

A Minimax-Based Review of Lead Removal from Wastewater: Current Technologies and Future Perspectives

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Abstract

Lead (Pb) contamination in wastewater is a pervasive global concern, with concentrations varying widely (e.g., <0.001 to 990 mg/L), its effective removal is crucial for environmental and public health. This review highlights that lead is a common toxic metal pollutant from industrial waste and batteries, occurs naturally at low levels which is increased by global production from manufacturing (e.g., automobiles, mobile phone batteries) that led to widespread soil, water, and air pollution and impact the ecosystems and wildlife. To mitigate these risks, various physical (e.g., membrane separation, adsorption), chemical (e.g., precipitation, ion-exchange), and biological (e.g., biosorption, bioremediation) techniques have been successfully employed for lead removal from wastewater. Furthermore, this review focusing on the adverse impacts of lead pollution and sustainable remediation strategies for lead-associated waste.

Keywords: Heavy metal, Pollution, Environment, Health, Lead removal strategies

1. Introduction

The ecology and human health are severely impacted by heavy metals present in water. Mercury, cadmium, arsenic, and particularly lead are examples of natural elements that are difficult to decompose. Rather, through a process known as bioaccumulation, they gradually accumulate in living organisms and can even reach larger concentrations in top-ranking species. Lead (Pb²⁺) is one of these heavy metals that is particularly dangerous and ubiquitous. Its toxicity is widely known, and exposure can happen in a number of ways, most commonly through polluted air and water (Wani et al., 2015). Lead may be effectively removed from wastewater through various Physical, Chemical and Biological methods. Lead removal from wastewater has advantages for the economy as well as the environment and public health and it can be obtained more cheaply by recovering and recycling it from wastewater, which eliminates the need for costly mining and smelting processes (Y. Zhang et al., 2019).

The inherent toxicity of lead was unequivocally established in the late 19th century, leading to a progressive reduction in its application across various industries. Nevertheless, a significant public health challenge persists globally, as numerous countries continue to permit the commercialization of lead-containing products. Notable examples include certain paint formulations and ammunition, which serve as ongoing sources of human exposure. Lead can enter the human body through three primary routes: inhalation, ingestion, or dermal absorption (Kansaraa & Solanki, 2019). Heavy metals primarily originate from both natural and anthropogenic sources. Natural contributors include processes such as soil erosion, volcanic activity, urban runoff, and atmospheric particulate matter. In contrast, human-driven activities like metal finishing and electroplating, mining operations, textile manufacturing, and nuclear power generation significantly contribute to heavy metal release (Moore, 1977).

1.1 Status of lead pollution in India

Particularly in industrial locations and places that use untreated or partially treated effluent, lead pollution in India's wastewater continues to be a major environmental and public health concern. Wastewater from industrial locations in Bikaner, Rajasthan, had lead levels between 0.047 and 0.106 mg/L, which was significantly higher than the Bureau of Indian Standards and World Health Organization guidelines (Rathore, D. S., Kaur, L., & Choyal, 2023).

Lead concentrations in Taloja (Mumbai) effluent from petrochemical and fine-chemical plants reached 9.5 mg/L, which is up to 190 times higher than the acceptable safe level of 0.05 mg/L. This poses an immediate toxicity danger to aquatic ecosystems (Lokhande, R. S., Singare, P. U., & Pimple, 2011). Lead-laden effluents are also released by Mandideep (Bhopal) electroplating factories, underscoring the insufficient treatment facilities in heavy-industry clusters (Saini et al., 2024). In Punjab, crops and soil that are irrigated with untreated sewage—which can be contaminated with lead—have up to four to five times the lead content of crops that are irrigated with groundwater (Dheri et al., 2007). Due to untreated industrial wastewater, the Jojari River in Rajasthan is still highly contaminated with lead and cadmium, which has an effect on the groundwater that 1.6 million people utilize (Meena, A. L., & Meghwal, 2019).

India still lacks enough wastewater treatment capacity, with only around 30% of sewage receiving basic treatment and heavy metals in industrial effluents frequently evading tertiary safeguards despite the Water (Prevention and Control of Pollution) Act and state pollution boards' efforts (Nath, R. S., & Parmar, N. D., 2023). Lead continues to enter wastewater due to inadequate heavy-metal discharge standards, uneven enforcement, and disjointed industry monitoring, causing long-term risks to human health, agriculture, and ecosystems. Important next initiatives to reduce lead pollution in India's wastewater include upgrading to strong industrial effluent treatment, enforcing stricter heavy metal regulations, and growing monitoring networks (Raj & Das, 2023).

1.2 Status of lead pollution in Gujarat

There is still a serious problem with lead pollution in Gujarat's wastewater, especially in industrial areas like Ahmedabad, Ankleshwar, Vadodara, and Vapi. Heavy-metal-laden sewage, tainted by industrial effluent, has been utilized for decades to irrigate farmland downstream of Ahmedabad. Research indicates that wastewater contains excessive amounts of lead (0.4–1.6 µg/mL), which can contribute to soil lead levels up to 12 times higher than permissible limits. Lead concentrations in Gujarat's major rivers, such as the Sabarmati, Tapi, Narmada, Damanganga, and Purna, are also higher than allowed limits, mostly as a result of untreated industrial discharge (Chaudhari et al., 2024).

Effluent treatment infrastructure remains fragmented and underperforming. GIDC estates like Ankleshwar, Panoli, and Jhagadia operate CETPs and a centralized FETP, yet these facilities often fail compliance, leading to moratoriums since 2007 and intermittent enforcement. (Brahmbhatt, 2012). In the meantime, despite laws, industrial centers like Vadodara's VECL continue to release untreated water into the Mahi estuary, containing heavy metals and other contaminants. (Nihalani et al., 2021).

The Gujarat Pollution Control Board has started enforcing Zero Liquid Discharge (ZLD) in phases and promoting industrial reuse of treated effluent to lower contamination in response to orders from the Supreme Court, High Court, and CPCB. Furthermore, temporary solutions like the 22-kilometer pipeline project on the Sabarmati are designed to redirect treated wastewater from direct disposal to irrigation (Mahida et al., 2022). The ongoing presence of lead in wastewater and soil reveals structural shortcomings in infrastructure, enforcement, and coordination, despite growing awareness and progress being made—such as preliminary ZLD adoption and court-enforced treatment. To safeguard Gujarat's ecosystems, agriculture, and public health, a unified policy with precise guidelines, efficient CETP/FETP oversight, increased ZLD implementation, and strict monitoring is still necessary (Clark et al., 2005).

2. Effect of lead contamination on Environment and Human health

Lead is used so widely in consumer and commercial products like paints, gasoline, and plumbing infrastructure, it has historically caused severe environmental contamination that continues to pose major health hazards to the general public. There are several ways to get exposed to lead. In addition, the breakdown from ancient water pipes can contaminate potable water supplies, while industrial emissions and the disturbance of polluted soil can aerosolize lead particles, making them easier to inhale. Upon entry into the human body via ingestion or inhalation, lead acts as a potent neurotoxin, precipitating severe damage to the central and peripheral nervous systems. This neurotoxic effect is particularly pronounced in children, whose developing brains exhibit heightened susceptibility to its detrimental impacts, leading to a spectrum of neuro developmental deficits including learning disabilities, diminished intellectual quotients, and behavioral abnormalities. Furthermore, lead exposure in adults is associated with a range of adverse

health outcomes, including neurological impairments, renal dysfunction, and hypertension. (Blanco et al., 2021).

