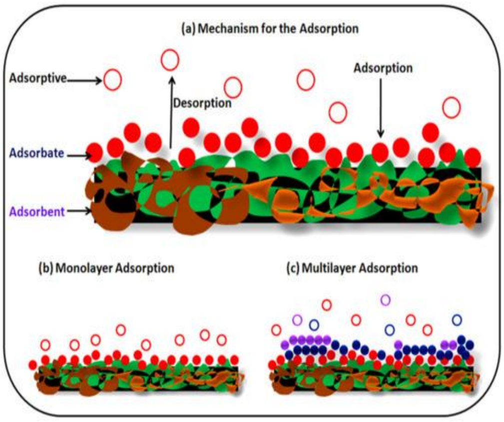


Figure 4. (a) General mechanism for the adsorption, (b) monolayer adsorption, and (c) multilayer adsorption (Gupta et al., 2021).

Figure 3 shows the adsorption process using a continuous column for heavy metal removal, where the solution containing metal ions passes through a column packed with adsorbent material to produce pure water (Chakraborty et al., 2022). Figure 4 illustrates the general mechanism of adsorption, including monolayer adsorption (b) and multilayer adsorption (c), highlighting the interaction between adsorbate and adsorbent (Gupta et al., 2021).

2.2 Membrane Filtration

Membrane filtration removes heavy metals by passing wastewater through semi-permeable membranes that selectively retain ions based on pore size, charge, and applied driving forces. Ultrafiltration and nanofiltration operate mainly through size exclusion and electrostatic repulsion, reverse osmosis uses high pressure to overcome osmotic pressure, and electrodialysis employs an electric potential to separate charged species. Despite high operational costs and membrane fouling, these systems require minimal chemicals and generate low sludge volumes (Chakraborty et al., 2022). Figure 5 illustrates different types of membrane filtration processes, including ultrafiltration, nanofiltration, reverse osmosis, and electrodialysis.

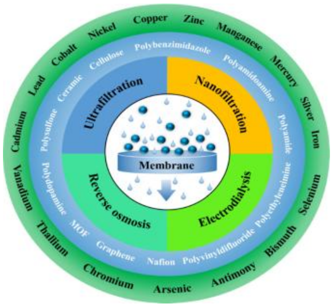


Figure 5: Types of Membrane Filtration (Chakraborty et al., 2022).

2.3 Chemical Precipitation

Chemical precipitation, also referred to as coagulation precipitation, is a widely applied physicochemical method for the removal of heavy metals from wastewater. The process functions by converting dissolved metal ions into insoluble solid particles through controlled chemical reactions, allowing their subsequent removal by sedimentation or filtration. This conversion is achieved by adjusting key operational parameters such as pH, co-precipitation conditions, and electro-oxidation potential (Ojovan et al., 2019). Figure 6 illustrates the chemical precipitation process, where chemicals (coagulants) are added to a solution containing metal ions. The coagulant traps the metal ions, causing them to settle at the bottom of the container as a precipitate.

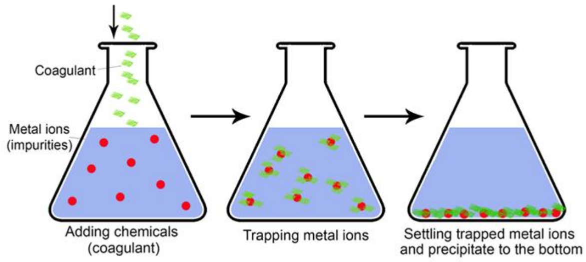


Figure 6: A simple schematic of the chemical precipitation process (Qasem et al., 2021)

Hydroxide precipitation is the most used form of chemical precipitation due to its operational simplicity, pH flexibility, and low cost. In this process, alkaline reagents are added to agitated wastewater, increasing the pH and promoting the formation of insoluble metal hydroxides. Optimal removal efficiencies are generally observed at pH values between 9 and 11. However, excessively high pH levels lead to increased sludge production, which can negatively affect process efficiency. Lime in the form of CaO or $Ca(OH)_2$ is frequently employed and has been reported to be effective in treating inorganic effluents containing up to 1000 mg/L of heavy metals (Kurniawan et al., 2006). This method is particularly effective for the removal of Zn^{2+}, Cu^{2+}, Ni^{2+}, Pb^{2+}, and Cr^{3+}.

