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Method Analysis For The Purification of Heavy Metal Ions From Water

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Abstract
This study investigates a review of the analysis of methods for removing metal ions from water to make the water fulfill drinking standards. The paper assesses physical and chemical separation methods and includes an overview, advantages, and limitations. The comparative analysis concludes that a combination of sedimentation and chemical precipitation can provide the best result due to its effectiveness and applicability for public use.

Keywords: Metal ions, water purification, physical and chemical separation, sedimentation, chemical precipitation

I. Introduction and Background Information

Water purification and its study has been pressing in today's society. As highlighted in the UN's Sustainable Development Goal No. 6, "Clean Water and Sanitation," removing harmful agents from water sources remains one of the world's most vital issues. As the research for water purification has advanced, most research has focused on a more popular harmful agent in water: bacteria; however, it overlooks another – metal. Metal ions are commonly found in household water, with the most common ones being arsenic, cadmium, nickel, mercury, chromium, and zinc. The safe limits for these metals are 10 µg/L, 3 µg/L, 70 µg/L, 6µg/L, 50 µg/L, and 5000 µg/L respectively (World Health Organization, 2017). The existence of such metals in water is typically a result of industrial-generated waste that is discharged into the environment, which, thus, goes into the water people use for household activities, causing further harm. When consumed, these metal ions can cause repercussions and are a detriment to one's health. It can cause life-threatening diseases, such as "damage to the central nervous system, hearing speech and visual disorders, hypertension, anemia, dementia, hematemesis, bladder, lung, nose, larynx, prostate cancer, and bone diseases" (Bansal). As noted previously, studying metal ions in water is vital, specifically the component of removing the metal ions from the waters people drink and use in their day-to-day activities. With this, a new question arises: what is the best method for removing this harmful agent? Several methods, each with its own advantages and disadvantages, have been previously researched; these methods can be separated into physical and chemical separation. Because determining the importance of one method's effectiveness over another can be subjective, this paper will also assess its applicability in its use to the public.

II. Physical Treatment

2.1 Ultrafiltration

2.1.1 Overview and Applications

Ultrafiltration is a method that uses a membrane to filter out contaminants based on their size and charge. The membrane has tiny pores, which allow the water molecules to pass through while retaining larger contaminants. The size and charge of the contaminants determine their ability to pass through the membrane. For example, negatively charged ions such as heavy metal ions are typically retained by the membrane, while neutral molecules such as organic contaminants can pass through more easily. Subsequently, the filter system needed for this method has a role in creating a large surface area for the particles to adhere to, which blocks and separates the heavy metal ions from water. The filter media can be made of various materials, including granular activated carbon, which is particularly effective at removing heavy metal ions due to its high surface area and chemical affinity for these ions. Granular activated carbon is a type of carbon that has been treated with oxygen to increase its surface area and porosity. Its high surface area allows activated carbon to adsorb contaminants, including heavy metal ions– thus, making it easier for the heavy metal ions to separate and be collected. Furthermore, according to research, filtration can be further enhanced by using a pre-treatment process, such as coagulation, which involves adding chemicals to the water to cause the heavy metal ions to form larger particles that are more easily captured by the filter media (Yu, et al. 2014).

