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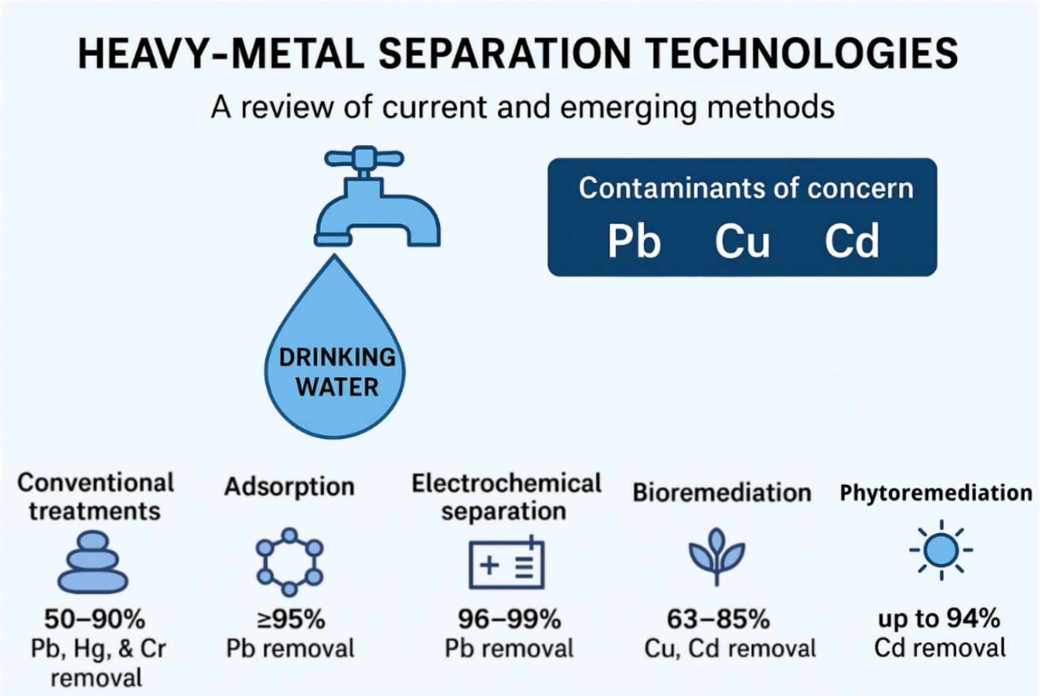
Heavy Metal Pollution in Water Supplies: Removal and Recovery

J. Dahdah[1], *M. Finlayson [1], S. Jirsa [1], B. Lynch[1], A. Whitehouse [1], B. Binwal[1], J. Kambanis[1], G. Rajarathnam[1]

[1] School of Chemical and Biomolecular Engineering, The University of Sydney, Sydney, Australia
*Corresponding author E-mail: mfin0937@uni.sydney.edu.au



Abstract

Heavy metal contamination in drinking water represents one of the most critical environmental and public health challenges worldwide, affecting an estimated 200 million people annually. This review evaluates the evolution and current state of heavy-metal separation technologies, focusing on lead, copper, and cadmium as key contaminants of concern. Conventional treatment methods, such as coagulation and filtration, achieve 50–90% removal for metals like Pb^{2+}, Hg^{2+}, and Cr^{3+} under optimal conditions but perform poorly for Cd^{2+}, Ni^{2+}, and Zn^{2+}. Emerging strategies including adsorption, electrochemical separation, photoreduction, and bioremediation, offer enhanced selectivity and efficiency under specific conditions. Adsorption using nanostructured carbons and zeolites achieves lead removal efficiencies exceeding 95%, while permeable reactive barriers report maximum adsorption capacities up to 476 mg/g. Electrocoagulation can achieve 96–99% Pb^{2+} removal at current densities of 5–10 mA/cm^2 and pH 5, whereas electrodialysis achieves ~75% Pb^{2+} removal under pilot-scale conditions (5 mg/L initial concentration, 0.6 V per cell pair, 4-hour batch time). Bioremediation of Cu^{2+} using bacteria, fungi, and algae achieves 63–85% removal in batch studies, while cadmium photoreduction using bismuth/sulphur co-doped carbon quantum dots reaches up to 94% removal at pH 8, 10 mg/L initial concentration, and 120 minutes contact time. Despite technological progress, achieving sub-µg/L metal concentrations under complex water chemistries continues to challenge current methods. Economic feasibility, secondary waste generation, and system resilience under dynamic contamination events remain major barriers. Future research must prioritise integrated, adaptive separation systems that couple advanced materials with digital optimisation, balancing performance with sustainability and energy efficiency. Such cross-disciplinary innovation is essential to ensure universal access to safe drinking water in the face of accelerating industrialisation, population growth, and climate uncertainty.

1 Introduction

Heavy metal contamination of drinking water poses serious risks to human and ecological health. Water supplies are particularly vulnerable to the downstream effects of increased metal pollution produced by the expanding global economy. It is currently estimated that over 200 million people are exposed to dangerously contaminated drinking water annually [1, 2]. Environmental heavy metal pollution from anthropogenic sources greatly exceeds natural sources, and it has been shown that the amount of lead mined and introduced into urban environments is over 100 times greater than lead introduced through natural leaching [3, 4]. This accelerating threat demands separations infrastructure and technology keeps pace with the growing risk.

