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Treatment of Common Heavy Metal Waste Liquids in Chemical Analysis Laboratories

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Abstract: This paper reviews the sources, main components and characteristics, hazards, and treatment technologies of heavy metal waste liquid in chemical analysis laboratories. Common treatment methods such as chemical precipitation, ion exchange, adsorption, and membrane separation are detailed, and the advantages and disadvantages of each technology are compared. Furthermore, the paper analyzes the treatment of heavy metal waste liquid from both environmental and economic perspectives, and discusses the importance of establishing a comprehensive management system for heavy metal waste liquid treatment, including waste liquid classification, collection and storage, personnel training and accountability, and the improvement of supervision and management systems. The aim is to provide theoretical reference and practical guidance for the treatment of heavy metal waste liquid in laboratories.

Keywords: Chemical laboratory; Heavy metal waste liquid; Treatment technology

1. Introduction

With the widespread implementation of chemical analysis experiments, the amount of heavy metal waste liquid generated in laboratories is increasing, posing a serious threat to the ecological environment and human health. Due to their difficulty in degradation and easy accumulation, heavy metal waste liquid can cause long-term harm to water bodies, soil, and ecosystems. This article will delve into the sources, characteristics, and treatment technologies of heavy metal waste liquid, aiming to provide a scientific basis and practical methods for the management of heavy metal waste liquid in laboratories.

2. Overview of Heavy Metal Waste Liquid from Chemical Analysis Laboratories

2.1 Common Sources of Heavy Metal Waste Liquid

In chemical analysis laboratories, heavy metal wastewater comes from a wide range of sources. The use and disposal of heavy metal salt reagents during experiments are common sources, such as solutions of lead nitrate and mercuric chloride. If the remaining portions are carelessly discharged after the experiment, they become heavy metal wastewater. Sample digestion also introduces heavy metals. To analyze sample composition, strong acids and strong oxidants are often used for digestion. If the sample itself contains heavy metals, these will enter the solution after digestion, and improper subsequent treatment will result in wastewater. Cleaning experimental equipment also generates wastewater containing heavy metals. After experiments, the cleaning of glassware, reaction vessels, and other equipment releases adhering heavy metals into the cleaning water. When this concentration accumulates to a certain level, it constitutes polluting wastewater.

2.2 Main Heavy Metal Components and Characteristics

Common heavy metals found in wastewater from chemical analysis laboratories include lead, mercury, cadmium, and chromium. Lead exists primarily in ionic form in wastewater and is relatively chemically stable, but it exhibits cumulative toxicity. Mercury can exist in various forms, including metallic mercury, inorganic mercury, and organic mercury. Organic mercury, such as methylmercury, is extremely toxic and easily accumulates in organisms. Furthermore, mercury's volatility increases its risk of spread in the environment. Cadmium is predominantly found in wastewater as cadmium ions, which are highly chemically reactive and can react with various substances. Its compounds are highly toxic, particularly harmful to organs such as the kidneys. Chromium commonly exists in trivalent and hexavalent forms. Hexavalent chromium is a strong oxidizing agent and far more toxic than trivalent chromium. It migrates more rapidly in the environment, easily polluting soil and water bodies.

2.3 Hazards of Heavy Metal Waste Liquid

In soil environments, the accumulation of heavy metals profoundly alters the soil's physicochemical properties, leading to a significant decline in soil fertility and inhibiting the activity of soil microorganisms. This poses a serious threat to plant growth and may result in reduced crop yields or even crop failure. When water bodies are polluted by heavy metal wastewater, aquatic ecosystems are damaged. Heavy metals accumulate in aquatic organisms, interfering with their normal physiological functions and causing a significant reduction in biodiversity. These heavy metals eventually enter the human body through the food chain, posing a significant threat to human health. For example, lead can damage the nervous, circulatory, and reproductive systems, adversely affecting children's intellectual development; mercury can cause nervous system disorders and kidney damage; cadmium can cause kidney dysfunction and bone lesions; chromium is highly irritating to the skin and respiratory tract, and long-term exposure may increase the risk of cancer. The hazards of copper ions are equally significant. In the ecological environment, excessive copper ions can disrupt the structure of soil microbial communities, hinder the decomposition of organic matter and nutrient cycling, and further deteriorate soil quality. In water bodies, copper ions are highly toxic to aquatic organisms, affecting the respiration, growth, and reproduction of fish and disrupting the aquatic ecological balance. For human health, excessive intake of copper ions can damage the liver and kidneys, interfere with normal metabolic processes, and may cause symptoms such as nausea, vomiting, and diarrhea. In severe cases, it can even lead to serious diseases such as cirrhosis, posing a great threat to human life, health, and quality of life.