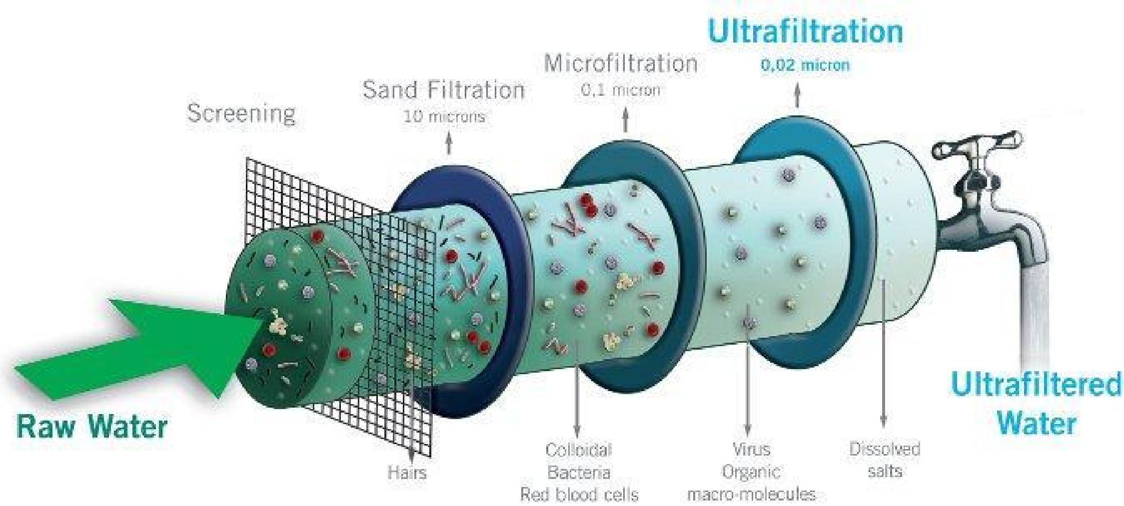

Figure 1: *Process of Ultrafiltration*

2.1.2 Limitations

However, there are some limitations to the use of ultrafiltration for removing heavy metal ions from drinking water. The efficiency of this method depends on the size and shape of the ions, as well as the size and type of the filter media. Some heavy metal ions, such as mercury and arsenic (common metals found in water), may be too small to effectively remove by filtration. Ultrafiltration and the use of the filter media, granulated activated carbon, is most effective for larger heavy metal ions Another limitation is the cost of the equipment and maintenance. It takes somewhere around 50-70 thousand US dollars to operate such machinery, and this cost would be at its most basic level (Drouiche, et al. 2001) (Yoo, 2018). Ultrafiltration systems can be expensive to purchase and operate, and the membranes must be replaced regularly to maintain their effectiveness. Similarly, the Granulated Activated Complex also requires periodical oversight as it can easily become saturated with contaminants. When saturated, it needs to be replaced or regenerated; however, the regeneration process involves using chemicals to release the contaminants of the GAC. If not done correctly, doing so can contaminate the water again, as there is a possibility that the regeneration process releases heavy metal ions back into the water. In summary, while ultrafiltration is an efficient process, it can be challenging to maintain.

2.2 Sedimentation

2.2.1 Overview and Applications

Sedimentation is another physical method that can be used to separate heavy metal ions from drinking water. This method allows the water to stand for some time, allowing heavier particles, including heavy metal ions, to settle to the bottom of the container. The clear water can then be separated from the sediment, leaving the heavy metal ions behind. To purify drinking water using sedimentation, the water is first treated with the adsorbent material. The mixture is then allowed to settle, with the heavy metal ions being adsorbed onto the surface of the adsorbent. The purified water can then be collected, while the adsorbent material can be removed and disposed of or reused.

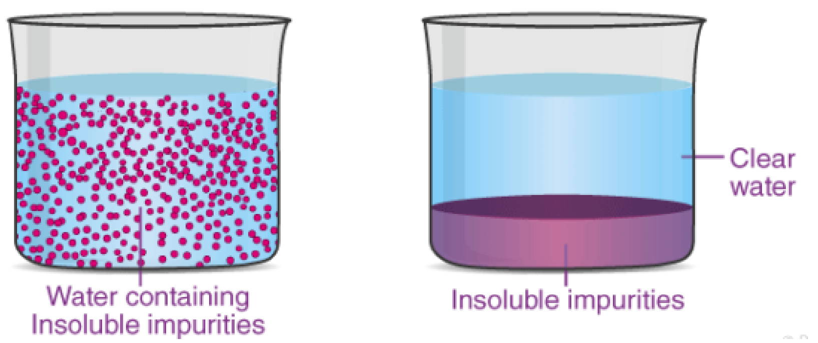

Figure 2: *Process of Sedimentation*

To enhance its effectiveness, like ultrafiltration, sedimentation can be enhanced by using a coagulant, as mentioned above, to cause the heavy metal ions to form larger particles that will settle more quickly (Abouzied et al., 2022). Although research on the combination of sedimentation with chemical coagulant has been done on algal removal from water (Abouzied et al., 2022), further research on sedimentation is needed to support that adding a chemical coagulant would advance the purification of metal ions from water.