Sulfide precipitation is more effective in removing heavy metal ions due to the low solubility of metal sulfides, but it can lead to issues like malodour from excess sulfide or incomplete removal of metals like zinc. It also poses a risk of releasing toxic hydrogen sulfide gas. An alternative, more controlled method is carbonate precipitation, which works well at lower pH levels. In this process, metal ions react with carbonate sources like calcium or sodium carbonate, forming insoluble metal carbonates, offering a safer and efficient solution for metal removal, especially under acidic conditions (Patterson et al., 1977) (Zueva, 2018).

$$\text{Metal}^{n+} + n\text{NaCO}_3 \longleftrightarrow n\text{Metal(CO)}_3 + n\text{Na}^+$$

$$n\text{Metal(CO)}_3 + \text{H}_2\text{O} \longleftrightarrow \text{CO}_2\uparrow + (\text{MeOH})_n\text{CO}_3\downarrow$$

Although carbonate precipitation can reduce sludge volume compared to hydroxide precipitation, it may result in CO_2 release and requires higher reagent dosages to achieve effective metal removal (Zueva, 2018).

2.4 Flocculation and Coagulation

Coagulation and flocculation are sequential physicochemical processes used to remove suspended and colloidal particles, including heavy metal bearing species, from wastewater. Coagulation involves the destabilization of colloids by neutralizing the electrostatic forces that keep particles dispersed in solution. This is typically achieved through the addition of inorganic coagulants such as ferrous sulfate, ferric chloride, and aluminum salts, which reduce surface charge and promote particle destabilization. Following coagulation, flocculation occurs through gentle mixing, allowing the destabilized particles to collide and aggregate into larger, settleable flocs. This aggregation is enhanced by the addition of polymeric flocculants such as polyaluminum chloride (PAC), polyferric sulfate (PFS), and polyacrylamide (PAM), which act by bridging particles and forming dense agglomerates. The resulting flocs are subsequently removed by sedimentation, as illustrated in Figure 7 (Nourani et al., 2016) (Qasem et al., 2021).

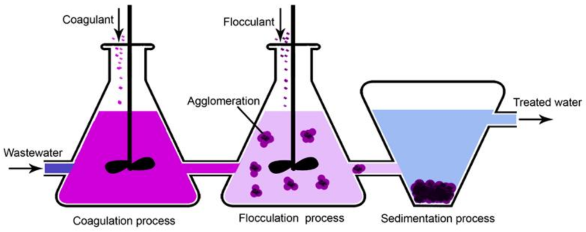


Figure 7: Coagulation-flocculation treatment process (Qasem et al., 2021)

Despite its effectiveness, the coagulation flocculation process has several limitations. These include the potential toxicity and health risks associated with inorganic coagulants, the generation of large volumes of sludge, limited selectivity toward specific metal species, and reduced efficiency in removing emerging contaminants. In addition, the process may increase effluent color, exhibit lower performance when natural coagulants are employed, and face operational challenges during scale-up. This treatment method is commonly effective for the removal of Cu^{2+}, Pb^{2+}, and Ni^{2+}, while metals such as As^{2+}, Se^{2+}, Cr^{2+}, Sb^{3+}, Sb^{5+}, and Ag^{2+} may also be partially removed.

2.5 Photocatalysis

Photocatalysis is an advanced oxidation process that removes heavy metals through light-induced redox reactions occurring on the surface of semiconductor materials. When exposed to ultraviolet or visible light, photocatalysts such as titanium dioxide (TiO_2) generate electron–hole pairs. These charge carriers migrate to the catalyst surface, where they participate in oxidation and reduction reactions that convert dissolved metal ions into less toxic or insoluble forms, facilitating their removal from wastewater. The photocatalytic mechanism generally involves three main steps: photogeneration of charge carriers, charge separation and diffusion to the catalyst surface, and surface redox reactions (Martinez & Ferro, 2006). Figure 8 depicts the schematic diagram of photocatalytic treatment for heavy metals, where a photocatalyst is activated by light ($h\nu \geq Eg$) to reduce metals like Cr(VI), Cu(II), Pb(II), As(III), and Hg(II) into less toxic forms (Xiang et al., 2022).

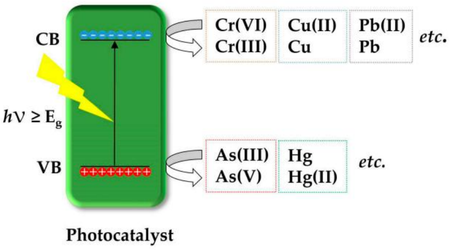


Figure 8: Schematic diagram of photocatalytic treatment of heavy metals (Xiang et al., 2022).

