Heavy Metal Pollution in Freshwater Systems: Current Detection Technologies and Sustainable Remediation Solutions

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Abstract. Heavy metal pollution in freshwater systems becomes a global problem. Heavy metals such as lead, cadmium, mercury, and arsenic, due to their persistence and high toxicity, can persist in the environment for a long time and cause bioaccumulation through the food chain, posing a serious threat to human health and aquatic biodiversity. Therefore, developing and applying accurate heavy metal detection technologies and effective pollution remediation methods are significant for ensuring the stability of aquatic ecosystems and human health. This research introduces three detection technologies; atomic absorption spectroscopy (AAS), inductively coupled plasma–optical emission spectroscopy (ICP-OES), and inductively coupled plasma–mass spectrometry (ICP-MS). And evaluates two types of remediation methods, physicochemical techniques such as precipitation, ion exchange, adsorption, and membrane filtration and advanced approaches including nanomaterials, photocatalysis, and hybrid systems. This study emphasizes the combination of detection and remediation. Comparing the advantages and disadvantages of different methods, assessing their applicability and limitations, providing a scientific basis for achieving efficient and sustainable freshwater resource management.

Keywords: Heavy metal pollution; freshwater remediation; detection technologies; physicochemical methods.

1. Introduction

Freshwater systems are vital yet vulnerable resources, they are essential for biodiversity and human life [1]. The level of biodiversity in these systems are very high, they support 6–10% of all known species and nearly one-third of vertebrate species on global scale, providing essential ecosystem services [2]. Freshwater systems also play an important role in supporting human life, because these systems such as rivers, lakes and groundwater provide drinking water, support agriculture and food supply, regulate floods, and improve water quality by filtering pollutants [3]. However, freshwater systems face severe threats from heavy metal contamination in recent decades years, particularly contaminated by lead (Pb), mercury (Hg), cadmium (Cd), and arsenic (As), which are persistent and toxic heavy metals [4]. There are many different anthropogenic sources of heavy metal pollution. Industrial activities are a major source of pollution, as demonstrated by lead levels in India's Ganges River, it exceeds WHO limits by more than ten times near the industrial area [5]. Mining operations have also caused devastating impacts, such as the Ok Tedi Mine disaster in Papua New Guinea, which released nearly 100,000 tons of metals into the Fly River, poisoning aquatic life and local communities [6]. Agricultural runoff further contributes to contamination; in Bangladesh, arsenic from agricultural activities has polluted groundwater, affecting more than 20 million people [7].

The persistence of heavy metals in freshwater systems poses significant risks to biodiversity and human health because they are able to bioaccumulate and biomagnify in the environment. Since these heavy metals cannot be degraded, they will continuously accumulate in sediments, water, and organisms. And subsequently magnify through food chains. Therefore, once heavy metals have entered the human body through food chain, cells in human are easily damaged by these heavy metals such as lead and mercury [8]. Chronic and acute health effects of heavy metal exposure include neurological damage from lead and mercury, as well as cancers and organ damage associated with arsenic and cadmium [4]. A well-documented case is the Minamata disease outbreak in Japan in the 1950s, caused by mercury exposure [9]. These risks are especially severe in developing countries, for example, over 226 million people worldwide are exposed to unsafe arsenic levels in food and drinking water. The most affected groundwater sources are located in South America and east and south Asian [10]. Because monitoring and treatment of heavy metal pollution in these countries are often inadequate. Therefore, it is essential to establish and implement detection systems, providing the reliable data of heavy metal contamination such as metal type and concentration. And selecting appropriate remediation strategies according to the type and concentration of metals. Furthermore, integrating detection with remediation efforts allows for continuous monitoring of progress and adaptation of strategies, ultimately protect freshwater systems.

At present, heavy metal pollution in freshwater systems has become a widely studied topic. However, there is still a significant gap in existing research: most literature often regards detection techniques and repair strategies as independent fields, focusing only on one of them, while lacking systematic research that links these two fields [11] [12]. This fragmented research model to some extent restricts the understanding and control of the entire process of heavy metal pollution and is also not conducive to the formation of an overall water quality management framework from monitoring to remediation. Therefore, combining detection with remediation to achieve higher quality and sustainable water quality management should become an important direction for future research. To fill this research gap, this study critically evaluated the existing detection technologies and remediation methods, and proposed an integrated framework that combines detection and remediation to promote the sustainable management of freshwater resources.

