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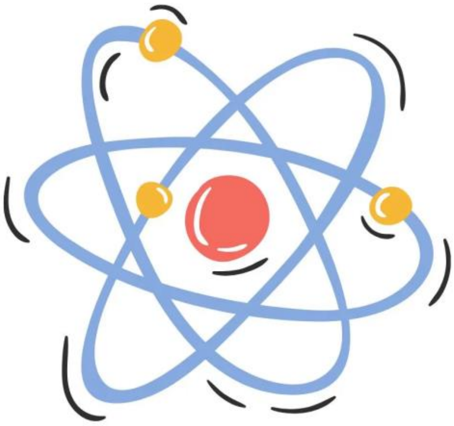

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STRATEGIES FOR EFFECTIVE CADMIUM REMOVAL: A COMPREHENSIVE REVIEW

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Abstract: *Cadmium contamination in wastewater, primarily from industrial activities, poses severe health hazards, underscoring the need for efficient treatment methods. This review evaluates several cadmium removal techniques, including precipitation, coagulation, flotation, membrane filtration, biosorption, and carbon-based nano sorbents, all showing substantial removal effectiveness and potential for reusability, though each has specific limitations. Emphasis is placed on adsorptive methods, with materials like activated carbon and low-cost biosorbents demonstrating high cadmium sorption capacities. Additionally, the regeneration of sorbents and safe disposal of cadmium-laden waste are discussed as essential components of sustainable remediation efforts. Together, these treatment strategies represent a comprehensive approach to mitigating cadmium pollution in wastewater, highlighting opportunities for advancing cleaner and more efficient water treatment solutions.*

Keywords: ***Cadmium, precipitation, adsorption, coagulation, flotation, membrane filtration***

1. Introduction

Cadmium (Cd) is a hazardous heavy metal frequently encountered in industrial environments, posing significant threats to both ecological and human health. It is considered a major environmental pollutant due to its toxicity, non-biodegradability, and tendency to bioaccumulate within organisms. Industrial activities such as metallurgy, smelting, mining, electroplating, and phosphate fertilizer production are prominent sources of cadmium contamination, while other anthropogenic sources include power plants, leaded gasoline, sewage disposal, and agricultural practices involving fertilizers and pesticides [1,2]. Natural sources, such as parent rocks and metallic minerals, also contribute to cadmium release into the environment, although human activities significantly exacerbate its presence. Cadmium is particularly concerning due to its ability to enter the food chain, where it accumulates in aquatic organisms, plants, and animals. This bioaccumulation poses serious health risks to humans, especially when cadmium-laden fish, seafood, and agricultural products are consumed [3]. Workers in industries that handle cadmium are at increased risk of exposure, but residents near industrial regions are also vulnerable. In humans, cadmium exposure can lead to chronic health conditions, including damage to the kidneys, liver, lungs, and bones. Additionally, cadmium has been linked to various cancers, such as kidney, prostate, and stomach cancers. Heavy metal also affects children's intellectual development, particularly in cases of long-term exposure [4].

One of the primary reasons for cadmium's widespread environmental impact is its high solubility in water, which allows it to be easily absorbed by aquatic organisms. This absorption can lead to oxidative stress in aquatic plants and animals, disrupting immune systems, damaging tissues, and affecting reproductive capabilities. Human health is further compromised when cadmium enters the body through contaminated water sources, fish, or crops, leading to serious issues such as neurological problems, bone damage, and organ toxicity [5]. For these reasons, regulatory agencies such as the World Health Organization (WHO) and the United States Environmental Protection Agency (EPA) have established strict permissible limits for cadmium in drinking water—0.003 mg/L and 0.005 mg/L, respectively [4]. These measures aim to limit the harmful effects of cadmium exposure on both humans and the environment. Despite these regulations, cadmium pollution continues to be a global issue, particularly in regions with weak enforcement of environmental laws. In developing countries, industrial waste is often discharged directly into water bodies without adequate treatment, contributing to the rapid accumulation of heavy metals in water, air, and soil [1]. As a result, various technologies have been developed to remove cadmium from industrial wastewater. Among these methods are chemical precipitation, ion exchange, solvent extraction, membrane filtration, and reverse osmosis [6]. However, each of these technologies has its limitations in terms of cost, efficiency, and scalability, with adsorption being one of the more cost-effective and practical methods for cadmium removal.

