Journal of Material Cycles and Waste Management (2023) 25:2559–2583
https://doi.org/10.1007/s10163-023-01720-w

SPECIAL FEATURE: REVIEW

Mercury cycles and their management

Mercury recycling technologies in its' end-of-life management: a review

Balakrishnan Subeshan[1] · Anh Pham[1] · Md. Shafinur Murad[1] · Eylem Asmatulu[1]

Received: 29 December 2022 / Accepted: 31 May 2023 / Published online: 18 June 2023

Abstract
Mercury (Hg) is a naturally occurring chemical found in rock and coal deposits that can exist in various forms, including elemental Hg, inorganic Hg compounds, methylmercury, and other organic compounds. Exposure to Hg, primarily inorganic Hg, can have severe environmental and occupational hazards and harm human health. Therefore, it is crucial to understand the complex natural transformations and cyclic environmental processes of Hg and its impact on human health and the ecosystem. Both natural and human activities are mainly responsible for the Hg cycles in the environment. Combustion of fossil fuel and subsequent smelting activities are the primary sources from nature for the Hg cycles, while human activities like industrial processes and the use of products containing mercury also contribute to Hg in the environment. These sources ultimately release elemental Hg into the environment, and this Hg vapor can stay in the atmosphere for years and spread throughout the environment via various media. Besides, the whole process repeats and completes the Hg cycle. This review provides detailed knowledge of Hg cycles in the environment, proper end-of-life management of mercury-contained products, and the most up-to-date compilation of Hg recycling technologies, emphasizing the importance of proper Hg waste management. The study also emphasizes the need for a clear understanding of the relationship between local conditions and Hg levels in the environment to forecast Hg concentrations and their ability to be absorbed by living matter. The study also highlights the significance of suitable collection and recovery of Hg waste to prevent its improper disposal, which may lead to contamination of the air, rivers, lakes, and drinking water, thus increasing the risk to the environment and human health.

Keywords Mercury recycles · Methylmercury · Recycling · Thermal desorption

Introduction

Mercury (Hg) is a naturally occurring chemical that is found in rock in the earth's crust. This chemical element is also found in deposits of coal. Hg may exist in several forms, like elemental (metallic) Hg, inorganic Hg compounds, methylmercury, and other organic compounds. If elemental Hg is exposed at room temperature, it can evaporate to become an invisible, odorless toxic vapor; if heated, it becomes a colorless, odorless gas. However, when this Hg reacts with other substances, it forms an inorganic Hg salt compound or methylmercury. Inorganic Hg compounds are abundant in the environment, primarily formed as the mineral's cinnabar and metacinnabar, and sometimes as impurities in other minerals. When these inorganic Hg salts encounter airborne particles, these particles fall on land through rain and snowfall [1].

Hg can freely blend with chlorine, sulfur, and other elements. Subsequently, the weather helps the formation of the inorganic salts, which are available freely in the environment. Moreover, the generated inorganic Hg salts can also be easily transferred to water and soil. Mining deposits or ores generate dust which contains Hg salt, a source of Hg that can also be transmitted to the environment. Many coal-fired power plants, burning of municipal and medical waste, and other factories that use Hg are significant sources of emissions of both elemental and inorganic Hg. The inorganic Hg can also contaminate the water and soil from the rocks that contain inorganic Hg salts, from various factories' waste

---

✉ Eylem Asmatulu
e.asmatulu@wichita.edu

[1] Department of Mechanical Engineering, Wichita State University, 1845 Fairmount St., Wichita, KS 67260, USA

disposal, and sometimes from effluent treatment facilities that release mercury-contained water into the soil, and water [1].

Human exposure to inorganic Hg has both occupational and environmental hazards. Occupational Hg exposure happens in mining, electrical equipment manufacturing, and chemical and metal processing. Using soaps, creams, topical antiseptics, and disinfectants containing Hg can also increase exposure to mercuric chloride [2].

Once Hg is released into the environment, it can be converted to various forms and move easily into air, water, soil, plants, and animals for prolonged periods, which is hazardous. The most dangerous elemental Hg usually stays in the air for quite a long time and can be transferred from one place to another by wind, either as vapor or particles. These emissions can circulate in the atmospheric environment for up to a year and can potentially travel longer distances to locations far from their original source before being deposited. Ideally, Hg that is emitted into the atmosphere can also be easily deposited on land and surface waters and can also get in contact with water bodies and soils. It also can be re-emitted from land, freshwater, and the oceans back into the atmosphere, a cyclic process. These natural transformations and cyclic environmental processes of Hg are very complex and significantly affected by many conditions, especially the local conditions. Therefore, very clear knowledge of the relationships between local conditions and Hg levels in the environment is key to forecasting the Hg concentration in the environment and its ability to be absorbed by living matter [3].

Methylmercury can easily affect human health by consumption of contaminated fish and rice, and elemental Hg vapor is very harmful to the central nervous system, while inorganic Hg compounds primarily affect the kidney. Hg is considered a hazardous waste since it doesn't disappear from mercury-containing products by itself and finds its way to get into the environment. That's why mercury-containing products cannot be disposed of with a regular trash bin or poured down the drain. Hg products and compounds must be recycled as hazardous waste and must need to follow the standard procedure [4].

Based on the information mentioned here, it is imperative to understand and get detailed knowledge of how Hg cycles in the environment and good collection and recovery of Hg waste. Hg can be recovered from various sources like automotive switches, electrical devices, fluorescent and high-intensity discharge (HID) lamps, medical equipment, Hg compounds, precision instruments and thermostats, dental amalgam, and so. Though Hg has traditionally been used in many medical apparatus, electrical devices, precision instruments, and other elements for various critical industrial applications, Hg is a highly toxic material that needs to be disposed of properly once it is completed its useful life. Improperly disposing of Hg may lead to contamination of the air, rivers, lakes, and drinking water, thus increasing risk to the environment and human health. So, knowledge of Hg cycles and their recovery process should be one of the prime focus areas to look after.

Bioaccumulation is another critical issue related to Hg contamination in the environment resulting from the improper disposal of Hg waste. Once Hg is released into the environment, it undergoes various transformations, and its different forms can enter the food chain. For example, microorganisms and algae can transform Hg into methylmercury, which is the most hazardous form of Hg. Through bioaccumulation, methylmercury is then accumulated in the tissues of aquatic organisms, especially fish and shellfish [5]. The bioaccumulation process results in the concentration of methylmercury in the tissues of these organisms, with the concentration increasing as it moves up the food chain. When humans consume contaminated fish and shellfish, they can be exposed to methylmercury, which can cause serious health problems, particularly for developing fetuses and young children. Methylmercury exposure can cause developmental delays, cognitive deficits, and other neurological problems. Pregnant women, and young children are particularly susceptible to the harmful effects of methylmercury. High levels of methylmercury exposure also can lead to a range of health problems, including damage to the nervous system, kidneys, and immune system [6].

Furthermore, the environmental impacts of Hg contamination resulting from improper disposal are not limited to bioaccumulation and subsequent exposure to humans. Hg contamination can also have severe ecological impacts, particularly on aquatic ecosystems. The accumulation of Hg in aquatic organisms can disrupt the food chain, leading to changes in the abundance, and diversity of aquatic species. Hg contamination can also affect some aquatic species' reproductive success and survival, particularly fish and amphibians. In summary, the improper disposal of Hg waste can result in the bioaccumulation of methylmercury in the food chain, leading to exposure to humans and potential health impacts [7]. Additionally, Hg contamination can have severe ecological impacts on aquatic ecosystems, disrupting the food chain and affecting the reproductive success and survival of some aquatic species. Therefore, it is essential to take measures to properly dispose of Hg waste, and prevent its release into the environment to minimize the potential for bioaccumulation, and exposure. This can include proper recycling and disposal of Hg-containing products, and reducing the use of Hg in various industries and applications [8].

Among the contaminants found in the environment, Hg is a heavy metal discharged from many chemical factories, where it is commonly applied as a catalyst, resulting in some concentrations of Hg being discharged with wastewater in the chemical industry [9–11]. There is a possibility that Hg can cause damage to the central nervous system, as it is a neurotoxin [12]. In addition, Hg can impair the lungs and kidneys' function, and cause chest pain, and dyspnea when found in high concentrations. Hg contamination in aqueous phase systems poses a serious threat to human health, and the environment since it is a severe contaminant both acutely, and chronically at low dosage levels. This metal adversely affects the human body [13–15]. Therefore, aqueous phase systems containing Hg must be treated to remove Hg to protect ecological, and human health.

It is important to note that the relative weight or possible impacts of the issues raised concerning Hg detection may differ depending on the specific context, and application. While some concerns are more pressing to the scale at which it is present. Moreover, the relative weight or importance of different issues related to Hg detection can vary based on factors such as geographical location, industry sector, or regulatory requirements. For example, at a global scale, Hg becomes a problem when it is released into the atmosphere and travels long distances, eventually settling in remote locations such as the Arctic and Antarctic, where it accumulates in the food chain, leading to bioaccumulation. This can significantly impact wildlife, such as marine mammals and birds, as well as humans who consume contaminated seafood. On the other hand, high concentrations of Hg at a local scale led to direct inhalation exposure for surrounding residents. Mainly, in areas where Hg is used in small-scale gold mining, the release of Hg during the gold extraction process led to high levels of Hg in the air, directly inhaled by nearby residents. This can result in neurological, and respiratory problems and other health issues [16, 17]. Therefore, a comprehensive understanding of the different scales of Hg pollution, challenges, and limitations of mercury detection is crucial for ensuring accurate and effective monitoring of this toxic element in various settings. This study is novel since it provides the most up-to-date compilation of Hg recycling technologies. The following part of this paper provides information regarding understanding the Hg cycles in the environment and proper end-of-life management of mercury-contained products.

Mercury cycle in environment

Mercury cycles can occur at various scales, ranging from local to global. At the local scale, mercury can cycle within a specific ecosystem, such as a lake or river, through various physical, chemical, and biological processes. For example, certain bacteria can convert mercury into methylmercury, which can then bioaccumulate in fish, and other aquatic organisms. This can result in high levels of mercury in the local food chain, and increase the risk of exposure to humans, and wildlife. At a regional or national scale, mercury can be transported through the atmosphere over long distances, and deposited in different areas, including remote regions. This is known as atmospheric deposition, and can contribute to the contamination of ecosystems far from the original source of mercury. Additionally, human activities such as mining, coal combustion, and waste incineration can also release large amounts of mercury into the environment, further contributing to its distribution at the regional scale. At the global scale, mercury can cycle through the ocean, atmosphere, and terrestrial environments, leading to its widespread distribution, and bioaccumulation in various ecosystems. This global mercury cycle is complex, and can involve various processes, including atmospheric deposition, oceanic uptake, and long-range transport. Global initiatives have been put in place to address this issue, such as the Minamata Convention on Mercury, which aims to reduce the global use, and release of mercury. Overall, understanding the different scales of mercury cycling is essential for effective management, and mitigation strategies. In addition, it highlights the need for global cooperation to reduce the long-range transport of mercury, and local actions to address specific sources of pollution [18–21].

