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A Comprehensive Review Of Water Treatment Methods For Heavy Metal Ion Removal From Wastewater

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Abstract

Wastewater pollution with heavy metals presents serious problems with not only environmental integrity but also human health safety. This review is a complete review that includes different removal methods and technologies for heavy metals from wastewater and proceeds to include the traditional techniques as well as the advanced ones. The traditional techniques such as chemical precipitation, ion exchange, adsorption, membrane filtration, coagulation, and flocculation along with their effectiveness and some of the pitfalls are provided in this discussion. Moreover, the developments of the past years such as nanotechnology, electrochemical methods, hybrid systems, and biological treatments are further outlined as ways to improve treatment outcomes and lower the environmental impact. Efficiency of treatments factors including the pH, temperature, metal concentration, the reactor design, operation parameters, and costs considerations are critically examined to provide ideas into how to improve the performance of the treatments. By means of the combination of state-of-the-art technologies and treated-liquid effectiveness components, this review seeks to supply information for the betterment of heavy metals removal in wastewater treatment, and as such give a cleaner and healthier surrounding to the future generations.

Keywords: WHO, coagulation, electrochemical, Mineral Adsorbents, heavy metals, USEPA, adsorbents, chelation, ions

1. Introduction

The continuously rising industrial activities and human interventions including plating and electroplating industries, battery production, pesticide application, mining operations and different manufacturing processes has been a major cause of heavy metal pollution in wastewater. Wastewater polluted with heavy metals poses a serious hazard to both human health and the environment because of its high toxicity. Heavy metals, non-biodegradable and potentially carcinogenic, are the commonly known pollutants. Therefore, if these metals are not in the water in a correct amount, they can cause serious problems such as the life of living organisms. This clearly shows the importance of the actions that should be taken to stop the contamination of wastewater with heavy metals and protect water and human health.

The World Health Organization (WHO) and the United States Environmental Protection Agency (USEPA) have established a high threshold of heavy metals content in water and this is an indication that efficient removal methods are needed critically. Particularly, heavy metals may remain in ecosystems, thus entering humans via the food chains, and affecting them subsequently with long term health risks. As a result, the improvement of fast, fool-proof, and large-scale methods of removing all heavy metal ions from sewage becomes a must necessity to secure the public health and provide safe drinking water for everyone.
The leading heavy metals "lead (Pb), zinc (Zn), mercury (Hg), nickel (Ni), cadmium (Cd), copper (Cu), chromium (Cr), and arsenic (As)" can be traced in small amounts. Table 1 gives a brief on some of heavy metals, noting their primary sources, health effects, and the recommendable limit in drinking water.

Table 1: Heavy metals commonly found in wastewater. [Demerial et al., 2021]

Heavy Metal	Main Sources	Main Organs/System Affected	Permitted Amounts (μg)
Chromium (Cr)	Steel and pulp mills, tanneries	Skin, lungs, kidneys, liver, brain, pancreas, taste, gastrointestinal, reproductive systems	50
Mercury (Hg)	Electrolytic production of chlorine, runoff from landfills/agriculture, electrical appliances, refineries	Brain, lungs, kidneys, liver, immune, cardiovascular, endocrine, reproductive systems	6
Zinc (Zn)	Brass coating, rubber products, cosmetics, aerosol deodorants	Stomach cramps, skin irritations, vomiting, nausea, anemia, convulsions	3000
Lead (Pb)	Lead-based batteries, solder, alloys, cable sheathing pigments, rust inhibitors, ammunition, glazes, plastic stabilizers	Bones, liver, kidneys, brain, lungs, spleen, immune, hematological, cardiovascular, reproductive systems	10
Cadmium (Cd)	Batteries, paints, steel industry, plastic industries, corroded galvanized pipes	Bones, liver, kidneys, lungs, testes, brain, immune, cardiovascular systems	3
Arsenic (As)	Electronics and glass production	Skin, lungs, brain, kidneys, metabolic, cardiovascular, immune, endocrine systems	10
Nickel (Ni)	Stainless steel and nickel alloy production	Lung, kidney, gastrointestinal distress, pulmonary fibrosis, skin	70
Copper (Cu)	Corroded plumbing systems, electronic and cables industry	Liver, brain, kidneys, cornea, gastrointestinal, lungs, immune, hematological systems	2000