Lead can also penetrate the placental barrier and expose a growing fetus to lead poisoning, which may lead to severe consequences for the mother and the unborn child, such as delayed fetal growth or premature birth (Charkiewicz & Backstrand, 2020). In addition to being harmful to human health, lead is a significant contaminant of soil, water, and the atmosphere. Because of this widespread contamination, even very small amounts can have significant environmental effects. Lead, for example, may disturb natural food webs, inhibit fish and other animals' growth and reproduction, and eventually threaten biodiversity in aquatic ecosystems. Because of the persistence of pollutants in the environment, contaminated areas can continue to cause issues for many years, highlighting the significance of preventative and cleanup initiatives (Wani et al., 2015).

The US Environmental Protection Agency (USEPA) and the International Agency for Research on Cancer (IARC) have classified lead as a potential human carcinogen due to its toxicity. The levels of lead in drinking water have been set by several health agencies. For instance, Health Canada bases its maximum acceptable concentration (MAC) at 5 µg/L on the idea that levels should be kept "as low as reasonably achievable" (ALARA). In contrast, the World Health Organization (WHO) and the European Community Directive have set a maximum permissible limit of 10 µg/L for lead in tap water. For drinking water, the USEPA has set an action level of 15 µg/L (USEPA (US Environmental Protection Agency) 2009)). Lead is usually found in nature as lead sulfide or as a complex combination which includes zinc sulfide and lead [(Hayes C, Hoekstra EJ 2010) (Acharya, 2013) (Meena et al., 2020)(WHO (World Health Organization), 2011)].

Through a variety of industrial processes, lead and its compounds contaminate our soil, air, and water. Lead release occurs during the manufacturing of matches, explosives, pigments, photographic materials, and even printing, storage batteries, television tubes, and paints. Furthermore, vehicle exhaust, sewage, burning fossil fuels, runoff from cities and farms, forest fires, and even volcanic eruptions are some of the ways that lead enters the environment. [(Cabral-Pinto et al., 2020) (Kumar et al., 2020)].

There are several ways that lead enters our surface and groundwater. It can enter into these essential sources through acidic rain that drains through soils and wastewater from homes and businesses that is dumped into water bodies. One of the main causes of lead pollution is industrial activity. In particular, industrial waste releases a large amount of lead that is used in ceramics, glass, paints, pigments, acid batteries, printed circuit boards, and weaponry into the environment. There are several different types of lead, such as sulfides, oxides, and salts. The lead starts to build up in sediments, soils, plants, and animals when industrial effluents containing these lead compounds are discharged into waterways, gradually increasing in the environment (Cabral-Pinto & Ferreira da Silva, 2019). This accumulation has serious implications that causes direct risks to human health and the environment due to its numerous negative impacts, which include declining plant growth and contaminating our food and drinking water resources (Mudgal S, 2016). Lead can enter wastewater from a number of sources, such as air deposition, municipal emissions, and industrial operations. The specific sources of Pb in wastewater in Asia may vary depending on the country and region. Pb levels in wastewater can be significantly raised by procedures used in battery manufacturing, electronic waste recycling, and metal mining and smelting.



Figure 1. various sources of heavy metal lead in environment.(Raj & Das, 2023)

Pb concentrations in wastewater from Pb-acid battery recycling facilities ranged from 47 to 1,038 mg/L, according to studies conducted in India. This is significantly higher than the US-EPA's recommended level of 0.05 mg/L for wastewater and the WHO's recommended limit of 0.01 mg/L for drinking water (Kumar et al., 2016). Lead which can originate from lead-based paints, plumbing fixtures, and lead pipes, may be found in wastewater from municipal facilities. For example, a study conducted in China found that the wastewater from a residential area with a Pb concentration of 0.27 to 1.39 mg/L was mostly caused by the Pb pipes and fittings in the water supply system (Tang et al., 2020).

Similar results were found in Thailand, where studies showed that the use of Pb-based paint in residential areas was associated with lead levels in municipal wastewater that ranged from 0.04 to 1.47 mg/L (Kaewkrajang et al., 2014). Additionally, Pb deposition in the atmosphere can result in lead pollution in wastewater. Pb-containing particles that are deposited by industrial processes or vehicle emissions may be the source of this. For example, a study conducted in Malaysia found that atmospheric deposition was a major contributor to Pb pollution in river water and that there was a strong correlation between atmospheric deposition and Pb concentrations in river water. (Mohd Nadzir et al., 2019). Similarly, a study conducted in India found a strong relationship between Pb concentrations in airborne particulate matter and wastewater (Kumar et al., 2016). A few hundred publications were reported on the removal of lead ions.

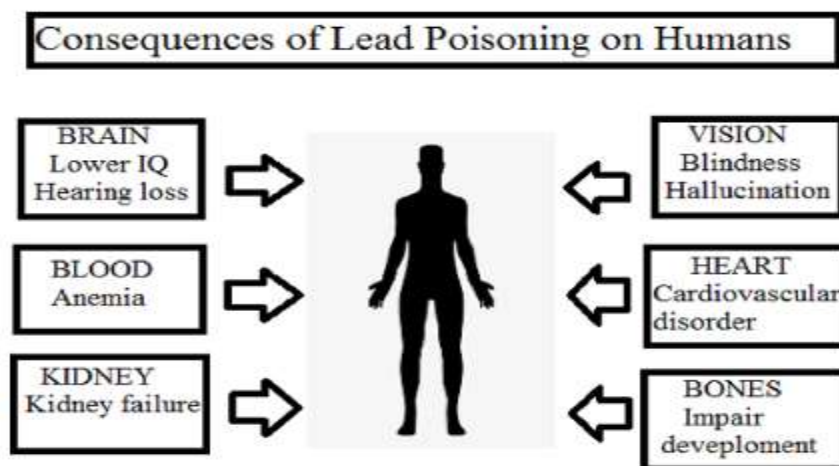


Figure 2. The consequences of Lead Poisoning on Human (Raj & Das, 2023)

3. Methodologies for the treatment of lead-contaminated wastewater

As we have covered in earlier parts, the contamination of our surrounding ecosystem by heavy metals has been growing over the past few decades, impacting our environment, food chain, and health in a number of ways. Finding a workable and long-term solution to this specific issue is now imperative. The surrounding environments and local creatures are primarily impacted by these heavy metal (Pb) contaminants where they are produced or discharged. As a result, certain methods concentrate on site-specific lead remediation to ensure the systematic elimination of contaminants (Wani et al., 2015).