1.1 Defining Heavy Metals

Heavy metals evade precise definition, but for this paper we define heavy metals as metals with a high atomic weight and a density at least five times greater than that of water [5, 6]. The heavy metals linked most often with human poisoning are lead, mercury, arsenic and cadmium [7]. The physical and chemical properties of heavy metals present unique challenges for separation and pose significant risks to humans and the environment.

1.2 Human health Impacts

Heavy metals pose two distinct risks – to public health and to the health of the broader ecosystem. When ingested by humans, heavy metals can induce remarkable toxicity at low doses [8]. Several, such as arsenic and cadmium, are well established carcinogens [1]. Lead is particularly harmful to the development of the nervous system in children, causing neurological and developmental impairments [9]. More broadly, exposure of heavy metals has been linked to cardiovascular disease, kidney damage and elevated blood pressure, highlighting the severe impact on human health. [10]. The risk of heavy metals is not confined to adverse health impacts; heavy metals present an equally significant threat to the broader environment.

1.3 Ecological and Environmental Impacts

Heavy metals pose risks to ecosystems through bioaccumulation and food chain transfer. Bioaccumulation is a major concern because, unlike many organic pollutants, heavy metals do not degrade over time. The accumulation first manifests in soils and sediments, with contamination spreading into plants and animals and terrestrial organisms, disrupting biological functions and normal growth [11, 12]. In aquatic systems, metals are transferred up the food chain, disrupting the growth, reproduction, and physiology of fish and other marine life [13]. More broadly, heavy metals persist within both terrestrial and aquatic environments, contributing to long-term ecosystem decline [12]. Separations technologies are vital in maintaining not only public health, but in ensuring ecological sustainability into the future.

1.4 Separation of Heavy Metals

Because heavy metals persist and accumulate, effective separation processes are essential to ensure safe drinking water remains accessible worldwide. In most contexts, heavy metals levels are naturally below contamination guidelines. The primary risk, as seen historically, is posed by human activity. Broadly speaking, separation can be understood in two forms: preventive and reactive.

The first is preventative separation under normal operating conditions. Given typically low levels, heavy metals are not explicitly targeted by water treatment plants but may be incidentally removed by coagulation or filtration [14]. Additionally, some metal contamination, such as lead and copper, originates from leaching in the plumbing system itself, after intended treatment has occurred [15]. This type of contamination is currently not treated through chemical separation, but rather expensive infrastructure replacements.

The second is in reactive separation under exceptional contamination events. This is required in areas without conventional treatment facilities, such as developing regions where people drink and bathe directly from rivers and streams. Contamination of these bodies of water often go unnoticed and untreated, resulting in significant human exposure and harmful ecological effects. In developed nations, reactive separation may also be required when treatment plants are overwhelmed or when a new pollutant source drives concentrations above safe limits. In such cases, immediate separative action is required to ensure access to clean and safe water is reinstated as soon as possible [16]. Historically, heavy metal contamination has been widespread, yet existing separations technologies have proven to slow or impractical for efficient mitigation of the contamination risks.

1.5 Historical and Contemporary Case Studies

There are numerous diverse historical examples of heavy metal contaminated drinking water, originating from two main sources. In developed nations, one of the most persistent risks has come from the plumbing system itself. Lead pipes and fittings have long been used in water infrastructure, and under specific conditions they may leach dangerous amounts of lead into the water supply [17]. This type of disaster occurred in Flint, Michigan in 2014, when a change in municipal water supply from Lake Huron to the Flint River increased erosion, causing widespread lead leaching from pipes [18]. The event remains one of the most significant environmental contamination crises in recent history [19]. To prevent similar disasters, modern utilities often use corrosion-control measures such as orthophosphate dosing, which reduces leaching [17].

The greatest risk currently is seen in developing nations. This stems from hazardous and unsafe practices in industrial processes such as mining and smelting. Heavy metals discharged into rivers and streams can contaminate drinking water, especially in regions lacking centralized water treatment infrastructure and water quality monitoring. Communities in Ghana, for example, have faced severe lead and mercury contamination of the Bonsa River due to illegal mining [20]. Similarly, in Bangladesh, waters surrounding a key granite mining region were found to contain dangerously high levels of heavy metals requiring immediate action [21]. These water sources are vital to the function and daily lives of the communities they serve, highlighting the unique vulnerability to contamination events seen in these regions.

Australia has also not been immune to metal contaminated water. Studies have documented widespread copper and lead contamination in household drinking water across New South Wales [22]. In South Australia, a 2018 survey reported that 89% of tested rainwater tanks contained lead levels exceeding national drinking water guidelines in at least one sample [23]. This reinforces the risk of metal contamination through leaching from water infrastructure. Contamination of town water supplies has also been seen near the Cadia gold mine in NSW, with elevated selenium and nickel levels [24].