Adsorption has gained widespread attention due to its simplicity, cost-effectiveness, and high efficiency. It involves using materials—either natural or synthetic—that can bind cadmium ions and remove them from contaminated water. Natural bio-materials such as agricultural by-products, coconut shells, and natural zeolites have been investigated for their cadmium adsorption capabilities due to their renewable and eco-friendly nature [7,8]. Additionally, advanced adsorbents such as activated carbon, activated carbon fiber cloth (ACC), and biochar have demonstrated improved cadmium adsorption properties [9,10]. Agricultural residues such as coconut shell powder, bagasse fly ash, and other waste materials have also shown promise as low-cost adsorbents capable of effectively removing cadmium from wastewater [11,12]. The development of nano-enhanced adsorbents has further revolutionized the field of heavy metal removal. By incorporating nanoparticles into bio-materials, researchers have observed significant improvements in the adsorptive capacity of these materials. For instance, nano-CeO2-loaded activated carbon composites and Zr-alginate beads have been shown to enhance the adsorption of cadmium ions while overcoming the limitations of nanoparticle agglomeration and filtration challenges [13,14]. These nanocomposite adsorbents have garnered attention because they facilitate easy filtration and provide a cumulative sorption effect, making them more efficient in cadmium removal. However, adsorption processes are influenced by several factors, including solution pH, temperature, contact time, initial metal ion concentration, and the nature of the adsorbent material. Therefore, optimizing these parameters is crucial to maximizing the efficiency of cadmium removal from wastewater. Researchers are also exploring hybrid technologies that combine adsorption with other treatment methods to enhance the removal of cadmium and other heavy metals from industrial effluents [14].

Despite these advances, the presence of cadmium in the environment remains a global concern, especially in developing countries where industrial activities continue to expand, and environmental regulations are not strictly enforced. The demand for effective, scalable, and eco-friendly solutions is higher than ever, given the risks posed by cadmium contamination to both human health and the ecosystem [8,15,16]. Ongoing research is focused on identifying new materials and technologies that can provide more efficient and cost-effective methods for cadmium removal, with an emphasis on sustainability and environmental safety.

2. Chemical Properties of Cadmium

Cadmium, a soft, silvery-white metal, belongs to Group XII of the periodic table. It shares physical and chemical similarities with zinc and mercury, as detailed in Table 1. As a post-transition metal, cadmium has two electrons in its s orbital and a filled d orbital. The Cd^{2+} ion is known for its corrosion resistance, making it useful for protective coatings. Although it is insoluble in water and non-flammable, cadmium burns in air, producing cadmium oxide [17].

Table 1. Physical and chemical properties of cadmium [18].

Atomic number	48
Atomic weight	112.41 u
Atomic radius	155 pm
Electronic configuration	[Kr]4d105s2
Melting point	321.07 °C
Boiling point	767.3 °C
Density at 20 °C	8.65 g/cm3
Reduction potential	−0.40 E°

$Cd2^{+} + 2e^{-} \rightarrow Cd(s)$	
Heat of fusion	6.21 kJ/mol
Heat of vaporization	99.6 kJ/mol
Electronegativity (Pauling scale)	1.69
First ionization energy	867.8 kJ/mol
Second ionization energy	1631.4 kJ/mol