Various techniques exist to reduce lead (Pb) concentrations in wastewater, falling into physical, chemical, and biological categories. While each method has its own strengths and limitations, all of them—whether used alone or in combination—have been successfully employed to treat lead-contaminated water. All of the physical, chemical, and biological techniques for treating wastewater polluted with lead have been covered here [(Ahmad et al., 2023) (Das et al., 2014)].

In general, managing wastewater that contains lead which requires determining a balance between downstream treatment of its byproducts, sustainability, cost, and removal efficiency. This review critically examines key treatment methods, focusing especially on emerging low-cost adsorbents and combined strategies that offer strong performance without generating hazardous waste. A comparative analysis of three popular wastewater treatment methods—coagulation-flocculation, ion exchange, and adsorption—was carried out to test and assess their efficacy in removing lead (Pb) from contaminated water in order to

gain a better understanding of how various approaches address lead pollution. The results of these studies showed that while all three techniques could effectively remove lead from wastewater, coagulation-flocculation was the most successful in significantly lowering lead levels in wastewater, demonstrating its high efficacy in removing lead contamination (Jabeen & Su, 2016).

Numerous treatment methods, such as chemical precipitation, adsorption, membrane filtration, ion exchange, and biological treatment, can be used to remove lead from wastewater. By using these methods, Pb may be effectively removed from wastewater and its concentration reduced to levels that are acceptable. Among the factors influencing the choice of treatment approach are the starting Pb concentration, wastewater volume, treatment expenses, and final disposal method. The characteristics of the effluent and the required level of lead removal determine the method to be used. The cost, operating requirements, and efficacy of these approaches vary. Lead can be removed from wastewater using one of three different types of treatment methods: physical, chemical, or biological (Ahmad et al., 2023).

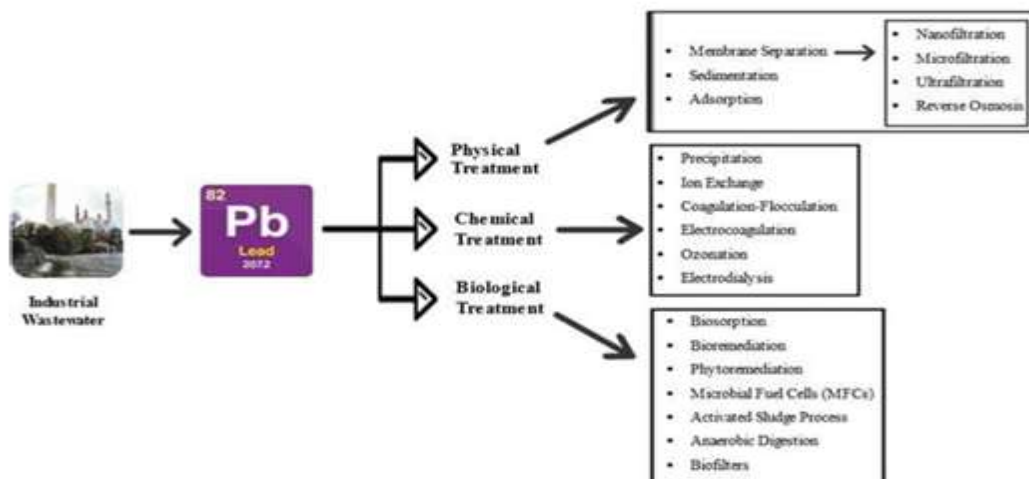


Figure-3: Lead-contaminated wastewater treatment process partitioned into various physical, chemical, and biological treatment methods for Pb removal (Ahmad et al., 2023)

3.1 Physical treatment

Following are the physical treatment methods used for removal of Pb from waste water.

3.1.1 Membrane filtration

One of the best physical treatment methods for eliminating lead (Pb) from wastewater is membrane separation. This technique separates different components from a liquid stream in a selective manner using a permeable membrane. Usually, the wastewater is forced through a porous membrane by applying pressure to it. Particles smaller than a specific size can pass through the membrane's properly sized pores, but bigger contaminants, like lead ions, are retained. Lead can be effectively removed using membrane filtration techniques such as ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO), which mainly work on the principle of size exclusion with additional mechanisms based on pore size. By creating a pressure gradient across a semipermeable membrane, these methods capture lead and other impurities while permitting cleansed water to flow through. Membrane filtration has been shown in numerous studies to be highly effective in eliminating lead from wastewater [(Gholami et al., 2016)(Khajeh et al., 2018)]. These methods have demonstrated a lot of promise for treating wastewater contaminated with lead. Due to their effectiveness, affordability, and environmental friendliness, these methods are a desirable choice for treating wastewater in municipalities and industries. These kinds of membrane techniques are primarily employed for Pb removal (Zhao et al., 2019).

Ultrafiltration

Ultrafiltration (UF) is a membrane-based technology used to remove lead (Pb) from wastewater. Its semi-permeable membrane, with pore sizes ranging from 0.001 to 0.1 μm , allows water and small molecules to pass through while retaining larger particles, including lead ions. Common membrane materials include cellulose acetate, polyether sulfone, and polyvinylidene fluoride. In practice, as lead-containing wastewater flows through the UF system, the membrane separates and concentrates the lead, yielding purified water as the permeate. The concentrated lead can then be recovered from the retained residue, often using techniques like ion-exchange or precipitation [(Rahmanian et al., 2012) (Mozia & Tomaszewska, 2004)].

Researchers have explored various methods for removing lead from industrial wastewater. One study investigated a combined approach of chemical precipitation and ultrafiltration (UF), demonstrating an impressive 99.9% lead removal, bringing concentrations well below discharge limits. Another study looked into a hybrid system using UF and adsorption. This combined process proved more effective than either method alone, achieving an even higher lead removal efficiency of up to 99.99%. These findings highlight the potential of integrated treatment approaches for robust lead remediation in industrial settings (Y. Zhang et al., 2019).

Ultrafiltration (UF) is a proven technology for treating lead-contaminated industrial wastewater. For example, one study at a battery production facility showed that UF successfully removed over 95% of lead from their wastewater. In some cases, UF can even achieve up to 99% lead removal. However, its effectiveness can vary depending on operational factors like pH, membrane pore size, and pressure. This suggests that UF is a promising solution for cleaning lead-contaminated wastewater, particularly in industries like battery manufacturing [(Chowdhury et al., 2021) (Wan et al., 2020)].

Overall, ultrafiltration (UF) has a lot of potential for eliminating lead (Pb) from wastewater, and when paired with other purification technologies, it can be much more successful. It has a number of benefits over conventional techniques, such as increased efficiency, reduced energy usage, and the capacity to function at room temperature and pressure. However, UF does have its limitations. To avoid fouling and scaling, which can lower efficiency, regular membrane cleaning and maintenance are crucial. Furthermore, pre-treatment is frequently necessary for wastewater in order to eliminate organic materials and bigger particles that could clog the membrane (Kulkarni RS, Dhanorkar SP, 2018).