Not much research has studied Hg's recycling and recovery process. However, a couple of researchers and some organizations have conducted a little research on it and tried to identify the Hg cycles in the environment and how Hg can be collected and recovered in the most effective and safest way. Understanding the Hg cycles in the environment is very critical to recovering Hg from mercury-contained waste. Lutter et al. studied the Hg cycles in the environment. It was found that Hg, which stays in the environment, is regularly cycled and recycled; this cycle and recycling process always follows a biogeochemical cycle. There are six major steps in this cycle. (a) Hg degassing from natural sources like rock, soils, and surface waters, or emissions from volcanoes as well as from various human activities, (b) then it moves in gaseous form all the way through the ambiance, (c) Hg particle disposition on the surface waters and land area, (d) then the Hg element converts into insoluble Hg sulfide, (e) particle's precipitation into more volatile and soluble forms like as methylmercury; this process is called bioconversion, (f) again, coming or returning into the environment which is called bioaccumulation in food chains [22, 23]. Figure 1 clearly shows the Hg cycles in the environment.

There is some modern research on the Hg cycle where the principle factors of the Hg cycle have been identified and discussed. For example, Abelsohn et al. studied Hg's adverse environmental health effects. In one of the studies conducted by The University of Wisconsin-Eau Claire, it was found that forest fires are one of the principal factors in the Hg cycle due to that fire has a very strong ability to volatilize Hg sequestered into the organic material inside

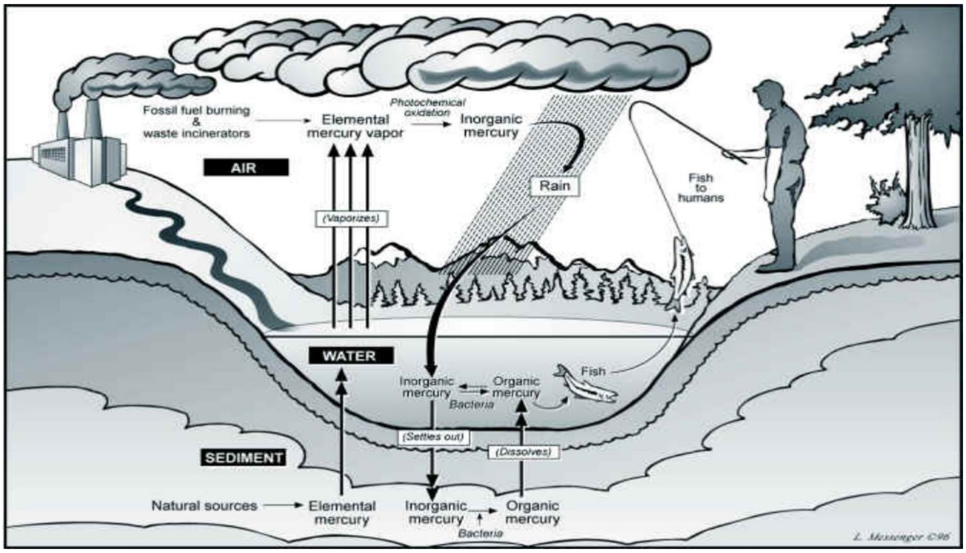


Fig. 1 The Mercury cycle [23]

the forest area which supports the thought that the fire always plays an important role in the Hg cycle in the forest area. However, if there is rain in the forest, then it reduces the Hg concentration in the forest but contaminates the water year after year. Eventually, it gradually increases the amount of Hg in the soil, water, and environment because this cyclic process happens for years. Another factor called petrochemical reactions is influenced by sunlight and plays a significant role in driving two critical photochemical processes involving Hg like photochemical reduction and photochemical demethylation. The first process is photochemical Hg reduction, which involves the transformation of ionic Hg(II) into elemental Hg(0). This elemental Hg(0) is relatively insoluble in water and has a higher tendency to evaporate from the water. In contrast, oxidized mercury, such as Hg(II) or their salts, are more soluble in water, and can contribute to wet deposition fluxes from air to surface water. Wet deposition is the primary mechanism for mercury deposition on a regional to global scale.

In contrast, dry deposition is more significant in the vicinity of local sources. as wet deposition tends to dominate over dry deposition at greater distances from emission sources. However, the relative contributions of wet and dry deposition can vary depending on a range of factors, including emission sources, meteorological conditions, and land use patterns [24]. Therefore, it is important to consider both the local, and global scales of mercury cycling when evaluating the sources, transport, and fate of mercury in the environment. Another form of Hg, named methylmercury, which is the most bio accumulative form of Hg, has the character of photosensitivity, and can undergo photochemical degradation to Hg, possibly lowering gaseous Hg. This is how circumvention possibly eliminates Hg from the aquatic ecosystem [25, 26].

Selin et al. studied the pathway of Hg deposited to the terrestrial system or cycling. Here it was discussed how wet and dry deposition produces Hg on the terrestrial surface by following various cycling processes. Fast cycling, or the process of newly deposited Hg, incorporation into vegetation and soil pools, shows that freshly deposited Hg does not immediately reduce, and volatilization is directly associated with vegetation Terrestrial Emissions by which Hg return to the atmosphere from soils due to diffusion are the terrestrial system or cycling process of Hg source. This article also talked about the basic understanding of the cycling of Hg in aquatic systems, which they called very critical to the environmental risk point of view. Both freshwater and marine systems are of major concern in the aquatic cycling process, which is directly impacting those two zones [27].

Storing, transporting, and disposing of Hg and mercury-contained waste is one of the major concerns because of its health hazard issues. United States Environmental Protection Agency (US EPA) has given a clear understanding and guidelines on storing, transporting, and disposing of Hg. Nevertheless, extreme cautionary steps must be taken if you have metallic Hg in your home to avoid any spills or leaks. The same principle is also applicable to a greater extent in the case of the industrial point of view. Therefore, the Resource Conservation and Recovery Act (RCRA) is the recycling and disposal requirement that should follow at the business and industry levels [28].

Mercury waste

Classification of mercury waste by the United States environmental protection agency

According to the US EPA restrictions program, Hg wastes are classified into two categories. Low Hg wastes comprise less than 260 mg/kg of total Hg, which should be treated up to 0.20 mg/L as measured utilizing the Toxicity Characteristic Leaching Procedure (TCLP) for Hg waste from retorting and 0.025 mg/L for all others. In contrast, high Hg wastes are considered hazardous, consisting of more than 260 mg/kg of total Hg needed to undergo roasting or to retort in a thermal processing unit able to volatilize Hg and afterward condense the volatilized Hg for recovery. Regardless of Hg level, no waste containing Hg should be discarded in the trash, put down the drain, or set in biohazard bags or sharps compartments [29–31].

Mercury-added products as a source of mercury wastes

According to UNITAR-SCYCLE in 2017, 6.2 million metric tons (Mt) of mercury-added product waste were generated universally, of which approximately 1300 tons were Hg waste. As a typical trend, the volume of mercury-added product waste increased by an average of 7% per year from 2010 to 2018 and will reach a level from 2018 to 2025 of about 6.4 Mt. Figure 2 shows the global trend of mercury-added wastes. Based on the Minamata Convention, after 2025, the countries will no longer be producing, importing, or exporting mercury-added products, so the waste is expected to decrease rapidly. Also, the amount of mercury-added to waste products is estimated to grow leisurely until 2025, up to a maximum of 1550 tons, and then decrease quickly due to the Convention's ban. Even though mercury-added products will not be produced after 2025, older products might be available for use. Thus, effective collection and treatment techniques are needed to develop for mercury-added products [32].

Hg might enter the environment through the service life of consumer, clinical and industrial products. The most significant utilization of Hg is in electrical items like fluorescent lights, thermostats, thermometers, and electrical switches. These items are discovered in homes, offices, businesses, industrial structures, and vehicles (Fig. 3). Other mercury-containing items include pressure-detecting gadgets, pulse pressure measurement gadgets, thermometers, and dental amalgams [33].

The following list organizes extra things that have been known to contain Hg. Even though the greater part of these items is not generally produced with Hg, older Hg products might be available for use. In total, these items might address a huge repository of toxins that might enter the environment. Hg includes barometers, thermometers, manometers, dyes and pigments, old latex and oil-based paints, solvents, batteries, fungicides, pesticides, vaccines, pharmaceuticals and cosmetics, lighted athletic shoes, old toys, pottery, scientific gadgets, and so on. Hg can turn into a piece of the worldwide Hg cycle when mercury-containing items are broken, and spilled Hg dumped, or when these items are discarded in landfills [34].

Recovery of mercury

Mercury is widely used in producing fluorescent lamps, thermometers, barometers, batteries, dental amalgam, electrical switches/relays, industrial processes (such as the production of Polyvinyl Chloride (PVC)), and so. However, when the life cycle of these products end, it raises a concern about the amount of Hg can be released back to

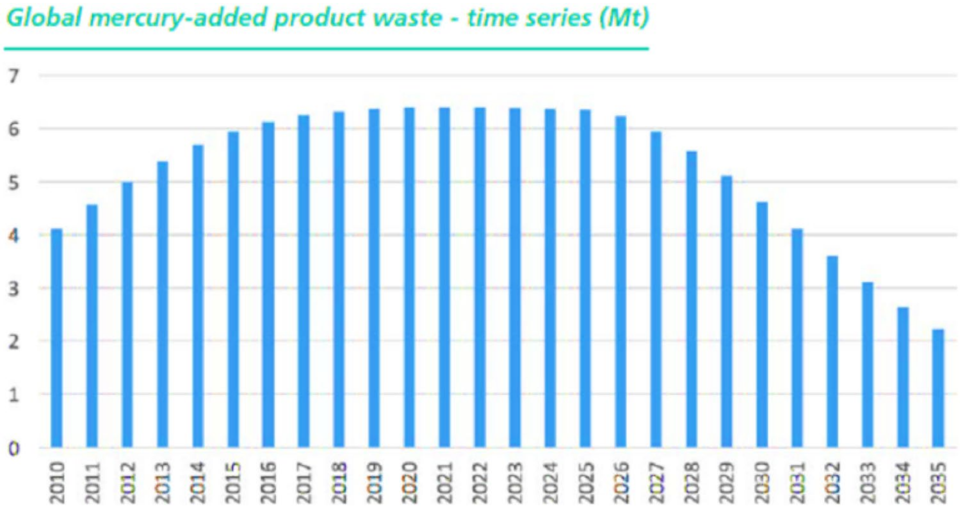


Fig. 2 Global mercury-added product waste-time series (Mt)

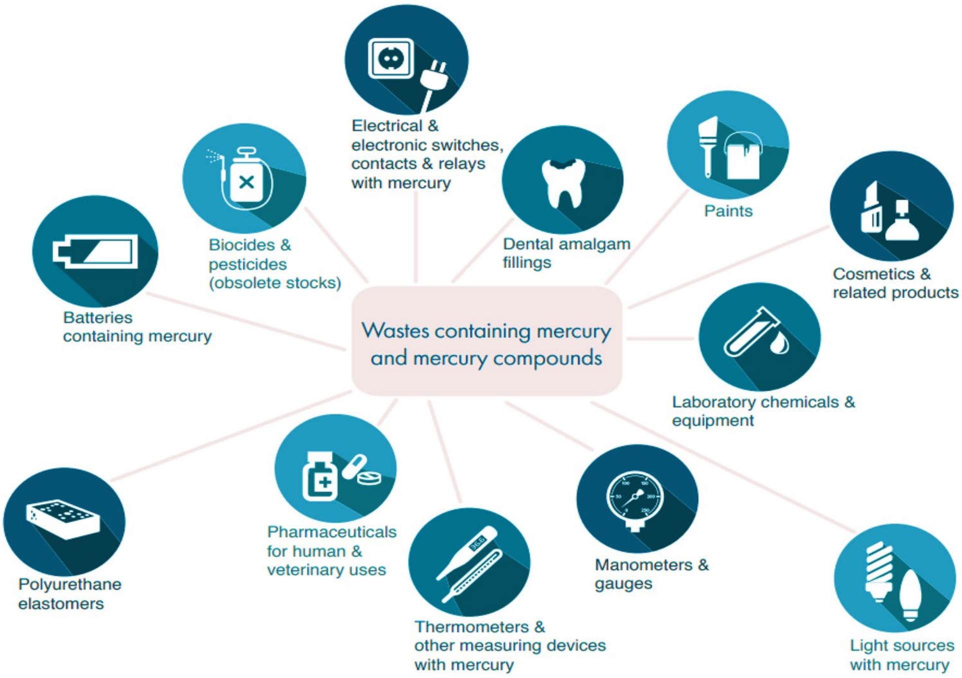


Fig. 3 Sources of wastes containing mercury or mercury compounds [31]

the environment. Therefore, many countries have regulations that require the recovery of mercury from waste to prevent environmental contamination, and protect public health. Some of the countries that have implemented such regulations include:

- United States: The US EPA has established regulations under the RCRA that require mercury recovery from various waste streams, including hazardous and universal waste.
- European Union: The European Union has implemented regulations, including the Waste Framework Directive and the Restriction of Hazardous Substances (RoHS) Directive, that requires the recovery of mercury from various waste streams, and restrict the use of mercury in certain products.
- Japan: The Japanese Ministry of the Environment has established regulations under the Law for the Promotion of Effective Utilization of Resources that require the recovery of mercury from waste and restrict the use of mercury in certain products.
- Canada: The Canadian Environmental Protection Act (CEPA) regulates the management of mercury-containing products and requires mercury recovery from waste streams.
- Australia: The Australian government has implemented regulations under the Environment Protection and Heritage Council that require the recovery of mercury from various waste streams and restrict the use of mercury in certain products.

These are just a few examples of countries that have implemented regulations requiring mercury recovery from waste. Many other countries have similar regulations to address the environmental and health risks associated with mercury contamination.

Furthermore, improper disposal of mercury-containing products can also lead to mercury leaching into soil and water. Once in the water, mercury can accumulate in sediment, and aquatic organisms, posing a risk to human and environmental health through bioaccumulation, and biomagnification [35]. Additionally, atmospheric deposition from industrial, and natural sources can deposit mercury into the water through precipitation. Human-made sources include industrial activities like coal combustion, and mining that release mercury into the air. For that reason, mercury is not only recovered from solid waste but also from the air and aqueous environment. In large-scale facilities such as industrial waste recovery plants, combinations of techniques are used to recovery mercury from solid waste. The processes are usually involved thermal desorption, distillation, chemical treatment, and specific filtration. Similarly, mercury can be treated from an aqueous environment (e.g., wastewater, ground water, and industrial effluent) through chemical treatment, filtration, ion exchange, and adsorption. A flue gas desulfurization system is commonly implemented for recovering the mercury in the atmosphere. However, this paper narrows the scope to mainly focus on the latest development, and recent progress of novel methodologies to recover mercury from solid waste, aqueous environment, and atmosphere (from fly ash). Thus, the majority of the studies presented in this review are still on the bench or lab scale.

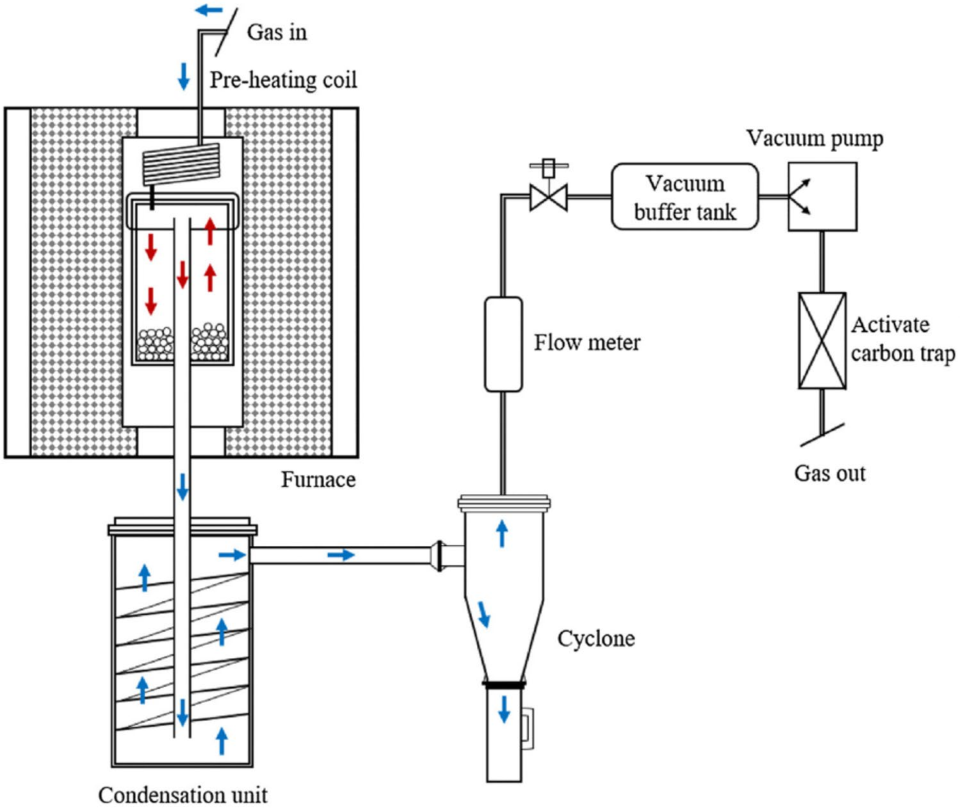
Solid waste

For decades, thermal desorption has been commercially used to recover Hg from Hg-containing waste due to its low boiling point (367 ℃) compared to other metals, which means that it starts to vaporize, and transform into its natural state (Hg^0) phase at this temperature. However, the decomposition temperature of (Hg^0) into other forms of mercury is much higher, around 600–800 ℃ [36, 37]. Under the heat, Hg is evaporated, and extracted from waste, then condensed to liquid form. Early investigations and usages of thermal desorption for Hg recovery are dated back in the 1970s, and the process has been applicable until the present [38, 39]. However, the main drawback of thermal desorption is heating, which can reduce energy efficiency as well as equipment durability; also, an additional unit for separation is required, and it is preferable to operate at reduced pressure to fasten the desorption process at a lower temperature [40].

Researchers have studied extensively to improve Hg recovery from Hg-containing waste, especially Hg at high concentrations, through the thermal desorption process. For example, Lee et al. attempted to develop equipment that can recover Hg from sludge under 6.67 kPa and at 400 ℃, referred to as vacuum thermal desorption [41]. Prior to the Hg recovering process, moisture in the waste was collected at 100 ℃; then the experiment proceeded at the given conditions. To reduce efficiency loss, a dust filtration unit was installed along to separate Hg vapor and others, during combustion since other fly ash was also produced. Jet pulse was also used to clean any ceramic filter clog build up. Hg was condensed in a shell-and-tube condenser by cold water at the final stage to have the recovered Hg collected. The results show a significant reduced boiling temperature of Hg and Hg compounds during thermal desorption under vacuum pressure compared to atmospheric one. Researchers claimed that vacuum thermal desorption could enhance Hg recovering efficiency to 98.6%. However, only As and As_2O_3 ash were considered to be separated from Hg vapor; other factors, such as sulfur in the waste, did not inhibit the recovery of Hg. Energy consumption for the recovery process was 6 kWh per 1 kg Hg-containing waste. Besides temperature, and pressure, the efficiency of Hg recovery can be improved by introducing NaOH to the thermal desorption, and condensation. Back et al. introduced a lab-scale apparatus, as seen in Fig. 4, to recover Hg from sludge [42].

The apparatus for Hg recovery using thermal desorption incorporated with NaOH consists of a gas preheater, furnace, condenser, cyclone, vacuum buffer tank, vacuum pump, and activated carbon trap. Nitrogen gas was passed through the preheater and furnace, which were pre-heated by electricity. Nitrogen gas in the chamber was the condition of the

Fig. 4 Schematic diagram of lab-scale apparatus [40]



process. The vapor that contained Hg was generated from heating sludge in the furnace and then condensed at the condenser (ice bath 10–15 ℃). A cyclone unit was installed to prevent dust from going to the vacuum pump, which minimized the pressure at the lab scale, then contaminated hazardous gas will be trapped by activated carbon. NaOH was added to industrial sludge that contained Hg to investigate its effect on Hg recovery efficiency. The amount of NaOH varied for each sample. All samples proceeded under 20 kPa at 650 ℃ for 20 min. The efficiency increased from 52.2 to 89.7% as pressure reduced from 101 to 20 kPa at 580 ℃. As the temperature increased, efficiency was found to be increased as well. Back et al. indicated that adding NaOH to Hg-containing sludge can increase Hg recovery from 48.3 to 64.1%. The researchers stated that this improvement was probably because NaOH reacted to As and S in the mixture to form $NaAsS_2$ and/or Na_3AsO_4 [42].

Thermal desorption is also common in recycling Hg from fluorescent lamps. Crushed fluorescent lamps contain crushed glass, phosphorous powder, and elemental Hg. Most recently, Esbri et al. and other researchers suggested that to optimize the recovery of Hg^0; certain conditions need to be achieved [43], such as (1) continuous heating from 35 to 660 °C, and preventing early Hg desorption by avoiding accelerations, (2) flow rate of 3 L/min and heat rate of 0.74 ℃/s are required to determine the desorption temperature, (3) to ensure appropriate starting temperature, 40 min. cooling is required. By following this methodology, 70% of Hg can be recovered at 437 ℃ operating temperature.

T.C. Chang et al. discussed another process of Hg recovery from cold cathode fluorescent lamps used for various applications using thermal desorption technology. As cold cathode fluorescent lamps (CCFLs) are widely used for various high-technology products, a huge volume of mercury-contained waste is generated from them. Hg can be removed from this waste using thermal desorption technology which is low efficiency and high-cost. This study focused on the Hg release behavior from mercury-containing waste like CCFLs using a bench-scale thermal desorption test technique. The results indicate that from 50 ℃ to 250, Hg was efficiently released from high-pressure Hg lamps and CCFLs. Moreover, the Hg release peak at much higher temperatures than that of commercial phosphor at 50–200 ℃ but the tricky part is that complete separation of the cracked CCFLs is required to effectively recover phosphor and Hg at low financial and energy costs [44, 45].