3. Cadmium as a pollutant in wastewater

Cadmium (Cd^{2+}) pollution arises from numerous sources, particularly in industrial effluents. Rapid industrialization, urbanization, and modern human activities such as fossil fuel combustion, municipal waste incineration, metal plating, and nuclear reactors are key contributors. Other sources include the production of iron, steel, cement, nickel-cadmium batteries, plastics, electroplating, phosphate fertilizers, pesticides, and the discharge of untreated toxic waste [18,19]. Cd^{2+} is recognized as a hazardous environmental pollutant and a Category-I carcinogen by the International Agency for Research on Cancer (IARC) and the World Health Organization (WHO). It accumulates in living organisms, posing a significant threat to human health and the environment. Cadmium pollution has a well-documented impact on aquatic ecosystems and public health. Ingestion of cadmium above permissible limits is linked to various health conditions, including kidney stones, bone disorders, cancer, hypertension, weight loss, Itai-Itai disease, endocrine disruption, renal failure, and chronic anemia [19–21]. Additionally, cadmium exposure has been associated with reproductive toxicity, including menstrual irregularities, pregnancy complications, and reduced birth weight [22]. Chemically, cadmium is resistant to corrosion, insoluble in water, and non-flammable, but it forms cadmium oxide when burned in air. It reacts with hydrochloric acid (HCl), sulfuric acid (H_2SO_4), and nitric acid (HNO_3) to form cadmium chloride ($CdCl_2$), cadmium sulfate ($CdSO_4$), and cadmium nitrate ($Cd(NO_3)_2$), respectively [23]. Natural sources of cadmium include its presence in zinc ores and environmental transportation via soil, water, and air. However, anthropogenic sources, such as metal industries, smelters, and electronic waste recycling, are major contributors to its environmental release. Since the 20th century, the use of cadmium has surged, particularly in nickel-cadmium batteries, foods, cigarette smoke, and PVC products [24].

Cd^{2+} exposure is highly toxic to animals and humans. In animals, high cadmium levels cause fatal malformations, while in humans, it leads to respiratory issues, kidney and liver damage, and bone diseases like osteoporosis, and cancer [25,26]. Cadmium accumulates in the kidneys due to metallothionein proteins, which bind to cadmium ions, preventing further cellular damage. Its role as a carcinogen has been confirmed by IARC, placing cadmium in Group 1 of human carcinogens, while the EPA classifies it as a potential human carcinogen (Group B1 [27]. Cadmium is widely used in industries for manufacturing nickel-cadmium batteries, corrosion-resistant coatings, pigments for plastics and paints, and as stabilizers for PVC polymers. It also has applications in catalysts, gas sensors, and solar cells. Despite its industrial importance, cadmium pollution is a severe environmental issue. It is non-biodegradable and bioaccumulates in food chains, leading to long-term ecological and health hazards [28]. Cadmium contamination in water is particularly concerning due to its high solubility, around 80–100% dissolving within 6 hours of exposure. Efforts to regulate cadmium discharge include standards set by environmental authorities, such as limits for cadmium concentrations in sewage and industrial effluents [29]. Various treatment techniques, including chemical processes, ion exchange, adsorption, and membrane technologies, are employed to remove cadmium from wastewater, aiming to prevent its harmful effects on ecosystems and provide safe water for industrial and agricultural use. The continuous release of cadmium into the environment, driven by both natural and human activities, poses significant risks to human health and ecosystems. Effective cadmium removal from wastewater and stringent regulation is essential to mitigate its adverse effects.

