



**HAL**  
open science

# Comparing Conventional and Advanced Approaches for Heavy Metal Removal in Wastewater Treatment: An In-Depth Review Emphasizing Filter-Based Strategies

Jana Ayach, Wassim El Malti, Luminita Duma, Jacques Lalevée, Mohamad Al Ajami, Hussein Hamad, Akram Hijazi

## ► To cite this version:

Jana Ayach, Wassim El Malti, Luminita Duma, Jacques Lalevée, Mohamad Al Ajami, et al.. Comparing Conventional and Advanced Approaches for Heavy Metal Removal in Wastewater Treatment: An In-Depth Review Emphasizing Filter-Based Strategies. *Polymers*, 2024, 16 (14), pp.1959-10.3390/polym16141959 . hal-04753607

**HAL Id: hal-04753607**

**<https://hal.science/hal-04753607v1>**

Submitted on 12 Nov 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# Comparing Conventional and Advanced Approaches for Heavy Metal Removal in Wastewater Treatment: An In-Depth Review, Emphasizing Filter-Based Strategies

Jana Ayach <sup>1,2</sup>, Wassim El Malti <sup>3,\*</sup>, Luminita Duma <sup>2</sup>, Jacques Lalevee <sup>4\*</sup>, Mohamad Al Ajami <sup>1</sup>, Hussein Hamad <sup>1</sup> and Akram Hijazi <sup>1</sup>

<sup>1</sup>Research Platform for Environmental Science (PRASE), Doctoral School of Science and Technology, Lebanese University, Beyrouth, Lebanon; akram.hijazi@ul.edu.lb; hussein.hamad@ul.edu.lb; jana.ayach.1@st.ul.edu.lb; mohamad.r.alajami@hotmail.com

<sup>2</sup>University of Reims Champagne-Ardenne, CNRS, ICMR UMR 7312, Reims, France; luminita.duma@univ-reims.fr

<sup>3</sup>College of Health Sciences, American University of the Middle East, Kuwait; wassim.elmalti@aum.edu.kw

<sup>4</sup>CNRS, IS2M UMR 7361, University of Haute-Alsace, Mulhouse, France; Jacques.lalevee@uha.fr

**Abstract:** Various industrial activities release heavy metal ions into the environment, which represent one of the major toxic pollutants owing to their severe effects on the environment, humans, and all living species. Despite several technological advances and breakthroughs, wastewater treatment remains a critical global issue. Traditional techniques are dedicated to extracting heavy metal ions from diverse wastewater origins, encompassing coagulation/flocculation, precipitation, flotation, and ion exchange. Their cost, side toxicity, or ineffectiveness often limit their large-scale use. Due to their adaptable design, simple operation, and reasonable cost, membrane filtration and adsorption have proven their efficiency in removing metals from wastewater. Recently, adsorption-based filters have appeared promising in treating water. Within this range, filters incorporating natural or hybrid adsorbents present an appealing alternative to conventional approaches. This review aims to list and describe the conventional and advanced wastewater treatment methods by comparing their efficiency, cost, and environmental impact. Adsorption-based filters were highlighted due to the significant advantages they can provide.

**Keywords.** Clean Water; Filters; Heavy Metals; SDG6; Wastewater

## 1. Introduction

Over time, environmental pollution has witnessed a persistent rise, impacting both human existence and the broader ecosystem. Water pollution is growing mainly due to wastewater from various industries dealing with paper and pulp, textiles, chemicals, etc [1]. As of July 2022, a report jointly published by the World Health Organization and the United Nations International Children's Emergency Fund (UNICEF) revealed that approximately 2.2 billion individuals remain without access to clean and safe drinking water [2]. Additionally, around 653 million people lack hand-washing facilities in their homes. The makeup of pollutants found in water effluents is contingent upon the industries in the vicinity responsible for generating the wastewater [3]. These effluents often contain harmful substances such as pesticides, dyes, aromatic hydrocarbons, oils, heavy metals, and more, which, when released into the environment, pose detrimental consequences for both humans and wildlife [4–6]. In addition, the continuous industrialization in developing countries significantly increased water demand [7]. Among several alternatives to preserve water resources, developing efficient and sustainable wastewater treatment technologies can provide a convenient way to reuse it [1].

Efficient wastewater treatment, encompassing the removal of heavy metals and their responsible utilization, plays a vital role in attaining the United Nations Sustainable Development Goal 6 (SDG6) of universal access to drinking water, sanitation, and hygiene by 2030 [8]. Wastewater treatment practices vary from one nation to another, exhibiting significant distinctions, particularly between developed and developing countries. While advanced countries mainly use centralized treatment, many developing countries use decentralized or no wastewater treatment. Although centralized treatment has some advantages, it may not be sustainable in the long term because of its high environmental impact related to resource consumption. In contrast, built-up treatment plants can be a sustainable solution for all countries, regardless of their development level. Most importantly, constructed washes may be a sustainable wastewater treatment for developed and emerging countries [9].

The pollutants generated in the water effluents are usually classified as organic and inorganic contaminants, depending on the types of molecules and their toxicity levels. Heavy metals are highly toxic inorganic pollutants, non-biodegradable, and their accumulation in wastewater yields a weighty environmental burden [10]. These heavy metals come from multiple industrial activities such as tannery and battery manufacturers, electroplating, mining, pesticides, and paint industries [11]. Hence, they stand out as the most enduring contaminants within wastewater, and their elevated toxicity can potentially impact critical bodily functions, including blood composition, brain activity, respiratory system, kidneys, liver, and other vital organs [12]. As a result, extended exposure may lead to the gradual onset of physical, muscular, and neurological degenerative conditions that exhibit similarities to diseases such as Alzheimer's, Parkinson's, muscular dystrophy, and multiple sclerosis [9,10]. As a result, heavy metals significantly harm human health, aquatic ecosystems, and the surrounding environment. Thus, it is becoming crucial to simultaneously reduce these numerous pollution sources, develop effective techniques for eliminating such dangerous pollutants from wastewater, and recycle them for other uses.

Several conventional methods, including coagulation, osmosis, ion exchange, and precipitation, are employed to decrease the elevated concentration of various metal ions in wastewater to meet the required regulatory levels [13]. However, many factors often limit these methods, such as cost and toxic environmental side effects [14]. Other relatively advanced techniques, such as adsorption and membrane filtration, have become excellent alternative treatments with improved removal effectiveness and reduced costs and environmental impact [15]. Indeed, the effective removal of heavy metal ions from wastewater necessitates the consideration of several critical factors, including their concentration, specific metal types, pH levels, chemical additives, removal efficiency, environmental consequences, and cost implications. In industrial settings, adsorption is widely acknowledged as one of the most efficient methods for wastewater treatment, effectively reducing the presence of harmful inorganic and organic pollutants in the treated wastewater released as effluents [16]. Heavy metal ions' adsorption results from physicochemical interactions, primarily involving ion exchange or the formation of complexes between the metal ions and the functional groups found on the surface of the adsorbent. Furthermore, cost-effective adsorbents derived from natural biomass materials, industrial solid waste, agricultural byproducts, and biosorbents as source materials emerge as promising alternatives [16,17]. They exhibit enhanced adsorption capabilities after subjecting raw biomass adsorbents to various physical or chemical treatments [18-20]. Nevertheless, natural, synthetic, and hybrid filters (a mix of natural and synthetic) show high adsorption capacity as they efficiently adsorb heavy metals and dye pollutants in aqueous solutions.

In this review, we have compiled and compared examples of the most common conventional and relatively advanced wastewater treatment methods used to remove heavy metals. We have described the most relevant features of the removal methods and discussed their performance with respect to the cost, environmental impact, and removal efficiency. In addition, we have focused on advanced techniques, especially membrane

filtration and adsorption, and highlighted the advantages of the different filter types and applications.

## 2. Heavy metals: sources and toxicity

Heavy metals in surface water systems can have natural origins or result from human activities. Geological or natural sources encompass volcanic eruptions, the weathering of rocks containing metals, sea salt spray, wildfires, and natural weathering processes that can initiate the release of metals into different environments. Heavy metals can take various forms, including hydroxides, oxides, sulfides, sulfates, phosphates, silicates, and organic compounds [21,22]. Furthermore, various industrial manufacturing processes discharge heavy metals, including Cr, Cd, Ni, Cu, Zn, As, and Pb, at varying toxicity levels. These metals exhibit high water solubility and can be absorbed by aquatic organisms, leading to their accumulation in the human body via the food chain. Exceeding the required concentrations of heavy metals when ingested can result in various health disorders [23]. Heavy metal contamination poses environmental risks due to its carcinogenic, teratogenic, and endocrine-disrupting effects, which can significantly impact children's behavior [24].

Table 1 summarizes the major sources and effects of common heavy metals, excluding cadmium, copper, and lead. These latter particular metals are discussed in detail in the following due to their prevalence in water contamination and the significant attention they have received over the decades.

Cadmium (Cd), a profoundly toxic metal, is primarily produced as a byproduct of zinc manufacturing. It becomes stored in plants and subsequently ingested by microorganisms and humans. Exceeding the threshold level ( $7\mu\text{g/L}$ ) of cadmium can lead to harmful effects. The metal shows a high transfer rate from soil to plants, resulting in elevated cadmium levels in fruits and vegetables. As a non-essential toxic metal, it significantly disrupts cellular enzymatic systems, leading to oxidative stress and nutrient deficiencies in plants. Additionally, cadmium is associated with hepatotoxicity, causing liver disease, by binding to cysteine-rich proteins like metallothionein. Furthermore, cadmium has an affinity for binding with ligands like glutamate, histamine, and aspartate, potentially causing iron deficiency [25].

Copper (Cu) exists in the environment due to natural and human activities. Anthropogenic sources of copper include mining, metal and electric production, fungicide use, leather processing, and vehicle brake pads. Also, natural copper contamination sources can arise from forest fires, volcanic eruptions, and windblown dust [26]. Copper is involved in many enzymatic systems in the organism but becomes toxic at high intake levels, exceeding  $2000\mu\text{g/L}$  [27]. Copper is crucial for nutrition and plays a vital role in brain function, but its presence is also associated with the development of Alzheimer's disease. Even small concentrations of copper in drinking water can notably impact individuals' learning and memory [28]. Moreover, prolonged exposure to copper primarily affects the liver, the first site where copper accumulates upon entering the bloodstream. Copper toxicity typically manifests as the development of cirrhosis, accompanied by episodes of hemolysis and damage to renal tubules, as well as affecting the brain and other organs. Prolonged and excessive exposure to copper can lead to hepatic necrosis, vascular collapse, coma, and ultimately, fatality [29].

Lead (Pb) primarily enters the environment through various sources such as lead paint, house dust, food, air, soil, pottery, solder, porcelain, and tin. It accumulates in the body and can lead to disruptions in the number of red blood cells and kidney and brain diseases. It poses a significant hazard to young children and pregnant women, affecting physical development and normal mental growth in adults. Drinking water contaminated with lead (threshold of Pb:  $25\mu\text{g/L}$ ) harms human health, especially for children consuming fruit juice and foods prepared with water containing lead [30-32].

**Table 1.** Common heavy metal ions in wastewater: sources and effects.

151

Heavy metal	Major source(s)	Common effects	Reference
Arsenic (As)	Insecticides and pesticides, treated wooden pulps, and smelting metals.	Cancer, skin color changes, Blackfoot disease, diabetes, and others.	[31,32]
Zinc (Zn)	Plating, galvanizing, other metal finishing processes, paper and pulp industries, battery industry.	Kidney failure, lung fibrosis and cancer, anemia, vomiting, and others.	[33]
Chromium (Cr)	Electroplating, leather tanning, and textile industries.	Dermatitis, kidney and gastric damage, lung cancer, respiratory tract and eyes irritation, and others.	[34,35]
Mercury (Hg)	Oil refinery processes, pesticides, and burning coal for power generation	Brain, central nervous system, heart, alimentary tract, kidney, and liver significant damages.	[36]
Nickel (Ni)	Electroplating, printing and dyeing, and pharmaceutical and metallurgical industries	Skin irritation, asthma, conjunctivitis, and cancer	[37,38]
Bismuth (Bi)	Chemical and pharmaceutical industries	Hypotension, insanity, and renal failure	[39]

### 3. Elimination of heavy metals from wastewater: conventional methods

152

A variety of traditional methods are employed for the extraction of heavy metals from wastewater. These techniques include coagulation and flocculation, chemical precipitation, ion exchange, flotation, electrochemical separation, and evaporation [40]. In the following, we describe the most common and significant conventional practices for wastewater treatment, along with their advantages and disadvantages.

153

154

155

156

157

#### 3.1. Coagulation and flocculation

158

Coagulation refers to destabilizing colloids by neutralizing their repulsive forces, while flocculation involves aggregating unstable particles [41]. Traditional coagulants such as aluminum, ferrous sulfate, and ferric chloride are employed to counteract ionic charges. On the other hand, flocculation entails the amalgamation of particles to form larger coagulates. These larger coagulates can be generated using materials like polyaluminum chloride, polyferric sulfate, polyacrylamide, and various polymer flocculants [42]. The coagulation-flocculation process demonstrated both effective performance and straightforwardness in removing heavy metals from wastewater [43]. According to previous works, polyethylene-glycol is one of the most practical flocculants [44]. This approach can efficiently eliminate a range of heavy metals, including Cu, Pb, Ni, As, Se, Cr, Sb, and Ag [45]. The removal efficiency for the mentioned heavy metal ions varied between 95%

159

160

161

162

163

164

165

166

167

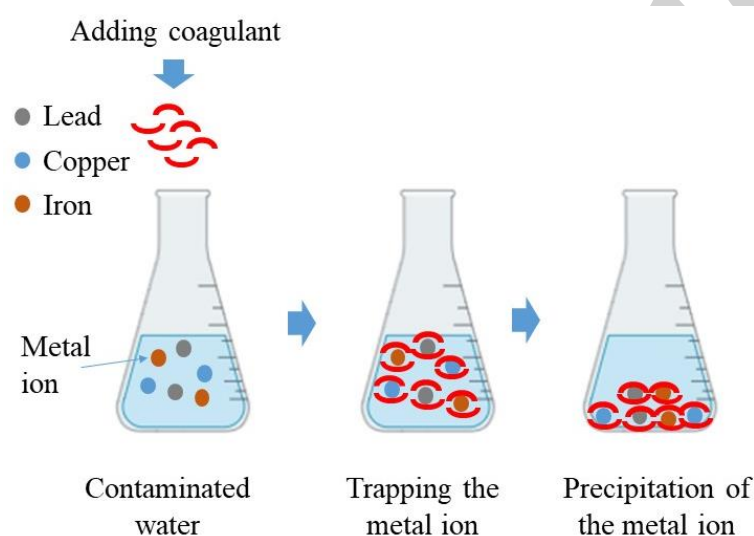
168

169

and 99%. However, there are several drawbacks associated with the application of flocculation that can be pinpointed. These include the health hazards posed by inorganic coagulants, the generation of significant amounts of sludge, limited selectivity for specific metals and inefficiency in addressing emerging pollutants, the potential for increased sewage colors, lower effectiveness when employing natural coagulants, and challenges in scaling up the process [46].