3. Heavy Metal Wastewater Treatment Technology in Chemical Analysis Laboratories

3.1 Chemical Precipitation Method

Chemical precipitation is a common technique for treating heavy metal wastewater. Its principle involves adding a suitable precipitant to the wastewater, causing heavy metal ions to react chemically with the precipitant to form a sparingly soluble metal precipitate. The heavy metals are then removed from the wastewater through precipitation and filtration. In hydroxide precipitation, sodium hydroxide and calcium hydroxide are commonly used as precipitants. Taking the treatment of copper-containing wastewater as an example, adding sodium hydroxide causes copper ions to react with hydroxide ions to form copper hydroxide precipitate. The reaction equation is:

$$Cu^{2+} + 2OH^- \rightarrow Cu(OH)_2$$

This method is relatively simple to operate, but the pH value of the reaction system must be strictly controlled. The optimal pH value for the formation of hydroxide precipitates varies for different heavy metals. For example, iron ions begin to precipitate at a pH of 2.7-3.7, while copper ions precipitate better at around a pH of 4.7. Improper pH control may lead to incomplete precipitation or redissolution of the metal ions.

Sulfide precipitation is also widely used. Commonly used sulfide precipitants include sodium sulfide and hydrogen sulfide. Since most heavy metal sulfides have lower solubility than their hydroxides, sulfide precipitation is often more effective at removing heavy metals. For example, adding sodium sulfide causes mercury ions to react with sulfur ions to form mercury sulfide precipitate when treating mercury-containing wastewater. The reaction equation is:

$$Hg^{2+} + S^{2-} \rightarrow HgS\downarrow$$

The advantage of sulfide precipitation is that it can effectively treat low-concentration heavy metal waste liquid, but it may introduce secondary pollution, and the generated sulfide precipitate may release toxic hydrogen sulfide gas under acidic conditions, so subsequent treatment requires extra care.

3.2 Ion Exchange Method

Ion exchange is based on the exchange reaction between ion exchange resin and heavy metal ions to remove heavy metals. Ion exchange resin is a type of polymer material with ion exchange function. According to the different active groups, it can be divided into strong acid, weak acid, strong base and weak base ion exchange resins [2].

Strongly acidic cation exchange resins contain sulfonic acid groups ($-SO_3H$) , which can react with heavy metal cations in wastewater, such as Cu^{2+} and Pb^{2+} . Taking the removal of copper ions as an example, the reaction formula is:

$$2R-SO_3\,H+Cu^{2+} \rightarrow (R-SO_3\,)_2\,Cu+2H^{+}$$

In practical applications, the selection of ion exchange resins should be based on factors such as the type and concentration of heavy metal ions in the waste liquid, as well as the pH of the waste liquid. For example, strongly acidic cation exchange resins are more suitable for strongly acidic waste liquids containing heavy metals, while weakly acidic cation exchange resins can be considered for alkaline waste liquids. The ion exchange process is affected by various factors; the flow rate of the waste liquid should not be too fast, otherwise the contact time between heavy metal ions and the resin will be insufficient, resulting in poor exchange efficiency. Increased temperature generally promotes the exchange reaction, but excessively high temperatures may damage the resin structure. When the resin reaches saturation after adsorbing heavy metal ions, regeneration treatment is required, usually using acid

Alkaline solution is used as a regenerator to restore the resin's exchange capacity.