These cases underscore the diversity of the problem, ranging from illegal mining induced contamination in rural Africa to rainwater tank leaching in regional Australia. These cases underscore the need for adaptable separations technologies capable of addressing the scope and severity of risks posed by drinking water contamination.

1.6 Evolution of Treatment technologies

The separation of heavy metals from drinking water has evolved significantly, though major gaps remain. Conventional water treatment plants are not designed to target metals, focusing instead on turbidity, pathogens, and nutrients [25]. Some metals are incidentally removed during coagulation and filtration if incorporated into suspended solids, but this approach is neither reliable nor sufficient in high contamination events [26]. Coagulation and flocculation followed by sedimentation with ferric chloride or alum has been used for more than a century, achieving 50-90% removal for species such as Pb^{2+}, Hg^{2+}, and Cr^{3+}, but performing poorly for cadmium, nickel, and zinc [27]. Preventive measures such as orthophosphate dosing have been especially important in developed nations, forming insoluble phosphate scales inside pipes to reduce lead leaching [28].

Adsorption using activated carbon and the deployment of ion exchange resins have introduced greater selectivity, while reverse osmosis (RO) and nanofiltration (NF) membranes have offered near complete removal of multiple metals [29]. Although RO is most associated with desalination, the removal of bulk salts from seawater and brackish sources, similar membrane principles have been adapted for trace-level heavy-metal separation. Unlike desalination, which targets total dissolved solids in the gL^{-1} range, heavy-metal removal aims to selectively reject toxic ions such as Pb^{2+}, Cd^{2+} and Hg^{2+} present at far lower (µg/L) concentrations, often with correspondingly lower energy demands. Typical RO systems require 2-6 kWh/m^3 of treated water and can achieve > 95% metal rejection under low-NOM conditions [30, 31]. Ion exchange processes can achieve comparable removal efficiencies but produce concentrated brines and spent regenerants that must be managed sustainably [31, 32]. Electrocoagulation (EC) and electrodialysis (ED) have also emerged as hybrid or polishing options for metal removal. Electrocoagulation can reach 90-99% Pb^{2+} removal at current densities of 5-10 mA/cm^2 using iron or aluminium electrodes although performance declines with increasing organic matter or competing ions [32, 33]. All membrane-based systems remain susceptible to fouling and require significant operational oversight.

These limitations highlight that while conventional and modern processes can reduce heavy-metal concentrations, they remain energy-intensive and generate secondary waste streams. Continued innovation toward more selective, resilient, and sustainable separation systems is therefore essential, leading to the challenges and research gaps discussed in section 1.7.

1.7 Current Challenges and Research Gaps

Today, despite decades of progress, several persistent challenges remain. Achieving sub µg/L concentrations for metals such as lead and arsenic remains difficult in high NOM waters without incurring prohibitive energy or chemical costs. Treatment systems also lack robustness to sudden contamination spikes from events such as mining spills, infrastructure failures, or corrosion incidents. In addition, residual waste streams such as brines, sludges, and exhausted sorbents risk creating secondary pollution if not properly managed. For example, residual sludges from Fe-based coagulation can reach 0.3-0.5 kg/m^3 of treated water, creating significant disposal burdens [34].

These gaps underscore the need for advanced separation strategies that are both selective and effective as well as resilient, energy-efficient, and sustainable. There is a growing imperative to develop integrated, adaptive systems capable of maintaining safe water quality under dynamic and resource-constrained conditions. To address these challenges, this review identifies key research directions and evaluates emerging separation methods through a series of guiding questions.

1.8 Scope of this Review

This review evaluates the state-of-the-art in separation methodologies for heavy metals in drinking water, focusing on the challenges of meeting sufficiently low concentration targets under realistic conditions of NOM, variable pH, and aging infrastructure. Emphasis is placed on energy and chemical usage, robustness to fouling and transients, and the management of residual waste, and the discussion is framed by three guiding questions.

1. How can existing and emerging separation methods be optimised to achieve sub-µg/L metal concentrations under complex water chemistries (e.g. high NOM, mixed contaminants, variable pH)?

2. How can digital and modelling tools, including machine learning, process simulation, and data-driven control, enhance predictive capability, operational efficiency, and design of adaptive separation systems?

3. How can advanced separation technologies be scaled and integrated into real-world drinking-water systems while maintaining sustainability across energy use, residuals management, and infrastructure constraints?

Accordingly, these three overarching research questions guide the evaluation of separation technologies, digital optimisation approaches, and implementation challenges. Together, these questions frame the discussion from the molecular to the system scale, moving from process performance under complex water chemistries, to the integration of data-driven tools, and finally to the translation of these technologies into real-world drinking-water contexts.

Finally, this paper contributes to the UN Sustainable Development Goal (SDG) 6: Clean Water and Sanitation, by addressing the need for safe and sustainable drinking water through improved heavy metal separation technologies. It also contributes to SDG 3: Good Health and Well-Being, by mitigating the severe health risks posed by toxic metal exposure, and SDG 12: Responsible Consumption and Production, by promoting energy-efficient, low-waste treatment methods that reduce environmental impact.