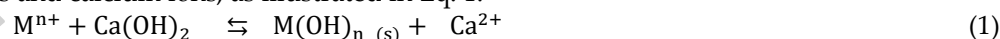
### 3.2. Precipitation

The chemical precipitation method, also known as coagulation precipitation, is extensively utilized in various industries and is regarded as one of the most efficient and well-established techniques. This method involves transforming dissolved metal ions into solid particles, facilitating precipitation (Fig. 1). The coagulant precipitates metal ions in many ways, such as changing pH, electro-oxidation potential, or co-precipitation, followed by removing deposits.



**Figure 1.** The precipitation technique for extracting heavy metals from wastewater.

Hydroxide precipitation is commonly utilized due to its cost-effectiveness, simplicity, and the ability to adjust pH as needed [46]. This is achieved by adding hydroxide to the agitated wastewater, forming insoluble metal hydroxide precipitates. For example, metal ions can react with calcium hydroxide (lime), producing metal hydroxide precipitates and calcium ions, as illustrated in Eq. 1.



In addition, sulfides are widely used to precipitate the metals polluting the wastewater (Eq. 2).



Despite its relatively high efficiency, about 95-99%, for most heavy metals present in wastewater, the precipitation method suffers various drawbacks [47]. High pH dependence and difficulty in removing large sludge volumes from the water are among the most critical limitations [48].

### 3.3. Ion exchange

The reversible chemical response used to transform unwanted metallic ions into less environmentally harmful ones makes the ion exchange treatment an alternative to the previously described methods [49]. A heavy metallic ion is eliminated from the wastewater by bonding to a motionless solid particle as an alternative to the solid particle cation. The ion-alternate technique can put off-target (a few or all) heavy metallic ions, including  $Pb^{2+}$ ,

Hg<sup>2+</sup>, Cd<sup>2+</sup>, Ni<sup>2+</sup>, V<sup>4+</sup>, V<sup>5+</sup>, Cr<sup>3+</sup>, Cr<sup>4+</sup>, Cu<sup>2+</sup>, and Zn<sup>2+</sup> from wastewater. The ion exchange occurs when the alternate cation of the ion exchanger exchanges the wastewater pollutant cation, as shown in Eq. 3, where M<sup>-</sup>EC<sup>+</sup> stays for the ion exchanger, EC<sup>+</sup> the exchange cation, WC<sup>+</sup> the wastewater cation, and M<sup>-</sup> the stable ion. Na<sup>+</sup> and H<sup>+</sup> are usually used as alternate cations [50].



Various types of resins were investigated for cation removal and described in the literature, such as Amberlite IRC86 chelating exchange resin [51] and Diaion weak cationic resin CR11 [52]. Both examined resins demonstrated an efficiency of approximately 90% in the removal of trivalent chromium from aqueous solutions [52]. In addition, zeolite exhibits an outstanding ion exchange capacity of up to 98% due to its inherent negative charge. This negative charge arises from Si<sup>4+</sup> in the center of the tetrahedron, which undergoes isomorphous replacement with Al<sup>3+</sup> cations. Furthermore, metal-organic frameworks (MOFs) have been extensively studied and proposed as highly promising materials for the ion exchange removal process [53]. Some reported MOFs were used for Cd<sup>2+</sup>, Pb<sup>2+</sup>, and Hg<sup>2+</sup> removal with a capacity of 97%, 95%, and 93%, respectively [54], ZIF-8 eliminated 95% of Cu<sup>2+</sup>[55], and ZIF-67 eliminated 98% of Cr<sup>6+</sup> [56]. Although the ion exchange method has shown promising results, further research is needed to investigate its stability and reusability [44].

### 3.4. Flotation

Flotation is a gravity separation typically implemented to separate minerals, such as sulfides. This procedure holds substantial importance in the economies of all developed nations [57,58]. Nowadays, it is used extensively for metal ion recovery from industrial wastewater and is applied to a wide range of heavy metal waste streams [59,60]. Several types of flotation separation were discussed in the literature, such as dissolved-air flotation and ion flotation, which are considered the most significant [61].

The dissolved air flotation consists of applying gas bubbles to the body of wastewater, which will selectively transfer the metal ions to the water's surface, forming a slug that can be easily eliminated. This process helped remove heavy metals, such as Cu, Cd, Fe, Ni, Mo, Mn, and As, from wastewater with good efficiencies [61].

On the other hand, ion flotation was implemented to eliminate Cr<sup>3+</sup>, Pb<sup>2+</sup>, and Cu<sup>2+</sup> from wastewater in the presence of different surfactants. Removal effectiveness was achieved at 95% for the mentioned metal ions [62].

Despite the simplicity, high selectivity, and high removal efficiencies obtained in flotation, the process is constrained by the removal rate and ineffectiveness when applied to large dosage amounts of metals in water. In addition, if biosurfactants are not used, the process is constrained by high toxicity [62].

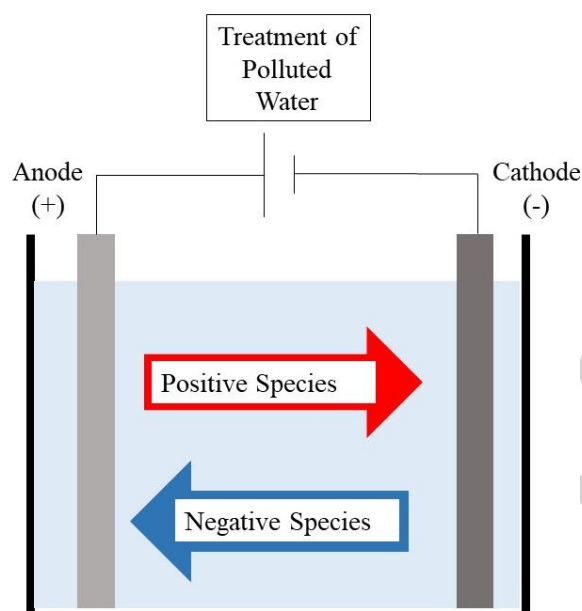
### 3.5. Electrochemical separation

Electrochemical techniques have recently gained substantial attention and recognition as a dependable method for treating industrial wastewater. In contrast to alternative systems, electrochemical systems offer numerous advantages, such as operation under ambient pressure and temperature conditions, dependable performance, and the ability to accommodate fluctuations in influent flow rate and composition. This process is known for its ability to degrade various contaminants, including heavy metals. The fundamental aspect of the electrochemical reaction involves the flow of electric current through an aqueous solution containing metals, a cathode plate, and an insoluble anode (Fig. 2) [63].

Heavy metals are managed through precipitation as hydroxides in electrolytes with a neutral or slightly acidic pH. In this way, the choice of electrode material plays a significant part in increasing the capabilities for various types of pollutants. Additionally, the number of ions created by the electrical current will determine the quality of the treated

effluent. Therefore, any factor impacting the charge in the process will also affect the process' overall efficiency [63].

Many metal ions, such as  $\text{Hg}^{2+}$ ,  $\text{Cd}^{2+}$ ,  $\text{Pb}^{2+}$ , and  $\text{Cu}^{2+}$ , were successfully removed with excellent efficiency using this process. To make this type of treatment viable for industrial applications, it is crucial to address the issue of energy consumption [64].



**Figure 2.** Electrochemical separation technique for wastewater treatment.

#### 4. Elimination of heavy metals from wastewater: Advanced methods

Over time, the adoption of advanced technologies for removing heavy metals from wastewater has seen substantial growth. In the subsequent sections, we outline and explore some of the more prevalent advanced techniques, such as membrane filtration and adsorption, which include filtration systems. These methods exhibit numerous notable advantages in comparison to traditional approaches.

##### 4.1. Membrane filtration

Among the array of wastewater treatment methodologies, membrane filtration is frequently employed as a separation technique within water purification systems. Membrane filters can prevent the formation and spread of bacteria and viruses but also remove particles like total suspended solids, turbidity, and sediment from water.

The attractive nature of membrane filtration to industry and central municipal wastewater recycling lies in its capability to remove suspended solids, organic compounds, and inorganic contaminants, including heavy metals. The pressure-driven membrane filtration process is primarily governed by the pressure difference between the feed and permeate sides (**Fig. 3**) [65]. Various membrane filtration methods can be applied for the extraction of heavy metals from wastewater, depending on the desired particle size retention [15], as illustrated in the filtration spectrum adapted from [66] (**Fig. 4**).



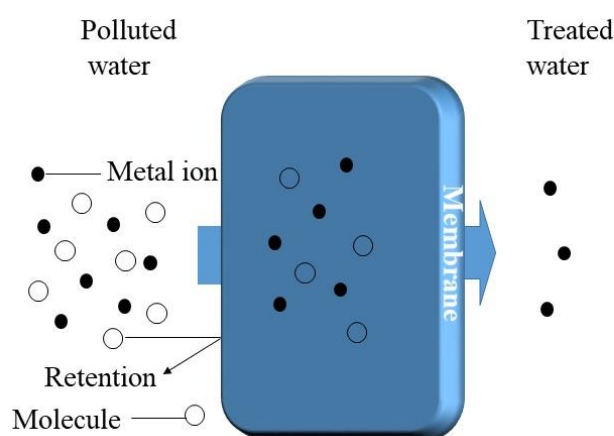


Figure 3. The generic membrane separation procedure.

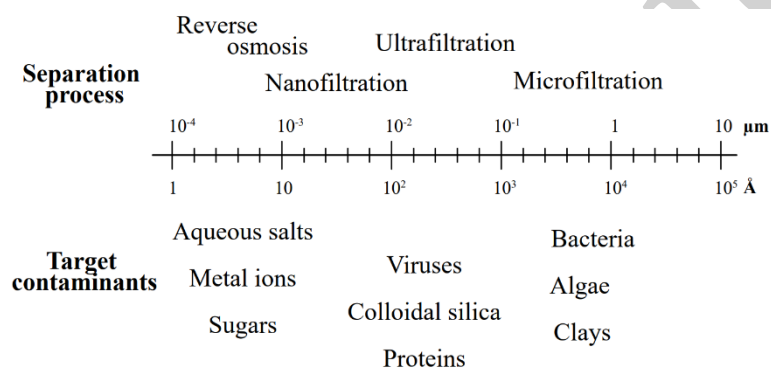
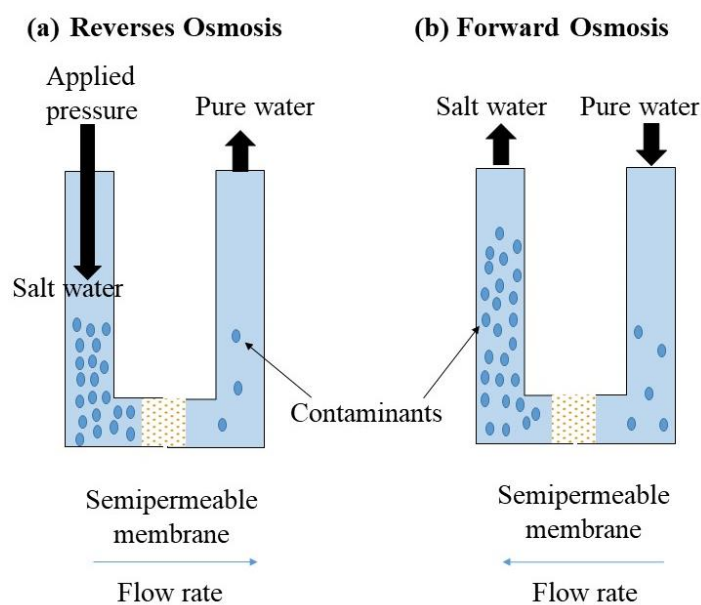


Figure 4. Filtration spectrum (Source: adapted from [66]).

Reverse osmosis (RO) is a separation process driven by pressure, employing a semi-permeable membrane with a pore size of 0.5-1.5 nm. This membrane explicitly allows the passage of molecules smaller than the size of its pores (Fig 5 (a)). The RO process works by exerting pressure values (ranging from 20 to 70 bar) higher than the feed solution's osmotic pressure. This effectively reverses the typical osmotic process. The solute molecules within the solution generally have a molecular size ranging from 0.25 to 3 nm [67]. The filtration yield was estimated at 95-99 % inorganic salts and charged organic matter removal. In the RO separation process, heavy metal ions present in electroplating wastewater, such as  $\text{Ni}^{2+}$ ,  $\text{Cr}^{6+}$ , and  $\text{Cu}^{2+}$ , are effectively removed with an efficiency surpassing 98.75% [68]. In recent times, the method has been utilized for the purification of industrial wastewater derived from mining activities in coaster-field, Victoria-Australia, with averaged extraction efficiency values dependent on the extracted metal:  $\text{Fe}^{3+}$  (10 %),  $\text{Zn}^{2+}$  (48 %),  $\text{As}^{3+}$  (66 %),  $\text{Ni}^{2+}$  (82 %), and  $\text{Sb}^{3+}$  (95 %) [44]. RO is a compact method with a high removal rate. Nonetheless, the exerted pressure can result in membrane fouling and deterioration as contaminants accumulate on the surface of the membrane [69].

Conversely, the forward osmosis (FO) procedure entails employing a semi-permeable membrane to partition the feed solution from the draw solution (Fig. 5 (b)). This approach balances selectivity and the flow rate of permeate water [70]. Typically, the draw solution has a higher osmotic pressure than the feed solution. This difference in osmotic pressure induces water movement from the feed solution to the draw solution, leaving behind undesired solutes in the feed solution while treating the water in the draw solution [71]. This method is eco-friendly and efficient, as it does not necessitate hydraulic pressure for the FO process. The devices based on FO are easy to clean, have a low fouling rate, and are widely used in wastewater treatment [63,64], with extraction efficiency reports for Pb, Cr, As, Cd, and Cu as high as 99.5%. In other studies, 98-99.96% removal efficiency was

achieved in removing  $\text{Co}^{2+}$ ,  $\text{Cu}^{2+}$ , and  $\text{Zn}^{2+}$  from acid mine drainage [72,73]. Despite its relatively effective removal capabilities, FO technology has its limitations. The choices for FO membranes are restricted [74], and the desired solute often needs to be regenerated through methods like membrane distillation [75,76], which can also entail increased energy consumption [72].



**Figure 5.** Reverse osmosis (a) and Forward osmosis (b) membrane separation methodologies.

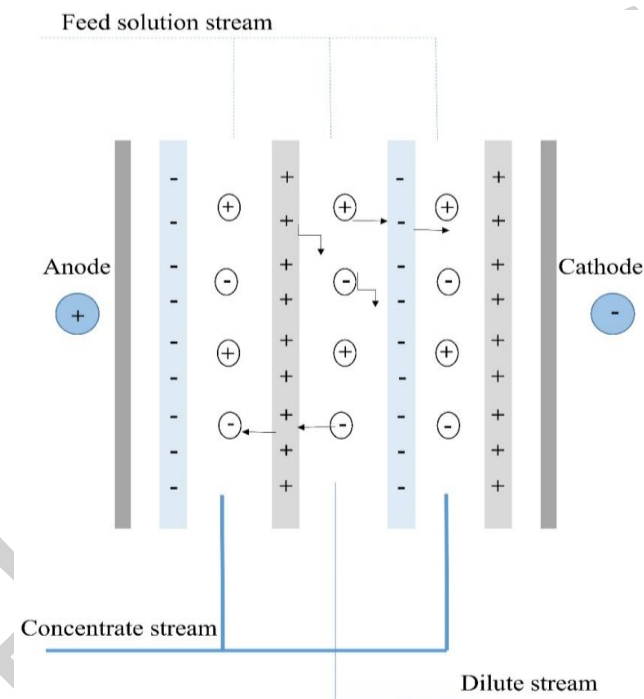
In contrast, in ultrafiltration (UF), both water and low molecular weight solutes permeate through the membrane, while larger macromolecules exceeding the membrane's pore size are retained. UF typically possesses a pore size range of 0.001-0.1  $\mu\text{m}$ , offering effective removal capabilities for wastewater treatment. Conversely, microfiltration (MF) normally operates with pore sizes that are up to an order of magnitude larger. While wastewater treatment often employs relatively open MF membranes with a pore size of 0.1-1.0  $\mu\text{m}$ , the current trend in water treatment favors using moderately tight MF membranes with pore sizes ranging from approximately 0.09 to 0.1  $\mu\text{m}$  [65]. The membrane filtration techniques applied to industrial wastewater can give effluent for disposal or feedstock for reusing [65]. UF membrane technology has been successfully used to eliminate heavy metals, such as iron, copper, and chromium, with a capacity ranging from 96 to 99% [77]. MF is usually used in municipal water treatment applications due to its removal capacity of viruses and, to some extent, its depth filter function. It also provides a barrier against bacterial and protozoan parasites [65].