4. Methods for removing cadmium

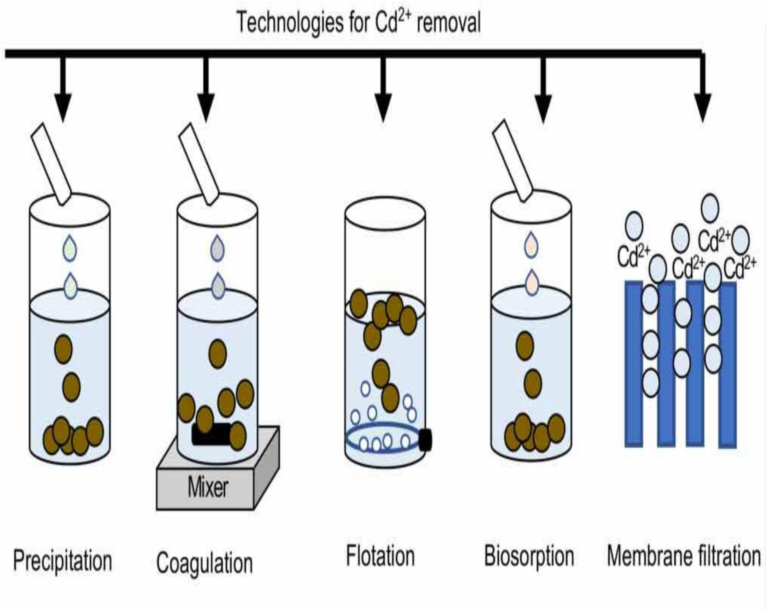

Figure 1: Schematic representation of cadmium removal methods [28]

4.1 Precipitation

Precipitation is a process in which a sparingly soluble solid forms quickly from a liquid solution through mechanisms like nucleation, crystal growth, Ostwald ripening, and agglomeration, which occur simultaneously [30-32]. It is widely used for removing heavy metals from industrial wastewater, where chemical reactions cause metal ions to form insoluble precipitates. These precipitates are then separated from the water through sedimentation or filtration. Approximately 75% of electroplating plants use precipitation methods like hydroxide, carbonate, or sulfide precipitation to treat [33]. However, managing supersaturation and secondary effects such as particle aggregation make the process challenging, influencing the quality of the precipitated materials [34,35]. Different types of precipitation processes are employed depending on the requirements. Hydroxide precipitation is the most commonly used due to its ease of application and cost efficiency, although it has limitations such as leaving high residual metal concentrations and difficulty handling amphoteric metals [36,37]. Microbially induced calcium carbonate precipitation (MICP) is gaining popularity for heavy metal removal and sustainable construction, although it presents challenges like the production of high pH wastewater and ammonia nitrogen [38-40]. Sulfide precipitation is more effective than hydroxide for removing toxic heavy metals, but controlling the dosage of precipitation agents and dealing with the release of hydrogen sulfide gas pose significant challenges [41,42].

Co-precipitation, which involves the simultaneous precipitation of multiple components, is another important technique for producing mixed crystals with desirable properties. It is instrumental in manufacturing multicomponent materials but requires additional processing steps such as washing, drying, and calcination [43-45]. The effectiveness of any precipitation method largely depends on pH, which dictates the optimal conditions for metal removal. Multiple stages of precipitation at varying pH levels may be necessary for effective treatment, and careful management of the resulting sludge is critical. Cement-based solidification and stabilization are commonly employed to prepare heavy-metal-laden sludge for safe landfill disposal [46,47].

4.2 Coagulation and floatation

Heavy metals are effectively removed from wastewater through various processes such as coagulation, flocculation, electrocoagulation, and flotation. Coagulation destabilizes colloidal particles by eliminating the forces that keep them apart. When the rate of precipitation decreases, coagulation can aid in separating mud and water, eliminating pollutants, and reducing turbidity

[48]. Traditional methods use coagulants like aluminum, ferric chloride, and ferrous sulfate, which neutralize charges and form metal hydroxide precipitates to trap impurities. However, these methods are often costly due to the substantial sludge produced [49,50]. Electrocoagulation (EC) is a promising alternative that combines coagulation, flotation, and electrochemistry. By using an electric current, it destabilizes particles, resulting in less sludge than traditional chemical coagulation [51]. EC has shown potential for removing cadmium (Cd^{2+}), achieving up to 99.92% removal in some studies, especially when combined with membrane techniques or ozonation [52,53]. Additionally, sawdust-based modified cellulose nanocrystals have demonstrated high cadmium adsorption capacity [54]. Current density, pH, and water matrix composition significantly influence EC efficiency [55]. Flotation methods, including dissolved air flotation (DAF) and ion flotation, are also highly effective in cadmium removal. These methods use surfactants to make non-surface-active materials hydrophobic, enabling their removal through air bubbles. Precipitate flotation combines precipitation and flotation to remove and recover metal ions simultaneously. DAF has achieved up to 98.44% cadmium removal efficiency [56,57]. Flotation processes are noted for their high metal selectivity and fast removal rates, though they come with high operational and maintenance costs.