Flue gas

Coal-fired power plants are accountable for a significant amount of Hg emission, and to date, wet flue gas desulfurization (WFGD) and electrostatic precipitators (ESPs) are the two common methodologies to eliminate divalent Hg (Hg^{2+}) and particulate Hg (Hg^p); however, recovering elemental Hg (Hg^0) remains a challenge [46]. It’s important to consider the potential risks associated with the methods used to remove Hg^0 from the environment. While adsorption with activated carbon is one potential method, it’s not always the best option depending on the specific circumstances. In general, Hg^{2+} is more toxic than Hg^0. This is because Hg^{2+} is more reactive, and can more easily bind to biological molecules in living organisms, leading to toxic effects. Hg^{2+} is also more water-soluble than Hg^0, which means it can easily dissolve in water, and be taken up by aquatic organisms. This can result in bioaccumulation, and biomagnification of Hg^{2+} in the food chain, which can further increase its toxicity to higher trophic levels. However, it's important to note that both forms of mercury are toxic, and exposure to either form can have harmful effects on human and environmental health [47]. Recently, magnetic materials have drawn great attention to recover Hg^0 from centralized control for high adsorption capacity, low toxicity, and ease of separation and recovery. Commercially, fly ash is captured by ESPs, and ultrafine particles are trapped by wet ESPs (WESPs); therefore, magnetic sorbents can become a great implementation with WESPs to recover Hg^0 [48]. Figure 5 illustrates the working principle of Hg^0 recovery process with the incorporation of magnetic adsorbents.

Some of the most promising magnetic adsorbents are magnetic iron-based, such as γFe_2O_3, Fe_3O_4, magnetic carbon-based, magnetic fly-ash-based, and magnetic mineral-based adsorbents [48]. For example, Mei et al. developed a magnetic sorbent named $MoS_x@\gamma Fe_2O_3$, which possessed high magnetic properties also thermal stability to enhance the recovery of Hg0 significantly. $MoS_x@\gamma Fe_2O_3$ is the formation of γFe_2O_3 grafted by phosphomolybdic acid (HPMo) by sulphuration. Within the operating temperature from 40 to 100 °C, the efficiency of Hg^0 was found to be 57–76%. Moreover, with the grafted HPMo, the magnetization of γFe_2O_3 during service was preserved. Fe_3O_4 is also an inexpensive material with a high magnetic property that has been investigated for recovering Hg from fly ash. Yang et al. have reported that $Fe_3O_4@CuS$ nanoparticles, when used as adsorbents, can recover up to 100% Hg^0 from coal-fired flue gas with the record of adsorption capacity and rate as 80.73 mg/g and 13.22 μg (g min)$^{-1}$, which are two order magnitude higher than other magnetic adsorbents for the same application [49].

Even though activated carbon and zeolite are well-known as natural adsorbents, they are frequently suffered from poor Hg removal performance [50]. Therefore, modifying activated carbon and zeolite with magnetic materials can eliminate the problem. For instance, Yang et al. reported successfully integrating activated carbon nanofibers (CNF) as a support for magnetic iron–manganese binary oxide ($Fe_{3-x}Mn_xO_4$/CNF). $Fe_{3-x}Mn_xO_4$ particles were well

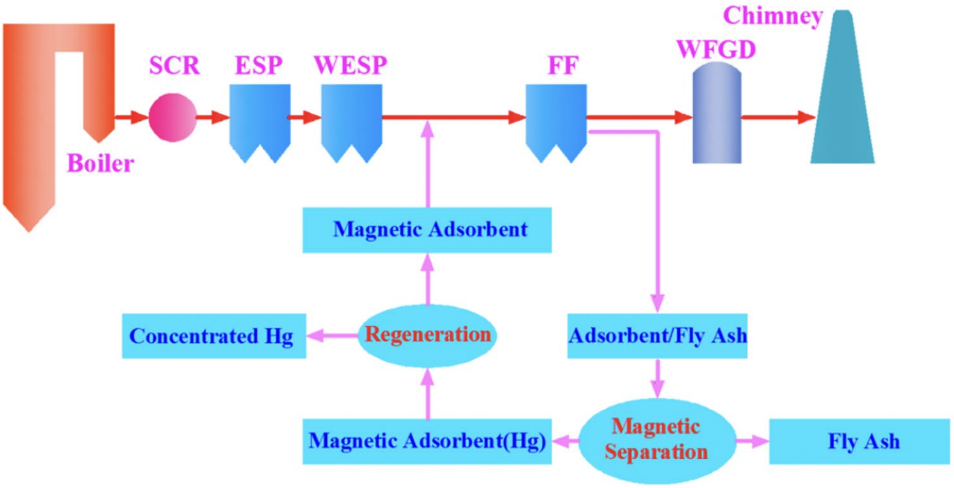


Fig. 5 Typical flow diagram of magnetic separation of mercury adsorption from flue gas, and recovery, and regeneration process of the magnetic adsorbent [46]

dispersed on CNF as the large surface area CNF provided, thus, facilitating the electron transfer process. The mechanism of Hg^0 adsorption and oxidation using $Fe_{3-x}Mn_xO_4$/CNF is described in Fig. 6 [51].

At the operating temperature of 150–200 ℃, the optimal sample Fe_2MnO_4/CNF was capable of removing 90% of Hg^0. Furthermore, by washing, thermal treating at 450 ℃, and calcinating in the air at 200 ℃, used $Fe_{3-x}Mn_xO_4$/CNF can be regenerated and show no sign of losing integrity. Similar to activated carbon, zeolite is used widely for many adsorbing applications. However, for the improvement of Hg^0 removal from flue gas, zeolites are incorporated with other magnetic agents to optimize their properties. Cao et al. designed and synthesized a responsive catalytic adsorbent to remove Hg0 and NO from flue gas effectively. The designed catalyst consisted of Fe_3O_4, molecular sieve (HZSM-5), supported by Ag nanoparticles and V_2O_5. Each component from this catalytic adsorbent has its unique functionality to capture and remove Hg^0. As a result, at 150 ℃, 32.4 μg/g was removed from the gas mixture, and the removal capability was elevated to 97% at high space velocity at the same operating temperature. The responsive catalytic adsorbent can also be regenerated for more cycles [52].

Aqueous solution

To remove Hg and Hg compounds (Hg^{2+}) from an aqueous environment, adsorption is the most common method, among others, such as chemical precipitation, electrolysis, ion-exchange solvent extraction, membrane separation,

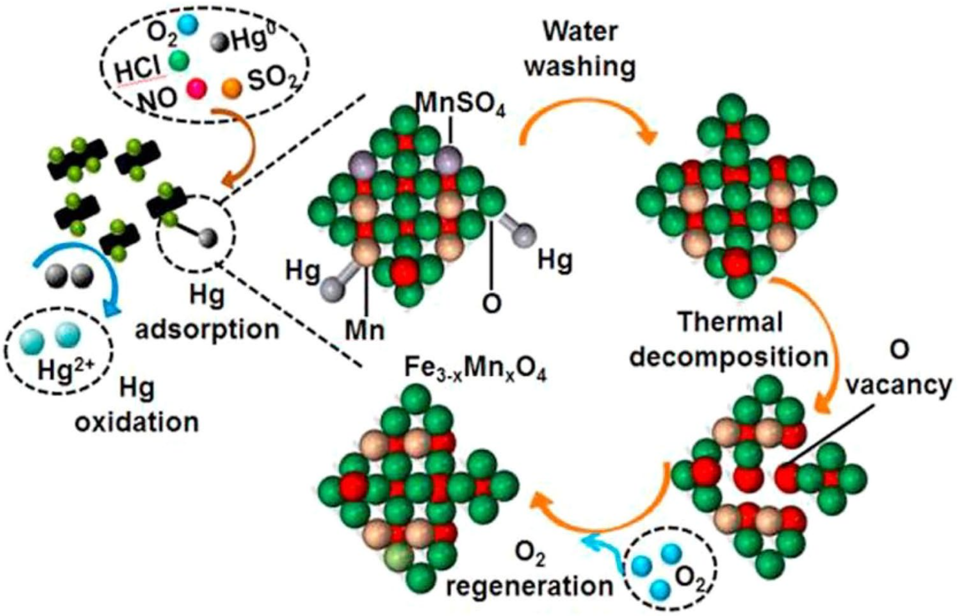


Fig. 6 Mechanism of the Hg^0 adsorption and oxidation using $Fe_{3-x}Mn_xO_4$/CNF [49]

photocatalysis, and bioremediation. Extensive studies on the removal of aqueous Hg^{2+} have focused on using activated carbon, carbon-based materials, metal oxides, silicates, polymer, resin, clay, metal–organic framework, functionalized polymers, and chitosan [53–57].

Adsorption High surface area, mesopores, low weight-to-volume ratio, and low cost make activated carbon (AC) the topmost selected adsorbing materials for VOCs, heavy metals, and other pollutants. Liu et al. investigated the effect of porous structures on AC adsorbing aqueous Hg^{2+}. This research used rice hulk (RH) to prepare AC by chemical activation using KOH [58]. Brunauer – Emmett – Teller (BET) graph in this study shows the distribution of micropores (< 4 nm) and mesopores (2–50 nm), where mesopores were accountable for 72.92% of total pore volume (0.48 cm^3/g). According to Liu et at., these micropores were responsible for diffusion and adsorption at a higher rate. The adsorption capacity of RHAC for Hg^{2+} was found to be 55.87 mg/g [58]. Similarly, Salcedo et al. functionalized mango seed into activated carbon by chemical activation using $CaCl_2$ and H_2SO_4. Researchers obtained the surface area of 2 and 33 m^2/g and pore volumes between 0.0007 and 0.019 cm^3/g from the particular functionalized AC, which then accounted for 85.6 mg/g Hg^{2+} adsorption capacity [59].

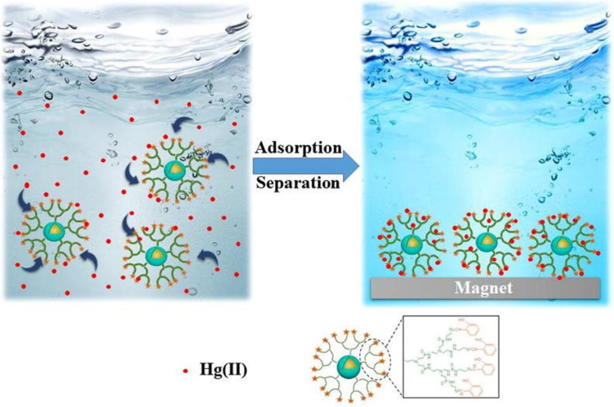


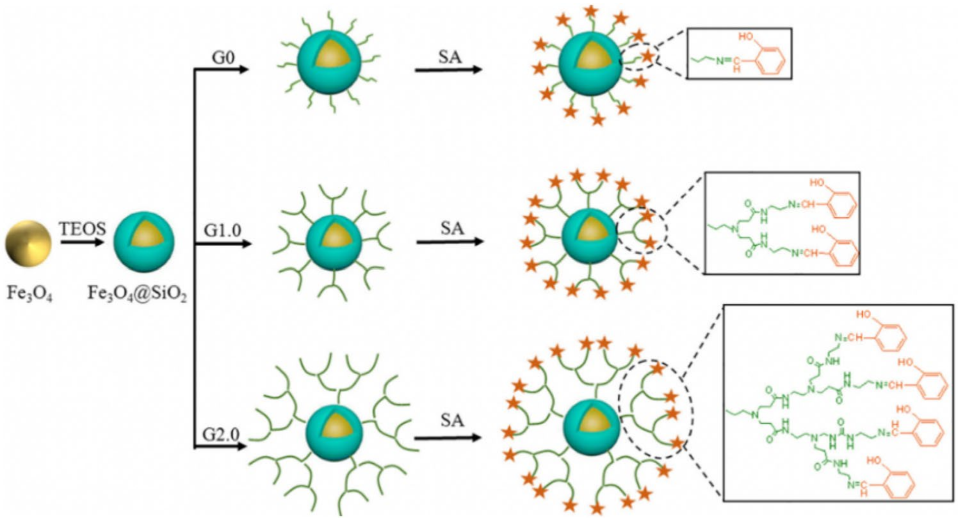
Fig. 7 Graphic abstract of Schiff-base decorated PAMAM dendrimer/magnetic Fe_3O_4 [59]

Besides activated carbon, magnetic materials have also been an interest for aqueous Hg and Hg compounds. For example, Zou et al. have loaded Fe_3O_4 onto aluminum-pillared bentonite to create a compound named magnetic bentonite that claimed to adsorb 26.18 mg Hg^{2+} per 1 g solution that contained 50 mg/L Hg^{2+} [60]. Zhou et al. also utilized the magnetic properties of Fe_3O_4 to fabricate a composite called Schiff-base decorated polyamidoamine (PAMAM) dendrimer/magnetic $Fe_3O_{4,}$ as shown in Fig. 7 [61].