Various other membrane types have been documented in the literature, including membranes composed of synthesized metal oxide/polyethersulfone (PES),  $\text{Al}_2\text{O}_3/\text{PES}$ , and  $\text{ZrO}_2/\text{PES}$ . These membranes were employed for the removal of metals from wastewater. They were crafted by incorporating PES,  $\text{Al}_2\text{O}_3$ , and  $\text{ZrO}_2$  nanoparticles, with particle sizes ranging from 40-50 nm and surface areas measuring between 20-34  $\text{m}^2/\text{g}$ . The membrane fabrication process involved the utilization of the phase inversion method. To prepare the 5% w/w metal oxides/PES membranes, the metal oxide nanoparticles were dispersed in a solution of N-methyl pyrrolidone. The effectiveness of these membranes in removing Cr and Pb from both synthetic and natural wastewater was tested. The results showed that the membranes achieved approximately 99% removal for Pb and 88% for Cr [70].

Electrodialysis (ED) is a membrane-based technology widely utilized for seawater desalination. It involves the arrangement of numerous anion exchange membranes (AEM) and cation exchange membranes (CEM) placed alternately between two electrodes (**Fig.**

6). The electrolyte solution flows through the electrode compartment, while the feed solution traverses the adjacent compartment. When a voltage is applied, a reduction reaction occurs at the cathode, during which hydroxide ions are formed. Similarly, within the anode compartment, an oxidation process occurs, leading to the production of protons. There are slight variations in selectivity for different ions among various membranes used in ED, and the accumulation of divalent ions often leads to membrane fouling. Furthermore, these membranes tend to be expensive. Additionally, ion-exchange nanofibrous membranes are frequently regarded as a means to enhance the flow and permeability of membranes that selectively filter monovalent and divalent ions [78–80].

Furthermore, ED was used to separate  $\text{Ni}^{2+}$  and  $\text{Pb}^{2+}$  from synthetic solutions by a novel heterogeneous ED-CEM (consisting of 2-acrylamido-2-methylpropanesulfonic acid hydrogel and PVC) with extraction efficiencies of 96.9% and 99% for  $\text{Ni}^{2+}$  and  $\text{Pb}^{2+}$ , respectively. A pilot-scale ED system was employed to extract  $\text{Cu}^{2+}$ ,  $\text{Ni}^{2+}$ , and small amounts of  $\text{Cd}^{2+}$ ,  $\text{Fe}^{3+}$ ,  $\text{Cr}^{6+}$ , and  $\text{Zn}^{2+}$  with elimination efficiencies exceeding 90%. ED removes  $\text{As}^{3+}$  and  $\text{As}^{5+}$  in metallurgical wastewater, and the removal efficiency reaches 91.38% [81].



**Figure 6.** Electrodialysis membrane separation technique.

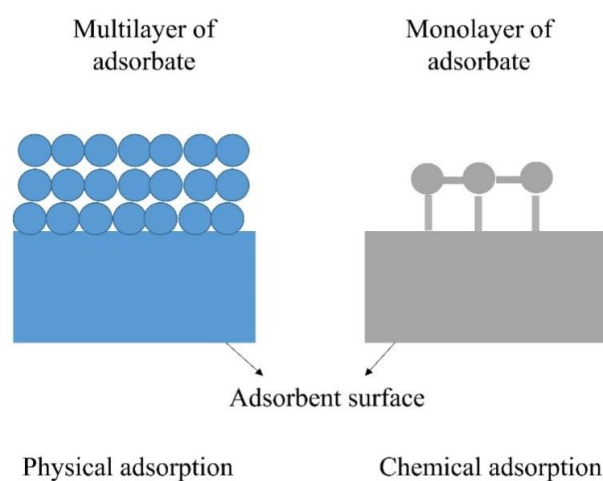
Although membrane filtration has significantly progressed in laboratory-scale studies, no pilot-scale or large-scale practical applications have been reported. In addition, its main disadvantage is the sludge generation [15]. In contrast, membrane filtration operated through direct pressure can facilitate wastewater treatment with reduced energy consumption and carbon dioxide emissions. In summary, membrane filtration-based wastewater treatment systems hold the potential to attain net energy gains and additional economic benefits, paving the way for self-sustaining municipal wastewater treatment [65].

#### 4.2. Adsorption

Adsorption is a good weapon in fighting against toxic metals threatening our environment. It is an interfacial physicochemical phenomenon accumulating solute molecules on a solid-liquid or solid-gas interface [82]. On the molecular scale, adsorption can be categorized into chemical and physical, contingent on the underlying interactions guiding

the adsorption mechanism. The physical process assumes greater significance when it comes to the removal of heavy metals from wastewater.

In the case of physical adsorption, the Van der Waals molecular attractive forces that retain the adsorbent on the surface are generally dominant, and the phenomenon is reversible. The energy involved in the interaction between the adsorbate and the adsorbent shares a similar order of magnitude with the interaction energy between the two. Nevertheless, it typically exceeds the energy associated with the condensation of the adsorbate (Fig. 7). Chemical adsorption, often referred to as activated adsorption, arises from a chemical bonding or interaction occurring between the solid substrate and the adsorbed substance.



**Figure 7.** Physical and chemical adsorption.

The growing ability of adsorption to remove hazardous substances without compromising water quality or generating harmful degradation products has led to its increased utilization over electrochemical, biochemical, or photochemical degradation processes. Additionally, adsorption provides a valuable alternative treatment choice, particularly when the adsorbent is cost-effective and readily obtainable [83]. Various adsorbents have been explored and detailed in existing literature, with these materials being obtainable from biological, organic, or mineral sources.

The significant costs tied to the creation and regeneration of activated carbon inspire researchers to explore alternative avenues. Furthermore, due to low metal adsorption capacity, synthetic materials like (E)-2-[(1H-imidazole-4-yl)methylidene]-Hydrazinecarbothioamide ligand (EIMH) often do not provide greater than 80% removal efficiency for heavy metals in wastewater treatment [84]. In recent years, novel adsorbent materials, particularly nanostructured substances like carbon nanotubes, graphene, fullerenes, and similar materials, have emerged. These materials are currently used to effectively adsorb 90% of heavy metals in wastewater because of their high specific surface area (500-1500 m<sup>2</sup>/g), large pore volume, and different intermolecular interactions [85]. Moreover, they exhibit non-corrosive properties and possess outstanding mechanical strength, thermal stability, and electrical conductivity. The adsorption performance of these nanostructured materials is generally better than that of classic synthetic adsorbents, such as iron oxide, titanium dioxide, activated carbon, etc. However, their limitations make scientific research challenging regarding functionality and durability, which are essential in environmental applications [86]. The adsorption efficiency can be improved by enhancing the carbon surface charge by adding surface functional groups such as carboxyl, phenyl, and lactone [87]. Surface modification typically reduces the surface area while increasing the concentration of surface functional groups. Conversely, increasing the surface area of the adsorbent, dosage of the adsorbent, initial concentration of metal ions, and contact duration

tend to enhance adsorption. Multiwalled carbon nanotubes have received significant attention for effectively removing heavy metals [88]. Their high hydrophobicity and the presence of strong Van der Waals forces have generated considerable interest in their ability to swiftly accumulate in aqueous solutions, thus enhancing their adsorption capacity. The complex preparation process of carbon-based adsorbents contributes to their high cost and limits their widespread industrial use. Therefore, it is necessary to continue exploring innovative, affordable, and environmentally friendly surface modification technologies [88].

Chemical adsorbents encompass metal salt accelerators, activated silica, synthetic polymers, and natural accelerators. Among these, metal salt adsorbents are widely employed in sewage treatment plants due to their effectiveness in removing diverse pollutants like heavy metals and turbidity. The notable advantage of metal salt adsorbents over other types lies in their efficiency in tackling various pollutants. Metal salt adsorbents are readily accessible in the market and can deactivate bacteria. This affordability and availability make them popular among users, especially compared to other chemical adsorbents [89]. The metal salt adsorbents commonly utilized are those based on aluminum and iron [90,91]. They show good efficiency (90-99%) for removal of heavy metals like copper, lead, and nickel. In addition, they have the advantage of being less expensive and having a wider pH range. Adsorption has several disadvantages, including the high cost of adsorbent, separation of the adsorbent from metals, and low surface area [90,91].

#### 4.2.1. Filters: classification and applications

The treatment of industrial and domestic wastewater commonly utilizes adsorption-based filters due to their advantages over other methods, such as cost reduction and lower energy consumption. However, several factors need to be considered and optimized for optimal performance of these filters. The primary factors include the choice of adsorbent material, which significantly impacts heavy metal removal efficiency. Adsorbent properties such as specific surface area, pore size distribution, and functional groups play a crucial role [92]. Additionally, the characteristics of the heavy metals themselves, including their concentration and the presence of competing ions, must be taken into account [93]. Operating conditions, such as pH, temperature, and contact time, are also critical to adsorption [94]. Furthermore, the design and configuration of the filters, encompassing parameters like porosity, depth, flow rate, and material leakage into the water effluents, require careful consideration and improvement [95]. Specific factors such as the regeneration and reusability of the adsorbents [96], the particle size distribution [97], and the potential for chemical modifications to enhance adsorption capacity are equally important [98]. The subsequent sections of this review delineate three categories of filters: synthetic, natural, and hybrid, each with unique properties and applications.

##### 4.2.1.1. Synthetic filters

Among the many synthetic filters designed and studied in the literature, polymer-enhanced filters perform relatively well in removing heavy metals from water. They consist of deploying water-soluble polymeric ligands able to bind metal ions selectively, producing metals-free effluents. **Fig. 8** (a) presents a schematic depiction of a synthetic filter's distinct constituents. To illustrate the different metals that such filters can remove and their filtration efficiency, **Table 2** summarizes various important examples of synthetic filters described in the literature.

**Table 2.** Metal ions elimination by synthetic filters.

Synthetic filter	Targeted metals	Metal ions removal (%)	Reference
PEI	Pb <sup>2+</sup>	80	[99]
	Cu <sup>2+</sup>	94	
	Cd <sup>2+</sup>	99	
PAN	Cu <sup>2+</sup>	96	[100]
Synthetic Zeolites	Pb <sup>2+</sup>	95	[101]
	Cd <sup>2+</sup>	90	
	Ni <sup>2+</sup>	85	
Dithiocarbamate resins	Pb <sup>2+</sup>	45	[102]
	Cu <sup>2+</sup>	78	
	Hg <sup>2+</sup>	80	
	As <sup>3+</sup>	55	
	Cr <sup>3+</sup>	76	
Metal Oxides (e.g., MnO <sub>2</sub> , Fe <sub>3</sub> O <sub>4</sub> )	As <sup>3+</sup>	80	[103]
	Pb <sup>2+</sup>	85	
	Cd <sup>2+</sup>	65	
	Cr <sup>3+</sup>	55	
MWCNTs	Cd <sup>2+</sup>	96	[104]

A filter layer may comprise a semi-interpenetrating polymer network composed of cross-linked polyvinyl alcohol (PVA) as the matrix, with the effective utilization of PEI for the removal of heavy metal ions, including Pb<sup>2+</sup>, Cd<sup>2+</sup>, and Cu<sup>2+</sup> from aqueous solutions. The PVA chains of the complexing polymer are entrapped in a cross-linked polymeric matrix. The latter is fabricated through exposure to gaseous 1,2-dibromoethane. The adsorption reactions followed pseudo-first-order kinetics with similar rate constants for the three cations, and the obtained equilibrium constants show the following affinity order: Pb > Cu > Cd [99].

In addition, PAN demonstrates a remarkable ability to effectively adsorb diverse metal ions, rendering it highly appealing for purification purposes. Notably, it is considered one of the most cost-effective polymers due to its abundant cyano groups at the ends, which provide ample opportunity for further modification [105,106]. PAN fibers are produced through free radical bulk polymerization, utilizing benzoyl peroxide as an initiator. To achieve a bead-free and consistent morphology, a series of experiments were carried out at different potential differences and flow rates. The electrospinning process was optimized at a potential difference of 3 kV cm<sup>-1</sup> and a flow rate of 2 mL h<sup>-1</sup>. At room temperature, the nitrile groups on the PAN fibers' surface react with H<sub>2</sub>NOH. Hydroxylamine engages in a nucleophilic addition to the fiber surface, subsequently forming carboximides. The fiber surface is then functionalized to chelate uranyl cations, and the resulting fiber can remove uranyl ion U(VI) pollutants [107]. By comparing the different PAN fibers, good sorption results of U(VI) ions were obtained (81%). In contrast, only 19% sorption is obtained when the PAN fibers remain unmodified. Most importantly, nanofibers have a high surface area, enhancing their adsorption efficiency and making them ready to link to various chelating agents [108].

Recently, a new filter to remove  $\text{Cd}^{2+}$  and  $\text{Pb}^{2+}$  from the water was described in the literature. It consists of fly ash ceramic foams with a 3-D interconnected porous structure and multiwalled carbon nanotubes (MWCNTs) that are used by a combination of carboxylate grafting and polydimethylsiloxane coating. The fly ash foam exhibited removal rates of 96.33% and 95.12% for Cd and Pb, respectively. This synthetic filter can save considerable economic effort due to gravity propulsion. It is suitable for front-end wastewater treatment on an industrial scale [104].

In a different investigation, PVA/SA beads were formulated by blending functionalized sodium alginate (SA) with polyvinyl alcohol (PVA), including glutaraldehyde as a cross-linking agent. Zeo/PVA/SA nanocomposite beads were made using zeolite nanoparticles (Zeo) and PVA/SA to remove heavy metals from wastewater with good efficiency: 99.5% ( $\text{Pb}^{2+}$ ), 99.2% ( $\text{Cd}^{2+}$ ), 98.8% ( $\text{Sr}^{2+}$ ), 97.2% ( $\text{Cu}^{2+}$ ), 95.6% ( $\text{Zn}^{2+}$ ), 93.1% ( $\text{Ni}^{2+}$ ), 92.4% ( $\text{Mn}^{2+}$ ), and 74.5% ( $\text{Li}^{2+}$ ) [109].