2.2.2 Advantages

An advantage of using this method would be its simplicity, as no specialized lab equipment or skills are needed to perform this method. Similarly, this method is cost-effective and can be scaled up to treat large volumes of water. Furthermore, it does not produce any harmful by-products or requires the use of chemicals, making it environmentally friendly.

2.2.3 Limitations

There are also some limitations to using sedimentation for purifying heavy metal ions from drinking water. It can be slow, requiring several hours or even days for the sedimentation process to be completed. In addition, it is ineffective at removing all types of heavy metal ions and may not be suitable for some water sources. Because this method relies on the metal ions and water to separate itself, all metal ions, especially the smaller ones, might not be collected. This presents a limitation since smaller metal ions, such as cadmium and copper, which are common in water, might not be effectively separated and could remain in the water's residue.

III. Chemical Treatment

3.1 UV Light treatment

3.1.1 Overview and Applications

Ultraviolet light's connection to water disinfection is not a foreign field; for instance, a highly researched area would be ultraviolet light's effect on water-borne bacteria. A detailed study by Henry Ricks highlights the success of using UV light to kill bacteria such as E-Coli as well as other bacteria with similar properties in water. Several commercially sold products have been created using this research, and thus far, ultraviolet treatment continues to be a leading solution in water purification from bacteria. The multitude of research regarding this methodology can be applied to research on metal ions in water using similar methodologies. Although not ideal, this study mentions research that showcases the criteria for using accurate ultraviolet light. To name a few would be the duration of ultraviolet exposure, the intensity of ultraviolet light, a controlled temperature, and the importance of warming up the UV light before use. Since this study on bacteria uses the same methodology, research on metal ions in water can be adapted by altering the listed components. Admittedly, there has been limited research on the relationship between ultraviolet treatment and the removal of metal ions. However, although the section on metal ions was brief, the review paper titled "Advances on Water Quality Detection by UV-Vis Spectroscopy" talks about ways to separate individual metals and ways to avoid spectral overlap. According to the research, to avoid overlaps between metals, one would need to determine the concentration of multi-metal ions, as UV irradiation allows the liberation of metals connected to the organic structure, which determines the amount of content of each element. In other words, this method helps with a crucial part of the metal removal process: determining which metals are in the water. As suggested by researcher Guo, using a UV-vis wave band and colorimetry, one could "[select] a suitable color reagent to react with the component to be tested to form a colored substance or to change the color of the solution, and then the generated colored substance is compared with the standard solution, the color of the reaction solution and the standard solution is observed, or the spectrum of its UV-Vis wave band is measured to determine the substance quantitatively." Nevertheless, research conducted so far has yet to prove the effectiveness of ultraviolet treatment in filtering out metals for complete water purification.

3.2 Chemical Precipitation

3.2.1 Overview and Applications

Chemical precipitation can be deemed one of the most researched and viable methods for removing heavy metal ions from water. This method involves the addition of chemicals to the water to encourage forming solid, insoluble precipitates that can easily be removed. A study conducted on chemical precipitation and its effects on removing heavy metals was done on common metals in water: lead, copper, and chromium. In this study, the researchers added a mixture of alum and calcium oxide, as well as sodium hydroxide and sodium carbonate; both mixtures served the role of "chemicals" (Oncel et al., 2013). A similar study supports this research; its mixture of sodium carbonate and magnesium oxide acted similarly to that of Yang and yielded similar results (Mahmood et al., 2011). Both these chemicals that were added to the water proved successful as not only was a solid precipitate formed, but the removal process of this precipitate was easy to accomplish. The precipitate is formed in this method due to the reaction's formation of a complex that reduces the bioavailability of the metal ions.