Traditional coagulation and flocculation methods are widely used, they are associated with high costs and significant sludge production. Electrocoagulation, with its reduced sludge generation and combined technology options, offers a more sustainable solution. Flotation, with its high removal efficiency, remains an essential technique, especially for cadmium. The choice of method depends on the specific wastewater matrix and economic considerations [58,59].

4.3 Carbon-based sorbents

Despite the high surface area and customizable functional groups that make carbon-based nano sorbents, such as activated carbon (AC), carbon nanotubes (CNTs), and graphene, attractive suols for heavy metal removal, especially cadmium, from wastewater, robust use has yet to occur in either industry or academia. The large surface areas and mechanical stability offered by CNTs, which exist in single-walled (SWCNT) and multi-walled (MWCNT) variants, make CNTs suitable adsorbents for cadmium ions. High-quality CNTs with useful adsorption characteristics can be achieved with methods such as chemical vapor deposition (CVD). Both the internal and the external surfaces of CNTs are adsorbed with different adsorption sites providing different adsorption potentials. Adsorption stability and efficiency is increased with functionalizing CNTs such as carboxylation which is amenable for reuse without frequent wash. Materials such as polythiophene or nickel nanoparticles grafted onto magnetic CNTs further improve cadmium removal due to improved adsorption capacity and reusability [60,61].

Due to their two-dimensional structure and electrochemical properties, graphene and its derivatives (graphene oxide, GO; and reduced graphene oxide, rGO) are extensively studied for adsorption. The adsorption of particles on functionalized graphene (graphene decorated with transition metal TiO_2 or organic material chitosan) can be enhanced through electrostatic and hydrogen bonding interactions. High cadmium removal efficiency and reusability in modified graphene composites (TiO_2/rGO) have been demonstrated [62]. Nevertheless, the tendency of graphene layers to stack through π–π interactions tends to hinder its application, though it may be prevented by modifying them with polymers or other functional materials. While functionalized carbon nanomaterials have excellent potential for cadmium removal, cost-effectiveness and stability are critical for large-scale applications. For example, natural options can be cheaper than hybrid CNT-based adsorbents and pure graphene oxide creates economic challenges. Future applications in wastewater treatment will depend on continued research into maximizing adsorbent stability, reusability, and production costs, notwithstanding these drawbacks [63,64].

4.4 Adsorption

A second, more commonly accepted method is through an adsorption process to remove heavy metal ions from aqueous solutions due to the low operational cost as compared to that of conventional methods. This method does not require complex design and operation because contaminants are made to adhere to the surface of the adsorbent giving high-quality treated water. Van der Waals forces lead to physical adsorption, chemical bonding between the adsorbent and the contaminant is responsible for chemical adsorption [65]. The adsorption system efficiency is mainly determined by the characteristics of the adsorbent, such as the surface charge, surface area, and functional groups. The removal process is influenced as well by operational factors, such as pH, adsorbent dose, contact time, and temperature [66]. Zeolites, activated carbon, and clay minerals are all commonly used conventional adsorbents. An example is Zeolite A, with a higher cation exchange capacity, thus being more effective in adsorbing Cd and Zn ions [67]. Studies reveal that the Freundlich isotherm model accurately represents heavy metal removal, following the order $Pb^{2+} > Cu^{2+} > Cd^{2+} > Ni^{2+}$. Globally studied adsorbent shapes are compared in a study in which hollow fiber structures are shown to show an increased Cd removal efficiency over that of powdered zeolite, with accumulation rates across media of sand, zeolite, and quartz sand, exceedingly more than 90 percent removal in all cases for [67]. Although oxide adsorbents are highly effective, separation challenges [65] require combining them with solid adsorbents such as granular activated carbon.They constitute a cost-effective, eco-friendly alternative to bio-adsorbents such as microbial biomass. Heavy metals can be eliminated by biosorption using intricate processes like complexation and electrostatic attraction. Metal ion binding is favoured by biomass functional groups such as carboxyl, hydroxyl, and amine. Compared to nonliving biomass, algae (organisms with chlorophyll) are more effective in removing Cd and ions [68]. Cellulose and chitosan are biopolymers used due to their degradability and efficiency, for heavy metal adsorption. High-capacity biochar for the removal of Cd produced through biomass pyrolysis has resulted in promising performance; however, surface modification may be needed to increase its low surface area and limited functional groups [69].A 40 mg/g removal capacity of Cd was found for biochar produced from corn stalks and activated with potassium hydroxide by Chen et al. Due to its high surface area and active binding sites, nanostructured adsorbents, metal oxides, and nanocomposites have high adsorption efficiency. But these materials work well, and run into problems with scalability on the commercial scale, for example, due to instability and separation [70,71]. Rapid Cd removal in 20 minutes by nitrilotriacetic acid-modified silica gel [72]. Polyacrylamide-modified compositions have enhanced capacity and reduced particle pressure drop, allowing commercial application in fixed bed systems. For example, composites of red mud with polyacrylic acid significantly improved Cd adsorption through numerous means[73].