Using synthetic adsorbents in filters presents an opportunity to explore the binding mechanisms of heavy metals with different compounds, whether in a specific or non-specific manner. The polymer-based adsorbents are particularly easy to produce and have been extensively used. The manufacture of these synthetic filters demands a substantial amount of energy. Furthermore, they are not environmentally friendly, as they are typically discarded after becoming saturated with pollutants, unlike natural or hybrid filters, which can be reused.

Furthermore, the production of synthetic zeolites involves using numerous chemical materials. While industrial waste products like cupola slag and spent fluid cracking catalysts are employed in synthesizing important zeolites (such as ZSM-5, NaA, and NaX), they pose environmental hazards. Additionally, specific types of municipal solid waste, such as non-recyclable glass and thin-walled aluminum scraps (including aluminum cans and foils), can serve as sources of silicon (Si) and aluminum (Al) for zeolite synthesis. In summary, zeolite stands as an exceptional adsorbent for effectively removing heavy metals from wastewater [110].

#### 4.2.1.2. Natural filters

Natural wastewater treatment systems, including constructed wetlands, biological sand filters, and other decentralized solutions, are gaining significance as viable alternatives to previously discussed systems (Fig. 8 (b)). This is primarily due to their low establishment costs, ease of use, minimal management requirements, and high efficiency in removing heavy metals from water [111,112].

In less-developed countries, natural coagulants are commonly employed as point-of-use technology due to their ability to be locally produced and easily processed into a usable form. These coagulants are biodegradable and present a cost-efficient substitute for chemical coagulants. Their mode of action involves an adsorption mechanism, followed by either charge neutralization or a polymeric combining effect [113]. Starch and cellulose derivatives, proteinaceous materials, and gums from polysaccharides are significant natural products used [88]. For example, Moringa and other native seeds can remove metals from drinking water. **Table 3** *Erreur ! Source du renvoi introuvable.* shows that Moringa seeds have higher removal rates of heavy metals than cowpea (*Vigna unguiculata*), urad (*Vigna mungo*), peanuts (*Arachis hypogaea*), and corn (*Zea mays*). Moringa has a metal removal rate of over 50%, with the highest removal efficiency for copper and lead (90% for both). Beans (black-eyed peas) and peanuts did not have high metal removal efficiency (<15% for Cu and Cd). Corn and urad beans exhibited limited capabilities for the removal of heavy metals. The adsorption of metals using Moringa is restricted to its surface, as Moringa is a cationic polyelectrolyte with a short chain and low molecular weight [114]. Compared to other seeds, Moringa is particularly effective in efficiently removing heavy metals and solids with charges higher than its colloidal surface. Nonetheless, additional

research is necessary to gain a deeper understanding of the molecular mechanisms underpinning this effective water purification. This insight will be crucial in refining the design of filters employing Moringa.

**Table 3.** Removal capacities of natural adsorbents.

Natural Adsorbents	Removal capacity (%)					Reference
	Cu <sup>2+</sup>	Pb <sup>2+</sup>	Cd <sup>2+</sup>	Cr <sup>3+</sup>	Zn <sup>2+</sup>	
Urad	30	40	10	20	15	[115]
Peanut	4	50	8	40	22	[116]
Bean	3	29	10	40	30	[117]
Corn	10	13	40	10	20	[118]
Moringa	90	90	60	50	55	[119]
Clay Minerals (e.g., Bentonite, Kaolinite)	-	80	70	50	-	[120]
Zeolites	90	75	-	-	60	[121]
Peat Moss	52	50	70	-	-	[122]
Sawdust	60	20	30	80	-	[123]
Algae (Biomass)	50	40	-	60	45	[124]

Large amounts of biomass waste, peels, leaves, husks, stems, branches, and pods can be valorized and used in biosorption [125]. Therefore, natural filters using biomass waste adsorbents are green and sustainable filtration devices. For example, natural zeolites have high ion exchange and adsorption performance due to their particular structure. The ion exchange capacity is influenced by various factors, such as the structure of the framework, the size and shape of the ions, the charge density of the anionic framework, the ionic charge, and the concentration of the external electrolyte solution [126,127].

Given the numerous advantages, the development and utilization of natural coagulants have promising prospects as an environmentally friendly and sustainable technology for wastewater treatment [128]. Without a doubt, the drawbacks of employing natural adsorbents primarily stem from the characteristics of the adsorbents themselves. Factors like seasonal variations and storage duration can impact natural adsorbents' production and consistent availability [129–131].

#### 4.2.1.3. Hybrid filters

Although natural filters are environmentally sustainable and broadly applied in water filtration, their affinity for heavy metals remains moderate, and this finding makes the raw materials less attractive. Improved heavy metal retention from wastewater has been obtained for filters that include modified natural products. Such filtration devices are called hybrid filters. Given their setup composition, they are environmentally sustainable. Fig. 8 (c) shows a schematic representation of a hybrid filter.

Two exemplary hybrid filters will be discussed in this context, specifically, those based on beetroot and limestone. Beetroot fibers, subjected to chemical modification using sodium dodecyl sulfate (SDS), an anionic surfactant, were prepared as representative examples. They proved their efficiency in cleaning water contaminated by organic and inorganic compounds and softening hard water (Table 4). In this specific system, Rahman et al. pinpointed the factors influencing wastewater purification efficacy, which include fiber



particle size, initial pollutant concentration, and wastewater pH. The findings indicate that the purification efficiency increases as the fiber size decreases (from millimeters to micrometers). The optimal pH for adsorption was determined to be in the range of 6.0-6.5. Next, the modified filter's dual function was investigated by assessing its ability to remove heavy metals and soften hard water through its chemical functionalities' positive and negative charges. Hybrid filters based on beetroot fibers were able to remove various pollutants: metals (lead, zinc, nickel, copper), total solid dissolved, and methylene blue. They exhibited high efficiency when particle size decreased due to increased contact surface area at pH values from 6.0 to 6.5. The maximum removal was 70 mg/g of filter for heavy metals like Pb, Cu, and Zn [132].

**Table 4.** Metal ions elimination by a hybrid filter.

Hybrid filter	Targeted metals	Metal ions removal (%)	Reference
Beetroot fibers and SDS	Pb <sup>2+</sup>	100	[132–135]
	Zn <sup>2+</sup>	99	
	Ni <sup>2+</sup>	99	
	Cu <sup>2+</sup>	99	
Limestone and activated carbon	Fe <sup>2+</sup>	100	[136–138]
Clay-EDTA	Pb <sup>2+</sup>	95	[139]
Chitosan Modified with Thiol Groups	Hg <sup>2+</sup>	90	[140]

The second hybrid filter example is based on limestone, a material with sedimentary rock origin consisting mainly of CaCO<sub>3</sub>, which in turn comes from calcite and then aragonite. The chemical composition of limestone renders it an appropriate material for water and wastewater treatment, as these elements possess the capability to adsorb a diverse range of pollutants. While limestone is an eco-friendly substance extensively utilized in water filtration, it exhibits a moderate affinity for heavy metals. Consequently, endeavors have been dedicated to developing an environmentally friendly filtration system by combining limestone and activated carbon to eliminate iron from wastewater. A filter composed of activated carbon and limestone in a 1:1 ratio successfully removed a 10 mg/l iron solution. Utilizing 1 kg of this filter, it only took 95 minutes, at pH 6, to completely eliminate iron ions from the contaminated solution [136].

Furthermore, hybrid inorganic/natural adsorbents primarily based on alumina and 4-amino antipyrine have been implemented to remove Pb, Cu, and Cr from industrial wastewater. The hybrid adsorbents have been effectively implemented for the selective elimination of the heavy metals mentioned above, with recuperation values between 92 and 98%. Hybrid alumina adsorbents are known for their exceptional thermal decomposition resistance and a sturdy balance that approaches acid-leaching conditions [141]. They were recently replaced by natural adsorbents, representing a safe, more eco-friendly, and energetically cheaper alternative [142].

Furthermore, modified zeolite can be easily obtained through basic or acidic treatment and surfactant modification. These alterations expand the range of potential applications for zeolites in wastewater treatment. As a result, surfactant-modified zeolites have the capability to not only adsorb anionic species but also undergo cation exchange with metal cations. This is due to the large size of the modifying agents' cations, preventing them from entering the inner channels. [110].

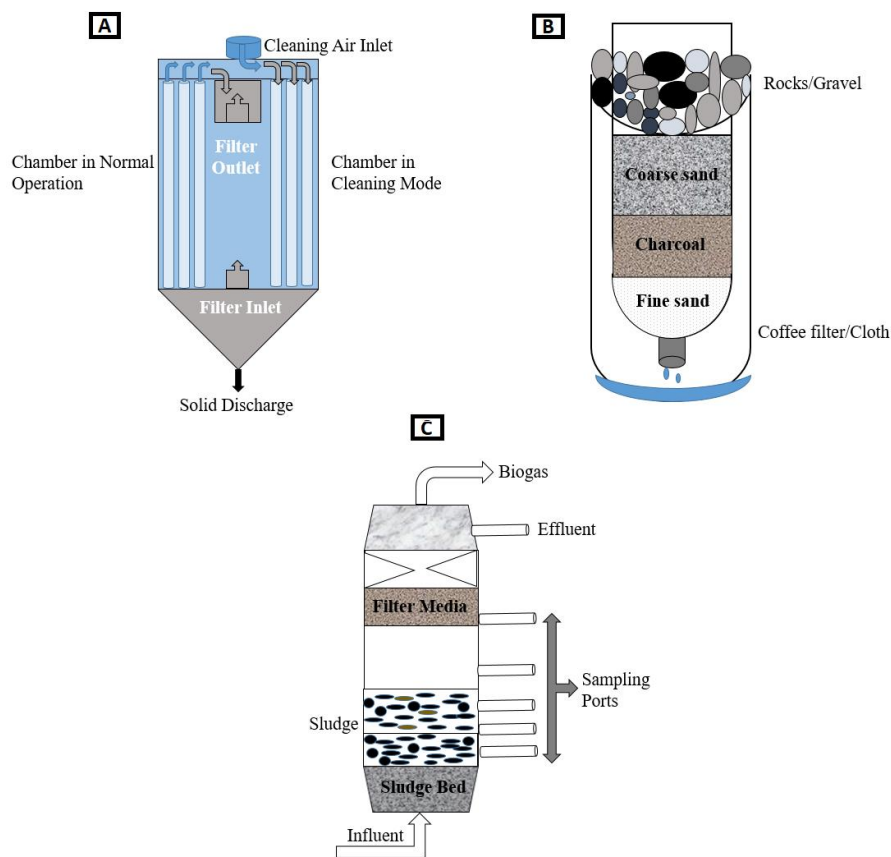


Figure 8. (a) synthetic filter, (b) natural filter, and (c) hybrid filter (Source: This work).

#### 4.2.1.4. Adsorbents regeneration/reuse

Spent adsorbents require regeneration after reaching their saturation point with contaminants to restore their adsorption capacity and facilitate reuse. The reusability of spent adsorbents depends on their recoverability, decontamination efficacy, and regeneration potential [143]. High recovery and regeneration capabilities are highly desirable for commercial and industrial applications, as they can significantly reduce the overall cost associated with adsorbent production [144]. Although the regeneration process can be cycled multiple times, regenerated adsorbents typically show a decrease in adsorption capacity compared to fresh ones [145]. Selecting the most appropriate regeneration technique is crucial for maximizing contaminant desorption efficiency. Several factors influence the feasibility of industrial-scale application, including the type of adsorbent, contaminant, adsorbent stability, toxicity, and the cost and energy demands of the regeneration process.

A diverse range of approaches can be employed to recover and regenerate spent adsorbents. These include magnetic separation [146], thermal desorption [147], solvent regeneration [148], microwave irradiation [149], supercritical fluid regeneration [150], and advanced oxidation processes [151].

- Magnetic separation leverages the magnetic properties of adsorbents to separate them from the wastewater after they have adsorbed heavy metals. By applying an external magnetic field, the magnetic adsorbents can be easily retrieved from the solution, facilitating their regeneration and reuse. The primary advantages are efficiency and simplicity, allowing for quick recovery of adsorbents, reducing the need for complex filtration methods, and lowering operational costs while minimizing secondary pollution [152,153]. However, the stability of the magnetic properties over multiple regeneration cycles needs to be ensured.

- Thermal desorption involves heating the adsorbent to volatilize the adsorbed metals, which are then captured and treated separately. Regeneration temperatures typically

range from 200-800°C [147]. Thermal desorption can achieve high regeneration efficiencies, often exceeding 90%, making it suitable for large-scale industrial applications [152]. It is effective for various adsorbents, including activated carbons, zeolites, and metal-organic frameworks (MOFs), but has drawbacks like high energy requirements and potential degradation of adsorbents over multiple cycles.

- Solvent regeneration involves using various solvents to desorb metals from the adsorbent surface, effectively restoring its adsorption capacity. Common solvents include acids (e.g., hydrochloric acid, nitric acid), alkalis (e.g., sodium hydroxide), and organic solvents (e.g., ethanol, methanol)[148,152,154]. This method is particularly effective for adsorbents with a strong affinity for certain heavy metals and is relatively cost-effective. However, it poses environmental risks due to the disposal of spent solvents and can lead to partial degradation of the adsorbent material over time. Recent advancements focus on developing eco-friendly solvents and integrating solvent recovery systems to enhance sustainability [152,154].

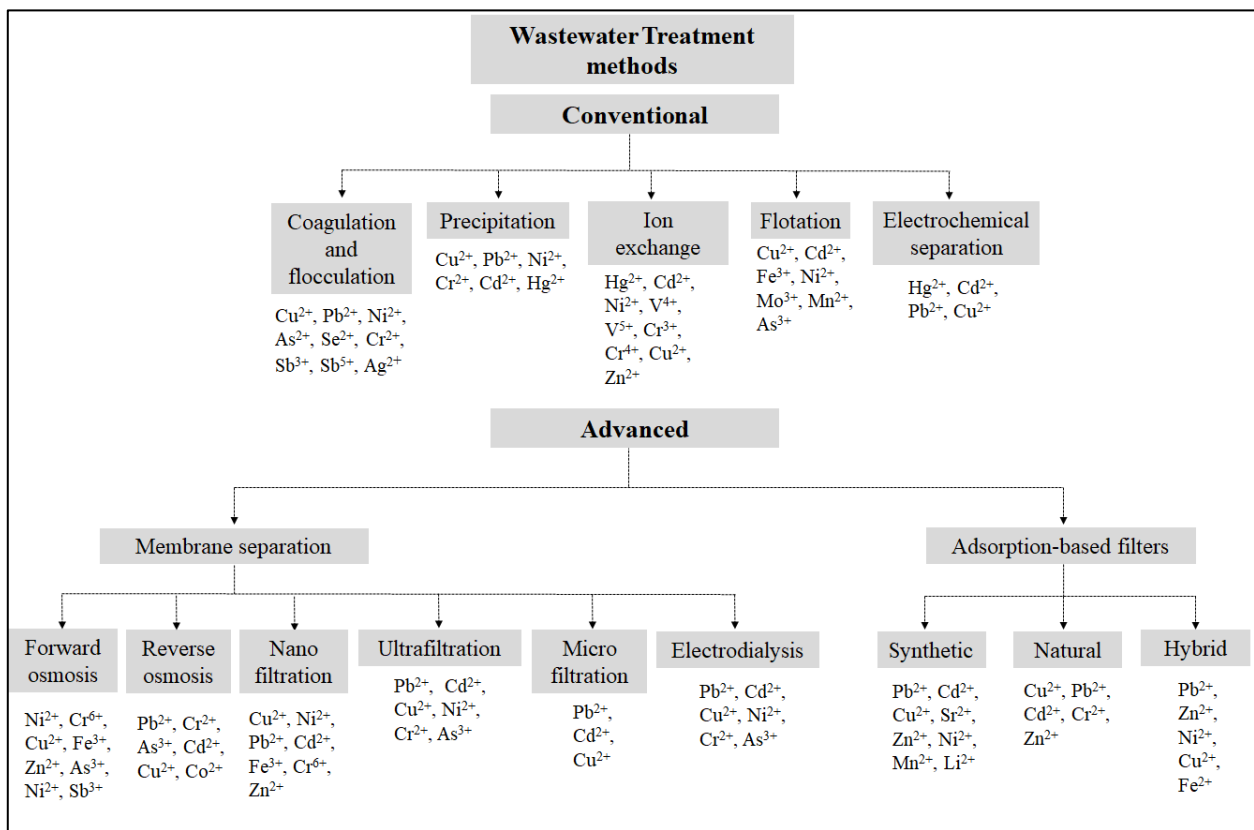
- Microwave irradiation heats the adsorbent using microwave energy, volatilizing the adsorbed contaminants and allowing for efficient desorption and regeneration. Studies have shown that microwave-assisted regeneration can recover up to 90% of the adsorptive capacity of activated carbon used in wastewater treatment [152,155]. This method is highly effective at targeting specific adsorbed species and is energy-efficient and environmentally friendly, offering rapid and selective heating that reduces operational costs and environmental impact [149].