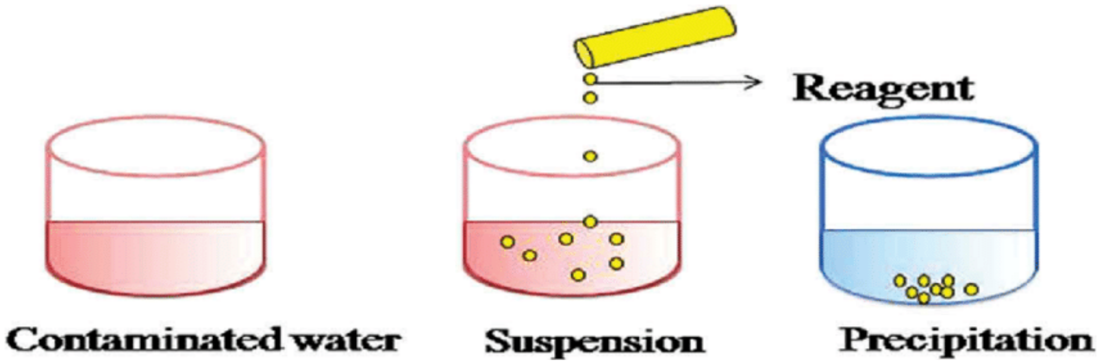

Figure 3: *Process of Chemical Precipitation*

3.2.2 Advantages

In addition to its effectiveness, chemical precipitation has several advantages as a method for removing heavy metal ions from water. Firstly, this method is inexpensive (which is one of the main reasons for extensive research on this method). The materials needed for this chemical precipitation are widely accessible, and no specific lab condition is needed to conduct this reaction. This also makes the method a viable option for treating water in both developed and developing countries. Second, this method is relatively simple to accomplish. Basic instructions are sufficient to conduct this experiment, as no expert supervision is needed. Third, it is a versatile method that can be applied to a wide range of water sources, including both surface water and groundwater; this versatility is vital as drinking water can come from a variety of sources. Lastly, this method produces minimal waste, as the solid precipitates that are formed can be easily disposed of.

3.2.3 Limitations

Despite its advantages, chemical precipitation has its limitations. The main limitation would be that the effectiveness of this method can be limited by the presence of other ions in the water, which can interfere with forming a solid precipitate. Calculations determining the type of mixture needed to form the solid precipitate rely on the existing metal in the water. Other ions that are unaccounted for would disrupt this process. Furthermore, the formed precipitate might not capture all the metals, potentially leaving traces of heavy metal ions in the water.

3.3 Ion Exchange System

3.3.1 Overview and Applications

An ion exchange system is a method that involves passing the contaminated water through a bed of ion exchange resin to remove the heavy metal ions. A study by Hubicki et al. (2012) investigated the use of an ion exchange resin specifically designed to remove heavy metal ions, such as copper and zinc, from contaminated water. To conduct the study, the author first prepared the ion exchange resin by soaking it in a solution of hydrochloric acid and sodium chloride. This process, known as “conditioning", removed the impurities from the resin and made it more usable for the ion exchange process. The resin was then placed in a column, and the researcher passed the contaminated water through it. As the water flowed, the heavy metal ions were attracted to the resin and bound to it, while the non-metal ions in the water passed through the column unchanged. The purified water can be collected at the bottom of the column, while the heavy metal ions would be collected at the top.

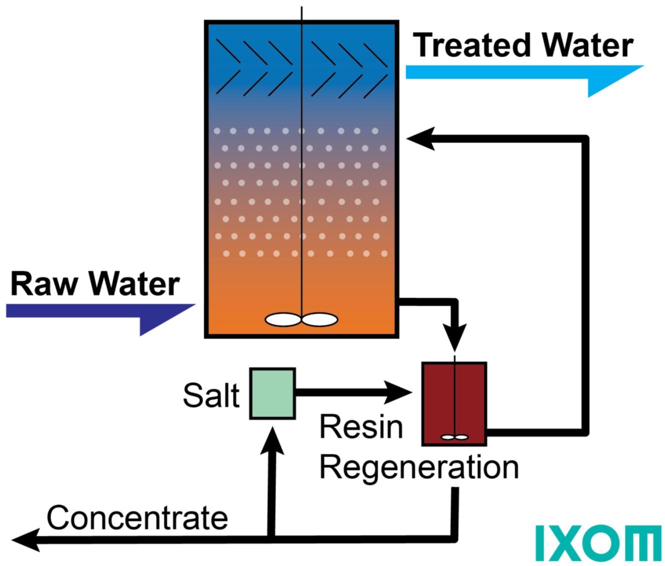

Figure 4: *Process of Ion Exchange System*

In the same research, the effectiveness of this method was also tested under different conditions, such as different flow rates and resin bed depths. The results showed that increasing the flow rate and resin bed depth improved the effectiveness of the resin in capturing metal ions. The researchers also found that these columns could be easily regenerated by soaking them in a solution of sodium hydroxide, allowing for multiple uses. Ultimately, the purified water collected at the bottom of the column effectively removed the metal ions and made the then-contaminated water able to meet the standards for drinking water.