2 Analysis of current State-of-the-Art Separation Technologies

2.1 Lead (Pb)

2.1.1 Physicochemical Separation

Physio-chemical approaches refer to methods that exploit the physical and chemical properties of substances to separate components in a mixture. In the context of lead, specifically in the form of Pb^{2+}, recent studies indicate that Adsorption and Permeable Reactive Barriers (PRB's) are particularly effective remediation techniques.

Adsorption is a physiochemical process in which solute molecules are transferred from the bulk phase of a fluid onto the surface of a solid substrate, driven either by van der Waals forces (physisorption) or by the formation of chemical bonds (chemisorption) [35]. In practice, adsorption is applied either in batch systems, where adsorbents are mixed with contaminated water, or in fixed-bed columns, where water passes through a packed layer of adsorbent and Pb^{2+} ions are retained on the surface. This method offers several advantages, including low operational costs, ease of implementation, a high degree of purification, high profitability and straightforward system design, making it a widely employed technique for the removal of Pb^{2+} from aqueous solutions [36]. Traditionally, activated carbons, natural and synthetic zeolites, and ion-exchange resins have been widely used as adsorption materials. However, modern research has shifted towards developing highly efficient adsorbents based on carbon nanomaterials, such as carbon nanotubes, nanofibers, graphene, and graphene oxide (GO), due to their large specific surface area and high thermal and electrochemical stability [37]. A key limitation of adsorption is that its removal efficiency is strongly influenced by multiple parameters, including pH, contact time, adsorbent dose, initial concentration, and temperature, which can complicate process optimisation [36]. To address these challenges, machine learning models, such as artificial neural networks (ANN), support vector regression (SVR), and multivariate linear regression (MLR), can been applied to accurately model optimise adsorption performance. These models capture nonlinear dependencies between process variables and adsorption capacity, allowing accurate performance prediction and data-driven optimisation for the design of high-efficiency biosorbents, reducing experimental effort and improving scalability [38].

Permeable reactive barriers (PRBs) operationalise adsorption in situ, extending this mechanism into a subsurface system for groundwater remediation. Using a ZSM-5 / Silica Aerogel composite (25% ZSM-5 / 75% SA) adsorbent enabled a max adsorption capacity of ~476.2 mg/g over a range of pH (3-11), with an initial Pb^{2+} concentration of 50 mg/L, contact time of 60 min, and an adsorbent dose of 0.05 g in 100 mL [39]. PRBs are passive remediation systems developed to intercept and treat contaminated groundwater, offering low cost, and broad applicability [40]. PRBs installation involves placing a permanent, semi-permanent or replaceable reactive media in the subsurface across the flow of groundwater, where it intercepts the contaminated plume and transform the pollutants over the reactive media into less harmful compounds [40, 41]. Depending on the barrier's composition, contaminants may be adsorbed, precipitated, or chemically transformed, facilitating their removal from the groundwater [42]. In the case of Pb^{2+} separation, activated carbons or zeolites - a class of crystalline naturally occurring aluminosilicate minerals - are commonly used as the reactive substrate embedded within the PRB [43, 44]. The primary limitation of PRBs is their reduced efficiency in treating complex contaminant mixtures, as pollutants often coexist rather than occurring in isolation, particularly in the presence of organic compounds [link]. Although research in this area is currently limited, machine learning approaches, such as compositional data analysis combined with k-means or hierarchical clustering, hold potential for classifying geochemical associations, identifying natural co-contaminants of lead, and guiding the design of more efficient separation strategies [44].

2.1.2 Electrochemical Separation Methodologies

Electrochemical approaches employ electric fields or electrode reactions to remove lead (Pb^{2+}) from aqueous solutions. These methods offer high removal efficiencies and can be integrated with other treatment technologies for enhanced performance. The most widely applied electrochemical techniques include electrocoagulation (EC) and electrodialysis (ED).

Electrocoagulation (EC) involves in situ generation of coagulant ions at sacrificial electrodes, commonly iron, aluminium, or zinc. These ions destabilize dissolved metals, suspended solids, and organic matter, forming flocs that can be separated by sedimentation or filtration [45, 46]. A study on Pb^{2+} removal from battery manufacturing wastewater using alternating current at a current density of 6 mA/cm² with iron electrodes obtained a 96.7% removal, indicating that under ideal conditions EC can achieve Pb^{2+} removal efficiencies exceeding 95%, using iron rod electrodes, direct current (6 mA/cm²), 30-40 min reaction time, pH 5, and mixing rate of 200 rpm [47]. The main advantages of EC include simultaneous pollutant removal and metal recovery. However limitations still arise, including electrode passivation and energy requirements, which are influenced by water chemistry and operational parameters [48].