- Supercritical fluid regeneration uses supercritical fluids, typically supercritical CO<sub>2</sub>, which operate under conditions above their critical temperature and pressure. This method achieves high efficiency in desorbing heavy metals from adsorbents and can achieve metal recovery rates exceeding 90%, making it highly effective for industrial applications. Supercritical CO<sub>2</sub> is non-toxic, non-flammable, and relatively low-cost. The process minimizes waste and environmental impact and preserves the structural integrity of the adsorbent material over multiple regeneration cycles. However, it requires high initial setup costs and precise control of operational parameters to optimize regeneration efficiency [156].

- Advanced oxidation processes (AOPs) generate highly reactive species, such as hydroxyl radicals, which degrade contaminants adsorbed onto the adsorbents, restoring their adsorption capacity [157]. AOPs can regenerate adsorbents without significant material degradation, allowing for multiple reuse cycles and reducing operational costs. These processes target a wide range of heavy metals, ensuring comprehensive removal and recovery. However, they require high initial setup costs and precise control of operational parameters [157].

## 5. Comparison between filters and other methods

The need for cost-effective technologies to remove heavy metals from contaminated soil and water is rising. The conventional and advanced metal removal methods described in this review are summarized in **Fig. 9**. The conventional methods have become insufficient to meet the current strict regulatory effluent restrictions and are sometimes expensive [128]. Adsorption is a commonly employed method for extracting toxic metals from aquatic environments, achieving an average removal rate of around 99% through the use of inexpensive adsorbents, including agricultural waste and activated carbon derived from agricultural waste [158,159]. Therefore, there is a great demand for alternative, cost-effective technologies. Selecting a specific treatment method relies on various factors, including the waste's type and concentration, the effluent's variability, the desired remediation level, and economic and energy considerations [40]. For example, filters use less energy than osmosis pumps, which remains true when compared to pressurized nano and ultra-filtration phenomena [68]. The pros and cons of different techniques for addressing heavy metals in wastewater are outlined in **Table 5**.



**Figure 9.** Summary of the conventional and advanced wastewater treatment methods described in this review.

**Table 5.** The primary benefits and drawbacks of diverse traditional and advanced approaches, including filtration methods, for eliminating heavy metals from wastewater.

Treatment method	Advantages	Disadvantages	Reference
Coagulation and flocculation or precipitation	Low cost; Simple operation	Sludge generation; The extra operational cost of sludge disposal	[160]
Ion exchange	Removal of metals and organic pollutants simultaneously; Less harmful byproduct	Long duration time; Limited application	[161]
Membrane filtration, forward and reverses osmosis	Small space requirement; Low pressure; High separation selectivity	High operational cost due to membrane fouling	[160]
Adsorption	Availability; High efficiency; Less expensive than other techniques; Works in a wide pH range	Hard separation of the adsorbent from metals	[162][163]
Adsorption by Filters	Synthetic filters High efficiency	High energy consumption	[164]

<b>Natural filters</b>	Low-cost; Eco-friendly	Moderate efficiency	[165]
<b>Hybrid filters</b>	High separation selectivity; Economical; 50% Eco friendly	50% harmful effect on the environment	[166]

## 6. Conclusion and perspectives

Ensuring the well-being of both human health and the environment entails the vital mission of eradicating heavy metals from wastewater. A plethora of treatment approaches, encompassing adsorption, membrane filtration, coagulation and flocculation, chemical precipitation, ion exchange, flotation, electrochemical processes, and filtration, have been the subject of extensive research and have proven their effectiveness in the removal of heavy metals from wastewater. Each method has advantages and limitations, and further research and development are needed to optimize efficiency, cost-effectiveness, and environmental sustainability. The integration of multiple treatment methods and the development of hybrid systems can enhance the overall effectiveness of heavy metal removal. Additionally, using advanced materials, such as nanostructured materials, natural coagulants, and modified natural products, shows promise in improving heavy metal removal efficiency.

Natural filters are cheaper and more eco-friendly than hybrid filters but are less efficient than synthetic ones in removing organic and inorganic pollutants. To limit the impact of such filters on the environment, efforts should be invested to develop efficient biomass-based biodegradable filters for water treatment. A sustainable and economically viable strategy for designing such filters is the use of what is currently considered as biomass-waste. Coupling between various sorts of natural and hybrid filter treatment could also be a promising alternative. Furthermore, adopting sustainable wastewater treatment practices and promoting public awareness and education are essential in addressing global water pollution. By continuing to advance and implement efficient and sustainable wastewater treatment technologies, we can mitigate the harmful effects of heavy metals, protect water resources, and ensure a cleaner and safer environment for future generations.

685

686

687

688

689

690

691

692

693

694

695

696

697

698

699

700

701

702

703

704

705

706

707

708

709

710

711

712

713

714

715

716

717

718

719

720

721

722

723

724

725

726

727

728

729

## References

1. Carolin, C.F.; Kumar, P.S.; Saravanan, A.; Joshiba, G.J.; Naushad, Mu. Efficient Techniques for the Removal of Toxic Heavy Metals from Aquatic Environment: A Review. *Journal of Environmental Chemical Engineering* **2017**, *5*, 2782–2799, doi:10.1016/j.jece.2017.05.029. 730-733
2. bica, J.; Chatterley, C.; Dönmez, A.; Johnston, R.; Mitis, F.; Slaymaker, T. *Progress on Household Drinking Water, Sanitation and Hygiene 2000-2022*; United state, 2023; 734-735
3. Carstea, E.M.; Bridgeman, J.; Baker, A.; Reynolds, D.M. Fluorescence Spectroscopy for Wastewater Monitoring: A Review. *Water Research* **2016**, *95*, 205–219, doi:10.1016/j.watres.2016.03.021. 736-737
4. John, M.J.; Anandjiwala, R.D. Recent Developments in Chemical Modification and Characterization of Natural Fiber-Reinforced Composites. *Polym. Compos.* **2008**, *29*, 187–207, doi:10.1002/pc.20461. 738-739
5. Wong, Y.C.; Szeto, Y.S.; Cheung, W.H.; McKay, G. Adsorption of Acid Dyes on Chitosan—Equilibrium Isotherm Analyses. *Process Biochemistry* **2004**, *39*, 695–704, doi:10.1016/S0032-9592(03)00152-3. 740-741
6. Xu, P.; Zeng, G.M.; Huang, D.L.; Feng, C.L.; Hu, S.; Zhao, M.H.; Lai, C.; Wei, Z.; Huang, C.; Xie, G.X.; et al. Use of Iron Oxide Nanomaterials in Wastewater Treatment: A Review. *Science of The Total Environment* **2012**, *424*, 1–10, doi:10.1016/j.scitotenv.2012.02.023. 742-744
7. Yenkie, K.M. Integrating the Three E's in Wastewater Treatment: Efficient Design, Economic Viability, and Environmental Sustainability. *Current Opinion in Chemical Engineering* **2019**, *26*, 131–138, doi:10.1016/j.coche.2019.09.002. 745-746
8. António Guterres Water and Sanitation - United Nations Sustainable Development Available online: <https://www.un.org/sustainabledevelopment/water-and-sanitation/> (accessed on 7 July 2023). 747-748
9. Gallego-Schmid, A.; Tarpani, R.R.Z. Life Cycle Assessment of Wastewater Treatment in Developing Countries: A Review. *Water Research* **2019**, *153*, 63–79, doi:10.1016/j.watres.2019.01.010. 749-750
10. Raval, N.P. Adsorptive Removal of Nickel(II) Ions from Aqueous Environment: A Review. *Journal of Environmental Management* **2016**, *20*. 751-752
11. Francisco R.-Peligro, L.M.; Ivana Pavlovic; Ricardo Rojas; Cristobalina Barriga Surface Charge Properties of and Cu(II) Adsorption by Spores of the Marine Bacillus Sp. Strain SG-1. *Appl. Environ. Microbiol.* **2016**, *64*, 1123–1129, doi:10.1128/AEM.64.3.1123-1129.1998. 753-755
12. Meena, A.K.; Mishra, G.K.; Rai, P.K.; Rajagopal, C.; Nagar, P.N. Removal of Heavy Metal Ions from Aqueous Solutions Using Carbon Aerogel as an Adsorbent. *Journal of Hazardous Materials* **2005**, *122*, 161–170, doi:10.1016/j.jhazmat.2005.03.024. 756-757
13. Zinicovscaia, I. Conventional Methods of Wastewater Treatment. In *Cyanobacteria for Bioremediation of Wastewaters*; Zinicovscaia, I., Cepoi, L., Eds.; Springer International Publishing: Cham, 2016; pp. 17–25 ISBN 978-3-319-26749-4. 758-759
14. Alikaj, M.; Brahushi, F. Heavy Metals Assessment in the Macrophytes of Viroi Lake. **2017**. 760
15. Barakat, M.A. New Trends in Removing Heavy Metals from Industrial Wastewater. *Arabian Journal of Chemistry* **2011**, *4*, 361–377, doi:10.1016/j.arabjc.2010.07.019. 761-762
16. Elkady, M.; Shokry, H.; Hamad, H. New Activated Carbon from Mine Coal for Adsorption of Dye in Simulated Water or Multiple Heavy Metals in Real Wastewater. *Materials* **2020**, *13*, 2498, doi:10.3390/ma13112498. 763-764
17. Rehman, M.S.U.; Kim, I.; Han, J.-I. Adsorption of Methylene Blue Dye from Aqueous Solution by Sugar Extracted Spent Rice Biomass. *Carbohydrate Polymers* **2012**, *90*, 1314–1322, doi:10.1016/j.carbpol.2012.06.078. 765-766
18. El malti, W.; Hijazi, A.; Khalil, Z.A.; Yaghi, Z.; Medlej, M.K.; Reda, M. Comparative Study of the Elimination of Copper, Cadmium, and Methylene Blue from Water by Adsorption on the Citrus *Sinensis* Peel and Its Activated Carbon. *RSC Adv.* **2022**, *12*, 10186–10197, doi:10.1039/D1RA08997H. 767-769
19. Wassim El Malti, W.E.; Hamieh, M.; Noaman, A.; El-Dine, R.N.; Hijazi, A.; Al-Khatib, W. Polyurethane Loaded with Vegetable Activated Carbon for Heavy Metals Removal from Water. *Journal of Ecological Engineering* **2021**, *12*. 770-771

20. Jiang, Z.; Ho, S.-H.; Wang, X.; Li, Y.; Wang, C. Application of Biodegradable Cellulose-Based Biomass Materials in Wastewater Treatment. *Environmental Pollution* **2021**, *290*, 118087, doi:10.1016/j.envpol.2021.118087. 772-773
21. N. Herawati, S. Suzuki, N.; Hayashi, K.; Rivai, I.F. Cadmium, Copper, and Zinc Levels in Rice and Soil of Japan, Indonesia, and China by Soil Type. *Bulletin of Environmental Contamination and Toxicology* **2000**, *64*, 33–39, doi:10.1007/s001289910006. 774-775
22. Kabata-Pendias, A. Soil–Plant Transfer of Trace Elements—an Environmental Issue. *Geoderma* **2004**, *122*, 143–149, doi:10.1016/j.geoderma.2004.01.004. 776-777
23. Babel, S.; Kurniawan, T.A. Cr(VI) Removal from Synthetic Wastewater Using Coconut Shell Charcoal and Commercial Activated Carbon Modified with Oxidizing Agents and/or Chitosan. *Chemosphere* **2004**, *54*, 951–967, doi:10.1016/j.chemosphere.2003.10.001. 778-780
24. Ali, H.; Khan, E.; Sajad, M.A. Phytoremediation of Heavy Metals—Concepts and Applications. *Chemosphere* **2013**, *91*, 869–881, doi:10.1016/j.chemosphere.2013.01.075. 781-782
25. Igiri, B.E.; Okoduwa, S.I.R.; Idoko, G.O.; Akabuogu, E.P.; Adeyi, A.O.; Ejiogu, I.K. Toxicity and Bioremediation of Heavy Metals Contaminated Ecosystem from Tannery Wastewater: A Review. *Journal of Toxicology* **2018**, *2018*, 1–16, doi:10.1155/2018/2568038. 783-785
26. Ab Hamid, N.H.; bin Mohd Tahir, M.I.H.; Chowdhury, A.; Nordin, A.H.; Alshaikh, A.A.; Suid, M.A.; Nazaruddin, N. 'Izzah; Nozaizeli, N.D.; Sharma, S.; Rushdan, A.I. The Current State-Of-Art of Copper Removal from Wastewater: A Review. *Water* **2022**, *14*, 3086, doi:10.3390/w14193086. 786-788
27. Fewtrell, L.; Kay, D.; MacGill, S. A Review of the Science behind Drinking Water Standards for Copper. *International Journal of Environmental Health Research* **2001**, *11*, 161–167, doi:10.1080/09603120020047573. 789-790
28. Schweitzer, L.; Noblet, J. Water Contamination and Pollution. In *Green Chemistry*; Elsevier, 2018; pp. 261–290 ISBN 978-0-12-809270-5. 791-792
29. Al-Saydeh, S.A.; El-Naas, M.H.; Zaidi, S.J. Copper Removal from Industrial Wastewater: A Comprehensive Review. *Journal of Industrial and Engineering Chemistry* **2017**, *56*, 35–44, doi:10.1016/j.jiec.2017.07.026. 793-794
30. Badr, E.A.E.; Agrama, A.A.E.; Badr, S.A.E. Heavy Metals in Drinking Water and Human Health, Egypt. *Nutrition & Food Science* **2011**, *41*, 210–217, doi:10.1108/00346651111132484. 795-796
31. Sun, L.; Lu, M.; Li, Q.; Jiang, H.; Yin, S. Research Progress of Arsenic Removal from Wastewater. *IOP Conf. Ser.: Earth Environ. Sci.* **2019**, *218*, 012142, doi:10.1088/1755-1315/218/1/012142. 797-798
32. Lu, Z.; Qi, X.; Zhu, X.; Li, X.; Li, K.; Wang, H. Highly Effective Remediation of High-Arsenic Wastewater Using Red Mud through Formation of AlAsO<sub>4</sub>@silicate Precipitate. *Environmental Pollution* **2021**, *287*, 117484, doi:10.1016/j.envpol.2021.117484. 799-801
33. Mansoorian, H.J.; Mahvi, A.H.; Jafari, A.J. Removal of Lead and Zinc from Battery Industry Wastewater Using Electrocoagulation Process: Influence of Direct and Alternating Current by Using Iron and Stainless Steel Rod Electrodes. *Separation and Purification Technology* **2014**, *135*, 165–175, doi:10.1016/j.seppur.2014.08.012. 802-804
34. Mitra, S.; Sarkar, A.; Sen, S. Removal of Chromium from Industrial Effluents Using Nanotechnology: A Review. *Nanotechnol. Environ. Eng.* **2017**, *2*, 11, doi:10.1007/s41204-017-0022-y. 805-806
35. Prasad, S.; Yadav, K.K.; Kumar, S.; Gupta, N.; Cabral-Pinto, M.M.S.; Rezanian, S.; Radwan, N.; Alam, J. Chromium Contamination and Effect on Environmental Health and Its Remediation: A Sustainable Approaches. *Journal of Environmental Management* **2021**, *285*, 112174, doi:10.1016/j.jenvman.2021.112174. 807-809
36. Chang, J.; Peng, D.; Deng, S.; Chen, J.; Duan, C. Efficient Treatment of Mercury(II)-Containing Wastewater in Aerated Constructed Wetland Microcosms Packed with Biochar. *Chemosphere* **2022**, *290*, 133302, doi:https://doi.org/10.1016/j.chemosphere.2021.133302. 810-812