The concomitant of industrialization with urbanization has given rise to the increased water resource demand as well as the pollution of the environment. Unseen by the eye, heavy metals can deposit without exhibiting symptoms until harmful levels have been reached. As non-biodegradable pollutants, heavy metals are recognized as a serious threat to environment and have become the leading issue for environmental regulations globally.
The purpose of this paper is to examine in detail the water treatment processes, which are currently used for the removal of heavy metal ions from the wastewater. The understanding of such factors is critical not only for the decision-making process in drinking water production but also to ensure the sustainable management of water resources in the context of increasing industrialization and other environmental challenges.

2. Methodology

An extensive review was adopted in which a systematic approach was employed. Firstly, the thorough strategy for the search was elaborated to find available studies which included different databases and search terms related to the heavy metal ion removal from wastewater. Similarly, study selection criteria were formulated so that only studies matching already defined eligibility criteria are included. The study selection procedure required me to filter out and review the chosen studies based on the criteria. I went on to extract data from the chosen studies by means of a special method. The methodological rigor and credibility of the studies included were analyzed via quality assessment of the studies. Working with data synthesis involved both aggregation and analyzing of extracted data to gain valuable knowledge. Publication bias was taken into consideration and was integrated into the review process to ensure the balance in the favor of unpublished or selective reports. Furthermore, the importance of ethics regarding the performance of the review was also acknowledged and the process was conducted in line with ethical standards and guidelines. The approach followed in this research was to first systematically screen, select and critically appraise the evidence regarding water treatment methods.

3. Physical Treatment Methods

3.1. Adsorption-based Separation

The adsorption mechanism employs the physical and chemical properties of the adsorbent and metal elements, as well as other parameters such as temperature, adsorbent dosage, pH value, sorption time and initial metal concentration. In general, heavy metal ions are anchored to the adsorbent surface, but an example is shown in Fig. 1a. The above approach has not only low maintenance costs but also higher removal capacity, ease of construction and simpler treatment because it only regenerates the adsorbed heavy metal ions. Currently, types of sorbents for water purification are being developed.

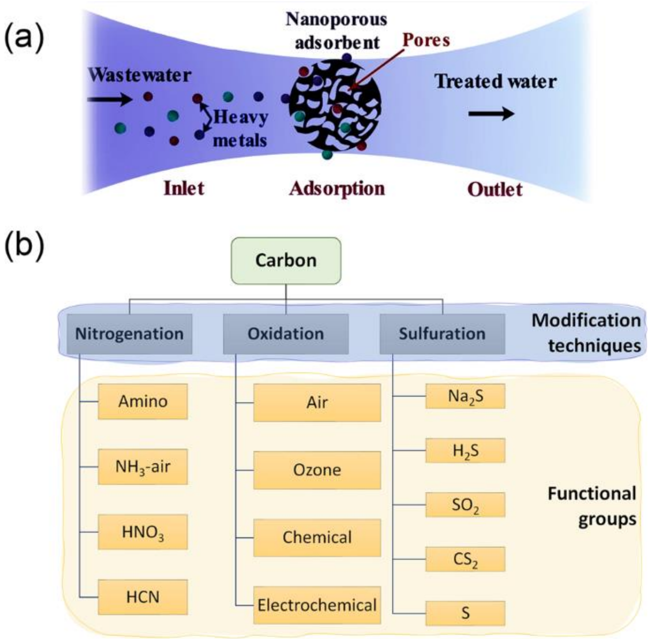

Fig. 1: Process of adsorption employed in water treatment. [Qasem et al., 2021]

- ***Carbon-based Adsorbents:*** Adsorbents like activated carbons (ACs), carbon nanotubes (CNTs), and graphene (GN) that are carbon-based nanoporous is the most popular type of adsorbents that are used in the process of heavy metal removal due to its high surface area (500–1500 m2/g). Surface functional groups, "for instance, carboxyl, phenyl, and lactone groups" can be used to increase the carbon surface charges to improve the capacity of the carbon to bind with heavy metals. Through different processes like nitrogenation, oxidation, and sulfuration different surface areas such as specific surface area, pore structure, adsorption capacity, thermal stability, and mechanical strength can be enhanced.