Recent studies have demonstrated the effectiveness of various photocatalytic materials for heavy metal removal. Rh/Sb co-doped TiO_2 nanorods achieved 70–80% degradation of dyes and bisphenol A under visible light irradiation (Dhandole, 2020). Three-dimensional Fe_2O_3 structures removed nearly 100% of As^{5+} and Cr^{6+} under solar irradiation, while $CeO_2/BiOIO_3$ composites achieved 86.5% removal of Hg^{2+} (Xiao, 2020). Additionally, CH-GEL/ZSPNC hybrid nanocomposites extracted 84–100% of various metals and dyes (Kaur & Jindal, 2018), whereas CS/Ag bio-nanocomposites removed up to 97% Cu^{2+}, 88% Pb^{2+}, and 89% Cd^{2+} (Al-Sherbini et al., 2019). Photocatalytic treatment offers benefits like no chemical additives, in-situ reactive species generation, and minimal sludge production. However, its use is limited by low throughput, pH sensitivity, reduced efficiency in multi-metal systems, and scalability issues, with most studies at lab or pilot scale. Despite these challenges, solar-driven systems show promising potential (Crini & Lichtfouse, 2019). For instance, a solar flat-plate photocatalytic system achieved removal efficiencies of 93.5% Cu^{2+}, 99.6% Fe^{3+}, and 99.4% Zn^{2+} from real soil-washing effluents (Onotri, 2017). Furthermore, TiO_2-based UV-solar photocatalysis has been reported to completely transform EDDS–Cu^{2+} complexes, with partial mineralization observed under synthetic wastewater conditions (Satyro, 2014).

2.6 Ion-Exchange

Ion exchange is a reversible physicochemical process in which undesirable heavy metal ions in wastewater are selectively replaced by benign ions through electrostatic interactions on a solid exchange medium (Dąbrowski et al., 2004). In this process, metal ions are removed from the aqueous phase by binding to fixed functional groups on an insoluble solid matrix, as illustrated in Figure 9.

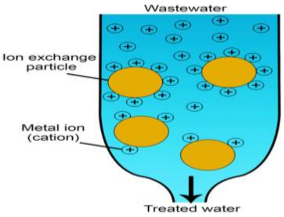


Figure 9: Schematic diagram of the ion exchange process (Qasem et al., 2021).

Ion-exchange materials, derived from natural and synthetic sources like polymer resins and zeolites, exchange metal ions in wastewater with mobile counter-ions (Na^+ or H^+) present in the medium. This mechanism enables effective removal of a wide range of heavy metals, including Pb^{2+}, Cd^{2+}, Hg^{2+}, Cr^{3+}, Ni^{2+}, Cu^{2+}, Zn^{2+}, V^{4+}, and V^{5+}.The ion-exchange reaction can be represented as follows:

$$M^{-}–EC^{+} + WC^{+} \rightleftharpoons M^{-}–WC^{+} + EC^{+}$$

Where M^- denotes the fixed anionic functional group of the exchanger, EC^+ represents the exchangeable benign cation initially bound to the matrix, and WC^+ is the heavy metal cation present in the wastewater. Although ion exchange offers high selectivity and regeneration capability, its efficiency may decrease in the presence of competing ions, and periodic regeneration of the exchange medium is required (Qasem et al., 2021).

2.7 Reverse Osmosis

Reverse osmosis (RO) is a pressure-driven membrane separation process that removes heavy metal ions from water using a semi-permeable membrane. In this process, hydraulic pressure greater than the natural osmotic pressure is applied to the concentrated side of the membrane, forcing water molecules to pass through while rejecting dissolved salts, metal ions, and other contaminants. As a result, purified water is collected on the permeate side, while pollutants are retained on the concentrated side, as illustrated in Figure 10 (Kurniawan et al., 2006).

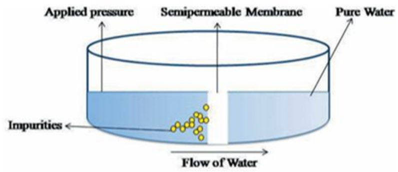


Figure 10: Schematic diagram showing removal of heavy metal ions by reverse osmosis process (Kurniawan et al., 2006).

RO is widely applied for the treatment of industrial effluents generated by tannery, textile, pulp and paper, and electroplating industries. The membranes typically retain solutes with molecular sizes ranging from 0.00025 to 0.003 µm and can remove approximately 95–99% of charged organic and inorganic salts (Wang et al., 2011). High removal efficiencies have been reported for heavy metals such as Cr^{6+}, Ni^{2+}, and Cu^{2+} in electroplating wastewater. Reverse osmosis (RO) offers high separation efficiency but is limited by high energy consumption, membrane fouling, and degradation, which increase operational and maintenance costs. While effective at small to medium scales, RO's long-term performance can be negatively impacted by fouling and scaling. Recent applications include the treatment of mining wastewater in Victoria, Australia, where average removal efficiencies of 10% for Fe^{3+}, 48% for Zn^{2+}, 82% for Ni^{2+}, 66% for As^{3+}, and 95% for Sb^{3+} were reported (Samaei et al., 2020).