37. Djaenudin; Widayarani; Hariyadi, H.R.; Wulan, D.R.; Cahyaningsih, S. Removal of Nickel Ion from Electroplating Wastewater Using Double Chamber Electrodeposition Cell (DCEC) Reactor Partitioned with Water Hyacinth ( *Eichhornia Crassipes* ) Leaves. *IOP Conf. Ser.: Earth Environ. Sci.* **2017**, *60*, 012020, doi:10.1088/1755-1315/60/1/012020.
38. Li, N.; Yuan, M.; Lu, S.; Xiong, X.; Xie, Z.; Liu, Y.; Guan, W. Highly Effective Removal of Nickel Ions from Wastewater by Calcium-Iron Layered Double Hydroxide. *Front. Chem.* **2023**, *10*, 1089690, doi:10.3389/fchem.2022.1089690.
39. Abbas, A.; Chen, L.; Liao, Y.; Wu, Z.; Yu, Y.; Yang, J. Removal of Bismuth Ion from Aqueous Solution by Pulverized Eggshells. *DWT* **2021**, *213*, 395–405, doi:10.5004/dwt.2021.26724.
40. Wang, J.; Chen, C. Biosorbents for Heavy Metals Removal and Their Future. *Biotechnology Advances* **2009**, *27*, 195–226, doi:10.1016/j.biotechadv.2008.11.002.
41. Ibarra-Rodríguez, D.; Lizardi-Mendoza, J.; López-Maldonado, E.A.; Oropeza-Guzmán, M.T. Capacity of 'Nopal' Pectin as a Dual Coagulant-Flocculant Agent for Heavy Metals Removal. *Chemical Engineering Journal* **2017**, *323*, 19–28, doi:10.1016/j.cej.2017.04.087.
42. Chang, Q.; Zhang, M.; Wang, J. Removal of Cu<sup>2+</sup> and Turbidity from Wastewater by Mercaptoacetyl Chitosan. *Journal of Hazardous Materials* **2009**, *169*, 621–625, doi:10.1016/j.jhazmat.2009.03.144.
43. Sakhi, D.; Rakhila, Y.; Elmchaouri, A.; Abouri, M.; Souabi, S.; Jada, A. Optimization of Coagulation Flocculation Process for the Removal of Heavy Metals from Real Textile Wastewater. In *Advanced Intelligent Systems for Sustainable Development (AI2SD'2018)*; Ezziyyani, M., Ed.; Advances in Intelligent Systems and Computing; Springer International Publishing: Cham, 2019; Vol. 913, pp. 257–266 ISBN 978-3-030-11880-8.
44. Samaei, S.M.; Gato-Trinidad, S.; Altaee, A. Performance Evaluation of Reverse Osmosis Process in the Post-Treatment of Mining Wastewaters: Case Study of Costerfield Mining Operations, Victoria, Australia. *Journal of Water Process Engineering* **2020**, *34*, 101116, doi:10.1016/j.jwpe.2019.101116.
45. Teh, C.Y.; Budiman, P.M.; Shak, K.P.Y.; Wu, T.Y. Recent Advancement of Coagulation–Flocculation and Its Application in Wastewater Treatment. *Ind. Eng. Chem. Res.* **2016**, *55*, 4363–4389, doi:10.1021/acs.iecr.5b04703.
46. Yadav, M.; Gupta, R.; Sharma, R.K. Green and Sustainable Pathways for Wastewater Purification. In *Advances in Water Purification Techniques*; Elsevier, 2019; pp. 355–383 ISBN 978-0-12-814790-0.
47. Qasem, N.A.A.; Mohammed, R.H.; Lawal, D.U. Removal of Heavy Metal Ions from Wastewater: A Comprehensive and Critical Review. *npj Clean Water* **2021**, *4*, 36, doi:10.1038/s41545-021-00127-0.
48. Kumar, M.; Nandi, M.; Pakshirajan, K. Recent Advances in Heavy Metal Recovery from Wastewater by Biogenic Sulfide Precipitation. *Journal of Environmental Management* **2021**, *278*, 111555, doi:10.1016/j.jenvman.2020.111555.
49. Dąbrowski, A.; Hubicki, Z.; Podkościelny, P.; Robens, E. Selective Removal of the Heavy Metal Ions from Waters and Industrial Wastewaters by Ion-Exchange Method. *Chemosphere* **2004**, *56*, 91–106, doi:10.1016/j.chemosphere.2004.03.006.
50. Tenório, J.A.S.; Espinosa, D.C.R. Treatment of Chromium Plating Process Effluents with Ion Exchange Resins. *Waste Management* **2001**, *21*, 637–642, doi:10.1016/S0956-053X(00)00118-5.
51. Kang, S.-Y.; Lee, J.-U.; Moon, S.-H.; Kim, K.-W. Competitive Adsorption Characteristics of Co<sup>2+</sup>, Ni<sup>2+</sup>, and Cr<sup>3+</sup> by IRN-77 Cation Exchange Resin in Synthesized Wastewater. *Chemosphere* **2004**, *56*, 141–147, doi:10.1016/j.chemosphere.2004.02.004.
52. Cavaco, S.A.; Fernandes, S.; Quina, M.M.; Ferreira, L.M. Removal of Chromium from Electroplating Industry Effluents by Ion Exchange Resins. *Journal of Hazardous Materials* **2007**, *144*, 634–638, doi:10.1016/j.jhazmat.2007.01.087.
53. Kobielska, P.A.; Howarth, A.J.; Farha, O.K.; Nayak, S. Metal–Organic Frameworks for Heavy Metal Removal from Water. *Coordination Chemistry Reviews* **2018**, *358*, 92–107, doi:10.1016/j.ccr.2017.12.010.
54. Fang, Q.-R.; Yuan, D.-Q.; Sculley, J.; Li, J.-R.; Han, Z.-B.; Zhou, H.-C. Functional Mesoporous Metal–Organic Frameworks for the Capture of Heavy Metal Ions and Size-Selective Catalysis. *Inorg. Chem.* **2010**, *49*, 11637–11642, doi:10.1021/ic101935f.



55. Zhang, Y.; Xie, Z.; Wang, Z.; Feng, X.; Wang, Y.; Wu, A. Unveiling the Adsorption Mechanism of Zeolitic Imidazolate Framework-8 with High Efficiency for Removal of Copper Ions from Aqueous Solutions. *Dalton Trans.* **2016**, *45*, 12653–12660, doi:10.1039/C6DT01827K. 854–856
56. Li, X.; Gao, X.; Ai, L.; Jiang, J. Mechanistic Insight into the Interaction and Adsorption of Cr(VI) with Zeolitic Imidazolate Framework-67 Microcrystals from Aqueous Solution. *Chemical Engineering Journal* **2015**, *274*, 238–246, doi:10.1016/j.cej.2015.03.127. 857–859
57. Shah, R. Ligational, Potentiometric and Floatation Studies on Cu(II) Complexes of Hydrazones Derived from p and o-Vanillin Condensed with Diketo Hydrazide. *Journal of Molecular Liquids* **2016**, *220*, 939–953, doi:10.1016/j.molliq.2016.04.047. 860–861
58. Dehghani, M.H.; Karimi, B.; Rajaei, M.S. The Effect of Aeration on Advanced Coagulation, Flotation and Advanced Oxidation Processes for Color Removal from Wastewater. *Journal of Molecular Liquids* **2016**, *223*, 75–80, doi:10.1016/j.molliq.2016.08.019. 862–863
59. Elehinafe, F.B.; Agboola, O.; Vershima, A.D.; Bamigboye, G.O. Insights on the Advanced Separation Processes in Water Pollution Analyses and Wastewater Treatment – A Review. *South African Journal of Chemical Engineering* **2022**, *42*, 188–200, doi:10.1016/j.sajce.2022.08.004. 864–866
60. Wang, G.; Nguyen, A.V.; Mitra, S.; Joshi, J.B.; Jameson, G.J.; Evans, G.M. A Review of the Mechanisms and Models of Bubble-Particle Detachment in Froth Flotation. *Separation and Purification Technology* **2016**, *170*, 155–172, doi:10.1016/j.seppur.2016.06.041. 867–869
61. Deliyanni, E.A.; Kyzas, G.Z.; Matis, K.A. Various Flotation Techniques for Metal Ions Removal. *Journal of Molecular Liquids* **2017**, *225*, 260–264, doi:10.1016/j.molliq.2016.11.069. 870–871
62. Jia, K.; Yi, Y.; Ma, W.; Cao, Y.; Li, G.; Liu, S.; Wang, T.; An, N. Ion Flotation of Heavy Metal Ions by Using Biodegradable Biosurfactant as Collector: Application and Removal Mechanism. *Minerals Engineering* **2022**, *176*, 107338, doi:10.1016/j.mineng.2021.107338. 872–874
63. Ajiboye, T.O.; Oyewo, O.A.; Onwudiwe, D.C. Simultaneous Removal of Organics and Heavy Metals from Industrial Wastewater: A Review. *Chemosphere* **2021**, *262*, 128379, doi:10.1016/j.chemosphere.2020.128379. 875–876
64. Jin, W.; Fu, Y.; Hu, M.; Wang, S.; Liu, Z. Highly Efficient SnS-Decorated Bi<sub>2</sub>O<sub>3</sub> Nanosheets for Simultaneous Electrochemical Detection and Removal of Cd(II) and Pb(II). *Journal of Electroanalytical Chemistry* **2020**, *856*, 113744, doi:10.1016/j.jelechem.2019.113744. 877–879
65. Hube, S.; Eskafi, M.; Hrafnkelsdóttir, K.F.; Bjarnadóttir, B.; Bjarnadóttir, M.Á.; Axelsdóttir, S.; Wu, B. Direct Membrane Filtration for Wastewater Treatment and Resource Recovery: A Review. *Science of The Total Environment* **2020**, *710*, 136375, doi:10.1016/j.scitotenv.2019.136375. 880–882
66. Amy, G.; Ghaffour, N.; Li, Z.; Francis, L.; Linares, R.V.; Missimer, T.; Lattemann, S. Membrane-Based Seawater Desalination: Present and Future Prospects. *Desalination* **2017**, *401*, 16–21, doi:10.1016/j.desal.2016.10.002. 883–884
67. Tijing, L.D.; Woo, Y.C.; Choi, J.-S.; Lee, S.; Kim, S.-H.; Shon, H.K. Fouling and Its Control in Membrane Distillation – A Review. *Journal of Membrane Science* **2015**, *475*, 215–244, doi:10.1016/j.memsci.2014.09.042. 885–886
68. Ozaki, H.; Sharma, K.; Saktaywin, W. Performance of an Ultra-Low-Pressure Reverse Osmosis Membrane (ULPROM) for Separating Heavy Metal: Effects of Interference Parameters. *Desalination* **2002**, *144*, 287–294, doi:10.1016/S0011-9164(02)00329-6. 887–889
69. Kajitvichyanukul, P.; Hung, Y.-T.; Wang, L.K. Membrane Technologies for Oil–Water Separation. In *Membrane and Desalination Technologies*; Wang, L.K., Chen, J.P., Hung, Y.-T., Shammas, N.K., Eds.; Humana Press: Totowa, NJ, 2011; pp. 639–668 ISBN 978-1-58829-940-6. 890–892
70. Abdullah, N.; Yusof, N.; Lau, W.J.; Jaafar, J.; Ismail, A.F. Recent Trends of Heavy Metal Removal from Water/Wastewater by Membrane Technologies. *Journal of Industrial and Engineering Chemistry* **2019**, *76*, 17–38, doi:10.1016/j.jiec.2019.03.029. 893–894