2. Analytical techniques

Freshwater systems contaminated by heavy metals such as lead and mercury, posing a significant threat to public health and the ecological environment [8]. Therefore, it is urgently necessary to develop and apply accurate and sensitive heavy metal detection methods, including quantitative analysis technologies. At present, the most commonly used analytical methods are atomic absorption spectrometry (AAS), inductively coupled plasma optical emission spectrometry (ICP-OES), and inductively coupled plasma mass spectrometry (ICP-MS) [13]. These technologies each have their own advantages in terms of sensitivity, selectivity, and operational feasibility, but they also have certain limitations. Therefore, this study will explore the basic principles of these three technologies, sort out their typical applications in freshwater analysis, then compare and evaluate their performance, aiming to provid references for heavy metal detection and water quality management.

2.1. Atomic Absorption Spectroscopy (AAS)

The principle of Atomic Absorption Spectroscopy (AAS) is that free atoms in the ground state can absorb light of a specific wavelength to become excited state. And different element has different and unique set of wavelengths, the wavelength corresponds to the energy difference between its ground and excited electronic states [14]. And the intensity of absorbed light is directly proportional to the number of ground-state atoms, the number of ground-state atoms is related to the concentration of elements in the solution. Therefore, quantitative analysis can be achieved by measuring the absorption intensity [15]. In freshwater analysis, sample will be prepared through acid digestion to release metal ion into solution [13]. For flame atomic absorption spectroscopy (FAAS), the liquid sample is aspirated into flame and atomized in flame, then a hollow cathode lamp emits light at a wavelength specific to the target metal, the attenuation of this light will be measured to determine concentration [14]. For graphite furnace atomic absorption spectroscopy (GFAAS), it has higher aspiration temperature and better sensitivity comparing to FAAS, because sample is electrothermally atomizing in graphite tube, allowing detection at parts-per-billion (ppb) levels [16]. There are many advantages of AAS in the detection of heavy metal in freshwater systems, it has high selectivity because element-specific light sources minimize spectral interferences [17]. Also, relatively low operational cost and straightforward instrumentation makes it possible use for routine monitoring and large-scale water quality testing [16]. Therefore, it is widely used in environmental analysis laboratories. However, this method also has certain limitations if applied to complex freshwater substrates. The sensitivity of AAS is relatively limited, particularly for trace metals in complex matrix [11]. And there will be a matrix effect which require sample dilution or chemical modifiers [15]. Therefore, although AAS has high practicality in daily water quality monitoring, it still needs to be combined with more sensitive methods such as ICP-OES or ICP-MS when ultra-low detection limits are required or when dealing with complex matrices.

2.2. Inductively Coupled Plasma-Mass Spectrometry (ICP-MS)

Inductively coupled plasma mass spectrometry (ICP-MS) combines the ionization ability of high-temperature plasma with the high sensitivity of mass spectrometry detection. In freshwater analysis, the samples are usually acidified first, then the sample goes into an argon plasma with a temperature of approximately 7,000 to 10,000 K in the form of aerosols. During this process, the metal elements in the sample are effectively atomized and ionized. The generated ions then enter the quadrupole mass analyzer, where they are separated based on their mass-to-charge ratio (m/z). Finally, metal ions will be detected and quantified by an electron multiplier [18]. To correct instrument drift, internal standard methods are often used for calibration during the analysis process [19]. Inductively coupled plasma mass spectrometry has an extremely low detection limit up to ultra-trace levels, high sensitivity up to parts per trillion and a wide linear dynamic range. It can be used to analyzed multiple elements simultaneous in a single determination, even for trace and ultra-trace heavy metals [20]. This makes it a useful tool for heavy metal detection in freshwater systems. However, ICP-MS also has many limitations, first its maintenance cost is relatively high, and it requires a continuous supply of high-purity argon gas, high-purity acid, and other consumables. Second it requires careful sample preparation and trained personnel to mitigate contamination and optimize sensitivity [21].

2.3. Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES)

Inductively Coupled Plasma–Optical Emission Spectroscopy (ICP-OES), also referred as ICP-AES (Atomic Emission Spectroscopy), one of the most widely used techniques for the detection and quantification of heavy metals in freshwater systems. The principle of ICP-OES is that atoms and ions are excited to higher energy states, then emit electromagnetic radiation at element-specific wavelengths as they return to their ground states [22]. In heavy metal analysis, a freshwater sample containing heavy metals is first introduced into an argon plasma as an aerosol through a nebulizer. The plasma is sustained by a radiofrequency (RF) electromagnetic field, it will reach extremely high temperature around 8000-10000K which sufficient to desolvate, atomize, and excite the analyte atoms and ions. Once excited, these species emit light at characteristic wavelengths unique to each element. The emitted radiation is then dispersed by a spectrometer, and its intensity is measured by a photodetector. Because the intensity of the emission line is directly proportional to the concentration of the heavy metal in the sample, therefore, quantitative determination of heavy metals can be achieved through calibration with standard solutions [23]. One of the key advantages of ICP-OES is its efficiency in terms of both analyzing speed and throughput. Because multiple elements can be detected simultaneously, the overall analysis time per sample is significantly reduced. There are also some limitations, the most notable drawback is its sensitivity, which is lower than ICP-MS. Furthermore, the operational cost of ICP-OES is much higher than AAS because its dependence on high-purity argon gas and more complex instrumentation, which increase maintenance and operation costs [24].