Nanofiltration

Nanofiltration (NF) is a highly effective method for removing lead (Pb) from wastewater, capable of filtering particles as small as 1 nanometer. Studies consistently demonstrate its high efficiency. For example, a commercial NF membrane was found to remove 98.5% of lead from wastewater by Gazi University in Turkey. Similarly, 98.7% lead removal was successfully achieved in a study conducted by the University of Tehran in Iran using a polyamide nanofiltration membrane. Both ultrafiltration (UF) and NF membranes were found to be effective in removing lead from synthetic wastewater. But NF was particularly better than UF, attaining a removal effectiveness of 99.9% as opposed to UF's 98.5%. The combined results of these studies demonstrate NF's great potential for lead remediation in wastewater, which is especially important in areas with strict environmental restrictions [(Gurses et al., 2011)(Gholami et al., 2016) (Khajeh et al., 2018)].

Reverse osmosis

Reverse osmosis (RO) is also highly effective membrane-based water treatment technology capable of removing lead (Pb) from wastewater. This process works by applying pressure to force water molecules through a semi-permeable membrane, which effectively blocks larger particles, including lead ions. A study conducted by researchers at the University of Bologna in Italy demonstrated the efficacy of RO in treating industrial wastewater contaminated with Pb and other heavy metals. Their reverse osmosis system, equipped with a polyamide membrane, successfully removed over 99% of lead from the wastewater. This research underscores the significant potential of reverse osmosis for robust lead remediation in industrial applications (Cavazzini et al., 2014). In short, reverse osmosis (RO) is a highly effective method for removing lead (Pb) from wastewater, with numerous studies confirming its success in treating both industrial wastewater and drinking water. Sometimes, ultrafiltration (UF) is used in conjunction with RO to boost system efficiency and prolong membrane life.

Microfiltration

Microfiltration (MF) is a proven membrane technology used to treat wastewater. It works by employing a microfiltration membrane to filter out particles, bacteria, and other contaminants, including lead (Pb) particles. These membranes have pores ranging from 0.1 to 10 μm , effectively removing various sizes of impurities. As wastewater passes through the membrane, lead particles are retained on the surface, allowing the cleaned water to be collected on the other side. Research supports MF's effectiveness in lead removal. For example, one study found that microfiltration, operating at a flux rate of 105 L/m²/h, could remove up to 98% of lead from synthetic wastewater. Another study explored a hybrid system combining microfiltration with adsorption, demonstrating its capability to remove lead from wastewater at a rate of 86

L/m² [(Jafari et al., 2017)(Khosravi et al., 2016)]. It is a very successful treatment for lead-contaminated wastewater from an electronic waste recycling business, according to research. These research showed that up to 99.6% of lead could be removed at a working pressure of 0.3 MPa using a polyether sulfone (PES) membrane with 0.2 µm holes. MF is a good choice for lead removal because of its capacity to remove both dissolved and particulate lead, as well as its small size and low energy consumption. But it's crucial to keep in mind that MF isn't a stand-alone remedy. Microfiltration should be combined with other treatment methods to completely remove lead from wastewater (Y. Wang et al., 2020).

3.1.2 Sedimentation

Sedimentation is a widely used method for treating wastewater containing heavy metals like lead (Pb). This method uses gravity to cause lead and other suspended particles to drop to the bottom of a tank. Chemicals like flocculants and coagulants can be added to assist the removal of lead. These facilitate the clumping of tiny lead particles into heavier, bigger aggregates that settle more readily. After that, the settled lead particles are taken out of the tank and disposed of appropriately [(W. Wang et al., 2021)(S. S. Ng et al., 2017)]. Studies show sedimentation can be highly effective. For example, one study found it could remove up to 99% of Pb from wastewater, with faster settling resulting in higher removal rates. Another study investigating real-world wastewater demonstrated that combining sedimentation with other techniques like coagulation and flocculation significantly increased Pb removal. Additionally, research indicates sedimentation can remove up to 95% of Pb from groundwater (S. K. S. Gupta et al., 2016). However, sedimentation alone may not be enough if lead is present as dissolved ions. In such cases, chemical precipitation might be necessary alongside sedimentation to ensure complete lead removal. It's crucial to remember that sedimentation usually works best when combined with other treatment methods for comprehensive lead removal. Also, proper disposal of the settled lead sludge is vital to prevent environmental contamination.

3.1.3 Adsorption

Adsorption is a popular and successful method for eliminating heavy metals like lead (Pb) from wastewater; it is valued for its affordability, ease of use, and effectiveness. For treating wastewater with moderate Pb concentrations, usually between 1 ppb and 100 ppm, it is an economically feasible option. An adsorbent substance that draws and retains metal ions is necessary for this procedure. Lead can be adsorbed by a wide range of materials, including zeolites, silica gel, chitosan, activated carbon, and other organic and inorganic substances. These were selected due to their price, accessibility, and user-friendliness, as well as their capacity to adsorb Pb ions selectively. The selected adsorbent is usually introduced to the wastewater and mixed for a predetermined amount of time throughout the adsorption process (Dahiya et al., 2020).

It is a relatively straightforward and economical technique. A key advantage of adsorption is that it does not produce sludge, and it offers a wide, affordable range of adsorbent materials tailored to specific heavy metals. This process works by leveraging the molecular force of attraction to separate impurities from water. Adsorbent media are carefully chosen for their ability to effectively extract dissolved target materials from a solution, holding them as a molecular or atomic film (called the adsorbate) on the adsorbent's surface. To ensure optimal performance and minimize environmental impact, careful consideration of the adsorbent material selection and process variables is crucial (Nasir et al., 2021).

Types of adsorbents

The low-cost adsorbents were divided into five categories in order to more accurately evaluate the development of the adsorbents: natural materials, industrial byproducts, agricultural waste, forest debris, and materials derived from biotechnology. The source materials are abundant in nature and/or disposed of as trash, suggesting that they have a significant potential to provide inexpensive adsorbents. These resources are shown below:

Natural materials

Various natural materials have been explored for removing lead ions from water. These include common substances like natural clay (Khalfa et al., 2021), sand particles (Lai et al., 2000), peat moss (Lubbad & Al-Batta, 2020), natural goethite (Abdus Salam & Adekola, 2005), natural bentonite clay (Pfeifer A, Škerget M, Čolnik M 2020), chitin (Kim et al., 2006), and talc surface (Chandra et al. 2005).. Notably, natural bentonite clay and its acid-activated form have shown impressive results, with reported maximum adsorption capacities of 83.0 mg/g and 92.9 mg/g of lead ions, respectively (Budsareechai et al., 2012). Studies show acid-activated bentonite clay can adsorb up to 92.9 mg/g of lead (Pb) ions, while natural bentonite clay can adsorb 83.0 mg/g. (Budsareechai S, Kamwialisak K, Ngernyen Y 2012).