As illustrated in Fig. 8, the composites are Fe_3O_4 grafted onto and from the PAMAM dendrimer. Researchers successfully prepared three samples $Fe_3O_4@SiO_2$-G0-S, $Fe_3O_4@SiO_2$-G1.0-S, and $Fe_3O_4@SiO_2$-G2.0-S, as shown in Fig. 8, which possessed high Hg^{2+} adsorption capacity and regeneration. For example, among three samples, $Fe_3O_4@SiO_2$-G2.0-S showed excellent adsorbing ability with the rate of Hg^{2+} 3.02 mmol/g, which was 100% in the solution consisting of Fe^{3+}, Fe^{2+}, Mn^{2+}, Zn^{2+}, Cd^{2+}, or Co^{2+}. After five cycles, the capacity was maintained at 91% [61].

Other Schiff-base materials, such as Silica-supported Schiff-base functionalized PAMAM and Schiff-base functionalized superparamagnetic Fe_3O_4 composites, possessed 1.52 and 0.86 mmol/g adsorbing capacity, respectively [62, 63]. Graphene oxide (GO) and reduced GO (rGO) have recently gained a lot of interest in water treatment and purification, especially to filtrate heavy metals since nanopores of graphene oxide facilitate metal ions separation when it is incorporated with membranes [64]. Furthermore, the oxygen

Fig. 8 The synthesis of $Fe_3O_4@SiO_2$-G0-S, $Fe_3O_4@SiO_2$-G1.0-S, and $Fe_3O_4@SiO_2$-G2.0-S [59]



functional groups in GO allow it to affiliate with metal ions easily [65]. Kazemi et al. reported that the fabricated magnetic graphene oxide (MGO–NH-SH) had the capacity to uptake Hg^{2+} to 208.8 mg/g, which was relatively high [66]. Tene et al. proposed reduced graphene oxide that exhibited Hg^{2+} adsorption up to 110.21 mg/g, with Hg^{2+} concentrations varying from 40 to 150 mg/L. After 20 min., the efficiency remained at 75% [67].

Chitosan is a promising material for adsorbing ions due to its -NH_2 and -OH functional groups, which contribute to the adsorption interface with adsorbates. Hence, enormous research has been focusing on utilizing these functional groups to fabricate functional material that adsorbs Hg and Hg compounds well. For example, Ge and Du grafted many amine groups onto chitosan-modified adsorbents (GMCS) by crosslinking chitosan and melamine using glutaraldehyde. The adsorption result of GMCS showed that GMCS could selectively filtrate Hg^{2+} at the rate of 490.7 mg/g [68]. Wang et al. introduced TSC-PGMA-MACS microspheres that claimed to adsorb Hg^{2+} with a capacity of 242.7 mg/g with five cycles, and they were able to maintain more than 86% of the initial saturated adsorption capacity. TSC-PGMA-MACS was fabricated by first esterifying malic acid (MA) with chitosan (CS) to form a microsphere, then glycidyl methacrylate (GMA) and thiosemicarbazide (TSC) were grafted onto the constructed spheres. These microspheres provided abundant -NH_2 groups for Hg^{2+} adsorption, as shown in Fig. 9 [69].

Chemical precipitation Several treatment technologies are available today to remove Hg from contaminated environments. Each of these treatment technologies achieves a different level of Hg removal in the effluent. In addition, each technology has a different level of effectiveness depending on the chemical aspects, initial concentration of Hg, and other contaminants in the wastewater that may cause disruptions in the treatment process [70, 71]. Therefore, several factors must be considered when selecting a Hg removal technology, including its performance, the generation of secondary waste, and its economics. Chemical precipitation occurs when a solution is converted into a solid by making the substance insoluble or by supersaturating the solution [72, 73].

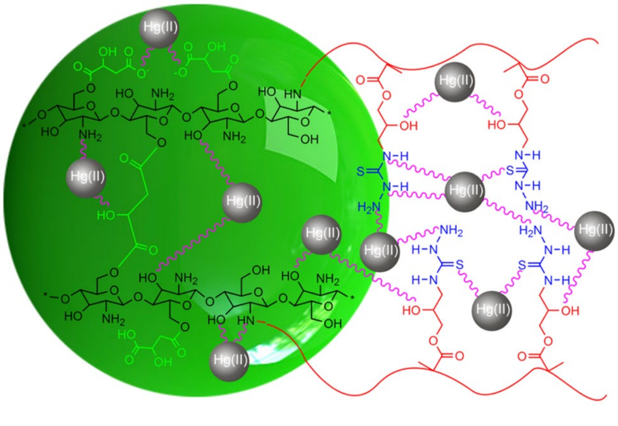


Fig. 9 Adsorption sides (-NH_2) and bonding mode of TSC-PGMA-MACS microsphere [67]

In Hg treatment technologies, chemical precipitation is one of the most common physical–chemical methods. Based on previous studies, it was found that heavy metals of less than one part per million could be effectively removed 100% by sedimentation through chemical precipitation in wastewater treatment, which has an excellent capacity to remove heavy metals in low concentrations [74]. Furthermore, chemical precipitation is an attractive process due to its simplicity and low operating costs. Additionally, it can be utilized for water softening, heavy metals can be removed from metal plating wastes, oils and greases can be removed from emulsified solutions, and phosphate can be removed from wastewater. It is generally understood that the precipitate obtained in the technological system is separated from the solution by sedimentation or filtration and that the treated water is then drained off and discharged or reused [75].

Several factors affect the efficiency of chemical precipitation, including the nature and concentration of metal ions in the solution, the precipitation reagent applied, the reaction conditions, and the occurrence of other compounds that influence the reaction [76]. A significant drawback of the chemical precipitation of Hg is the generation of excess sulfuric wastes that make it difficult to transport, handle and dispose of the final reaction products [77]. To remove metals from wastewater, chemical precipitation is usually performed using hydroxide precipitation or sulfide precipitation. Zhuang et al. reported a new technology for the treatment of mercury-contaminated water and soil with lignin derivatives [78]. Blue et al. stated that a thiol compound (1,3-benzenediamidoethanethiol, BDTH2) could be applied to mercury-containment water as acidic, basic, and ethanolic solutions. In extremely acidic and basic conditions, the BDT-Mercury precipitate leaches low levels of Hg [79].

Hydroxide precipitation: Hydroxide precipitation is the most widely used chemical precipitation method due to its relative simplicity, ability to control pH, and low cost. There is a minimum solubility of various metal hydroxides in the pH range of 8.0–11.0 [80]. Flocculation and sedimentation can remove the metal hydroxides. It has been used to precipitate metals from wastewater with various hydroxides because of their low cost and ease of use, and lime is the most commonly used base in hydroxide precipitation. Even though hydroxide precipitation is widely used, it also has some limitations [81]. First, large quantities of relatively low-density sludge are generated during hydroxide precipitation, which can pose a challenge in dewatering and disposal. Next, certain metal hydroxides are amphoteric, and the mix of metals creates a complex hydroxide precipitation process since the ideal pH for one metal may make another metal dissolve once more. Additionally, complexing agents inhibit metal hydroxide precipitation when present in wastewater [82].

Sulfide precipitation: Sulfide precipitation is one of the most frequently reported methods for removing inorganic Hg from wastewater. Treating toxic heavy metal ions using sulfur dioxide precipitation is also possible. The primary advantage of using sulfides is that the solubilities of the metal sulfide precipitates are much less soluble than hydroxide precipitates and are not amphoteric. Consequently, compared to hydroxide precipitation, sulfide precipitation can remove metal over a broad pH range. Additionally, metal sulfide sludges display excellent thickening and dewatering properties than the equivalent metal hydroxide sludges. Although sulfide precipitation is adequate, there are probable dangers associated with it. Whenever heavy metal ions are present in acid conditions and sulfide precipitants are present in acid conditions, toxic H_2S fumes can be formed. In order for this precipitation process to be successful, a neutral medium or a basic solution must be used. It should also be noted that the precipitation of metal sulfides tends to produce colloidal precipitates, which cause separation complications in settling and filtering operations [83]. This process involves adding sulfide (such as sodium sulfide or another sulfide salt) to the wastewater stream as a way of converting the soluble Hg to the relatively insoluble Hg sulfide. The sulfide precipitation treatment process is usually followed by pH adjustment, flocculation, and solids separation by gravity settling and filtration. This method involves adding the sulfide precipitant to wastewater in a stirred reaction vessel, resulting in the precipitation of Hg sulfide from the soluble Hg. It is then possible to remove the precipitated solids by gravity settling in an air clarifier. To enhance the removal of precipitated solids, flocculation is used with or without a chemical coagulant or settling aid. This precipitation occurs most effectively when minimizing sulfide dosage is evident in the pH range close to neutral [84].

Ion exchange It has been widely accepted that using ion-exchange processes to remove heavy metals from wastewater is beneficial since they possess several advantages, including high removal efficiency, high treatment capacity, and fast kinetics [85]. During the process of removing heavy metal ions from a wastewater solution, the heavy metal ions are attached to an immobile solid particle, replacing the heavy metal ion with the solid particle cation, as shown in Fig. 10 [84]. Synthetic or natural solid resins, known as ion-exchange resins, have the specific aptitude to exchange their cations with the metals in wastewater. It is commonly preferred to use synthetic resins in the ion-exchange process since they are efficient at almost removing the heavy metals from the solution. Cation exchangers consist primarily of strongly acidic resins with sulfonic acid groups and weakly acidic resins with carboxylic acid groups. A resin containing a sulfonic or carboxylic group can contain hydrogen ions that can be exchanged with metal cations as exchangeable ions. Due to their low cost and availability, in addition to synthetic resins, natural zeolites have been used widely to remove heavy metals from aqueous solutions [86].