3. RESULTS AND DISCUSSIONS

Table 3: Efficiency of heavy metal removal by using verious adsorbants

Name of adsorbants	Types of Metal	Efficiency (% removal)	References
Fe3O4/PMA-g-PVA	Ag(I)	0.8634 mg/g	(Fu et al., 2014)
Magnetic nanoparti cles (MNP) (HPG) polymer	Al	0.790 mg/g	(Almomani et al., 2020)
IO@CaCO3	As(V)	184.1 mg/g	(Islam et al., 2017)
MAMNPs	Cd(II)	91.55 mg/g	(Madrakian et al., 2015)
HDI-IC-PEHA	Cr(II)	3.15 mg/g	(Cegłowski et al., 2018)
Fe3O4 magnetic NPs	Cu(II)	0.170 mmol/g	(Giraldo et al., 2013)
Magnetite nanorods	Fe(II)	127.01 mg/g	(Karami, 2013)
SNHS	Ni(II)	8.375 mg/g	(Hasanzadeh et al., 2013)
Glycine MNPs (GF MNPs)	Pb(II)	555.5 mg/g	(Gupta et al., 2016)
Magnetite nanorods	Zn(II)	107.27 mg/g	(Karami, 2013)
Chitosan–alginate	Hg(II)	217.39 mg/g	(Dubey et al., 2016)
Al2O3NPs in zeolite	Co(II)	101.31 mg/g	(Deravanesiyan et al., 2015)

Table 4: Efficiency of heavy metal removal by using verious techniques

Name of Techniques	Efficiency	References
Membrane Filtration	85.58%, (1.27 mol/L $MgCl_2$)	(Naghdali et al., 2019)
Chemical Precipitation	70%–95%	(Wang et al., 2005)
Flocculation and Coagulation	90%-97%	(Amuda et al., 2006)
Photocatalysis	(Cd^{2+}) reached 99.8 %, (Pb^{2+}) reached 99.2 % Under optimal conditions	(Rahimi et al., 2014)
Ion Exchange	99.9%	(Al-Enezi et al., 2004)
Reverse Osmosis	100% for Pb and Ni, 89% for Cr,	(Qasem et al., 2021)

The study evaluated various heavy metal removal techniques from wastewater. Adsorption emerged as the most promising, achieving 127–555 mg/g for Fe^{2+}, Pb^{2+}, and Hg^{2+} using materials like chitosan–alginate, magnetite nanorods, and glycine-modified nanoparticles, offering simplicity, cost-effectiveness, and eco-friendliness, though regeneration remains challenging. Membrane filtration and reverse osmosis reached near 100% removal for Pb and Ni but are limited by fouling, high energy, and cost. Photocatalysis exceeded 99% for Cd^{2+} and Pb^{2+} but is hard to scale. Chemical precipitation and coagulation-flocculation (70–97%) generate hazardous sludge, while ion exchange achieves 99.9% removal at high cost. Overall, low-cost natural or nanomaterial adsorbents are most effective, with future focus on hybrid systems and reusable adsorbents for sustainable, economical wastewater treatment.

4. PROSPECTIVES AND CHALLENGES

Methods for removing heavy metal ions from wastewater are adsorption, membrane filtration, and reverse osmosis (RO), which offer solutions for reducing environmental and health risks. In spite of being cost-effective and efficient (Table 3), adsorption can be slow and requires regeneration of adsorbents, making it less suitable for large-scale applications (Bilal et al., 2013). Though Membrane filtration technologies, including RO, show high removal efficiencies, it can be cost-effective; they face challenges like high operational costs, energy consumption, and membrane fouling (Wang et al., 2011). Although chemical precipitation effectively removes metals, it also generates large amounts of sludge that must be disposed of (Ojovan et al., 2019). However, overcoming the economic and technical challenges of these methods is crucial for their widespread and long-term use in wastewater treatment.

5. CONCLUSION

Because of being thrown away carelessly, the problem of heavy metals is getting worse every day. We need solutions like long-term ones that will protect both people and the environment. There are many ways to get rid of heavy metals in wastewater, such as reverse osmosis, ion exchange, chemical precipitation, and photocatalysis. Another method is adsorption, but it needs a lot of changes and takes a long time to work well. Its low price is a big plus, but it also has some downsides. Membrane filtration and reverse osmosis work very well, but they cost a lot and use a lot of energy. Chemical and ion exchange techniques are also used a lot, but they do not always work well. The materials needed for those processes are often very expensive and make a lot of sludge. So, if we want to keep heavy metal pollution in wastewater under control for a long time, we still need to find easy, cheap, and eco-friendly ways to do it. In the end, it all comes down to being responsible and taking care of trash the right way.

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