3.3.2 Advantages

An advantage of using the ion exchange process is that this method offers high efficiency with relatively low processing requirements (Sole, 2017). The ion exchange systems are able to remove a wide range of contaminants due to its versatility and long life span. Its versatility is valuable as it can work in different settings including large treatment plans or smaller decentralized systems. In other words, this method can be easily integrated into existing water treatment systems.

3.3.3 Limitations

There are also some limitations to ion exchange for purifying heavy metal ions from drinking water. It requires using chemicals to regenerate the resin, which can produce harmful environmental impacts. Additionally, the resin has a limited lifespan, requiring periodic replacement (Wang et al., 2016).

3.4 Ligand-Attached Chelate Surfactant

3.4.1 Overview and Applications

Chelate surfactants are compounds that consist of both a surfactant and a chelating agent. A chelating agent, a compound consisting of ligands (molecules that can bind to metal ions through coordination bonds), when added to water, can separate into its constituents– properties that can form a complex with the metal ions in the water, helping separate the metal ions from the water molecules. A surfactant such as C14-ED3A3Na (Peng et al., 2020), on the other hand, can help to solubilize the metal ions.

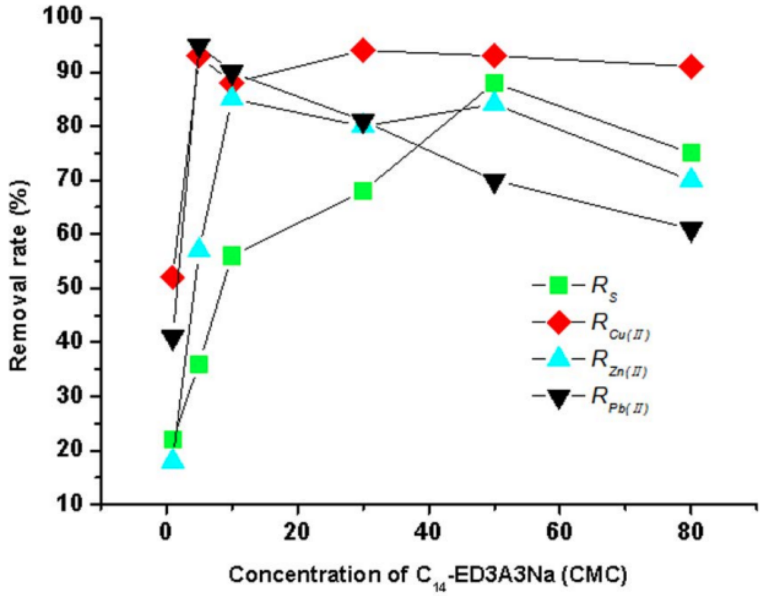

Figure 5: *Effectiveness of C14-ED3A3Na (surfactant) on metal removal rate*

Thus, both the chelates and surfactants contribute to making the ions easier to remove. A chelating surfactant can be used to increase the effectiveness of ligands further. By attaching ligands to the chelating agent, the affinity of the chelate surfactant for specific metal ions can be enhanced, leading to more efficient removal of the targeted ions from the water.