71. He, M.; Wang, L.; Lv, Y.; Wang, X.; Zhu, J.; Zhang, Y.; Liu, T. Novel Polydopamine/Metal Organic Framework Thin Film Nanocomposite Forward Osmosis Membrane for Salt Rejection and Heavy Metal Removal. *Chemical Engineering Journal* **2020**, *389*, 124452, doi:10.1016/j.cej.2020.124452. 895  
896  
897
72. Cui, Y.; Ge, Q.; Liu, X.-Y.; Chung, T.-S. Novel Forward Osmosis Process to Effectively Remove Heavy Metal Ions. *Journal of Membrane Science* **2014**, *467*, 188–194, doi:10.1016/j.memsci.2014.05.034. 898  
899
73. Abdullah, N.; Tajuddin, M.H.; Yusof, N. Forward Osmosis (FO) for Removal of Heavy Metals. In *Nanotechnology in Water and Wastewater Treatment*; Elsevier, 2019; pp. 177–204 ISBN 978-0-12-813902-8. 900  
901
74. Cui, Y.; Wang, H.; Wang, H.; Chung, T.-S. Micro-Morphology and Formation of Layer-by-Layer Membranes and Their Performance in Osmotically Driven Processes. *Chemical Engineering Science* **2013**, *101*, 13–26, doi:10.1016/j.ces.2013.06.011. 902  
903
75. Ge, Q.; Ling, M.; Chung, T.-S. Draw Solutions for Forward Osmosis Processes: Developments, Challenges, and Prospects for the Future. *Journal of Membrane Science* **2013**, *442*, 225–237, doi:10.1016/j.memsci.2013.03.046. 904  
905
76. Chung, T.-S.; Zhang, S.; Wang, K.Y.; Su, J.; Ling, M.M. Forward Osmosis Processes: Yesterday, Today and Tomorrow. *Desalination* **2012**, *287*, 78–81, doi:10.1016/j.desal.2010.12.019. 906  
907
77. Groves, G.R.; Buckley, C.A.; Cox, J.M.; Kirk, A.; Macmillan, C.D.; Simpson, M.J. Dynamic Membrane Ultrafiltration and Hyperfiltration for the Treatment of Industrial Effluents for Water Reuse. *Desalination* **1983**, *47*, 305–312, doi:10.1016/0011-9164(83)87085-4. 908  
909  
910
78. Zheng, G. Nanofiber Membranes by Multi-Jet Electrospinning Arranged as Arc-Array with Sheath Gas for Electrodialysis Applications. *Materials and Design* **2020**. 911  
912
79. Swanckaert, B.; Geltmeyer, J.; Rabaey, K.; De Buysser, K.; Bonin, L.; De Clerck, K. A Review on Ion-Exchange Nanofiber Membranes: Properties, Structure and Application in Electrochemical (Waste)Water Treatment. *Separation and Purification Technology* **2022**, *287*, 120529, doi:10.1016/j.seppur.2022.120529. 913  
914  
915
80. Vickers, N.J. Animal Communication: When I'm Calling You, Will You Answer Too? *Current Biology* **2017**, *27*, R713–R715, doi:10.1016/j.cub.2017.05.064. 916  
917
81. Min, K.J.; Kim, J.H.; Park, K.Y. Characteristics of Heavy Metal Separation and Determination of Limiting Current Density in a Pilot-Scale Electrodialysis Process for Plating Wastewater Treatment. *Science of The Total Environment* **2021**, *757*, 143762, doi:10.1016/j.scitotenv.2020.143762. 918  
919  
920
82. Nazir, A.; Khan, K.; Maan, A.; Zia, R.; Giorno, L.; Schroën, K. Membrane Separation Technology for the Recovery of Nutraceuticals from Food Industrial Streams. *Trends in Food Science & Technology* **2019**, *86*, 426–438, doi:10.1016/j.tifs.2019.02.049. 921  
922  
923
83. Yang, X.; Wan, Y.; Zheng, Y.; He, F.; Yu, Z.; Huang, J.; Wang, H.; Ok, Y.S.; Jiang, Y.; Gao, B. Surface Functional Groups of Carbon-Based Adsorbents and Their Roles in the Removal of Heavy Metals from Aqueous Solutions: A Critical Review. *Chemical Engineering Journal* **2019**, *366*, 608–621, doi:10.1016/j.cej.2019.02.119. 924  
925  
926
84. Houari, B.; Louhibi, S.; Tizaoui, K.; Boukli-hacene, L.; Benguella, B.; Roisnel, T.; Dorcet, V. New Synthetic Material Removing Heavy Metals from Aqueous Solutions and Wastewater. *Arabian Journal of Chemistry* **2019**, *12*, 5040–5048, doi:10.1016/j.arabjc.2016.11.010. 927  
928  
929
85. Di Natale, F.; Gargiulo, V.; Alfè, M. Adsorption of Heavy Metals on Silica-Supported Hydrophilic Carbonaceous Nanoparticles (SHNPs). *Journal of Hazardous Materials* **2020**, *393*, 122374, doi:10.1016/j.jhazmat.2020.122374. 930  
931
86. Chai, W.S.; Cheun, J.Y.; Kumar, P.S.; Mubashir, M.; Majeed, Z.; Banat, F.; Ho, S.-H.; Show, P.L. A Review on Conventional and Novel Materials towards Heavy Metal Adsorption in Wastewater Treatment Application. *Journal of Cleaner Production* **2021**, *296*, 126589, doi:10.1016/j.jclepro.2021.126589. 932  
933  
934
87. Demiral, İ.; Samdan, C.; Demiral, H. Enrichment of the surface functional groups of activated carbon by modification method. *Surfaces and Interfaces* **2021**, *22*, 100873, doi:10.1016/j.surfin.2020.100873. 935  
936

88. Burakov, A.E.; Galunin, E.V.; Burakova, I.V.; Kucherova, A.E.; Agarwal, S.; Tkachev, A.G.; Gupta, V.K. Adsorption of Heavy Metals on Conventional and Nanostructured Materials for Wastewater Treatment Purposes: A Review. *Ecotoxicology and Environmental Safety* **2018**, *148*, 702–712, doi:10.1016/j.ecoenv.2017.11.034. 937–939
89. Crini, G.; Lichtfouse, E. Advantages and Disadvantages of Techniques Used for Wastewater Treatment. *Environ Chem Lett* **2019**, *17*, 145–155, doi:10.1007/s10311-018-0785-9. 940–941
90. Jagaba, A.H.; Kutty, S.R.M.; Hayder, G.; Latiff, A.A.A.; Aziz, N.A.A.; Umaru, I.; Ghaleb, A.A.S.; Abubakar, S.; Lawal, I.M.; Nasara, M.A. Sustainable Use of Natural and Chemical Coagulants for Contaminants Removal from Palm Oil Mill Effluent: A Comparative Analysis. *Ain Shams Engineering Journal* **2020**, *11*, 951–960, doi:10.1016/j.asej.2020.01.018. 942–944
91. Badawi, A.K.; Zaher, K. Hybrid Treatment System for Real Textile Wastewater Remediation Based on Coagulation/Flocculation, Adsorption and Filtration Processes: Performance and Economic Evaluation. *Journal of Water Process Engineering* **2021**, *40*, 101963, doi:10.1016/j.jwpe.2021.101963. 945–947
92. Foo, K.Y.; Hameed, B.H. Insights into the Modeling of Adsorption Isotherm Systems. *Chemical Engineering Journal* **2010**, *156*, 2–10, doi:https://doi.org/10.1016/j.cej.2009.09.013. 948–949
93. Wu, F.-C.; Tseng, R.-L.; Juang, R.-S. Initial Behavior of Intraparticle Diffusion Model Used in the Description of Adsorption Kinetics. *Chemical Engineering Journal* **2009**, *153*, 1–8, doi:https://doi.org/10.1016/j.cej.2009.04.042. 950–951
94. Mohan, D.; Pittman, C.U. Arsenic Removal from Water/Wastewater Using Adsorbents—A Critical Review. *Journal of Hazardous Materials* **2007**, *142*, 1–53, doi:https://doi.org/10.1016/j.jhazmat.2007.01.006. 952–953
95. Bhatnagar, A.; Sillanpää, M. Utilization of Agro-Industrial and Municipal Waste Materials as Potential Adsorbents for Water Treatment—A Review. *Chemical Engineering Journal* **2010**, *157*, 277–296, doi:https://doi.org/10.1016/j.cej.2010.01.007. 954–955
96. Singh, K.K.; Rastogi, R.; Hasan, S.H. Removal of Cr(VI) from Wastewater Using Rice Bran. *Journal of Colloid and Interface Science* **2005**, *290*, 61–68, doi:https://doi.org/10.1016/j.jcis.2005.04.011. 956–957
97. Mohan, S.V.; Karthikeyan, J. Removal of Lignin and Tannin Colour from Aqueous Solution by Adsorption onto Activated Charcoal. *Environmental Pollution* **1997**, *97*, 183–187, doi:https://doi.org/10.1016/S0269-7491(97)00025-0. 958–959
98. Gupta, V.K.; Ali, I.; Saleh, T.A.; Nayak, A.; Agarwal, S. Chemical Treatment Technologies for Waste-Water Recycling—an Overview. *RSC Adv.* **2012**, *2*, 6380–6388, doi:10.1039/C2RA20340E. 960–961
99. Bessbousse, H.; Rhallou, T.; Verchère, J.-F.; Lebrun, L. Removal of Heavy Metal Ions from Aqueous Solutions by Filtration with a Novel Complexing Membrane Containing Poly(Ethyleneimine) in a Poly(Vinyl Alcohol) Matrix. *Journal of Membrane Science* **2008**, *307*, 249–259, doi:10.1016/j.memsci.2007.09.027. 962–964
100. Li, P.; Jiang, H.; Barr, A.; Ren, Z.; Gao, R.; Wang, H.; Fan, W.; Zhu, M.; Xu, G.; Li, J. Reusable Polyacrylonitrile-Sulfur Extractor of Heavy Metal Ions from Wastewater. *Adv Funct Materials* **2021**, *31*, 2105845, doi:10.1002/adfm.202105845. 965–966
101. Velarde, L.; Nabavi, M.S.; Escalera, E.; Antti, M.-L.; Akhtar, F. Adsorption of Heavy Metals on Natural Zeolites: A Review. *Chemosphere* **2023**, *328*, 138508, doi:10.1016/j.chemosphere.2023.138508. 967–968
102. Perea, O.; Bode-Aluko, C.; Laatikainen, K.; Nechaev, A.; Petrik, L. Morphology, Modification and Characterisation of Electrospun Polymer Nanofiber Adsorbent Material Used in Metal Ion Removal. *J Polym Environ* **2019**, *27*, 1843–1860, doi:10.1007/s10924-019-01497-w. 969–971
103. *Adsorbents for Water and Wastewater Treatment and Resource Recovery*; Santos, S., Botelho, C., Pintor, A., Eds.; MDPI, 2022; ISBN 978-3-0365-4721-3. 972–973
104. Zhou, W.; Wu, P.; Zhang, L.; Zhu, D.; Zhao, X.; Cai, Y. Heavy Metal Ions and Particulate Pollutants Can Be Effectively Removed by a Gravity-Driven Ceramic Foam Filter Optimized by Carbon Nanotube Implantation. *Journal of Hazardous Materials* **2022**, *421*, 126721, doi:10.1016/j.jhazmat.2021.126721. 974–976

105. Li, X.; Zhang, C.; Zhao, R.; Lu, X.; Xu, X.; Jia, X.; Wang, C.; Li, L. Efficient Adsorption of Gold Ions from Aqueous Systems with Thioamide-Group Chelating Nanofiber Membranes. *Chemical Engineering Journal* **2013**, *229*, 420–428, doi:10.1016/j.cej.2013.06.022. 977–979
106. Meng, J.; Cao, J.; Xu, R.; Wang, Z.; Sun, R. Hyperbranched Grafting Enabling Simultaneous Enhancement of the Boric Acid Uptake and the Adsorption Rate of a Complexing Membrane. *J. Mater. Chem. A* **2016**, *4*, 11656–11665, doi:10.1039/C6TA02348G. 980–982
107. Horzum, N.; Shahwan, T.; Parlak, O.; Demir, M.M. Synthesis of Amidoximated Polyacrylonitrile Fibers and Its Application for Sorption of Aqueous Uranyl Ions under Continuous Flow. *Chemical Engineering Journal* **2012**, *213*, 41–49, doi:10.1016/j.cej.2012.09.114. 983–985
108. Fu, F.; Wang, Q. Removal of Heavy Metal Ions from Wastewaters: A Review. *Journal of Environmental Management* **2011**, *92*, 407–418, doi:10.1016/j.jenvman.2010.11.011. 986–987
109. Isawi, H. Using Zeolite/Polyvinyl Alcohol/Sodium Alginate Nanocomposite Beads for Removal of Some Heavy Metals from Wastewater. *Arabian Journal of Chemistry* **2020**, *13*, 5691–5716, doi:10.1016/j.arabjc.2020.04.009. 988–989
110. Yuna, Z. Review of the Natural, Modified, and Synthetic Zeolites for Heavy Metals Removal from Wastewater. *Environmental Engineering Science* **2016**, *33*, 443–454, doi:10.1089/ees.2015.0166. 990–991
111. Ahluwalia, S.S.; Goyal, D. Microbial and Plant Derived Biomass for Removal of Heavy Metals from Wastewater. *Bioresource Technology* **2007**, *98*, 2243–2257, doi:10.1016/j.biortech.2005.12.006. 992–993
112. Shreya; Verma, A.K.; Dash, A.K.; Bhunia, P.; Dash, R.R. Removal of Surfactants in Greywater Using Low-Cost Natural Adsorbents: A Review. *Surfaces and Interfaces* **2021**, *27*, 101532, doi:10.1016/j.surfin.2021.101532. 994–995
113. Ahmad, A.; Kurniawan, S.B.; Abdullah, S.R.S.; Othman, A.R.; Hasan, H.A. Exploring the Extraction Methods for Plant-Based Coagulants and Their Future Approaches. *Science of The Total Environment* **2022**, *818*, 151668, doi:10.1016/j.scitotenv.2021.151668. 996–998
114. Ueda Yamaguchi, N.; Cusioli, L.F.; Quesada, H.B.; Camargo Ferreira, M.E.; Fagundes-Klen, M.R.; Salcedo Vieira, A.M.; Gomes, R.G.; Vieira, M.F.; Bergamasco, R. A Review of Moringa Oleifera Seeds in Water Treatment: Trends and Future Challenges. *Process Safety and Environmental Protection* **2021**, *147*, 405–420, doi:10.1016/j.psep.2020.09.044. 999–1001
115. Raghuwanshi, P.K.; Mandloi, M.; Sharma, A.J.; Malviya, H.S.; Chaudhari, S. Improving Filtrate Quality Using Agrobased Materials as Coagulant Aid. *Water Quality Research Journal* **2002**, *37*, 745–756, doi:10.2166/wqrj.2002.050. 1002–1003
116. Nand, V. Water Purification Using Moringa Oleifera and Other Locally Available Seeds in Fiji for Heavy Metal Removal. **2012**, *2*, 125–129, doi:https://doi.org/10.5696/2156-9614-11.31.210911. 1004–1005
117. Etoriki, A.M.; El-Rais, M.; Mahabbis, M.T.; Moussa, N.M. Removal of Some Heavy Metals from Wastewater by Using of Fava Beans. *AJAC* **2014**, *05*, 225–234, doi:10.4236/ajac.2014.54028. 1006–1007
118. Zvinowanda, C.M.; Okonkwo, J.O.; Shabalala, P.N.; Agyei, N.M. A Novel Adsorbent for Heavy Metal Remediation in Aqueous Environments. *Int. J. Environ. Sci. Technol.* **2009**, *6*, 425–434, doi:10.1007/BF03326081. 1008–1009
119. Muyibi, S.A.; Mohd. Noor, M.J.M.; Leong, T.K.; Loon, L.H. Effects of Oil Extraction from Moringa Oleifera Seeds On Coagulation Of Turbid Water. *International Journal of Environmental Studies* **2002**, *59*, 243–254, doi:10.1080/00207230210924. 1010–1011
120. Wang, F.Y.; Wang, H.; Ma, J.W. Adsorption of Cadmium (II) Ions from Aqueous Solution by a New Low-Cost Adsorbent—Bamboo Charcoal. *Journal of Hazardous Materials* **2010**, *177*, 300–306, doi:10.1016/j.jhazmat.2009.12.032. 1012–1013
121. Zhang, H.; Zhao, D.; Chen, L.; Yu, X.J. Investigation of Cu(II) Adsorption from Aqueous Solutions by NKF-6 Zeolite. *Water Science and Technology* **2011**, *63*, 395–402, doi:10.2166/wst.2011.233. 1014–1015
122. Sen Gupta, B.; Curran, M.; Hasan, S.; Ghosh, T.K. Adsorption Characteristics of Cu and Ni on Irish Peat Moss. *Journal of Environmental Management* **2009**, *90*, 954–960, doi:10.1016/j.jenvman.2008.02.012. 1016–1017