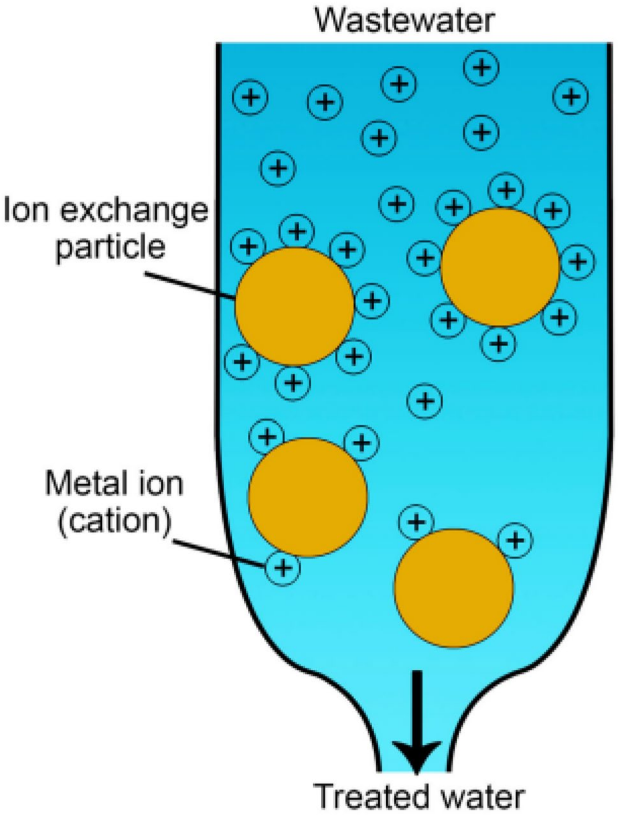


Fig. 10 Pictorial representation of the ion-exchange process [82]

Several variables play a role in the uptake of heavy metals by ion-exchange resins, including pH, temperature, the initial concentration of metal, and the length of contact. In addition, the ionic charge determines a large part of the ion-exchange process [87]. Mercury-contaminated water is generally passed through resin typically used as packed columns in ion-exchange technologies. Wastewater containing heavy metals is pumped into ion-exchange columns and passed through beds to remove the heavy metals. The column was regenerated if it had become saturated with heavy metals and was then backflushed to remove the deposited metals [88].

Anionic resins have been the primary source of removing cationic Hg from waste streams. However, some cationic resins have recently been reported to remove cationic Hg from waste streams. It has been noted that cationic resins containing thiol groups can remove ionic Hg. There have also been reports of chelate resins with high Hg removal capacity. Although ion exchange is a widely used technique, the chemicals that are used to regenerate ion-exchange resins create serious secondary pollutants as they are being used. There must be proper handling of these secondary pollutants. A large amount of resin is required for the ion-exchange process to treat the large volume of wastewater with lower metal ions concentrations. While ion exchange-based technologies remove high amounts of Hg, many of these resins are mechanically not strong [89].

JM Monteagudo et al. examined a treatment to remove Hg from wastewater using an ion-exchange treatment. Several commercial resins have been evaluated in this study as ion exchangers, and the Hg content of the wastewater, ranging from 70 to 90 ppm, is reduced to a reasonable level of 34 ppb. Dowex XZS-1, a strong cationic ion exchanger in a gel form [90]. A novel nanocrystal sorbent (ZnS) was reported by Qu et al., which showed an extraordinary adsorption capacity (2000 mg/g) to aqueous Hg^{2+} based on ion exchange [91]. Moreover, the as-prepared ZnS nanocrystals sorbent efficiently removed over 99.9% Hg^{2+} in 1 min., and lowered the Hg^{2+} concentration from 297.5 mg/L (ppm) to 1.0 µg/L (ppb) within 5 min. Smith et al. reported a new strategy based on Hg cation exchange in non-polar solvents to prepare bright, and compact alloyed quantum dots [92].

Membrane-based separation The development of membrane technology has increased the use of membranes to separate heavy metal ions from wastewater over the past few decades. The membrane is a complex structure containing nanometer-scale dynamic elements. It is mainly the membrane's chemical and physical properties that determine the water's permeability and the rejection of heavy metal ions in the membrane [93]. In addition to a higher removal efficiency, this method requires less space, and is easier to operate. This method is among the most effective for removing dissolved metals from wastewater. In membrane filtration, particles are separated from their size by removing them across a membrane with a pressure gradient. Membrane-based separation technologies, including ultrafiltration, charged filtration, cross-flow microfiltration, and magnetic filtration, have also proved that Hg can be removed from contaminated water [94–96].

The ultrafiltration process is performed at low transmembrane operating pressures. Furthermore, a combination of additives to metal ions may increase the size of the metal ions since ultrafiltration membrane pores may be more than heavy metal ions. As a result, micellar-enhanced ultrafiltration and polymer-enhanced ultrafiltration have been proposed [97]. Polymer-enhanced ultrafiltration can provide adequate polymer bonding, effective extraction, recovery, and reprocessing complexation polymers of retentate, and require low energy and minimal operating costs. However, developing this technology continues to be challenging due to the difficulty in selecting appropriate water-soluble polymer macro-ligands. In the case of charged filtration, the membrane utilized is negatively charged, thereby minimizing the fouling of the membrane. The cross-flow microfiltration has a movable membrane for performing filtration. Ultrafiltration, and cross-flow microfiltration require pretreatment of the Hg feed since size exclusion alone cannot remove Hg from the solution [98]. The microfiltration process is also an ultra-low pressure membrane process with pores ranging from 0.1 to 10 microns. The microfiltration system is applied in treating wastewater by removing particles from the rinse water. Magnetic filtration creates an insoluble magnetic Hg precipitate which is then removed from the solution by applying a magnetic field to ferromagnetic wires. Membrane treatment technology can be used to remove toxic heavy metals from wastewater, but these technologies are complex in the process, expensive, result in membrane fouling, and has a low permeate flux [99].

The membrane-based separation concept achieved Hg removal from dilute and concentrated water streams. The Fumatech FKE membrane was found to achieve the highest Hg flux. Hg removal to levels below the 1 ppb drinking water limit was achieved [100]. Bessbousse et al. used semi-interpenetrated polymer networks technology to immobilize the polymerized matrix of polyvinyl alcohol crosslinked by gaseous dibromoethane into a complex membrane, which has high Hg^{2+} removal ratio less than 99.4% [101]. Urgun-Demirtas et al. evaluated the membrane's ability to remove Hg^{2+} in an oil refinery's wastewater. The experimental test results indicated that microfiltration and ultrafiltration membranes with an operating pressure of less than 2.8 bar were highly effective in removing Hg [102]. Yu et al., the gold nanocluster embedded bovine serum albumin nanofibers-graphene hybrid membrane, has been used to separate Hg^{2+} [103].

Photocatalysis Today accessible methods for treating mercury-contaminated aqueous solutions incorporate precipitation as sulfide, ion exchange, membrane filtration, adsorption, electrodeposition, and coagulation. However, most of these traditional techniques exhibit some drawbacks to accomplishing the low Hg levels required these days. Consequently, many investigations are dedicated to working on the laid-out techniques or fostering novel treatment systems for removing Hg from the polluted surface and ground waters [104, 105]. In that regard, heterogeneous photocatalysis with titanium dioxide can be a promising option since it has exhibited its viability in removing and recovering different types of metal particles from aqueous effluents [106].

The working principle of this technique relies on the irradiation of a semiconductor which is usually titanium dioxide to promote electrons from its valence band to the conduction band with the concurrent generation of holes in the former band. Furthermore, the holes and electrons can either recombine in mass or at the semiconductor surface or else respond with adsorbed species to achieve redox reactions. Water molecules, hydroxyl ions, and organic compounds are the theoretically oxidizable species in aqueous TiO_2 suspensions. In contrast, photogenerated electrons can reduce either adsorbed oxygen as long as the potential of the semiconductor's conduction band edge is more negative than the reduction potential of the $Mn^+/M(nm)^+$ pair, molecules can produce superoxide radicals or metallic ions. If the reduction of metal ions continues, metal is deposited on the surface of the titania, from which it can be removed chemically or physically.

López-Muñoz et al. studied the photocatalytic removal of Hg(II) from aqueous solutions of $HgCl_2$ using TiO_2 as per catalyst. The authors also examined the effect of pH levels such as 2, 4.5, 7, and 10, and the addition of methanol, oxalic acid, and formic acid as sacrificial additives on the extent of Hg(II) adsorption and photocatalytic reduction. Due to both the considerable fluctuations in Hg speciation and the charge of the titania surface with pH, the results show that the adsorption of Hg species on the titania surface strongly relies on the solution's pH. $Hg(OH)_2$ species exhibit a strong affinity for TiO_2, most likely due to interaction with surface-bound TiOH and TiO entities, in contrast to $HgCl_2$ species that are scarcely adsorbed on titania surfaces. Even without organic compounds, Hg(II) was effectively removed at pH 10, leading to final Hg concentrations in the solution at trace amounts. Sacrificial organic compounds considerably accelerated the rate and volume of aqueous Hg(II) elimination under acidic environments. It was clear from a comparison of the adsorption and reaction outcomes that there was no direct relationship between the effectiveness of the Hg(II) photoreduction process and the amount of Hg(II) dark adsorption on the TiO_2 surface [107].

Fluorescent lamps are being used more frequently than ever, which has raised concerns about how to properly dispose of them to prevent Hg leakage into the environment after used bulbs are broken and thrown away. Recycling has the benefit of reusing some raw materials, including Hg, compared to other solutions [108]. Bussi et al. investigated Hg recovery from fluorescent lamps, and they used a combined process, including extraction with an oxidant and follow-up treatment of the aqueous solution by heterogeneous photocatalysis. The entire procedure uses sodium hypochlorite aqueous solution to remove Hg chemically. Following pH modification of the generated aqueous solution, titanium dioxide and citric acid are employed as auxiliary organic agents in the photocatalytic reduction of Hg. As a result, combined techniques (extraction with an oxidant plus heterogeneous photocatalysis) were used on fluorescent light bulbs, and Hg was recovered. The most efficient leaching agent was NaOCl at pH 5.5, which caused total Hg breakdown and additional selective precipitation during the photocatalytic process. This allowed for the recovery of more than 99.9% of the Hg as solid compounds, which could then be conveniently redissolved in a slight amount of an aqueous NaOCl solution. The concentrated Hg(II) solution might then be cemented with metallic iron as a reducing agent to produce metallic Hg [109].

Coskun et al. also studied the hydrometallurgical extraction of Hg using hypochlorite leaching and heterogeneous photocatalysis using three distinct forms of TiO_2 (anatase, rutile, and anatase+rutile), identifying the pertinent variables for high percentage Hg extraction and Hg recovery from spent fluorescent lamps. The authors used different concentrations of NaOCl and NaCl as chemical (oxidative) leaching reagents to extract Hg from pulverized lamp samples. Based on the preliminary studies pH did not significantly change Hg extraction, also 2 h. interval was sufficient for the leaching equilibrium to be reached for the Hg. Thus, the authors used a 2 h. of leaching with pH 7.5 values for all the Hg recovery tests. For the leaching experiments, the test factors were identified as follows; mass/volume (lamp sample weight/leaching solution volume) ratio, leaching reagent (NaOCl/NaCl) dosage, and temperature (20, 50, and 90 ℃). In addition, the illumination time (10, 30, and 60 min.), photocatalyst amount (0.5, 1, and 2 g/L), and pH (3, 5.5, and 7) were projected as process variables for the photocatalysis tests [110].

The leaching experiments exhibited a greater Hg leaching yield (up to 95%) from pulverized lamp samples under the following conditions: temperature 50 ℃, mass/volume ratio 1/2, and leaching dosages 0.5 M NaOCl/0.2 M NaCl. Furthermore, based on the heterogeneous photocatalytic experiment results, a greater extent of Hg recovery (up to 95%) from leaching solutions was obtained under the following conditions; illumination time 60 min., pH 7, and amount of anatase phase TiO_2 2 g/L. The overall result reveals that almost 73–95% of the Hg was leached after 2 h. through NaOCl/NaCl reagents. In addition, close to 95% photocatalytic efficiencies were measured for the conversion of Hg(II) to Hg(0) using citric acid as the reductant agent. After photocatalysis, the anatase form of TiO_2 was found to be the most effective photocatalyst for the application of Hg recovery, consistent with filtered and solid residual samples. This conclusion is nearly supported by the XRD patterns and SEM–EDX elemental analyses [110].