Researchers successfully created new adsorbents by coating expanded clay (exclay) aggregates with activated carbon nanoparticles to remove lead (Pb) from water. These treated aggregates proved highly effective, achieving a maximum adsorption capacity of 22.8 mg/g and removing 99% of Pb from a 100 mg/L solution using an adsorbent dose of 10 g/L (Ghahremani A, Manteghian M, Kazemzadeh H 2021). Aloi clay is highly effective at removing lead (Pb) ions, boasting an adsorption capacity of 333.3 mg/g and capable of removing up to 97.3% of Pb^{2+} from solutions with concentrations ranging from 30–150 mg/L (Obayomi KS, Auta M 2019). Saudi Arabian clay can adsorb up to 30 mg/g of lead (Pb) ions. Meanwhile, natural goethite proved even more effective, completely removing Pb ions at concentrations as high as 750 mg/L (Abdus Salam & Adekola, 2005). Bentonite exhibited its best performance for adsorption between a pH of 7 and 8.5, achieving a maximum capacity of 119.7 mg (Pfeifer et al., 2021).

(Katoh et al., 2016) investigated how well apatite removes lead (Pb) ions, both with and without organic acids. Their experiments showed that the maximum removal capacities varied depending on the acid used: 1330 mg/g with formic acid, 1010 mg/g with no acid, 896 mg/g with malic acid, and 782 mg/g with citric acid. In the absence of organic acid, lead was removed through the precipitation of lead phosphate minerals primarily on the surface of the apatite particles. When formic acid was present, the dissociation of hydrogen ions led to a decrease in pH, which in turn boosted the apatite's capacity to remove lead. Apatite primarily removes lead (Pb) ions through a process of dissolution followed by the precipitation of lead phosphate [(Kaludjerovic-Radoicic & Raicevic, 2010) (Oliva et al., 2012)]

(Rashed, 2001) found that chalcopyrite is an effective adsorbent for lead (Pb) ions, demonstrating a maximum adsorption capacity of 99 mg/g. It achieved 100% removal of Pb^{2+} from an initial concentration of 50 mg/L with a contact time of 96 hours. Other studies showed that sphagnum peat moss (Ratoi et al., 2008) and peat moss (Akinbiyi A 2000) also performed well, with maximum Pb^{2+} removal capacities of 98% and 96%, respectively.

Industrial Byproducts as Adsorbents

Industrial byproducts are proving to be effective adsorbents for removing heavy metals from water. Key examples of these waste materials include iron slag, steel slag, fly ash, sawdust, and red mud [(H. Chen et al., 2020)(V. K. Gupta & Ali, 2004)].

Red mud, a waste product from processing bauxite ore, has shown remarkable effectiveness in removing lead (Pb) ions from water. Studies indicate it can completely remove Pb^{2+} from a 50 mg/L initial concentration within just 60 minutes across a broad pH range of 2–8 (Ghorbani et al., 2013). Its adsorption capacity improved from 16.4 to 19.2 mg/g after acid treatment, boosting removal efficiency from 79.6% to 85.2%. Further enhancements, achieved by coating it with iron oxide, increased the removal efficiency to 93.6% and the adsorption capacity to 27.0 mg/g (Narayanan et al., 2018).

Steel dust, an industrial byproduct from steel production, has shown promise in removing lead (Pb) from water. Specifically, Ladle Furnace steel dust demonstrated a high adsorption capacity of 208.9 mg/g, while Cyclone steel dust achieved 39.8 mg/g (Bouabidi et al., 2018).

Fly ash has proven effective as a column adsorbent for lead (Pb), achieving a 95–96% removal efficiency for initial concentrations ranging from 5.0–70.0 mg/L (V. K. Gupta & Ali, 2004). Coal fly ash itself has demonstrated a significant capacity, removing up to 352.2 mg/g of Pb (Woolard et al., 2000). Furthermore, modified coal fly ash has been successfully used in simultaneous adsorption studies to remove both Pb and zinc (Zn) ions, showing impressive adsorption capacities of 31.4 mg/g for Pb and 27.0 mg/g for Zn, respectively (Astuti et al., 2021).

Sawdust activated carbon has shown excellent performance in removing lead (Pb) ions, achieving a maximum adsorption capacity of 109.8 mg/g for initial concentrations ranging from 51.8 to 414.4 mg/L. Its effectiveness is attributed to specific surface characteristics: a particle size of 0.096 mm, 5.31% ash content, 1.02 g/mL apparent density, 3.16 meq/g cation-exchange capacity, 4.02 meq/g total acidic sites, and 1.95 meq/g carboxylic acid content (Sreejalekshmi et al., 2009). Overall, industrial byproducts show significant promise as effective and affordable adsorbents for removing lead (Pb) from waste water (Jahangiri et al., 2021).

3.2 Chemical treatments

3.2.1 Precipitation

Precipitation is a common and effective method for removing lead (Pb) from wastewater. This process involves adding a chemical reagent to the wastewater, which reacts with dissolved lead ions to form solid particles called "precipitates." These solid precipitates can then be easily separated from the liquid. Various

chemical agents can be used to precipitate lead, including lime, sodium hydroxide, and sulfide. The choice of reagent depends on factors such as the wastewater's pH, the concentration of lead, and the presence of other contaminants. Typically, the process begins by adjusting the wastewater's pH to optimize the reaction with the chosen reagent. The reagent is then slowly added with continuous stirring until all lead ions have precipitated. Finally, the resulting slurry of lead precipitates can be separated from the treated water using methods like filtration, settling, or centrifugation [(X. Chen et al., 2017)(P. Sharma & Pant, 2016)]. It is important to note that precipitation by itself might not be sufficient to remove lead from wastewater, especially when Pb concentrations are high. In order to achieve the appropriate level of treatment, other procedures like reverse osmosis or ion exchange could be required.

3.2.2 Ion exchange

Ion exchange is an effective method for removing lead (Pb) from wastewater. This process utilizes ion exchange resins, which are porous, insoluble materials with a large surface area. These resins work by selectively capturing target ions, like lead, from a solution and releasing other ions of the same charge in their place. Typically, lead-contaminated wastewater is passed through a column packed with ion exchange resin. The resin then adsorbs the lead ions, simultaneously releasing ions such as sodium or hydrogen into the water. Once the resin becomes saturated with lead, it can be regenerated by flushing it with a solution that removes the captured lead ions and restores the resin's original capacity (A. K. Sharma et al., 2019).

In a study, researchers used a cation exchange resin with sulfonic acid groups to treat lead (Pb)-contaminated wastewater from a battery manufacturing plant. This resin effectively removed Pb with an impressive adsorption capacity of 95.8 mg/g. The study also highlighted the resin's economic viability, as it could be regenerated and reused multiple times (Yang et al., 2018). Although ion exchange is a very effective method for removing lead at extremely low concentrations, it can also be expensive, particularly when extended treatment is needed. Other possible disadvantages of ion exchange include the need for the formation of concentrated waste streams during resin regeneration, as well as for the regular replacement and disposal of resin.

3.2.3 Coagulation-Flocculation

Coagulation and flocculation are widely employed methods for lead (Pb) removal from wastewater, working by adding chemicals to form settleable or filterable flocs. The process typically begins with pH adjustment to an optimal range of 6.5-7.5, followed by the addition of a coagulant like aluminum sulfate to neutralize particle charges and induce clumping. A flocculant, often a polymer, is then introduced to enhance floc growth and settling efficiency. The resulting flocs are subsequently removed via sedimentation or filtration. Studies confirm the efficacy of these methods; for example, one study showed a natural coagulant removed up to 89% of Pb from wastewater. While highly effective, the choice of coagulant, which can include aluminum sulfate, composite coagulants, and chitosan-coated magnetite nanoparticles, depends on the specific wastewater characteristics and the required level of lead removal [(Karimi et al., 2018) (Nourmoradi et al., 2019)].