Recent studies report up to 232.5 mg/g for Cd removal using nanofibers produced from chitosan, nanocellulose, and polyethylene oxide [74]. Multiple interaction mechanisms, such as chelation and ion exchange, are exploited to enhance such nanofibers' Cd removal performance.

Adsorption capacities up to 142 mg/g of Cd onto silica-functionalized dried orange peel powder (DOPP) under optimized conditions have been studied. Divers chemical interactions, such as complex by the functional groups e.g., carboxylate ions and hydroxyl oxygen [75]. The major limitation hindering the application of these adsorbents are their production costs, their reuse potential, and competition adsorption in multi-ion systems. A new type of biochar, called animal-derived biochar (ADB), has been developed through pyrolysis of animal biomass, characterized by high calcium hydroxyapatite (HAP) content. ADB, containing calcium (29%), phosphorus (16%), and carbon (7%), differs from high-carbon biochar and effectively absorbs heavy metals, providing a novel use for animal remains [76]. The hexagonal crystal structure of HAP (space group P63/m) forms ion-transport channels, enhancing ion exchange capacity for metals like Cd(II), Cu(II), and Zn(II) [77]. Studies reveal ADB's strong cadmium (Cd) removal capacity. Cattle-derived biochar, for example, shows an adsorption mechanism dominated by ion exchange (57.6%–61.0%), followed by precipitation (24.4%–29.9%), and surface complexation (12.5%–13.4%) (Lei et al., 2020). Rendering animal carcass residue char (RACR-C), produced at 500 K, offers a Cd adsorption capacity of 73.5 mg/g, supported by Langmuir isotherm behavior and multiple adsorption mechanisms, including Cd-P precipitation and functional group interactions [78]. Furthermore, cattle carcass-derived biochar with nanoscale iron hydroxide aggregates exhibits an adsorption efficiency of 1.55 mmol/g for Cd, supporting its potential in heavy metal remediation [79].

Microbial biomass has emerged as an effective and eco-friendly solution for heavy metal removal, including Cd. For example, humic acid derived from horse dung (HD-HA) demonstrated Cd (II) uptake capacities of 1.329 mmol/g (monolayer) and 26.46 mmol/g (multilayer), with the Langmuir model fitting well [71]. Cyanobacterium Nostoc muscorum removed 92% of Cd within 24 hours at pH 8.0 [80], and Weissella viridescens achieved 69.45–79.91% Cd removal efficiency, with Cd binding primarily through cell wall hydroxyl, amino, carboxyl, and phosphoric groups [81]. Fungal biomass like Aspergillus spp. also shows high biosorption efficiency, reaching over 99% for Cd removal following pretreatment [82]. The effectiveness of microbial biomass for bioremediation hinges on rigorous control to mitigate potential health risks, as pathogens in microbial biomass could lead to disease transmission. As heavy metals accumulate globally in densely populated areas, optimizing microbial bioremediation requires advanced ecological tools and thermodynamically informed models for wastewater treatment, particularly in anaerobic environments.