- ***Chitosan-based Adsorbents***: Chitosan (CS), a chemically-active and biodegradable adsorbent with amino (–NH2) and hydroxyl (–OH) groups, easily attaches to various pollutants in wastewater. Nevertheless, to reach a substantial level the mechanical strength and stability should be improved, otherwise, the process will be unsuccessful. Structural or chemical modifications, including cross-linking and grafting, have been recommended to lessen these challenges. Employing CS with other absorbent materials or utilizing the ion-imprinting technique can increase the material's ability to absorb and selectively remove target metal ions and improve its mechanical strength.

- ***Mineral Adsorbents:*** The minerals such as zeolite, silica and clays have operating cost low and they possess high cation exchange capacity as well as selectivity and surface properties. Based on commonly applied mechanisms of physical adsorption, chemical adsorption, and ion exchange, mineral adsorbents are a fundamental part of wastewater treatment. In addition to several methods of modifications like calcination and impregnation, however, most of which have been suggested to increase their removal efficiencies, some of these processes may need more money and cause of environmental concerns.

- ***Magnetic Adsorbents:*** Magnetic adsorbents consisting of small particles of iron (Fe3O4) not only are a low-cost and easy to synthesize solution, but they have also the ability to be reused. Factors such as surface morphology, magnetic response, pH, adsorbent concentration, wastewater temperature, and the initial concentrations of contaminants affect their performances. In effluents, the iron particles can get iron ions in an efficient way.

- ***Biosorbents*****:** Biosorption with biosorbers having many functional groups (carbonyl, amine, hydroxyl) on their surface, is widely used for wastewater treatment. The bonding of pollutants and biosorbents takes place with the help of such mechanisms as electrostatic interaction, complexing, ion exchange, as well as oxidation and reduction processes. Solution pH is a critical factor in terms of the surface charge density of biosorbents as well as the ionization of functional groups; consequently, the level of adsorption process is changed.

3.2. Ion exchange

Ion exchange results in less sludge amount and other advantages, which are, being specific components and being able to achieve high effluent standards accordingly (Lee et al., 2007; Zewail and Yousef, 2015). Therefore, different kinds of resins were adopted for the convention of ion exchange process (Dorfner, 1991). Natural resins (eg. rosin) and synthetic resins (eg. epoxy resins) are also classified as resins. By contrast various resin (Na-form) was used by different authors to remove heavy metal in the ion exchange process. Chloride process employed by different scholars shows diverse resin (Na-form) was used to remove heavy metal in cation exchange process. Purolite C100 was successfully tested by Badawy and al. (2009) to separate lead ions from the binary solutions. The SPE method was proved to be the most suitable tool for such tasks due to the high speed, simplicity and cost saving features (Liang et al. 2006).

While Zewail and Yousef (2015) applied spouted bed with AMBERJET 1200 Na resin for nickel and lead removal from wastewater, this type of design has many advantages, according to them, such as several mixing conditions between solid phase and spouted bed ,and their intensive heat and mass characteristic between fluid and According to the report by the Author, the performances for lead and nickel were 99% and 98% eliminations respectively.

3.3. Membrane Filtration

The emergence of membrane filtration technologies in the determination of heavy metal removal generates several benefits which include high efficiency, compact design, and ease of operation. They include the technologies comprised of these processes like reverse osmosis, ultrafiltration, electrodialysis and nanofiltration.