3.2.4 Electrocoagulation

Electrocoagulation (EC) is a promising electrochemical process for removing heavy metals like lead (Pb) from wastewater. It works by applying an electric current to electrodes submerged in the wastewater, which causes charged pollutants, including lead ions, to coagulate and settle out. This process forms a metal hydroxide floc that effectively adsorbs and traps lead ions, carrying them out of the water as the floc settles. Research has demonstrated impressive results, with one study showing 99.9% Pb removal efficiency from synthetic wastewater. A significant advantage of EC is its versatility; it can treat diverse wastewater types and is easily scalable for large volumes. Furthermore, it's a relatively straightforward process that avoids the need for chemical additives and the generation of hazardous byproducts. While electrocoagulation offers a powerful solution for lead removal, it's essential to consider the specific characteristics of the wastewater and the desired treatment outcomes before implementing this approach [(Ayodele et al., 2020) (Kumar et al., 2019) (Khataee et al., 2018)].

3.2.5 Ozonation

Ozonation is a promising technology for removing lead (Pb) from wastewater. This process uses ozone gas, a powerful oxidizing agent, to break down and eliminate pollutants. When ozone is introduced into water, it reacts with and oxidizes pollutants like lead, transforming them into harmless byproducts. The effectiveness of ozonation for removing lead (Pb) from wastewater is influenced by several key factors: the concentration of Pb in the wastewater, the pH of water, the presence of other contaminants, and the contact time between the ozone and the water. Because these variables can differ significantly, the optimal

conditions for treating Pb-contaminated wastewater with ozonation will vary depending on the specific situation, and you'll need to determine them through testing and analysis (Saleh et al., 2020).

Research highlights the effectiveness of ozonation in treating lead (Pb) contaminated wastewater. A study by (Diao et al., 2018) showed that combining activated carbon with ozonation improved Pb removal. Furthermore, (S. Wang et al., 2018) found that ozonation alone could remove up to 95% of Pb ions in real-world applications, noting that factors like pH, ozone dosage, and initial Pb concentration influenced the removal efficiency. Even more impressively, ozonation treatment of wastewater from the lead-acid battery industry achieved up to 99% Pb ion removal, proving efficient even with low ozone dosages and quick reaction times (L. Zhang et al., 2020). Additionally, (Khataee et al., 2018) demonstrated that integrating photocatalysis with ozonation significantly boosted Pb removal efficiency from wastewater.

Overall, ozonation presents a viable option for treating wastewater contaminated with lead (Pb). However, its effectiveness and feasibility must be evaluated case-by-case for each unique situation. It's important to remember that ozonation is often employed as a pre-treatment step to eliminate organic compounds and other pollutants. Consequently, it might not be a standalone solution for Pb removal. For comprehensive treatment, other techniques like coagulation, precipitation, and ion exchange may need to be used in conjunction with ozonation (Tahoon et al., 2020).

3.3 Biological treatment methods

Biological approaches offer an environmentally friendly and pollution-free way to remediate heavy metals.

3.3.1 Biosorption

Biosorption is an effective and eco-friendly method for removing heavy metals like lead (Pb), a common and toxic industrial pollutant, from wastewater. This technique utilizes various forms of biomass, including bacteria, fungi, algae, and plants, to adsorb lead. For instance, one study investigated agricultural waste biomass for Pb removal. It found that maize cob powder and peanut shell powder exhibited impressive maximum adsorption capacities of 42.13 mg/g and 50.65 mg/g for lead, respectively (Ogunkunle et al., 2021). Biological methods, leveraging organisms or their byproducts, effectively detoxify soil and water. They achieve this without harmful side effects, preserving the natural properties and quality of the environment. Microorganisms are key players in this process, with prominent examples including species like *Pseudomonas*, *Nitrosomonas*, and *Mycobacterium* [(Ghosh & Das, 2017) (Ghosh et al., 2021)].

3.3.2 Bioremediation

Bioremediation utilizes microbial cells to remove heavy metals from water. A study investigating the effectiveness of various microorganisms in lead (Pb) removal from wastewater found that *Candida albicans* and *Pseudomonas aeruginosa* demonstrated high clearance efficiencies, at 91.1% and 93.4% respectively. Another study also explored the use of fungal biomass for Pb removal from wastewater (Rani et al., 2020). It may effectively remove lead (Pb) from wastewater, but its success depends on factors like the specific microbes or plants used, environmental conditions, and the initial Pb concentration. This method isn't a complete solution on its own; it needs to be combined with other treatments to ensure safe Pb levels. Additionally, careful monitoring is crucial to confirm that Pb ion concentrations are adequately reduced (Hamzah et al., 2020) (Bayuo et al., 2022).

3.3.3 Phytoremediation

Phytoremediation is an economical and environmentally friendly method for removing lead (Pb) and other heavy metals from contaminated soil and water. This technique addresses the significant threat of lead pollution by using plants, such as water hyacinth, duckweed, and water lettuce, to absorb, accumulate, and detoxify heavy metals through a process called phytoextraction. It can be implemented in various settings like constructed wetlands or phytoreactors. While effective, its efficiency can vary based on factors such as the plant species, lead concentration, and treatment duration. A major advantage of phytoremediation is its ability to be combined with other treatment technologies for improved removal rates, and after absorption, the lead-laden plants can be harvested for disposal or lead recovery (Yadav et al., 2019).

Numerous studies highlight the efficiency of phytoremediation in removing lead (Pb) from wastewater. For example, water hyacinth (*Eichhornia crassipes*) has demonstrated a remarkable ability to remove up to 95.8% of lead from simulated wastewater. Another study investigated the Pb removal capabilities of four different plants: morning glory, purslane, spearmint, and sweet basil. All four proved effective, with purslane achieving the highest success, eliminating up to 98.5% of Pb from the wastewater (El-Naggar et al., 2020).

3.3.4 Microbial-Bioremediation

Microbial bioremediation, also known as microbial remediation, is a process where microorganisms extract contaminants, such as heavy metal pollutants, from soil and water by metabolizing them into less toxic substances. A modern application of this is bio-leaching, a technology that relies on metal-extracting microorganisms and their metabolites to recover metals. Given the widespread industrial use and production of lead (Pb) and its residues, a thorough, molecular-level understanding of the microbial metabolites produced by specific microorganisms is crucial; this knowledge will facilitate the discovery and application of novel microorganisms for enhanced bioremediation efforts (Bal & Das, 2020).