4.5 Membrane filtration

Semi-permeable membranes, operating under hydrostatic pressure, are utilised to remove substances based on particle size and molecular weight[83], i.e., retaining high molecular weight solutes and suspended solids. Ultrafiltration (UF), nanofiltration (NF), reverse osmosis (RO) and electrodialysis (ED) are common membrane technologies for the heavy metal removal. There is more research attention to UF and RO among these and the citations ratio are higher. Ultrafiltration (UF) has a group of pore size filter method used to separate macromolecules, suspended particles and heavy metals. Nevertheless, it suffers from limited effectiveness due to common pore size of 5–20 nm, which is usually larger than the diameter of dissolved metal ions. Therefore, for metal ion [84], UF needs some modification namely polymer enhanced ultra-filtration (PEUF) and micellar enhanced ultra-filtration (MEUF). Micellar-enhanced ultrafiltration (MEUF) is a combination between a UF membrane with surfactant that forms charged micelles when added at the critical micelle level (CMC). These charged micelles bind metal ions such as cadmium, and these subsequently become trapped in the membrane. MEUF efficiency are surfaceactant dependent, solution pH dependent and membrane parameter dependent. Yet, MEUF's high surfactant demand (often surpassing the CMC) poses secondary contaminant issues for permeate, increasing treatment costs. Reducing surfactant concentration has been studied to reduce surfactant into sodium dodecyl sulfate (SDS) and it was shown to improve cadmium rejection as an adsorption and cake layer on membrane form [85]. Non-ionic surfactants improve the removal percentage of cadmium as catalysts by increasing the foam properties, but high amounts may hamper cadmium adsorption on gas–liquid interface [86].

Polymer adherently enhanced ultrafiltration (PEUF) applies chelating polymers that form complexes with metal ions, such as cadmium, by generating covalent and electrostatic bonds. To enhance rejection efficiency, solute molecules are bonded into macromolecular component using polymers with functional groups capable of donating electron pairs (Huang & Feng, 2019). For instance, cadmium concentrations in the permeate of a poly(acrylate) sodium complexing agent were less than 0.005 mg/L, assigning it to drinking water standards in China [87]. A complexation-enhanced UF system capable of employing rotating disk membranes has 99.7% cadmium rejection at pH 6 and a poly (acrylic acid sodium) to cadmium mass ratio of 30 and subsequent regeneration methods such as shear-induced dissociation allowing reusability without acid or alkali consumption [87]. Wastewater treatment using the strong ion retention abilities of nanofiltration (NF) and reverse osmosis (RO) are widespread. In desalination, water treatment and effluent processing, NF is a pressure driven separation method. The high rejection of divalent ions and low rejection of monovalent ions of NF membranes with the strong positive charge and hydrophilicity are very important for heavy metal removal [88]. Recently, functionalized nanoparticles such as mesoporous silica or phytic acid have been deposited onto NF membranes for cadmium removal with rates of up to 100% removal and retained efficiency in multiple filtration cycles [89]. However, cadmium rejection further enhanced by positively charged membrane surfaces, resulting in up to 90.49% removal at 1,000 ppm [90].

Metal ion removal, which has high selectivity with low energy demand, can be accomplished through liquid membrane technologies, such as emulsion liquid membranes (ELM) and polymer inclusion membranes (PIM). High Cd extraction rates are attained for ELMs, which are carriers and surfactant dissolved in an organic phase, owing to their large interfacial area for mass transfer [91]. Benderrag et al. demonstrated over 98% extraction efficiency for ELMs comprising kerosene, Triton X-100 surfactant and di-(2-ethylhexyl) phosphoric acid at optimized conditions ([Cd] = 500 ppm, pH = 7.6). Since SLM also possess high selectivity and efficiency, low energy requirements, they can be also used for metal ion removal; however, the losses of the carrier reduce the durability. This is overcome by incorporating carriers into the polymer structure as polymer inclusion membranes (PIM) and have achieved 99.47% cadmium removal with enhanced stability [92]. Fouling and high energy demands form key challenges, resulting in the evolution of membrane technology. Membrane filtration has great promise as an interesting option for large-scale water treatment: membrane fouling resistant membranes, effective pre-treatment techniques, and optimum temperature polarization in membrane distillation.