3. Remediation methods

3.1. Physicochemical methods

Physicochemical methods are currently one of the most widely applied strategies for remediating heavy metal pollution in freshwater systems [22]. They have many advantages, such as they can remove various metal ions efficiently and the operation processes are relatively simple. Therefore, physicochemical method is widely used in both industrial and municipal wastewater treatment [23]. The four most significant physicochemical approaches are chemical precipitation, ion exchange, adsorption, and membrane filtration [22] [23]. These methods rely on different removal mechanisms respectively and have unique advantages and limitations [23].

Chemical precipitation is one of the earliest and most widely used heavy metal removal technologies at present. The principle of this method is adding chemical reagents such as lime, sodium sulfide or carbonate to the wastewater, converting dissolved heavy metal ions into insoluble hydroxides, sulfides, or carbonates, forming precipitates. Then using sedimentation, flocculation, or filtration methods to remove these precipitates [24]. The advantages of chemical precipitation are lower cost, simple operation and strong processing capacity. So, it is particularly suitable for treating high concentration and large volume industrial wastewater, especially effective in removing metal ions Pb^{2+}, Cu^{2+} and Cd^{2+} [25] [26]. However, its efficiency decreases significantly at low concentrations or trace heavy metal pollution, it also generates large amounts of hazardous sludge that require safe disposal, raising secondary environmental concerns. Meanwhile, this method is very sensitive to water pH, temperature and ionic strength conditions, the precipitation reaction may be incomplete if these conditions are not controlled properly [24] [26].

Ion exchange is a more selective technology for removing heavy metals. The basic principle of ion exchange is to replace toxic heavy metal ions in water with benign ions (such as Na^+ or H^+) on the resin matrix. Research has proved that both synthetic resins and natural zeolites can remove trace amounts of ions such as Pb^{2+}, Zn^{2+} and Cr^{3+} efficiently [27]. This method not only has high efficiency on removing heavy metals ions, but it also has good sustainability because of resin regeneration, and there is no sludge generation. However, the application of ion exchange method in large-scale water treatment is still subject to some limitation because the ion exchange materials and regeneration processes are expensive [24].

Adsorption method has received increasing attention due to its highly efficient ability to remove heavy metals at extremely low concentrations. The principle of this method is to make metal ions combine to the surface of solid adsorbents through ion exchange, electrostatic interaction or complexation reaction. Traditional adsorbents such as activated carbon are still widely used in recent years, but research trends have gradually shifted towards low-cost and highly sustainable alternative materials, such as biochar and agricultural by-products. Nanomaterial such as graphite oxide also be considered due to its high specific surface area and reactivity [26] [28]. High efficiency and flexibility are main advantages of adsorption method. However, the adsorbent gradually becomes saturated with use, which requires regeneration treatment or replacement. This not only increases operating costs but also poses a challenge to the sustainability of practical applications [24].

Membrane Filtration technology, including nanofiltration (NF) and reverse osmosis (RO), is one of the most advanced physicochemical water treatment methods at present [29]. These processes can efficiently remove almost all dissolved heavy metal ions and produce reusable high-purity water. And this method is capable to treat trace pollutants and complex wastewater [24]. However, membrane filtration still faces significant challenges in large-scale applications because its operation relies on high energy consumption, and the membrane is easy to be fouled and clogged, besides the cost on operation and maintenance are high. All these factors have to some extent restricted its wide promotion [26].

3.2. Advanced and emerging methods

In recent years, advanced and emerging remediation technologies have gradually attracted widespread attention from the scientific community. These methods serve as alternatives or complements to classical methods such as physicochemical methods. Compared with classical methods, they usually demonstrate higher removal efficiency, stronger environmental adaptability, and more prominent sustainability in treating heavy metal contaminated water. Nanomaterials, photocatalysis, and hybrid treatment systems represent some of the most promising development directions [30-31].

Nanomaterials has extremely high specific surface area, controllable surface chemical properties and enhanced reactivity, it demonstrates unique advantages in the remediation of heavy metal pollution in water bodies [32]. Although nanomaterials have demonstrated extremely high removal efficiency in experiments and small-scale applications, their large-scale promotion still faces multiple challenges. First is the high cost of preparation and application. Second may nanomaterials are toxic to environment, there are unpredictable effects of nanoparticles entering the ecosystem. Third recycling and reusing of used nanoparticles are still a challenge [31].