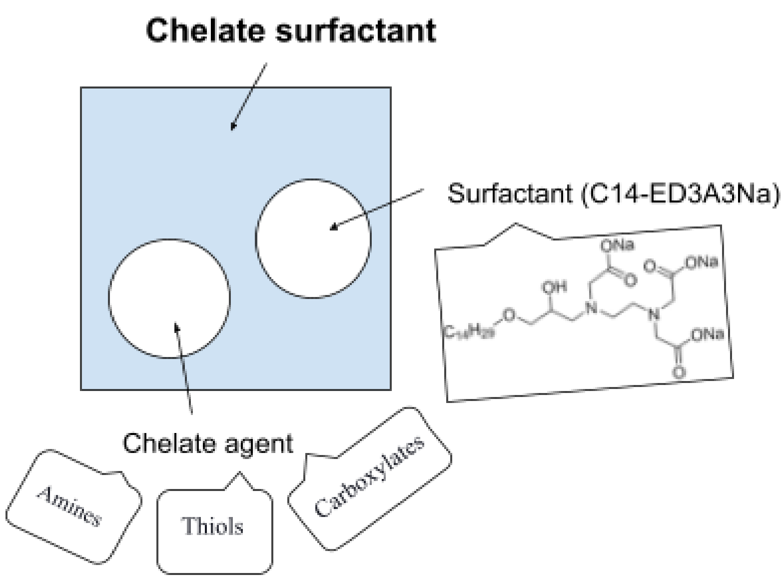

Figure 6: *Process of Creating Chelate Surfactant*

Several types of ligands can be attached to chelate surfactants, including amines, thiols, and carboxylates. Each type of ligand has its specific properties and binding strength depending on the different metal ions, as different metal ions have different individual properties. Therefore, the choice of which ligand to use depends on the specific metal ions that need to be removed. In addition to their ability to remove heavy metal ions from drinking water, chelate surfactants have several other advantages.

3.4.2 Advantages and Limitations

Ligand-attached chelate surfactants are effective at low concentrations and exhibit high removal efficiency., even at low pH values. They also have low toxicity to humans and the environment, making them a safe and effective option for purifying drinking water.

3.4.3 Limitations

However, there are some limitations to using chelate surfactants for purifying drinking water. One potential challenge is the formation of stable metal-ligand complexes that may not be easily removed from the water. Although this method separates the metals from the water, the removal process itself could be difficult to achieve and would require another method. Additionally, ligand-attached chelate surfactants might perform better in removing specific metal ions over others. For example, this method may not effectively remove certain types of heavy metal ions, such as arsenic and selenium, but work more effectively on others, such as cadmium and copper (Wang et al., 2016). This limitation presents a drawback to this method because an ideal method should effectively work on common metals, yet this method does not fulfill this requirement.

IV. Analysis and Discussion

Further research should be conducted, but in this researcher's opinion, sedimentation and chemical precipitation are the most beneficial among all the methods. Both these methods are simple to do and cost-effective. Sedimentation requires no materials, while the method of chemical precipitation only needs non-harmful chemicals– readily available and safe materials for household use. Limitations that sedimentation poses, chemical precipitation fulfills, and vice versa: sedimentation is effective at collecting heavier metal ions and not so much on smaller metal ions, while, on the other hand, chemical precipitation is effective at collecting smaller metal ions but not effective at collecting heavier metal ions. Therefore, combining these methodologies and considering their respective advantages and limitations can prove effective in purifying household drinking water from metal ions.

V. Limitations of Paper and Conclusions

This research paper, while offering a thorough analysis of methods for removing heavy metal ions from water, has certain limitations that should be acknowledged to ensure a clear understanding of the study's scope and potential implications. A notable limitation pertains to the absence of quantitative analysis within this paper. The focus of this paper was primarily directed towards qualitative aspects of the examined removal techniques. As a result, the quantitative analysis is beyond the scope of this research. Nonetheless, it is crucial to recognize the essentiality of quantitative analysis in comprehensively assessing the effectiveness and efficiency of removal methods. Future research endeavors should thus incorporate quantitative analysis to facilitate precise measurements and enable a comprehensive evaluation of the techniques for the elimination of heavy metal ions from water.

The listed methods above all serve their respective advantages and limitations. While some methods excel in certain aspects, they may fall short in others. As mentioned previously, naming one advantage more beneficial than another is subjective to what a researcher prioritizes. In the case of the purification of metal in drinking water, because the aim is more so on the public, an important aspect of the chosen method would be its affordability and cost-effectiveness and applicability to different types of metals regardless of their sizes and properties. Through thorough comparative analysis, this paper concludes that sedimentation and chemical precipitation are the best methods to do so.

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