3.3 Adsorption Method

Common adsorbents include activated carbon, bentonite, and chitosan. Their adsorption processes involve both physical and chemical adsorption. Physical adsorption is based on van der Waals forces, while chemical adsorption occurs due to the chemical reaction between functional groups on the surface of activated carbon and heavy metal ions. For example, oxygen-containing functional groups on the surface of activated carbon can form complexes with heavy metal ions, thus achieving adsorption. Bentonite is a clay mineral with montmorillonite as its main component, possessing a large cation exchange capacity and adsorption performance. Its mechanisms for adsorbing heavy metal ions include ion exchange adsorption and surface complexation adsorption. When treating lead-containing wastewater, the exchangeable cations in bentonite exchange with lead ions, and simultaneously, the negatively charged sites on its surface can adsorb lead ions through electrostatic attraction. Chitosan is a natural polymer containing a large number of active groups such as amino and hydroxyl groups, exhibiting a strong chelating ability for heavy metal ions. Under acidic conditions, the amino group in chitosan molecules becomes protonated, adsorbing heavy metal ions through electrostatic attraction and chelation. Adsorption methods for treating heavy metal waste liquid have advantages such as simple operation and good treatment effect. However, the adsorption capacity of the adsorbent is limited. When the adsorbent reaches adsorption saturation, it needs to be desorbed or replaced. Moreover, the desorption process may generate secondary pollution, which requires further treatment.

3.4 Other Processing Techniques

Membrane separation technology demonstrates unique advantages in treating mixed heavy metal waste liquids. Although copper and zinc typically exist as divalent cations in solution, nanofiltration membranes exhibit varying retention capacities for different heavy metal ions due to the combined effects of pore size and charge selectivity. When treating mixed heavy metal waste liquids containing copper and zinc, nanofiltration membranes may preferentially retain copper ions. This may result from stronger interactions between copper ions and the membrane material or membrane pore sizes that are more favorable for copper ion retention. Factors such as the concentration difference between copper and zinc ions in the waste liquid, the pH of the waste liquid, and membrane operating conditions may also influence the retention order of ions. Therefore, when applying nanofiltration membranes to treat mixed heavy metal waste liquids, process optimization based on specific conditions is necessary to achieve optimal separation and concentration results.

4. Environmental and Economic Analysis of Heavy Metal Waste Liquid Treatment

4.1 Environmental Benefits

By employing appropriate treatment technologies such as chemical precipitation and ion exchange, the concentration of toxic substances in heavy metal waste liquids can be significantly reduced, thereby lowering their environmental pollution risks. From a water protection perspective, treating heavy metal waste liquids prevents heavy metal ions from entering rivers, lakes, and other water bodies, avoiding toxicity to aquatic organisms and safeguarding the health and stability of aquatic ecosystems. After treatment, heavy metal concentrations in water bodies can be reduced below safety standards. For example, lead levels in a water sample may decrease from 5 mg/L before treatment to below 0.01 mg/L afterward. Additionally, reducing heavy metal pollution safeguards the safety of human drinking water sources and lowers the risk of health issues caused by heavy metal intake. Regarding soil protection, proper treatment of heavy metal waste liquids prevents soil contamination by heavy metals, preserving soil fertility and ecological balance. Accumulation of heavy metals in soil can hinder plant growth, affecting crop yield and quality, and may even enter the human body through the food chain, posing a threat to human health.

4.2 Economic Analysis

The economic analysis of heavy metal waste liquid treatment requires consideration of multiple factors, including the cost of treatment technologies, long-term operational expenses, potential environmental penalties, and the resource recovery value of treated materials. First, significant cost variations exist among different treatment technologies. For instance, chemical precipitation typically involves lower costs, with equipment investment ranging from 50,000 to 100,000 yuan, making it suitable for large-scale waste liquid treatment. Conversely, ion exchange may require higher initial investment, with equipment costs approximately 150,000 to 250,000 yuan, but offers relatively simpler operation and maintenance, and demonstrates superior treatment efficacy for low-concentration heavy metal waste liquids. When selecting a treatment technology, comprehensive consideration must be given to the nature of the waste liquid, treatment scale, and economic affordability [3]. Second, long-term operational expenses are also a significant factor. Maintenance of treatment equipment, energy consumption, and replacement of consumables all contribute to increased operating costs. Taking chemical precipitation as an example, annual operating costs are approximately 20,000–30,000 yuan, while ion exchange incurs annual costs of about 30,000–50,000 yuan. When selecting a treatment technology, it is crucial to evaluate its long-term operational stability and economic viability to ensure the treatment process can be sustained effectively.