Electrodialysis (ED) is another electrochemical approach which employs cation and anion-exchange membranes to selectively transport ions under an electric field, effectively separating Pb^{2+} from aqueous matrices [49]. Traditionally ED technology is utilised the field of water desalination, however recent developments in membrane design, including multi-section ED cells and improved ion-selective materials, have enhanced efficiency, selectivity, and applicability to complex wastewater streams [49]. The application of ED to Pb^{2+} removal offers many advantages, including high separation efficiency for positively and negatively charged ions, effectiveness at low metal concentrations, and low operating pressure [50]. Despite these benefits, ED efficiency is not yet comparable to EC, with pilot-scale studies using an anion exchange membrane (AEM: PC SA) and a cation exchange membrane (CEM: PC SK) achieving ~75% Pb^{2+} removal in a pilot scale plant using an applied voltage of 0.6 V per cell pair (across 66 pairs), 2 cm/s velocity, 4 hour batch time, initial Pb^{2+} concentration of 5 mg/L and pH 1.6-2.9 [51]. ED and similar membrane-based desalination systems are also associated with high significant energy requirements and sensitivity to operational parameters, which can limit their large-scale applicability [52].

2.2 Copper (Cu) – Bioremediation

Emerging research on separation technologies for copper are largely focussed on bioremediation utilises biological agents such as plants and microbes to remove or lessen the effects of environmental pollutants [53]. In the context of copper pollution, particularly in the form of cupric ions Cu^{2+}, engineered strains of *Escherichia coli* and the green alga *Chlamydomonas reinhardtii* have shown great potential as low-cost and eco-friendly bioremediation agents.

2.2.1 Bacterial Bioremediation

Escherichia coli (*E. coli*) is a type of bacteria that naturally possesses several copper efflux systems to survive when exposed to toxic levels of copper [54]. One such system is regulated by the CueR protein, which controls the transcription of copper tolerance genes, CopA, a P-type ATPase located on the cytoplasmic membrane, and CueO, a multi-copper oxidase [55]. In this system, CopA exports Cu^{+} from the cytoplasm to the periplasm [56], and CueO converts periplasmic Cu^{+} to the less toxic form Cu^{2+} [57]. Recent advances in genetic engineering have leveraged these mechanisms to enhance bioaccumulation, the process by which copper ions are actively transported and sequestered within the cell [58].

Specifically, wild-type E. coli strains can be modified via recombinant DNA technology to remove or downregulate efflux pathways, while introducing plasmids encoding both copper-sensing and copper-binding elements. These modifications enable the bacteria to bind Cu^{2+} ions and actively accumulate them within the cell, thereby reducing copper concentrations in the surrounding aqueous environment [59]. This bioremediation approach allows for high selectivity for copper ions with minimal generation of secondary chemical waste, however it exhibits slower kinetics relative to physicochemical methods, and may be susceptible to fluctuations in environmental parameters such as pH and temperature [60].

2.2.2 Fungal Bioremediation

Fungal bioremediation has also gained recent traction for heavy metal removal, due to the natural metabolic capabilities of fungi to degrade and detoxify a wide array of pollutants [61]. Fungal species such as Trichoderma, or *Penicillium simplicissimum* have ability to remove copper through simultaneous surface adsorption and intracellular bioaccumulation. In this process, biosorption occurs whereby functional groups on the fungal cell wall passively bind Cu^{2+} ions, while intracellular sequestration simultaneously occurs within the cytoplasm and vacuoles [62]. In batch studies, actively growing T. lixii CR700 was reported to remove up to 84.6% of Cu^{2+} at an initial concentration of 10 mg/L [63], whereas *P. simplicissimum* achieved approximately 63% Cu^{2+} removal at an initial concentration of 100 mg/L [64]. These fungi are capable of maintaining removal activity across varying pH values and in the presence of co-occurring contaminants, however, large-scale implementation requires careful management of metal-laden fungal biomass to prevent secondary contamination, as it can be hazardous if not properly handled [61, 64].

2.2.3 Algal Bioremediation

Green algae, such as *Chlamydomonas reinhardtii*, have also demonstrated significant potential for copper bioremediation. C. reinhardtii removes Cu^{2+} through both biosorption to cell wall components and intracellular bioaccumulation, while simultaneously facilitating the biosynthesis of valuable sub-10 nm copper nanoparticles (Cu NPs) [65]. The effectiveness of this copper removal depends largely on algal viability, as active metabolic processes enable reduction of Cu^{2+} to Cu NPs and proper intracellular accumulation [66]. In batch experiments with wastewater-like nutrient media containing 10 mg/L Cu^{2+}, viable *C. reinhardtii* removed ~20-30 % of initial Cu^{2+} under experimental conditions, depending on light and growth parameters, while forming well-dispersed, polydisperse Cu NPs [67]. Altough this is a relatively low removal rate compared to the other bioremediation agents, *C. reinhardtii* offers the advantage of simultaneously producing recoverable copper nanoparticles in a low-cost and environmentally sustainable manner.