Another innovative method is photocatalysis, which employs semiconductor materials such as titanium dioxide (TiO_2) and zinc oxide (ZnO). Photocatalysis catalysts can generate reactive oxygen species under ultraviolet or visible light irradiation, then the toxic metal ions will be converted into less toxic or more stable forms, the stable ions can be removed by co-precipitation or adsorption [31]. Although photocatalysis shows significant potential for environmental remediation, its application is still subject to some limitations because the reaction efficiency is relatively low under natural light conditions, and the used catalysts particles are difficult to separate and recover. These challenges restrict the application of photocatalytic technology in large-scale water treatment [33].

Hybrid remediation technology often integrates biological mechanisms with physicochemical methods by combining multiple treatment processes to achieve higher treatment efficiency. For instance, the coupled process of adsorption and biodegradation, or the combined application of nanomaterials and membrane filtration, all demonstrate the advantages of this comprehensive strategy. Compared with single technologies, such systems can make up for their respective deficiencies and perform more prominently in terms of removal efficiency and application scope. However, its design and operation process are usually rather complex. Before achieving large-scale promotion, more research is still needed in terms of process optimization and cost control [34].

4. Result

Atomic absorption spectrometry (AAS) has been one of the most widely used metal detection techniques in environmental laboratories due to its lower cost, simple operation, and the results are reliable [16] [17]. AAS is suitable for routine monitoring of single metals, it can be used to finish rapid and targeted detection of key pollutants like Pb, Cd and Cr. However, it unsuitable for the simultaneous analysis of complex water samples due to limited sample throughput, and there is a limitation to analyze trace metals in complex matrix [11]. Compared with AAS, ICP-OES has higher efficiency and wider applicability. it is highly suitable for large-scale environmental monitoring, regional water quality assessment, and long-term trend analysis due to its multi-element simultaneous analysis capability. Although ICP-OES has higher cost and energy consumption, its high throughput and multi-functionality offer obvious advantages in scenarios where many samples need to be processed [24]. ICP-MS represents the most advanced and sensitive detection technology among the three. it usually used for trace pollutant monitoring, drinking water quality assessment, human health risk research and high-precision scientific research because ICP-MS offers ultra-trace detection capability up to ppt level, extremely wide linear dynamic range, and isotope resolution ability [20]. The value of ICP-MS is particularly prominent when dealing with tasks that require extremely high sensitivity and accuracy.

In real world applications, the appropriate method should be selected based on the research objective, sample size, detection sensitivity and resource conditions: when the target is the routine detection of a single pollutant, AAS remains the most practical tool. ICP-OES is more efficient if it is necessary to monitor multiple metal elements over a large range. ICP-MS is irreplaceable when ultra-trace sensitivity, isotope information or high-precision data are required. These three methods do not replace each other but complement each other, they jointly form an important technical system for environmental heavy metal detection.

For remediation strategies, because of advantages of traditional physicochemical methods such as mature processes, low costs and simple operations, it still dominates large-scale and cost-sensitive applications, especially suitable for treating high-concentration and industrial wastewater. However, these methods often have limitations on the removal of low-concentration trace pollutants, selective control, and secondary pollution issues [24] [26]. In contrast, advanced methods have demonstrated advantages in treating low-concentration pollutants, complex water quality, and application scenarios that require high selectivity and high efficiency. However, their promotion is still restricted by factors such as high costs, insufficient environmental risk assessment, and high operational complexity [31] [32-33].

Therefore, the future water treatment strategy can integrate traditional physicochemical methods with advanced remediation approaches instead of only choosing single technology. For example, physicochemical methods can be used for primary removal in high concentration heavy metal pollution, advanced methods can further refine the treatment of low-concentration residues, then the balance among efficiency, cost and sustainability can be achieved.

5. Conclusion

Heavy metal pollution in freshwater system is one of the major environmental challenges due to persistence, bioaccumulation and high toxicity of heavy metals. Addressing this issue not only relies on accurate and reliable detection technologies, but also requires the coordination of effective repair measures. AAS, ICP-OES and ICP-MS has different advantages, ranging from economical single-element monitoring to rapid multi-element analysis, and then to precise detection at the ultra-trace, which can meet the monitoring needs in different situations. For remediation strategies, traditional physicochemical methods dominate large-scale application due to their high maturity and strong applicability. Advanced methods have shown potential in trace removal and sustainable treatment. The key to the future is integrating detection and remediation as a system. While reducing costs and by-product risks, promoting the large-scale application of new technologies. It is expected to provide a guarantee for the long-term security and sustainable management of freshwater resources.

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