- *Ultrafiltration (UF):* UF (Ultrafiltration) is used during low pressure filtration to get rid of the dissolved and colloidal material. The holes in UF have a bigger size than the sizes of metal cations (hydrated) which is less than MW of the complexes thus allows them to pass through the membrane. MEUF and PEUF are the two innovations which have been applied to boost the rejection rate.
- *Reverse Osmosis (RO):* RO utilizes filtering using semi-permeable membrane which only let hydrated water molecules pass through. The technology has proven to be efficient in eliminating a wide variety of contaminants and one of its common applications is in desalination processes. Just recently, it was used in treating wastewater and various engineering works.
- *Nanofiltration (NF):* Nanofiltration (NF) which is the combination of the advantages of UF and RO is especially effective in removing heavy metal ions “like nickel, chromium copper and arsenic from waterbodies”.

4. Chemical Treatment Methods

4.1. Chemical precipitation

It is indeed an efficient tool for of the heavy metals in wastewater effluents. During this operation, chemicals bind with the heavy metals available in effluents and there is home formation of insoluble precipitates. In such kind of wastewater treatment, the next step would be the removal of the precipitates with the sedimentation technique, and the cleaned water is decanted. Chemical precipitation can be divided into two groups: the hydroxide precipitation and the sulphide precipitation.

- *Hydroxide precipitation*: The hydroxide precipitation is achieved by reacting the hydroxide with the heavy metals and thus, metal hydroxides are produced. $Ca(OH)_2$ and NaOH have been used by the authors, Mirbagheri and Hosseini (2005), in the precipitation of Cu(II) and Cr(VI) ions using $FeSO_4$ and H_2SO_4 as a reducing agent to convert Cr (VI) into Cr(III). Conversion rate of Cr^{3+} was highest in the pH range 2.0 - 2.3 and was precipitated from the solution by the calcium hydroxide at pH 8.7. 0.01 mg/L for chromium and 0.694 mg/L for copper were the levels of reduction who removal efficiency of the model reached 98.56%–99.9%. Lime is chosen also due to its low price and then fly ash is also employed because of it as a grain material. CaO as a precipitant also has its some limitations such as high dose of lime being compared to others.
- *Sulphide precipitation*: Sulphide precipitation is a process that results in a sulphide-base compound easily forming insoluble precipitates when it reacts with heavy metal compounds. Matalk and co-workers (2001) have applied pyridine thiol ligand to adsorb copper, cadmium and we have gotten the advantages like availability of poly-donor site for the binding of heavy metals and precipitation of stable metal-thiol complexes. It is the member of the sulphur family, and its role is forming of stable precipitates by bonds with heavy metals. Hence, the 99.99% elimination for copper and 99.88% elimination for cadmium were obtained at the pH value of 4.5 and 6 respectively when the experiments were performed under the same pH value.
- *Chelating precipitation*: In water treatment plant, a large toxin complexing agent as EDTA has been discharged to the environment, which causes a severe pollution (Fu et al., 2012). The detoxification process not only involves removal of heavy metals like cadmium/lead but also EDTA chelating agent. For that the procedure of chemical precipitation of Fenton was used. In the case of Fenton-chemical precipitation, the soluble Fe ions interact with H_2O_2 under the participant of the process (Fu et al., 2012). Hence, there is a possibility of using an advanced process of Fenton-chemical precipitation for wastewater containing heavy metal chelated like the one has been worked by Fu et al. (2012).

Table 2: commercial analytical laboratories use to remove heavy metals

Heavy Metal	Initial Metal Conc.	Precipitant	Optimum pH	Removal Efficiency
Ni	50 mg/L	Alkali	2.5	98.4%
Ni	50 mg/L	Alkali	11	92.8%
Ni	100 mM	$FeSO_4$	3	99.9%
Cu, Zn, Cr, Pb	100 mg/L	Lime	7–11	99.37%–99.6%
Cu, Cr	48.51 mg/L	$Ca(OH)_2$ and NaOH	8.7, 12	98.56%
Cu, Cd	50 mg/L	Pyridine based thiol ligand	4.5	99.99%, 99.88%
Zn	200 mg/L	Sulfate reducing bacteria	6.8	–
Cd, Cu, Pb, Ni, Zn	–	Sodium decanoate	4–8	> 90%
Cu	100 mg/L	1, 3, 5	3–9	99.6%
Fe	194 mg/L	1, 3-	4.5	> 90%
Cu	25 mg/L	$Ca(OH)_2$	12–13	> 99%