2.3 Cadmium (Cd)

2.3.1 Photoreduction of Cadmium

Cadmium can be removed from water through photoreduction, where it is reduced from its toxic ionic form, Cd^{2+}, to its metallic form, Cd, from water by reacting it with reactive oxygen species. This often occurs in conjunction with the use of a catalyst to maximise the amount of Cd^{2+} that can be reduced in a system by reducing charge recombination and providing active sites for the reduction process. A significant amount of research in Cd^{2+} reduction is focussed on producing and optimising these catalysts and the reaction conditions, depending on the desired application. There is research focussed on the removal of Cd^{2+} under visible-solar light, with a range of catalysts being used, such as Eosin Y-sensitised titanium dioxide in triethanolamine, or bismuth/sulphur co-doped carbon quantum dots [68]. Other research focused on the removal of Cd^{2+} under ultraviolet light, with different catalysts being developed, such as bentonite-supported Zn oxide (ZnO/BT), or adsorption into MnO_2 by sulphite–sulphate cycling [69, 70]. Additionally, reaction conditions such as pH, temperature and reactant concentrations, as well as the presence of other chemical additives, greatly affect the success of Cd^{2+} removal by these catalysts. The photocatalytic activity of the Sulphur and bismuth co-doped carbon quantum dot (S,Bi-CQDs) catalyst was investigated under the addition of scavenger solvents, including ethanediamine, formaldehyde, acetic acid, and methanol. At 300ppm, ethanediamine improved the effectiveness of Cd^{2+} removal by the Bi/S catalyst, reaching a maximum removal of 94% at pH 8.0, initial Cd^{2+} concentration of 10mg and contact time of 120 minutes, temperature of 25 °C [71, 72].

Photoreduction techniques have been in use and developed for water purification since the 1970s, with the optimisation of reaction conditions and production of catalysts in a range of systems remaining a large area of research [73]. In recent years, machine learning and AI are increasingly being used for optimising Cd^{2+} photoreduction techniques, greatly assisting in the speed in which research and development can take place. Machine learning has produced a greater understanding of what features of catalysts and photooxidative conditions are most important for maximising the removal of pollutants. One study used machine learning to determine the optimal pH levels for sulphite–sulphate cycling in radical-based photoreduction processes, while machine learning is also being used to determine and map sources of cadmium pollution, allowing for a targeted response to cadmium pollution at its source [74, 75, 76]. Another study used AI assisted machine learning to investigate the important parameters for cadmium reduction using a UV/malathion/sulphite reaction [77]. The study used Gradient Boosting Regression, Support Vector Regression, and Genetic Algorithm to successfully identify optimal reduction conditions, and develop a model capable of regulating UV intensity and sulphite and Malathion concentration to maximise cadmium reduction efficiency, highlighting the importance of AI in enhancing research and development for environmental protection.

2.3.2 Phytoremediation of Cadmium

Plants are known to absorb cadmium present in soil, with the bioavailability of cadmium largely dependent on soil conditions such as acidity, chelating agents, soil layer structure and the microbial profiles, with the irrigation of cadmium contaminated water causing cadmium to be deposited in soil [78]. Cadmium accumulation in plants is highly toxic, reducing uptake and movement of nutrients and water, increasing oxidative stress, and disrupting metabolism pathways [79]. The ability for plants to absorb cadmium can be exploited to reverse cadmium contamination, with research focusing on how to prevent the toxic effects that cadmium has on plant growth and nutrient uptake or enhance the natural ability for plants to uptake cadmium.

Recent development in phytoremediation has determined that dosing plants with combinations of hormones can improve the ability of the plant to uptake cadmium, among other pollutants [80]. These phytohormone combinations were investigated to determine their effect on plants already classified as cadmium hyperaccumulators such as *Bidens Pilosa* and found that certain combinations of phytohormones could modulate key physiological responses, significantly increasing cadmium phytoremediation of soil. One study found that cultivating soil nitrate reductase producing rhizobacteria drives a strong symbiotic relationship, significantly increasing a plant's ability to phytoremediate soil [81]. To avoid the uptake of cadmium by edible plants, cross breeding and genetic modification are being explored, intending to produce non-edible plants that are hyperaccumulators of cadmium, reducing the concentration of bioavailable cadmium in agricultural areas [82, 83]. Since effective phytoremediation relies on the survival and stable growth of plants in soil containing heavy metal contamination, effective methods to stabilise plant growth and bioavailability of cadmium are necessary to effectively phytoremediate cadmium contamination [83]. In high concentrations, heavy metals can inhibit plant growth, preventing phytoremediation. Biochar can be added to soil to supplement phytoremediation, where its porous structure enables adsorption of heavy metals, reducing the concentration of heavy metals that are available for immediate biosorption, while its carbon-based physicochemical properties improve water retention and soil fertility, promoting plant growth [84, 85]. Machine learning has assisted the development of biochar assisted phytoremediation, with one study using neural networks to investigate 24 soil characteristics and predict and optimise the efficiency of cadmium fixation by biochar in soil, providing valuable insights that can guide further research and optimisation of biochar applications in soil remediation [86]. Studies on the large-scale or industrial application of phytoremediation and photoreduction for cadmium removal remain rudimentary, with current known reaction and activation conditions not notable.

3 Discussion of Challenges and Future Perspectives

3.1 General Identified Challenges

Within the field of heavy-metal remediation in water systems, multiple challenges exist and continue to be identified as technology further develops. On a broad scale, the most prevalent consideration is economic, with scale-up of many remediation technologies being an expensive process, for newly advanced techniques in particular.