Microbial bio-leaching of lead (Pb) involves various microorganisms whose metabolite production is significantly influenced by environmental factors like climate. These microbial strains employ diverse strategies to convert toxic lead into less harmful forms. To enhance the degradation of metal ores in contaminated soil or waste, the population of these microorganisms needs to be increased which boosts the secretion of their beneficial metabolites. However, it is crucial to have a thorough understanding of both the specific microbe and the toxic compound being treated, as enzymatic transformations can sometimes inadvertently create metabolites that are more toxic than the original pollutant. Therefore, the process begins with an examination of the contaminated soil and water to confirm the presence of a particular heavy metal. Subsequently, indigenous bacteria are carefully selected through rigorous performance testing. The most suitable bacteria are then reintroduced into the soil, where they grow, thrive, and effectively digest and convert heavy metal pollutants into their less harmful metabolites (Bhattacharjee et al., 2022).

A few key elements need to be carefully managed for microbial lead (Pb) treatment to be successful: choosing the appropriate contaminant-degrading microbial residents is critically important. A sufficient amount of oxygen is necessary, specifically 0.5 mg/L in soil and water and 2-3% in gas form. Microbial survival depends on maintaining a soil water-holding capacity of 60–70%, a pH of 6.5–7 for ideal growth, and a temperature range of 0–40 °C (Dasa et al., 2013). Additionally, key nutrients like nitrogen, sulfur, and phosphorus are necessary to support microbial health. Various bacterial species such as *Bacillus* sp., *Enterobacter cloacae*, and *Alcaligenes* sp., along with fungal species like *Aspergillus niger*, are known for their ability to adsorb or extract Pb, with some fungal strains achieving up to 90% extraction via bio-leaching. Algal species including *Spirulina maxima*, *Cladophora* sp., and *Palmaria* sp. are also recognized for their significant role in the bio-leaching of heavy metals (Das & Ghosh, 2022).

Microbial-assisted phytoremediation is an innovative technique that utilizes the potential of plants and their associated rhizosphere microorganisms (like *Beijerinckia*, *Flavobacterium*, and *Erwinia*) to clean up contaminated soil and water. To identify the most effective microbial species for this process, scientists use various molecular techniques such as PCR, gel electrophoresis, and RISA (Das et al., 2011).

(Sdiri et al., 2016) demonstrated that natural clay minerals, particularly those from the Early Cretaceous period in Tunisia, are highly versatile and cost-effective adsorbents for lead (Pb) ions due to their excellent ion exchange capacity, catalytic support, and large surface area. Composed mainly of silica, alumina, and iron and magnesium oxides, these clays showed a remarkable ability to remove Pb ions, achieving an efficiency of approximately 86.4 mg/g. The adsorption process was rapid, with over 95% removal occurring within 30 minutes and full completion within an hour, following pseudo-second-order kinetics. Notably, 1.0 g of the clay could adsorb up to 133.60 mg of lead, a process well-described by the Langmuir isotherm model, confirming their strong potential as natural adsorbents for lead in water.

(Wen et al., 2018) developed a novel biosorbent by immobilizing *Bacillus licheniformis* with sodium alginate in magnetic polyvinyl alcohol (PVA), which exhibited excellent lead adsorption fitting pseudo-second-order kinetics and a Langmuir monolayer model. Separately, (Bhat et al., 2015) investigated the removal of lead (Pb(II)) ions using γ -Alumina, prepared via the gel combustion method. Their experimental data, best described by a non-linear Type I isotherm, showed that γ -Alumina is an effective lead adsorbent, capable of being regenerated up to three times with significant adsorption levels, as confirmed by a Box–Behnken Method (BBM) statistical analysis.

Removing heavy metals from industrial wastewater is a global challenge, as these non-biodegradable inorganic pollutants persist in nature, harming humans, plants, animals, and aquatic systems when they enter the food chain. This study focused on removing lead from water using unmodified bentonite clay from the Bhavnagar area as an adsorbent. XRD characterization confirmed montmorillonite as the primary clay mineral. Batch experiments demonstrated the clay's effectiveness, with experimental data fitting the Langmuir adsorption isotherm and showing a maximum adsorption capacity of 26.3 mg/gram (correlation

coefficient 0.955). These findings strongly support the field application of Bhavnagar bentonite clay for lead removal from aqueous solutions (M. R et al., 2017).

(Aslan & Özçayan, 2019) demonstrated that calcium hydroxyapatite, synthesized from phosphogypsum waste, is a highly efficient adsorbent for removing lead-210 (^{210}Pb) from water. Under optimal conditions, it achieved a 95% adsorption rate. Kinetic analyses confirmed its excellent performance, highlighting its potential as an effective adsorbent for radioactive and industrial waste treatment (Awual, 2019) emphasized the critical need for treating toxic water contaminants due to severe anthropogenic pollution. They highlighted the demand for sensitive and selective novel materials for water remediation. Their research suggests that a specially designed solid composite material offers an efficient, cost-effective, and promising solution for the selective detection and removal of lead (Pb(II)) ions from wastewater.

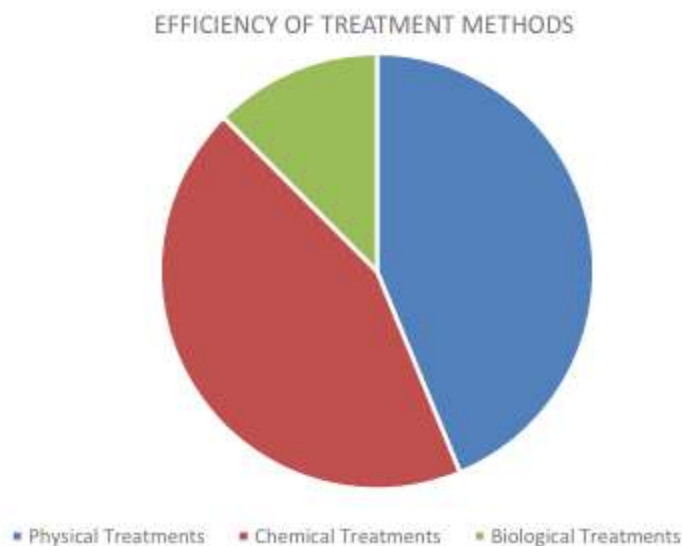


Figure 4: Treatment methods and their relative efficiency for removal of Lead from waste water.

(Anwar, 2018) successfully created an easy-to-make and eco-friendly manganese oxide nanoparticles dispersed in chitosan (CS-MnO_2) nanocomposite using a chemical precipitation method. They confirmed its formation through various spectroscopic techniques, including X-ray scattering, scanning electron microscopy, Fourier transform infrared spectroscopy, thermogravimetric analysis, and zeta potential. Additionally, antibacterial studies showed that this bionanocomposite exhibited moderate activity against specific bacterial strains.

(Novais et al., 2016) developed new porous biomass fly ash-containing geopolymer monoliths through a simple and adaptable method. They created geopolymers with varying total porosities (from 41.0% to 78.4%) and low apparent densities (between 0.44 and 1.21 g/cm^3). Their research then explored using these novel materials to adsorb lead (Pb) under different conditions. The findings revealed that both the geopolymers' porosity and the pH of the lead ion solution significantly influenced their adsorption capacity. Lead adsorption ranged from 0.95 to 6.34 mg Pb/g geopolymer. More porous geopolymers showed better lead removal, while higher solution pH actually reduced removal efficiency due to increased metal precipitation. Research in Scientific Reports demonstrated that unmodified pomelo peels effectively adsorb lead(II) from water. Using Doehlert designs, a predictive model identified optimal conditions (pH 3, 50 °C, 210 min contact for 20 mg/L initial Pb(II)) achieving 99.9% removal. The study also found that other common metal ions did not interfere, suggesting pomelo peels' potential for simultaneous heavy metal adsorption (Y. S. Ng et al., 2016).