123. Meez, E.; Rahdar, A.; Kyzas, G.Z. Sawdust for the Removal of Heavy Metals from Water: A Review. *Molecules* **2021**, *26*, 4318, doi:10.3390/molecules26144318. 1018  
1019
124. Caliceti, M.; Argese, E.; Sfriso, A.; Pavoni, B. Heavy Metal Contamination in the Seaweeds of the Venice Lagoon. *Chemosphere* **2002**, *47*, 443–454, doi:10.1016/S0045-6535(01)00292-2. 1020  
1021
125. Bilal, M.; Rasheed, T.; Sosa-Hernández, J.; Raza, A.; Nabeel, F.; Iqbal, H. Biosorption: An Interplay between Marine Algae and Potentially Toxic Elements—A Review. *Marine Drugs* **2018**, *16*, 65, doi:10.3390/md16020065. 1022  
1023
126. Alpat, S.K.; Özbayrak, Ö.; Alpat, Ş.; Akçay, H. The Adsorption Kinetics and Removal of Cationic Dye, Toluidine Blue O, from Aqueous Solution with Turkish Zeolite. *Journal of Hazardous Materials* **2008**, *151*, 213–220, doi:10.1016/j.jhazmat.2007.05.071. 1024  
1025
127. Kallo, D. Applications of Natural Zeolites in Water and Wastewater Treatment. *Reviews in Mineralogy and Geochemistry* **2001**, *45*, 519–550, doi:10.2138/rmg.2001.45.15. 1026  
1027
128. Bahrodin, M.B.; Zaidi, N.S.; Hussein, N.; Sillanpää, M.; Prasetyo, D.D.; Syafiuddin, A. Recent Advances on Coagulation-Based Treatment of Wastewater: Transition from Chemical to Natural Coagulant. *Curr Pollution Rep* **2021**, *7*, 379–391, doi:10.1007/s40726-021-00191-7. 1028  
1029  
1030
129. Yimer, A.; Dame, B. Papaya Seed Extract as Coagulant for Potable Water Treatment in the Case of Tulte River for the Community of Yekuset District, Ethiopia. *Environmental Challenges* **2021**, *4*, 100198, doi:10.1016/j.envc.2021.100198. 1031  
1032
130. Merenstein, J.L.; Bennett, I.J. Bridging Patterns of Neurocognitive Aging across the Older Adult Lifespan. *Neuroscience & Biobehavioral Reviews* **2022**, *135*, 104594, doi:10.1016/j.neubiorev.2022.104594. 1033  
1034
131. Zhang, Q.; Zhang, F.; Ni, Y.; Kokot, S. Effects of Aluminum on Amyloid-Beta Aggregation in the Context of Alzheimer's Disease. *Arabian Journal of Chemistry* **2019**, *12*, 2897–2904, doi:10.1016/j.arabjc.2015.06.019. 1035  
1036
132. Rahman, N.S.A.; Yhaya, M.F.; Azahari, B.; Ismail, W.R. Utilisation of Natural Cellulose Fibres in Wastewater Treatment. *Cellulose* **2018**, *25*, 4887–4903, doi:10.1007/s10570-018-1935-8. 1037  
1038
133. Rima, J.; Rahme, K.; Assaker, K. The Use of Modified Beetroot Fibers by Sodium Dodecyl Sulfate (SDS) Cleaning Water Contaminated by Organic and Inorganic Compounds. *JFR* **2014**, *3*, 19, doi:10.5539/jfr.v3n5p19. 1039  
1040
134. Rima, J.; Assaker, K. B-Cyclodextrin Polyurethanes Copolymerised with Beetroot Fibers (Bio-Polymer), for the Removal of Organic and Inorganic Contaminants from Water. *JFR* **2013**, *2*, 150, doi:10.5539/jfr.v2n1p150. 1041  
1042
135. Rima, J.; Ghauch, A.; Ghaouch, M.; Martin-Bouyer, M. Cleaning of Water Contaminated by Heavy Metals Using Beetroot Fibers as Biofilter. *Toxicological & Environmental Chemistry* **2000**, *75*, 89–97, doi:10.1080/02772240009358895. 1043  
1044
136. Abdulla, G.; Kareem, M.M.; Hashim, K.S.; Muradov, M.; Kot, P.; Mubarak, H.A.; Abdellatif, M.; Abdullhadi, B. Removal of Iron from Wastewater Using a Hybrid Filter. *IOP Conf. Ser.: Mater. Sci. Eng.* **2020**, *888*, 012035, doi:10.1088/1757-899X/888/1/012035. 1045  
1046  
1047
137. Hussain, S.; Aziz, H.A.; Isa, M.H.; Ahmad, A.; Van Leeuwen, J.; Zou, L.; Beecham, S.; Umar, M. Orthophosphate Removal from Domestic Wastewater Using Limestone and Granular Activated Carbon. *Desalination* **2011**, *271*, 265–272, doi:10.1016/j.desal.2010.12.046. 1048  
1049  
1050
138. Bakar, A.A.A.; Razak, N.F.; Akbar, N.A.; Daud, N.M.; Ali, K.A.M. Removal of Cr (III) from Industrial Wastewater Using Coconut Shell Carbon and Limestone as Adsorbent. *IOP Conf. Ser.: Earth Environ. Sci.* **2021**, *646*, 012063, doi:10.1088/1755-1315/646/1/012063. 1051  
1052  
1053
139. Li, Z.; Pan, Z.; Wang, Y. Preparation of Ternary Amino-Functionalized Magnetic Nano-Sized Illite-Smectite Clay for Adsorption of Pb(II) Ions in Aqueous Solution. *Environ Sci Pollut Res* **2020**, *27*, 11683–11696, doi:10.1007/s11356-020-07766-9. 1054  
1055
140. He, H.; Meng, X.; Yue, Q.; Yin, W.; Gao, Y.; Fang, P.; Shen, L. Thiol-Ene Click Chemistry Synthesis of a Novel Magnetic Mesoporous Silica/Chitosan Composite for Selective Hg(II) Capture and High Catalytic Activity of Spent Hg(II) Adsorbent. *Chemical Engineering Journal* **2021**, *405*, 126743, doi:10.1016/j.cej.2020.126743. 1056  
1057  
1058

141. Mahmoud, M.E.; Hafez, O.F.; Alrefaay, A.; Osman, M.M. Performance Evaluation of Hybrid Inorganic/Organic Adsorbents in Removal and Preconcentration of Heavy Metals from Drinking and Industrial Waste Water. *Desalination* **2010**, *253*, 9–15, doi:10.1016/j.desal.2009.11.044. 1059–1061
142. Chen, S.; Yuan, Z.; Hanigan, D.; Westerhoff, P.; Zhao, H.; Ni, J. Coagulation Behaviors of New Covalently Bound Hybrid Coagulants (CBHyC) in Surface Water Treatment. *Separation and Purification Technology* **2018**, *192*, 322–328, doi:10.1016/j.seppur.2017.10.036. 1062–1064
143. Yang, J.; Shen, M.; Wen, H.; Luo, Y.; Huang, R.; Rong, L.; Xie, J. Recent Advance in Delivery System and Tissue Engineering Applications of Chondroitin Sulfate. *Carbohydrate Polymers* **2020**, *230*, 115650, doi:10.1016/j.carbpol.2019.115650. 1065–1066
144. Gupta, V.K.; Agarwal, S.; Ahmad, R.; Mirza, A.; Mittal, J. Sequestration of Toxic Congo Red Dye from Aqueous Solution Using Ecofriendly Guar Gum/ Activated Carbon Nanocomposite. *International Journal of Biological Macromolecules* **2020**, *158*, 1310–1318, doi:10.1016/j.ijbiomac.2020.05.025. 1067–1069
145. Harikishore Kumar Reddy, D.; Vijayaraghavan, K.; Kim, J.A.; Yun, Y.-S. Valorisation of Post-Sorption Materials: Opportunities, Strategies, and Challenges. *Advances in Colloid and Interface Science* **2017**, *242*, 35–58, doi:10.1016/j.cis.2016.12.002. 1070–1072
146. Tamjidi, S.; Esmaeili, H.; Kamyab Moghadas, B. Application of Magnetic Adsorbents for Removal of Heavy Metals from Wastewater: A Review Study. *Mater. Res. Express* **2019**, *6*, 102004, doi:10.1088/2053-1591/ab3ffb. 1073–1074
147. Hwang, S.Y.; Lee, G.B.; Kim, J.H.; Hong, B.U.; Park, J.E. Pre-Treatment Methods for Regeneration of Spent Activated Carbon. *Molecules* **2020**, *25*, 4561, doi:10.3390/molecules25194561. 1075–1076
148. Jiang, D.; Chu, B.; Amano, Y.; Machida, M. Removal and Recovery of Phosphate from Water by Mg-Laden Biochar: Batch and Column Studies. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* **2018**, *558*, 429–437, doi:10.1016/j.colsurfa.2018.09.016. 1077–1079
149. Zhang, X.N.; Mao, G.Y.; Jiao, Y.B.; Shang, Y.; Han, R.P. Adsorption of Anionic Dye on Magnesium Hydroxide-Coated Pyrolytic Bio-Char and Reuse by Microwave Irradiation. *Int. J. Environ. Sci. Technol.* **2014**, *11*, 1439–1448, doi:10.1007/s13762-013-0338-5. 1080–1082
150. Momina, M.; Shahadat, M.; Isamil, S. Regeneration Performance of Clay-Based Adsorbents for the Removal of Industrial Dyes: A Review. *RSC Adv.* **2018**, *8*, 24571–24587, doi:10.1039/C8RA04290J. 1083–1084
151. Acevedo-García, V.; Rosales, E.; Puga, A.; Pazos, M.; Sanromán, M.A. Synthesis and Use of Efficient Adsorbents under the Principles of Circular Economy: Waste Valorisation and Electroadvanced Oxidation Process Regeneration. *Separation and Purification Technology* **2020**, *242*, 116796, doi:10.1016/j.seppur.2020.116796. 1085–1087
152. Lata, S.; Singh, P.K.; Samadder, S.R. Regeneration of Adsorbents and Recovery of Heavy Metals: A Review. *International Journal of Environmental Science and Technology* **2015**, *12*, 1461–1478, doi:10.1007/s13762-014-0714-9. 1088–1089
153. Ruthiraan, M.; Mubarak, N.M.; Abdullah, E.C.; Khalid, M.; Nizamuddin, S.; Walvekar, R.; Karri, R.R. An Overview of Magnetic Material: Preparation and Adsorption Removal of Heavy Metals from Wastewater. In *Magnetic Nanostructures: Environmental and Agricultural Applications*; Abd-Elsalam, K.A., Mohamed, M.A., Prasad, R., Eds.; Springer International Publishing: Cham, 2019; pp. 131–159 ISBN 978-3-030-16439-3. 1090–1093
154. Younas, F.; Mustafa, A.; Farooqi, Z.U.R.; Wang, X.; Younas, S.; Mohy-Ud-Din, W.; Ashir Hameed, M.; Mohsin Abrar, M.; Maitlo, A.A.; Noreen, S.; et al. Current and Emerging Adsorbent Technologies for Wastewater Treatment: Trends, Limitations, and Environmental Implications. *Water* **2021**, *13*, doi:10.3390/w13020215. 1094–1096
155. El Messaoudi, N.; El Khomri, M.; El Mouden, A.; Bouich, A.; Jada, A.; Lacherai, A.; Iqbal, H.M.N.; Mulla, S.I.; Kumar, V.; Américo-Pinheiro, J.H.P. Regeneration and Reusability of Non-Conventional Low-Cost Adsorbents to Remove Dyes from Wastewaters in Multiple Consecutive Adsorption–Desorption Cycles: A Review. *Biomass Conversion and Biorefinery* **2022**, doi:10.1007/s13399-022-03604-9. 1097–1100

156. Tiwari, A.K.; Pal, S.L.; Srivastava, N.; Shah, M.; Ahmad, I.; Alshahrani, M.Y.; Pal, D.B. Bioadsorbent and Adsorbent-Based Heavy Metal Removal Technologies from Wastewater: New Insight. *Biomass Conversion and Biorefinery* **2023**, *13*, 13335–13356, doi:10.1007/s13399-022-02343-1.
157. Bello, M.M.; Raman, A.A.A. Synergy of Adsorption and Advanced Oxidation Processes in Recalcitrant Wastewater Treatment. *Environmental Chemistry Letters* **2019**, *17*, 1125–1142, doi:10.1007/s10311-018-00842-0.
158. Ahalya, N.; Kanamadi, R.D.; Ramachandra, T.V. Biosorption of Chromium (VI) from Aqueous Solutions by the Husk of Bengal Gram (Cicer Arientinum). *Electron. J. Biotechnol.* **2005**, *8*, 258–264, doi:10.2225/vol8-issue3-fulltext-10.
159. Wang, W.; Wang, R.; Zhang, C.; Lu, S.; Liu, T. Synthesis, Characterization and Self-Assembly Behavior in Water as Fluorescent Sensors of Cationic Water-Soluble Conjugated Polyfluorene-b-Poly(N-Isopropylacrylamide) Diblock Copolymers. *Polymer* **2009**, *50*, 1236–1245, doi:10.1016/j.polymer.2008.12.026.
160. Kurniawan, T.A.; Chan, G.Y.S.; Lo, W.-H.; Babel, S. Physico-Chemical Treatment Techniques for Wastewater Laden with Heavy Metals. *Chemical Engineering Journal* **2006**, *118*, 83–98, doi:10.1016/j.cej.2006.01.015.
161. Barakat, M. Removal of Toxic Cyanide and Cu(II) Ions from Water by Illuminated TiO<sub>2</sub> Catalyst. *Applied Catalysis B: Environmental* **2004**, *53*, 13–20, doi:10.1016/j.apcatb.2004.05.003.
162. Chakraborty, R.; Asthana, A.; Singh, A.K.; Jain, B.; Susan, A.B.H. Adsorption of Heavy Metal Ions by Various Low-Cost Adsorbents: A Review. *International Journal of Environmental Analytical Chemistry* **2022**, *102*, 342–379, doi:10.1080/03067319.2020.1722811.
163. *Adsorption Processes for Water Treatment and Purification*; Bonilla-Petriciolet, A., Mendoza-Castillo, D.I., Reynel-Ávila, H.E., Eds.; Springer International Publishing: Cham, 2017; ISBN 978-3-319-58135-4.
164. Abdullah, R.; Abustan, I.; Ibrahim, A.N.M. Wastewater Treatment Using Bentonite, the Combinations of Bentonite- Zeolite, Bentonite-Alum, and Bentonite-Limestone as Adsorbent and Coagulant. **2013**, *4*, 13.
165. Zheng, R.; Chen, Y.; Wang, J.; Song, J.; Li, X.-M.; He, T. Preparation of Omniphobic PVDF Membrane with Hierarchical Structure for Treating Saline Oily Wastewater Using Direct Contact Membrane Distillation. *Journal of Membrane Science* **2018**, *555*, 197–205, doi:10.1016/j.memsci.2018.03.041.
166. Boulaadjoul, S.; Zemmouri, H.; Bendjama, Z.; Drouiche, N. A Novel Use of Moringa Oleifera Seed Powder in Enhancing the Primary Treatment of Paper Mill Effluent. *Chemosphere* **2018**, *206*, 142–149, doi:10.1016/j.chemosphere.2018.04.123.

**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.