3.1.1 Data Availability and Monitoring

One common challenge across most water treatment systems is the lack of data availability and insufficient monitoring. Traditional in-situ sampling methods are costly and time-consuming, leading to a general lack of consistent monitoring. Heavy metal contaminants often exhibit a dynamic nature, with sudden influxes occuring without the real-time monitoring required to detect these changes early. Such influxes could occur due to natural events such as flooding, which can wash agricultural or industrial contaminants into waterways [12]. Improper waste management can also cause sudden contamination, with the discharge of mining or manufacturing byproducts directly entering water systems. Advancements are being made however, with researchers in Nanchang, China developing remote sensing methodologies to detect heavy metals in aquatic environments, using the reflectance and absorbance characteristics of these elements [87].

3.1.2 Emerging Contaminants

There are also a number of emerging contaminants that utility systems and treatment plants aren't designed to handle. These are synthetic or naturally occurring substances, that are not commonly detected within an environment. [88]. Prominent examples of these contaminants include pharmaceuticals, pesticides, surfactants and fire retardants. Further dangers to public health and the aquatic environment arise from these contaminants, with the extent of these impacts considerably under-researched. For example, PFAS (forever chemicals), have recently been identified in tap water around the Greater Sydney Area. The current studies of these chemicals in Australia are sparse, highlighting the need for further assessment, and more frequent monitoring [89].

3.1.3 Climate Change and Population Growth

It is important to address the increasingly releveant discourse surrounding climate change, and the rapidly growing global population. As global population continues to grow, so too does the demand for treated water. This demand is also now coming from regions further away from the existing central infrastructure. The combination of rapid urban development with the uncertainty of climate change, particularly flooding events, means there is rising concerns about urban water quality risks.

3.2 Challenges associated with Lead Separation

3.2.1 Adsorption

Adsorption capacity refers to the quantity of adsorbate that a given mass of adsorbent can capture in specific conditions. [90]. This capacity is strongly influenced by a range of factors, which includes the properties of the adsorbent and adsorbate respectively, as well as the process conditions. One of the main limitations of this technique is the adsorption capacity in most applications is still relatively low compared to the concentration of contaminants. This correlates to large expenses to effectively remove the required amounts of adsorbate. Furthermore, with the vast range of influencing factors impacting the adsorption process, it can a complex process to optimise. Addressing this problem could integrate machine learning models such as ANNs and various regression models. These could offer process optimisation in terms of parameter tuning, as well as improved predictive modelling, capturing the complex and non-linear relationships within this technique.

3.2.2 Electrochemical techniques

It is important to address the inherently higher energy demand of the electrochemical techniques discussed. There is a baseline energy required to produce an electric current, which can further increase with certain factors and reaction conditions. For electrocoagulation this includes current density, heavy metal concentration, and reaction time [91]. For electrodialysis, the energy requirement depends on salinity and membrane resistance. In terms of the removal of lead from water, adsorption is the far less energy intensive option as it Is primarily pump driven. Whilst energy demand is not the only factor when implementing these separation techniques, it is a prominent feasibility consideration.

Whilst electrocoagulation offers the advantage of simultaneous removal of heavy metals and other pollutants, there are numerous constraints that are required for the successful removal of Pb^{2+} to a high degree. Tight pH control is required, and the process is severely inhibited by the presence of competing ions such as Cd^{2+}, Zn^{2+} and Ni^{2+} [91]. This presents challenges in real-life water systems, in comparison to the idealised experimental conditions that produce these high efficiencies.

Currently, electrodialysis has had limited applications in waterway treatment due to problems associated with the membranes. This includes membrane fouling, scaling and concentration polarisation [92]. Like other removal techniques discussed, pH has a significant impact on the efficiency of electrodialysis. There is a small pH range to which concentration polarisation, current efficiency (number of ions through the membrane relative to the electric potential difference) and energy consumption are optimised [93]. This pH range is estimated to be optimal between pH 3 and pH 6. The applied voltage is also an important factor to balance, as the membrane can undergo ion exchange when the voltage is too low, and regeneration when it is too high.

Furthermore, the generation of secondary pollution is an issue in for electrodialysis based processes. Several toxic and hazardous organic, and inorganic chemicals are required in these processes, as cleaning and pH control agents [94]. Therefore, the application of electrodialysis on a wider scale remains a technical and economical challenge, not yet feasible compared to other techniques.

3.3 *Challenges associated with Copper Separation*

3.3.1 *Bioremediation*

There are several hurdles surrounding the wider-scale implementation of bioremediation for the removal of copper from water. In general, there is a high dependency of this process on a variety of environmental factors, such as pH, temperature, and the concentration of the heavy-metal contaminant. Whilst copper is an essential micronutrient, vital to life, it can also become toxic at elevated levels. Many of the microorganisms used in the bioremediation process have a sensitivity tolerance, above which the microbial activity is limited, and eventually the concentration can become toxic. Other environmental conditions can also lead to inefficiencies via bioremediation, such as hyper-salinity and acidic conditions [95]

As an emerging separation technology, many of the longer-term impacts of this technique are yet to be studied. There are a range of potential secondary risks, such as contaminant desorption, nanoparticle release, and ecotoxic impacts that still need to be assessed, to ensure long-term environmental safety [84].