Generally, the scientist picked 100 mg/L as an initial quantity of Hg for recovery studies. However, little research was done on Hg removal at trace levels, or about 100 μg/L of Hg. The presence of mg/L Hg waste streams is uncommon due to current Hg laws and health issues, and < 10 μg/L Hg concentrations are preferred in the environment. Thus, it is crucial to remove trace-level Hg to address current and future Hg management demands. Byrne et al. conducted a study to find out how much Hg could be removed by adsorption and photocatalysis, silica-titanium composites (STCs) were used with trace-level Hg solutions (100 g/L). STCs are made of a porous, large surface area (> 200 m^2/g) silica substrate that has been impregnated with TiO_2 nanoparticles using the sol–gel process. The performance of this substance was compared to that of its antecedents, silica as well as Degussa P25 TiO_2. Degussa P25 is a titania photocatalyst that has been widely used since high activity levels in many photocatalytic reaction systems. As a result, STCs were able to remove about 90% of the Hg under adsorption alone (without UV light), which is equal to Degussa P25. Comparatively, TiO_2, free of silica, performed inadequately and was slightly impacted by UV light. Furthermore, UV irradiation did not affect Degussa P25's performance, while the same exposure had a negative impact on the STC. Caused by photochemical processes, elemental Hg was created under UV irradiation with or without TiO_2, reducing the Hg removal by STC. The results show that altering the STC pore size and adding TiO_2 also improved adsorption kinetics. Overall, the authors achieved enhanced Hg removal by adsorption and photocatalysis conditions [111]. Table 1 summarizes some of the research works on Hg recovery in terms of the level of the achievement of the recovery technologies.

Benefits of recycling mercury

Reusing mercury-containing waste goes quite far in protecting the environment. Hg is tracked down in a few great spots around the home and working environment, including batteries, lighting, PCs, TVs, and even teeth fillings. While the Hg in these items is securely contained for everyday use, even a limited quantity of the poisonous material can have a horrendous effect when it is unloaded in a landfill. Although mercury-recycling keeps improving consistently, numerous organizations still need to discard items containing Hg securely [157]. Recycling Hg brings the following benefits.

(a) Keep toxic material out of the climate.

Hg can devastatingly affect the climate and the local area when disposed of recklessly. While mercury-containing items are tossed into the general waste receptacle, they end up in landfill, where they can leak into water bodies. Hg can be converted into methylmercury, where small fish can consume it and afterward bioamplified up the food chain.

(b) Reduce business costs.

There are a few significant investment funds for organizations to consider about running a recycling program. Landfill costs are rising as neighborhood government specialists attempt to manage the ecological effect of general waste. Recycling companies can frequently charge organizations less to remove a truck heap of waste since they can counterbalance their costs by recovering, and selling materials. Organizations also need to keep an eye out for fixing guidelines, similar to prohibiting dumping electronic waste in a landfill.

(c) Recuperate non-renewable resources.

Reusing Hg from old items decreases the need to mine more out of the ground. Massive amounts of Hg are required consistently to make new items all over the globe, yet there are recycling companies and projects that are pursuing a closed-loop technique.

For instance, Hg from the old dental blend, or fillings, can be recuperated and reused in a new mixture whenever it has been gathered and handled.

(d) Exhibit a promise to responsible recycling.

By making a recycling program at your business, you make an impression on your clients and representatives that you care about your environmental footprint. In addition, recycling companies give reusing confirmations to demonstrate that your business is consenting to the organization and government necessities by specifying the sum and sort of waste reused. This can give you a benefit over your competitors in drawing in clients, while likewise making a positive work environment culture.

(e) Recycling is simple.

Reusing mercury-containing waste has never been simpler. Recycling companies offer a range of administrations to organizations, from one-off assortments to extensive recycling programs [157].

Challenges and safety precautions during recycling mercury

Hg has conventionally been used in various mechanical and electrical devices, especially in the medical industries, and precision equipment for industrial and commercial applications. However, regardless of the wide use of Hg, it is a highly toxic material that requires a high-level level of attention in terms of safety during the recycling of the Hg as well requires proper disposal into the environment after its effective use. Therefore, it is crucial to develop an effective design process that will ensure two important aspects of one is the safety of humans, and other is the regulatory compliance to protect the environment from not harming by Hg recycling, handling, and disposal [158].

Table 1 Summary of research on mercury recovery methods

Year	Source of Mercury Waste	Material	Methodology	Efficiency	References
2020	Flue gas	Selenide-decorated copper foam (Cu-hs)	Adsorption	The removal rate of 100%	[112]
2019	Wastewater	Spherical chitosan/gelatin (CG) hydrogel particles	Adsorption	The removal rate of 98%	[113]
2017	Aqueous solutions	Ag^+ and graphene oxide (GO)	Adsorption	Removal rate higher than 98%	[114]
2017	Aqueous solutions	Thiol-rich 3D-porous hyper crosslink polymer	Adsorption	The removal rate of 98%	[115]
2015	Aqueous solutions	Chelex 100 resin	Adsorption	The removal rate of 98%	[116]
2015	Aqueous solutions	Electrospun cellulose-graphene nanocarbon fibers	Adsorption	The removal rate of 77%	[117]
2016	Aqueous solutions	Molybdenum disulphide (MoS_2)	Adsorption	2506 mg/g	[118]
2018	Water	Montmorillonite capped iron-iron oxides (MtFe)	Adsorption	~ 1900 mg/g	[119]
2020	Solid state materials	Phenothiazine-chitosan hydrogels and metal ion solutions	Adsorption	1673 mg/g	[120]
2018	Aqueous solutions	Magnetite single walled carbon nanotubes–cobalt sulfide (MSWCNTs–CoS)	Adsorption	1666 mg/g	[121]
2018	Aqueous solutions	Novel sorbent (HPACB) functionalized corn bract with hypo phosphorous acid	Adsorption	1293.71 mg/g	[122]
2012	Aqueous solutions	Polypyrrole–reduced graphene oxide (PPy-rGO) composite	Adsorption	980 mg/g	[123]
2018	Aqueous solutions	N-((3-(triethoxysilyl)propyl) carbamothioyl) benzamide functionalized graphene oxide (CTBz-GO)	Adsorption	950 mg/g	[124]
2018	Aqueous solutions	Fe_3O_4-nanocellulose	Adsorption	926.3 mg/g	[125]
2022	Aqueous solutions	Xerogels from chitosan and phenothiazine	Adsorption	900 mg/g	[126]
2018	Aqueous solutions	Interconnected lamella-shaped polymer grafted with 2-aminoethanethiol (IPOP-NS)	Adsorption	769 mg/g	[127]
2017	Water	Silica-coated magnetite nanoparticles ($TiO_2/SiO_2/Fe_3O_4$) nanoparticles	Adsorption	745.6 mg/g	[128]
2017	Water	Thiol-functionalized nanocellulose aerogel	Adsorption	718.5 mg/g	[129]
2013	Aqueous solutions	Zinc oxide (ZnO) nanoparticles	Adsorption	714 mg/g	[130]
2017	Wastewater	Thiol-functionalized magnetic porous organic Polymers (MOP-SH)	Adsorption	703 mg/g	[131]
2017	Water	$CoFe_2O_4$ nanoparticles coated by SiO_2 and functionalized with thiol groups ($CoFe_2O_4@SiO_2$–SH)	Adsorption	641 mg/g	[132]
2018	Aqueous solutions	L-cysteine–graphene oxide (L-Cys-GO)	Adsorption	600 mg/g	[133]

Table 1 (continued)

Year	Source of Mercury Waste	Material	Methodology	Efficiency	References
2018	Solid state materials	Sustainable carboxymethyl chitosan biochar (CMC-SSBC)	Adsorption	594.17 mg/g	[134]
2016	Aqueous solutions	Graphene oxide modified with 2-pyridinecarboxaldehyde thiosemicarbazone (GO/2-PTSC)	Adsorption	555 mg/g	[135]
2017	Aqueous solutions	Organoalkoxysilane-grafted lignocellulosic waste biomass (OS-LWB)	Adsorption	523.54 mg/g	[136]
2013	Aqueous solutions	graphite oxide nanofilled with magnetic chitosan (GO/mCS)	Adsorption	397 mg/g	[137]
2015	Water	Poly(1-vinylimidazole)-grafted Fe_3O_4@SiO_2 magnetic nanoparticles	Adsorption	346 mg/g	[138]
2018	Drinking water	2, 2-dithiodisalicylic acid graphene oxide nanocomposite (Fe_3O_4@DTSA-GO)	Adsorption	283.5 mg/g	[139]
2015	Water	EDTA functionalized magnetic graphene oxide (EDTA-mGO)	Adsorption	268.4 mg/g	[140]
2016	Synthetic wastewater	Amino and thiolated multi-walled carbon nanotubes (MWCNTs)	Adsorption	204.64 mg/g	[141]
2020	Water	Chitosan-based magnetic materials	Adsorption	152 mg/g	[142]
2014	Water	Thiol modified Fe_3O_4@SiO_2-SH Sorbent	Adsorption	148.8 mg/g	[143]
2017	Water	Chitosan-stabilized magnetic FeS nanoparticles (CTO-MFeS)	Adsorption	132 mg/g	[144]
2017	Aqueous solutions	MOF-74-Zn	Adsorption	63.3 mg/g	[145]
2020	Contaminated groundwater	Iron sulfide nanoparticles stabilized by carboxymethyl cellulose (CMC-FeS)	Chemical precipitation, ion exchange, and surface complexation	3358.28 mg/g	[146]
2020	Surface water	Mg_2Al layered double hydroxide supported iron sulfide composite (FeS@Mg_2Al-LDH)	Chemical precipitation, ion exchange, and surface complexation	116.96 mg/g	[147]
2008	Fluorescent lamps	Aqueous Hg(II) and synthetic iron sulfides (FeS)	Chemical precipitation	The removal rate of 77%	[58]
2018	Aqueous solutions	Iron sulfide nanoparticles stabilized by carboxymethyl cellulose (CMC-FeS)	Chemical precipitation	~ 1726 mg/g	[148]
2017	Aqueous solutions	Fe_3O_4 nanocomposites/magnetic chitosan modified with glutaraldehyde (MCS-GA)	Chemical precipitation	96 mg/g	[149]
2018	Wastewater	Zinc sulfide (ZnS) and $HgCl_2$ solution	Ion exchange	The removal rate of 99.9%	[150]
2015	Water	Fumatech FKE membrane	Ion exchange	Removal rate higher than 98%	[100]
2015	Contaminated water	Copper (I) sulfide and copper chloride ($CuCl_2·2H_2O$)	Ion exchange	3096 mg/g	[151]

Table 1 (continued)