5. Construction of a Heavy Metal Wastewater Treatment Management System for Chemical Analysis Laboratories

5.1 Waste Liquid Classification, Collection, and Storage Management

In chemical analysis laboratories, the treatment of heavy metal waste liquids must begin at the source through strict classification, collection, and storage management. Laboratories generate a wide variety of waste liquids, among which heavy metal waste liquids warrant special attention due to their potential environmental risks and resource recovery value. Such waste liquids typically contain heavy metal elements such as iron, cobalt, copper, manganese, lead, silver, and zinc. To effectively manage these waste liquids, laboratories should establish a clear classification system, ensuring strict separation between heavy metal-containing waste liquids and other types of waste liquids, such as waste acids, waste alkalis, and organic waste liquids. Laboratories should use specialized containers that meet safety standards for storing heavy metal waste liquids. These containers must be corrosion-resistant, well-sealed, and made of materials and linings compatible with the waste liquid to prevent chemical reactions. Additionally, containers should be clearly labeled with the waste liquid type, collection date, and storage requirements to facilitate subsequent tracking and processing.

5.2 Personnel Training and Responsibility Implementation

Laboratories should regularly train relevant personnel on the knowledge and skills required for heavy metal waste liquid disposal, including classification, collection, storage, transportation, and treatment.

Through training, environmental awareness and operational proficiency should be enhanced to ensure strict compliance with regulations during heavy metal waste liquid handling. Laboratories must clearly define the responsibilities and obligations of personnel at all levels in heavy metal waste liquid disposal. From laboratory supervisors to operational staff, each individual should understand their scope of duties and work requirements. Laboratories should establish robust accountability mechanisms. Violations of regulations must be promptly corrected and penalized to ensure effective implementation of all management measures[4].

5.3 Improvement of Supervision and Management System

Laboratories should establish a comprehensive monitoring system to regularly inspect and evaluate the treatment of heavy metal waste liquids, ensuring all treatment measures are effectively implemented. Concurrently, laboratories must implement strict management protocols that clearly define waste liquid treatment procedures and requirements, standardizing the conduct of operating personnel. To further enhance management standards, laboratories can draw upon advanced waste liquid treatment technologies and management practices from both domestic and international sources, continuously refining and innovating their management systems based on their specific circumstances. Furthermore, laboratories should strengthen communication and collaboration with environmental protection authorities to stay informed about the latest environmental policies and requirements, ensuring that heavy metal waste liquid treatment complies with national laws, regulations, and environmental standards.

6. Conclusion

In summary, the effective treatment of heavy metal waste liquids from chemical analysis laboratories holds significant importance for environmental protection and human health. By adopting appropriate treatment technologies and management measures, the environmental pollution risks posed by heavy metal waste liquids can be substantially reduced. In the future, with continuous technological advancements and increasingly stringent environmental requirements, laboratory heavy metal waste liquid treatment technologies and management systems will undergo ongoing refinement and innovation, making greater contributions to achieving sustainable development and advancing ecological civilization.

References

[1] Zhao, W., & Ma, L. (2022). Exploration and practical research on project-based experimental teaching guided by core literacy: A case study of automated treatment of waste liquid in middle school chemistry laboratories. *China Modern Educational Equipment*, (06), 4–8. https://doi.org/10.13492/j.cnki.cmee.2022.06.002

[2] Deng, W., Fang, Z., Chen, C., & Tan, L. (2022). Greening of chemical analysis experiments and treatment of waste liquid. *University Chemistry*, 37(06), 108–111.

[3] Zhao, J., Shi, Q., & Wu, J. (2022). Homemade devices for pretreatment of waste liquid in university chemistry laboratories. *Chemical Industry Times*, 36(5), 61–62.

[4] Cao, J., Sun, S., & Li, S. (2022). Research and practice on the classification, recycling, and treatment of chemical laboratory waste liquid. *China Standardization*, (19), 187–190.