3.4 *Challenges associated with Cadmium Separation*

3.4.1 *Photocatalytic Reduction of Cadmium*

The feasibility of Cd removal via photoreduction is most significantly limited by the catalysts used, and their properties. For example, ZnO based systems rely primarily on UV light for reduction, but UV is only 4-8% of natural sunlight [96]. A much larger proportion of sunlight is made up of visible wavelengths, yet the catalyst systems that rely on these wavelengths are still maturing in terms of cost and catalyst stability when applied to Cadmium. Furthermore, ZnO based catalysts are prone to photo-corrosion under UV light, meaning the breakdown of the crystal lattice and a loss of photocatalytic effectiveness [97]. Further research is still required to raise the photostability of many catalyst systems when exposed to prolonged light irradiation.

3.4.2 *Phytoremediation of Cadmium*

Despite adequate levels of research into phytoremediation, there are significant constraints associated with adoption in field. One of the main risks is the uptake of Cadmium into edible plants, entering the food chain and posing danger to human and animal health. Genetic modification is being explored, with the intention of producing a plant that is a hyperaccumulator of Cd and not edible, therefore reducing the bioavailable concentration of Cd in agricultural areas.

In comparison to other separation techniques, phytoremediation is considered quite a slow process, with large variability in performance between real-life sites. It is a promising option when tested experimentally, but in when implemented in real water systems the results have been inconsistent, and scaling strategies are immature and unproven. There is also limited understanding of the longer-term environmental risks of this method, in terms of human and ecological health.

There is potential for further development of this technique, extending the process to metal recovery as well, termed phytoextraction. This dual benefit is a prime example of the circular approach that could be implemented in a range of current technologies and practices, moving towards a more sustainable future society.

3.5 *Future Perspectives*

3.5.1 *Implementing Circular Approaches*

One consideration for the future is around aligning with the approach of Circular Economies. The traditional, linear model of find, use, dispose, is being shifted to focus on the recovery and repurposing of resources. In the context of contaminated waterways, valuable heavy metals can be recovered, alongside treatment materials which can be reused.

In terms of tackling the challenge of population growth, and the rising demand for water in regional population centres, the transition to modular systems could also be considered. This could involve more compact, mobile separation units for small or crisis-affected communities. Potentially a closed-loop system, a modular system could follow the principles of a circular approach, reusing treatment materials like adsorbents, minimising the discharge of byproducts. This would mean less dependence on centralized infrastructure, making treated water accessible for everyone, and on a much shorter timeframe than the full development of treatment plants.

3.5.2 *Infrastructure and Asset Management*

As seen in the case of the Flint Water crisis, proactive management of water-related infrastructure is pivotal in ensuring ongoing safety and success. Effective asset management by governments and other stakeholders is required, with careful consideration of budgeting, climate risk, growing populations and public policy. There is a strong argument in this sense to incorporate the use of artificial intelligence into this process, modelling the lifetime of assets to better understand the system and the early signs of degradation. Furthermore, with the uncertainty surrounding climate-related risks, machine learning models could be implemented to forecast demand and system operation under future scenarios, providing operators with more information regarding risk, resource allocation and optimisation [98].

4 Conclusion

Heavy metal contamination of drinking water continues to pose a significant environmental and public health concern in many regions of the world. Difficulties such as industrialisation, population growth and ageing infrastructure are becoming increasily prevalent, driving the need for improved separation technologies that are both efficient and sustainable.

Conventional physicochemical techniques, including coagulation, adsorption and membrane separation, have demonstrated high removal efficiencies under controlled conditions, yet remain limited by high energy demand, maintenance requirements and secondary waste generation. Recent advances in electrochemical, biological and photocatalytic techniques have emerged as potential options, but remain costly, difficult to scale, and sensitive to environmental conditions. Future approaches must prioritise systems that are modular, resilient and aligned with circular economy principles. This includes the recovery and reuse of valuable by-products, the regeneration of treatment materials, and the minimisation of process waste. The integration of digital tools, including artificial intelligence and machine learning, presents a further opportunity to enhance process optimisation, predictive maintenance and adaptive control of treatment systems.

In summary, the sustainable removal of heavy metals from water systems will require continued collaboration across the engineering, materials, digital, and government fields, ensuring access to safe water through adaptive and resource-efficient treatment strategies.

Author Contributions

J. Dahdah produced part of section 2, the abstract, graphical abstract; M. Finlayson produced section 3 and 4; S. Jirsa contributed to section 1; B. Lynch contributed to section 1; A. Whitehouse contributed to section 2; B. Binwal and J. Kambanis provided task direction and project assistance, and Dr. Gobinath Rajarathnam provided conceptual direction, research and writing guiding frameworks, facilitated project resources, and direct project supervision.

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AI Declaration

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