4.6 Bioremedeation

High maintenance cost, limited eco friendliness as well as generation of secondary pollutants are the challenges of conventional wastewater treatment methods. Bacterial mechanisms capable of countering high cadmium concentrations are ecofriendly and relatively cost-effective alternative to bioremediation. Cadmium accumulation, enzymatic detoxification, active cadmium efflux, and ion sequestration are these mechanisms [93,94]. The CadA and CadB gene systems encode proteins involved in the efflux mechanism of bacteria using to expel cadmium from cells [95]. But metal ions can enter cells through the metabolism-dependent H^+-ATPase system, which is then loaded by metallothionein, which deposits heavy metals inside the cell. The chemisorption of cadmium by bacteria with surface functional groups, such as phosphate and carboxyl, is also possible [96]. Moreover, some bacteria that detoxify cadmium use enzymes that make their membranes impermeable to the metal [97]. The efficiency in cadmium bioremediation is also enhanced by genetically engineered bacteria, which revealed improvement in pollutant removal efficiencies [98]. Bio electrochemical systems as metal recovery and wastewater treatment are also notable for their use of microbial or enzymatic activity in combination with traditional electrochemical methods to attack organic pollutants in the presence of simultaneously recovering metals. Though further research is required to optimise metal recovery mechanisms, this system could be used for the removal of cadmium ions in wastewater [97,99]. Furthermore, algae-based bioremediation has been shown to have potential, especially with metabolically active immobilized microalgae like Desmodesmus species with a maximum adsorption capacity of 64.1 mg/g , and is also relatively low cost to cultivate [100,101], . With transgenic microalgae used in the environment, however, there are concerns regarding the accumulation of cadmium into food chains, requiring a thorough environmental risk assessment [102,103]. Careful consideration of an ecological impact is required to realize the potential of transgenic algae as a market product.

5. Conclusion and Future Perspectives

Cadmium (Cd) is a heavy metal that poses serious threat to the ecosystem and human health, and therefore its pollution from industrial wastewater requires controlling. Several removal techniques, including chemical processes, solvent extraction, electrocoagulation, ion exchange, adsorption and membrane filtration, have been developed and its advantages and limitations are different. Chemical methods continue to be used because they are easy and efficient but they can also produce lots of sludge that poses environment challenges. Efficiency and reusability of adsorption has high potential especially with low-cost material, but optimization is needed for broader application. However, membrane technologies are promising but possibly suffer from lack of solutions for fouling, inefficiency with large effluent, and pretreatment and fouling resistant materials such as PVDF HFP. Further improvements in practical application would be the development of cost-effective adsorbents for areas that do not have many resources and the running of adsorption on our actual wastewater. Unique synergy between biochar and root-adherent microbes for heavy metal immobilization renders biochar and root adherent microbes a sustainable cleanup strategy. Immobilized algae biosorption and life cycle assessment of these materials may help to provide an ecofriendly treatment for cadmium. As with other touchscreen devices, there is great potential for artificial intelligence (AI) to optimise processes, improve energy efficiency and ensure effective water quality monitoring. However, large scale studies are still necessary but novel methods, like microbial induced carbonate precipitation (MICP), may afford a more sustainable alternative to conventional precipitation techniques. High cadmium adsorption capacities of carbon-based nano adsorbents suggests that additional research on material modification is promising. These strategies move us toward a bio-based economy based upon eco-friendly, scalable wastewater treatment solutions.

6. Conflict of Interest

The author declares no conflict of interest.

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