4.2. Coagulation-Flocculation

Coagulation and flocculation are notable processes that are generally used together with sedimentation and filtration to collect precipitated small particles like heavy metals from wastewater. Among the coagulants used in wastewater treatment are aluminium, ferrous sulphate, and ferric chloride, which act by the neutralization of charges on the particles, flocculation of them, and those resulting particulates can be taken out of the wastewater.

Coagulation: Coagulation process is constructed by including the chemicals in the wastewater to destabilize and aggregate contaminants for the subsequent removal. Innovating is one of the approaches, and they use amphoteric polyelectrolytes including sodium xanthogenate with polyethyleneimine which successfully separate soluble heavy metals and insoluble substances.

***Flocculation*:** Bonds between suspended particles are formed using polymer and flocculation proceeds as the aggregates become larger which can be more conveniently separated from the water. Meanwhile, typical flocculants such as PAC, PAM or PFS are widely known to be applicable in absorbing heavy metals in wastewater, but they may not be effective in this case.

4.3. Oxidation-Reduction Processes

Among the most applied processes for removing heavy metals from wastewater treatment are redox processes (oxidation-reduction ones), which make metal ions less harmful or even insoluble. Such processes are electron-delivery-related redox reactions that lead to heavy metal oxidation state transfers.

a. *Chemical Precipitation*: In the chemical precipitation strategy, metal ions are converted into insoluble precipitates through the addition of chemicals that facilitate the oxidation or reduction reactions. The regularly occurring precipitants which include hydroxides, sulphides, and carbonates react with heavy metal ions to form insoluble compounds which when separated from the wastewater, are easy to remove.
b. *Redox Reactions*: Redox reactions are characterized by electron transfers between chemical species which (in turn) lead to different oxidation states for the heavy metals. Oxygen containing agents, e.g. chlorine, ozone, and hydrogen peroxide can oxidize metal ions to higher oxidation states or give rise to insoluble metal oxides/hydroxides. On the other hand, reducing agents such as sulphur dioxide, sodium bisulfite, and ferrous sulphate can help in lessening the toxicity of metals ions. They can reduce metals into their less toxic forms or precipitate them as insoluble compounds.

Implementation:

- Chlorination represents the process of combining chlorine-based compounds to wastewater, oxidizing the heavy metal ions into less soluble forms or precipitating them as metal oxides/hydroxides. This technique is well-known to be effective at removing such heavy metals as iron, manganese, and arsenic from water in the process particularly carried out in water treatment plants.
- Ozonation processes use ozone gas to oxidize heavy metal ions in wastewater, so these heavy metal ions can be converted to insoluble metal oxides or hydroxides or less toxic forms. Ozonation is an effective technique for removal of a wide variety of heavy metals and organic pollution, which is applied widely as the pre-treatment step in water purification systems.
- Biological oxidation process includes the use of microbes so as to achieve the catalysis of oxidation-reduction reactions with the ultimate goal of removing heavy metal ions from wastewater. Some microorganisms are capable of enzymatically changing metal ions into non-toxic forms or of reallocating metals into their biomass, thus reducing their concentration in the water.

Tables 3: Oxidation-Reduction Process

Oxidation-Reduction Process	Application	Removal Efficiency (%)
Chlorination	Water Treatment	95-99
Ozonation	Pre-treatment	90-95
Biological Oxidation	Wastewater Treatment	80-85

4.4. Chelation

Chelating is a means to eliminate harmful metals from wastewater by creating strong bonds between cheating agents, usually known as chelators or ligands. These chelating agents contain multiple donor atoms possessing the potential of forming coordination covalent bonds with heavy metal ions which in turn trap the metals and stop them from reacting with other compounds in the effluent.