(Yan et al., 2017) developed a porous adsorbent for lead(II) by activating chrome-tanned leather waste with sodium hydroxide (NaOH). They optimized preparation parameters including NaOH concentration, particle size, activation time, and temperature. The resulting alkali-activated porous leather particles (AAPLP), characterized by BET, SEM, FT-IR, TG, and XPS, exhibited a doubled BET surface area compared to unactivated waste. The study suggested that ion exchange and complexation were key adsorption mechanisms. They also investigated the impact of solution pH, temperature, and contact time on adsorption capacity. Experimental data best fit the Freundlich isotherm and followed pseudo-second-order kinetics, with the kinetic data further indicating a three-stage intraparticle diffusion process.

(Rajkumar V. Raikar, Sefra Correa, 2015) investigated lead(II) removal from water using four forms of rice husk: natural (RH), carbonized ash (RHA), and those pretreated with phosphoric acid (PRH) or acetic acid (ARH). All forms exhibited favorable adsorption. Batch studies confirmed that adsorption efficiency was dependent on pH, contact time, adsorbent dosage, and adsorbate concentration. Maximum removal rates varied from 93.36% (RH) to 99.35% (ARH). While RH, RHA, and PRH fit the Freundlich isotherm, ARH followed the Langmuir model. Both RH and RHA displayed pseudo-second-order kinetics.

(Bouabidi et al., 2018) investigated using steel-making dust from a local factory to remove hazardous lead (Pb(II)) ions from water. Their study found that the Dubinin-Radushkevich model best described the adsorption, with high Akaike weights (0.91 for Ladle Furnace dust and 0.83 for Cyclone dust). The optimal pH range was 4–5, preventing lead precipitation. Maximum adsorption capacities, derived from the Langmuir isotherm, were 208.9 mg/g for Ladle Furnace steel dust and 39.8 mg/g for Cyclone steel dust. Overall, steel-making dust proved highly efficient at reducing lead concentrations in aqueous solutions, suggesting its potential for industrial adsorption applications.

(Lawal et al., 2017) investigated the ability of black walnut (*Juglans nigra*) seed husk (WSH) biomass to biosorb lead (Pb(II)) ions from water. Using batch adsorption techniques, they examined how factors like pH, contact time, initial Pb(II) concentration, and temperature influenced the process. Their analysis revealed that the adsorption equilibrium was best explained by the Freundlich model, and the adsorption kinetics fit a pseudo-second-order model. Thermodynamic studies further indicated that the biosorption of Pb(II) ions onto WSH was both spontaneous and endothermic. Additionally, an FTIR study identified O-H, C=O, C-O, C-H, and N-H functional groups as crucial for binding Pb(II) ions to the biomass.

(Ravulapalli & Kunta, 2018) explored the use of nitric acid-activated carbon derived from *Caryota urens* seeds (ACSCU) and calcium alginate beads doped with this active carbon (CABCU) as adsorbents for removing lead (II) ions from contaminated water through batch extraction. They characterized the active carbon using XRD, FESEM, and FT-IR, and their investigation into the sorption mechanism revealed that the **Freundlich model** best described the adsorption process. Thermodynamic analysis indicated that the adsorption was **endothermic and spontaneous**, while the **pseudo-second-order model** accurately defined the adsorption kinetics. Furthermore, **separation parameter (RL) values less than 1.0** confirmed the favorable adsorption of Pb(II) onto the zeolite-NaX, demonstrating the successful application of their developed methodology to various industrial effluent samples.

4. Critical analysis and future trend

Lead (Pb) in water is a major global concern because it is highly toxic and causes severe, long-term health implications for humans and plants due to its inherent toxicity. This review specifically examines various technologies of lead removal from contaminated water and wastewater, with a strong emphasis on low-cost adsorbents. While diverse physical, chemical, and biological treatment methods exist, adsorption has emerged as a particularly suitable and widely favored technology for addressing both municipal and industrial lead pollution. It is mostly preferred because of its cost-effectiveness, ease of application, and demonstrated high removal efficiency (Kamal & Rafey, 2023).

Wastewater pollution causes widespread harm, from degrading ecosystems to endangering lives. Industrial discharge, laden with heavy metals, dyes, and other organic pollutants, severely impacts aquatic ecosystems by deteriorating water quality and disrupting natural balances. Current wastewater treatment methods, however, have notable drawbacks. These include the incomplete removal of contaminants (especially with conventional technologies), insufficient nutrient removal (which can cause issues like eutrophication and harmful algal blooms), high energy consumption, heavy reliance on chemicals (leading to disinfection by-products and residues in treated water), and the creation of byproducts that pose further environmental risks and limit resilience to climate change. Developing countries, in particular, face challenges such as inadequate treatment of industrial and hazardous waste, which can lead to new pollutants like organic matter and pathogens, along with limited public awareness and engagement. Ultimately, these flaws can have serious implications, leading to continued environmental harm even after treatment (Mahmoud & Mostafa, 2023).

While methods like chemical precipitation are popular for high heavy metal concentrations due to their simplicity and low cost, they often fall short of meeting strict regulatory limits, requiring further treatment, a challenge also faced by coagulation-flocculation. Electrochemical cells offer selective removal without added chemicals but are energy-intensive, and membrane separation, despite its high efficiency, is

hampered by cost and fouling. For lower metal content, ion exchange is used but incurs high investment and resin issues, while adsorption, though cost-effective, struggles with regeneration (Gong et al., 2021). Consequently, developing novel and environmentally acceptable approaches to remove heavy metals is crucial; this necessitates further research into aspects like energy consumption, resource recovery potential, technological innovation, environmental regulations and policies, compliance frameworks, the environmental footprint of byproducts, capital and operational costs, political enforcement, and the resilience of infrastructure to climate change impacts (Mohanapriya et al., 2023).

Future research in wastewater treatment must prioritize the development of cost-effective, efficient, and environmentally friendly materials. It is crucial to evaluate each proposed treatment approach from laboratory to pilot scale to thoroughly assess its practical viability. Furthermore, total wastewater management can be greatly improved by integrating cutting-edge technologies like blockchain, IoT sensors, and artificial intelligence (AI) with onsite and community-scale treatment solutions. Predictive maintenance, process optimization, and real-time monitoring can all be enhanced by these technologies. It is also crucial to take climate change resilience into account while developing infrastructure. Additionally, handling the growing amounts of wastewater will need the development of portable and flexible treatment facilities. Developing financially and environmentally sound technologies to efficiently prevent heavy metal contamination and protect our priceless water resources is the ultimate goal.

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