Mechanism: Chelating substances which are very effective agents, "such as ethylenediaminetetraacetic acid (EDTA), diethylenetriaminepentaacetic acid (DTPA), and nitrilotriacetic acid (NTA)" (table 4) possess electron lone pairs that can coordinate with heavy metal ions, creating stable complexes through the formation of multiple bonds. These coordination complexes are soluble in water and can be filtered or precipitated out using the precipitation techniques. By chelation, the metal ions are denied the capacity to bind to biomolecules, freeing them off toxicity and ecological harm.

Table 4: Chelation methods employed for the removal of heavy metals

Chelation Method	Chelating Agent	Target Metal	Removal Efficiency (%)
EDTA Complexation	EDTA	Lead	95-98
DTPA Chelation	DTPA	Cadmium	90-95
NTA Complexation	NTA	Copper	85-90

5. Biological Treatment Methods

Biological treatments comprise the use of living organisms as an integrated approach into the pollution removal of heavy metals in the effluent. It would be more useful if these procedures were employment dearer for heavy metal extraction as well as cost friendly.

5.1. Phytoremediation

Phytoremediation utilizes plants' power to extract, stabilize and detoxify heavy metals from contaminated water or soil. Plants uptake heavy metals from the ground using their roots and then they are stored in their tissues. Once the plants are harvested, the metals can be transported and disposed of safely. There are several mechanisms (phytoextraction, rizo-filtration, and phyto-stabilization) which play key roles in the efficiency of phytoremediation in taking out heavy metals from wastewater.

Table 5: Phytoremediation Methods for Heavy Metal Removal

Phytoremediation Method	Target Heavy Metals	Efficiency (%)
Phytoextraction	Cd, Pb, Zn	70-90
Rhizo-filtration	Cu, Ni, Cr	60-80
Phyto-stabilization	As, Hg	80-95

5.2. Microbial Bioremediation

The microbial bioremediation approach utilizes microorganisms, including the bacteria, fungi, and algae to degrade the, or otherwise transform metals into less toxic forms. These bacteria are able to do so by either biochemical transformation of metals or their precipitation, which causes a reduction of their mobile form in the environment. The tactic that consists in bioaugmentation and biostimulation is focused on increasing the microbial activity levels and, thus, make the process of bioremediation more effective.

Table 6: Microbial Bioremediation Strategies

Bioremediation Strategy	Target Heavy Metals	Efficiency (%)
Bioaugmentation	Cu, Cr, Pb	75-95
Bio stimulation	Cd, Ni, Zn	80-98
Mycoremediation	Hg, As, Cd	85-99

5.3. Bioaccumulation

The concept of bioaccumulation is that of microorganisms up taking and accumulating heavy metals, which largely occurs among aquatic organisms. Due to some organism's special ability of immobilizing and accumulating heavy metals in their tissues at a concentration more than that in the surrounding environmental area is possible. These organisms are called bio accumulators or hyperaccumulators. They can fasten this process through biomass harvesting, phytoextraction, or phytoremediation technologies.

Table 7: Bioaccumulation in Living Organisms

Bioaccumulator	Target Heavy Metals	Accumulation Rate
Chlorella vulgaris	Cu, Zn, Cd	500-1000 mg/g
Brassica juncea	Pb, Cr, As	2000-5000 mg/kg
Phragmites australis	Ni, Co, Mn	100-300 mg/g

7. Current breakthroughs and new developments

In recent years, technological advances have resulted in the design of novel methods of removing heavy metals from wastewater. These emerging technologies represent a higher level of efficiency, lower cost as well as their sustainability compared to the conventional ones.

7.1. Nanotechnology Applications

Nanotechnology refers to the process of working with materials at the nanoscale to develop certain properties and functionalities. At the wastewater treatment field, nano materials including nanoparticles, nanocomposites, and nanofibers have been demonstrated to be effective in the removal of heavy metals. Such materials tend to have high surface area-to-volume ratios, enhanced reactivity, and controllable properties; hence, they can be used as efficient adsorbents, catalysts, and membranes for the removal of heavy metals.

7.2. Electrochemical Methods

Electrochemical methods utilize electrical energy to cause chemical reactions that leads to the removal of heavy metals from wastewater. Techniques like electrocoagulation, electroflotation, and electrooxidation offer several benefits such as high removal efficiency, selectively metal removal and minimal sludge formation. Electrochemical methods are well-suited for treating both low levels and high concentrations of heavy metals and can be added to the present wastewater treatment systems.

7.3. Hybrid Systems

Hybrid systems consist of different treatment techniques that work together to achieve the removal of heavy metals from wastewater. These integrated approaches benefit from the individual strengths of each method and overcome their limitations, leading to better overall performance. Mixture of technologies may include physical, chemical, biological and advanced treatment processes for the purpose of complete heavy metal removal and complete wastewater remediation.
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8. Factors Affecting the effectiveness of the treatment

Some of the factors that determine the effectiveness of heavy metal treatment processes in wastewater are as follows. Having these factors in view is vital for maximizing treatment effectiveness and getting the desired outcomes.

8.1. pH, Temperature, and Metal Concentration

The level of pH, temperature and the initial concentration of heavy metals in wastewater greatly influence the treatment efficiency. An ideal pH value supports chemical precipitation, adsorption, and microbial activity, while temperature regulates reaction rates and biomass growth. Metals of heavy concentrations can affect mass transfer kinetics and saturation capacities of treatment media.

8.2. Reactor Design and Operation Parameters

The design and operation parameters of reactors are of utmost importance in ensuring treatment effectiveness. Factors including hydraulic retention time, mixing intensity, aeration, and media design affect mass transfer, reaction kinetics, and wastewater residence time within the system. Adequate reactor design and optimization is the key factor to achieving maximum contaminant removal and the least amount of energy consumption.

8.3. Cost and Feasibility Factors

Cost and feasibility issues refer to the economic sustainability and practical realizations of treatment options. The decision on which treatment options to use is influenced by factors like capital and operational costs, access to resources, regulatory compliance and scalability. Cost-efficient measures which are in harmony with environmental regulations and sustainability objectives are preferred for long-term wastewater management.
These recent developments, the emerging technologies and factors that may affect the treatment efficiency are responsible for the ongoing evolution of heavy metal remediation strategies in wastewater treatment.

Conclusion

Heavy metal wastewater treatment is an important industrial approach that is an effective tool for ensuring that the water environment is safe, and that people are healthy. This article has taken several routes and techs to have a comprehensive list on the removal of heavy metals from wastewater, including traditional ones to the recent innovations and the modern ones. Among the conventional methods, chemical precipitation, ion exchange, adsorption, membrane filtration, and coagulation are important ones that have been applied for a long time in the sludge treatment technology. These principles are widely applied due to their high efficiencies in the removal of heavy metals from wastewater, but they may have drawbacks including the elevated operational cost, secondary wastes creation and dependency on the particular operating conditions. However, the new technologies both existing nowadays and those coming are most likely to introduce new ideas and effective strategies to address the issue and to increase the reliability of heavy metal elimination from water. Nano-technological solutions, electrochemical methods, hybrids systems, and biosystems are capable of bringing in new mechanisms that will boost the efficiency of treatment, reduce costs, and minimize the ecological footprint.

Numerous variables involved in treatment efficacy, among which are pH, temperature, metal concentration, reactor design, operating parameters, and cost issues, often have great influence on the effectiveness of treatment procedures. Recognizing these factors is of crucial importance in order to improve the effectiveness of treatment and in selecting a proper treatment method appropriate for the type of wastewater. Through integrating both conventional and innovative technology with due attention to the operational details and the cost-effectiveness, we can successfully implement the strategy that would lead to the reduction of heavy metals pollution as well as the sustainability of water resources for the generations to the come. Pooling efforts of the researchers, technological innovations, and incorporating preventive environmental care measures, we would be able to curtail heavy metal impurities in the effluent and ascertain cleaner and healthy environment.

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