Year	Source of Mercury Waste	Material	Methodology	Efficiency	References
2016	Aqueous solutions	CuS particles (PCuS) synthesized by wet-treatment of a Cu-based metal–organic framework (HKUST-1)	Ion exchange	2105 mg/g	[152]
2014	Water	ZnS Nanocrystals (ZnS NC) Sorbent	Ion exchange	2000 mg/g	[91]
2018	Wastewater	Fly ash-derived zeolites	Absorption in wet flue gas desulfurization system	The removal rate of 99%	[153]
2017	Coal combustion flue gas	Catalytic sorbent consists of magnetite (Fe_3O_4), molecular sieve (HZSM-5)	Absorption in wet flue gas desulfurization system	The removal rate of 97%	[52]
2020	Coal combustion flue gas	Magnetic iron-carbon (Fe-C-x) sorbents	Absorption in wet flue gas desulfurization system	The removal rate of ~ 95%	[154]
2018	Coal combustion flue gas	Magnetic iron–manganese binary oxide supported on carbon nanofiber ($Fe_{3\text{-}x}Mn_xO_4$/CNF)	Absorption in wet flue gas desulfurization system	The removal rate of 90%	[51]
2020	Coal combustion flue gas	Magnetite $MoSe_x$(inter)Fe_3O_4 adsorbent	Absorption in wet flue gas desulfurization system	135 mg/g	[48]
2018	Coal combustion flue gas	Fe_3O_4@CuS nanoparticles	Absorption in wet flue gas desulfurization system	80.73 mg/g	[49]
2019	Coal combustion flue gas	O_2 and NO co-doped porous carbon (PCO4N2T3)	Absorption in wet flue gas desulfurization system	12.3 mg/g	[46]
2017	Mercury-containing wastes (sludge)	Stainless steel (STS316)/steel (SS400)	Vacuum thermal desorption	The removal rate of 96.75%	[155]
2021	Fluorescent lamps	Elemental Hg (Hg0), Hg chloride (Hg_2Cl_2), and crushed glass Hg (Hg)	Thermal desorption	The removal rate of 70%	[43]
2020	Simulated mixture wastes and waste sludge	NaOH plus Hg compounds (HgS and HgO), simulated waste (mixtures of $HgCl_2/As_2O_3$ and HgS/As_2O_3)	Thermal desorption	The removal rate of 62.5%	[42]
2009	Fluorescent lamps	Fluorescent tubes containing Hg/fluorescent-powder	Thermal desorption	1.68% of hg	[44]
2010	Fluorescent lamps	Aqueous NaOCl solution	Photocatalysis	Removal rate higher than 99%	[109]
2013	Fluorescent lamps	Mixed phases of TiO_2	Photocatalysis	The removal rate of 95%	[110]
2011	Aqueous solutions	$HgCl_2$ using TiO_2 as catalyst	Photocatalysis	The removal rate of 90%	[107]
2009	Aqueous solutions	Silica–titania composites (STCs)	Photocatalysis	The removal rate of 90%	[111]
2018	Aqueous solutions	Platinum (Pt) films	Electrolysis	The removal rate of 99% (171 h.)	[156]
2011	Wastewater	Poly(vinylalcohol)/poly(vinylimidazole) complexing membrane	Membrane separation	Removal rate higher than 99%	[101]

The Hg-contained household items are relatively simple to recycle as long as the device's integrity is not damaged, but the Hg-contained debris from the industries are more dangerous than the household items. Moreover, mercury-contained industrial debris also has the potential risk of higher exposure to mercury in contact. Hg is most dangerous when it is inhaled, and ingested. However, physically ingesting elemental Hg is a highly unusual occurrence. Nevertheless, Hg can contaminate water bodies (e.g., lakes, streams, and other water sources). Then, microorganisms convert the spilled Hg into methylmercury, an organic form of Hg. Fish, and other creatures we might consume are then exposed to methylmercury. The minute levels of Hg in tiny organisms move up the food chain in a process known as bioaccumulation, and build up in larger, and larger species like fish and birds. Methylmercury can harm the kidneys, the neurological system, and the lungs. Children's neurological development can also be impacted by exposure. The best defense against all of these risks is containment. Avoid direct touch, inhalation, and environmental contamination with Hg waste [158].

As we know, inhaling Hg vapor can be more severe because of the extreme toxicity of the elemental Hg vapor. In addition, the Hg vapor emits faster even in low vapor pressure with an ambient temperature that can create severe inhalation hazards. However, increasing the temperature can increase evaporation, and create further potential hazards, and living a prolonged time in that condition or repeated exposure can trigger severe neurological impairment, and loss of life. Moreover, organic Hg compounds are even more harmful compared to metallic Hg. So, following a standard operating procedure is essential for using organic Hg compounds in the laboratory and industry. Figure 11 shows the affected human organs caused by general, and occupational Hg exposure [159].

The RCRA defines mercury-containing wastes as "Universal waste," indicating the widely generated hazardous waste. These wastes include, but are not limited to specific batteries, thermostats, temperature gauges, barometers, manometers, certain switches, bulbs, and so. To ensure the safety of the workers at the plant, maintaining the RCRA guideline for handling, and disposing of the waste is a must for all business operations, but household applications are exempt from these regulations. Maintaining safety for the workers during Hg operation is the critical area of focus that needs to be followed at every step while recycling Hg from mercury-contained waste [160]. In summary, proper handling, storage, contamination prevention, monitoring, testing, training, and education, and compliance with regulations are critical to ensuring the safety of workers, and minimizing environmental impacts. Proper handling, and storage of mercury are crucial to prevent exposure to workers. Mercury is a liquid at room temperature, and can easily evaporate into the air, increasing the risk of inhalation. Workers

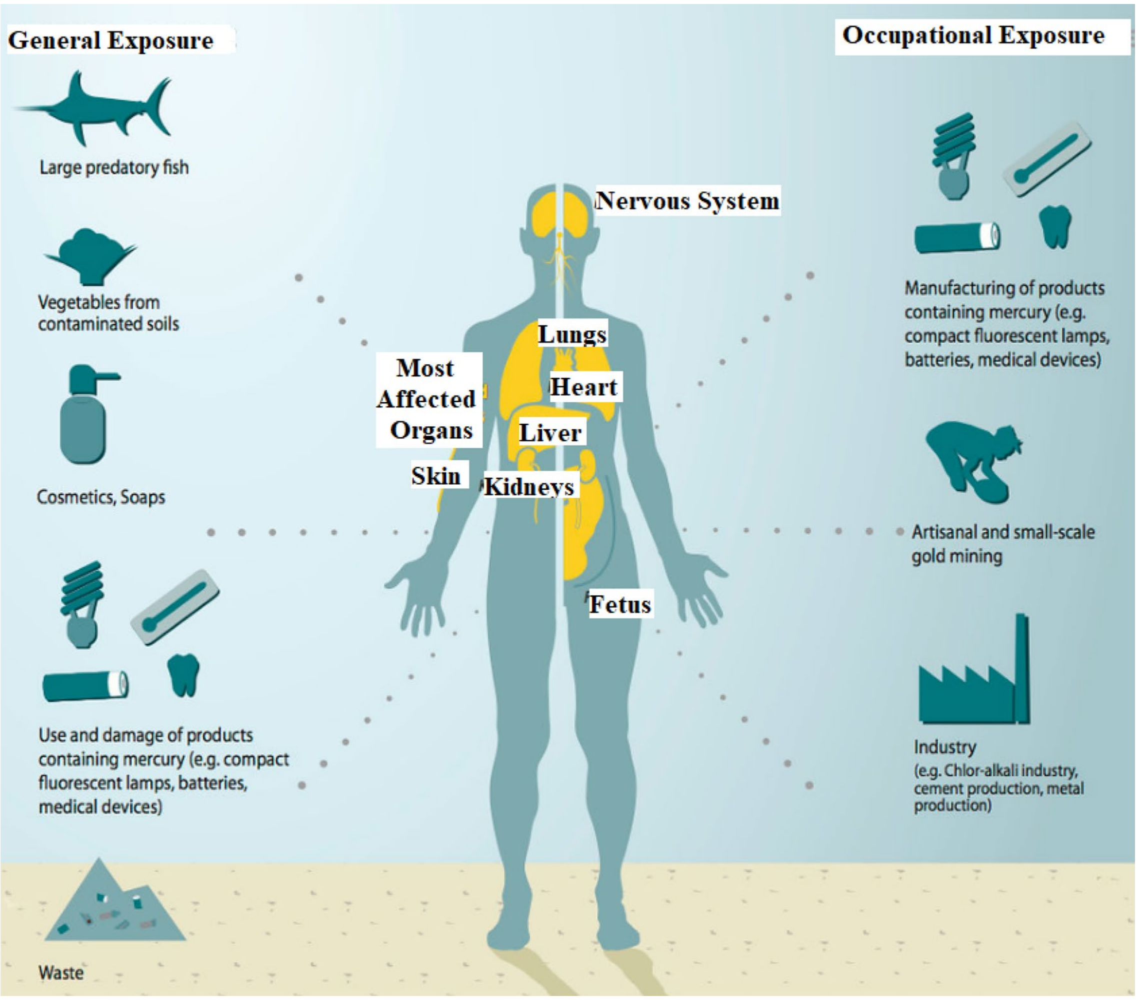


Fig. 11 Mercury and human health. It is adapted from Grid Arendal [157]

should wear protective equipment such as gloves, goggles, and respirators to avoid skin contact, inhalation, or mercury ingestion. All containers used to store mercury should be labeled with the proper warning labels, and the storage area should be secure, with limited access to authorized personnel only. Contamination prevention is crucial during the recycling process to avoid mercury exposure. Contamination can occur if mercury spills or leaks from containers, equipment, or surfaces. The recycling process should occur in a controlled environment with designated work areas, tools, and equipment. Workers should avoid eating, drinking, or smoking in areas with mercury. Any equipment used in the recycling process should be thoroughly cleaned to prevent cross-contamination. Contaminated materials should be appropriately disposed of, and contaminated areas should be decontaminated.

Regular monitoring and testing of air quality, and worker exposure to mercury are essential to identify potential hazards, and prevent overexposure. The workplace should be equipped with air monitoring systems to detect the presence of mercury in the air. Workers should wear personal air monitors to measure their exposure levels. Medical surveillance should also be performed to detect any health effects caused by exposure to mercury. Workers involved in the recycling process should receive adequate training, and education on the hazards of mercury and the proper handling, and disposal procedures. They should be aware of the symptoms of mercury exposure, which include headaches, dizziness, tremors, and memory loss. Workers should also know how to respond in case of an emergency, such as a spill or exposure incident. The recycling facility must comply with all applicable regulations, and guidelines set by local, state, and federal agencies. These regulations may include worker protection, environmental protection, waste disposal, and record-keeping requirements. The facility should have a written plan outlining the procedures for handling, storing, and disposing of mercury. The facility should also have an emergency response plan in case of a spill or exposure incident. Therefore, the challenge of recycling mercury-containing products lies in ensuring that the process is conducted to minimize the potential for mercury to cycle back into the environment and that it is economically feasible for all parties involved [160].

Conclusion

Understanding of the Hg cycles is the key pathway to working on the Hg recovery method. The better the understanding of the Hg cycle from all perspectives, the more contribution will turn out to develop an efficient Hg recovery process by which mercury-contained wasted can be collected and stored safely for further processing to recover the Hg from those waste materials. Thermal desorption technology can be a starting point for the recovery of Hg. The removal process of Hg from the environment, like from water, can be a great area to work in the future. Moreover, exploring new and more efficient technology to recover Hg from the mercury-contained waste that comes from industry can be a great field to work in.

Data availability All data underlying the results are available as part of the article, and no additional source data are required.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or relationships that could have appeared to influence the work reported in this paper.

References

1. USEPA (2020) Basic information about mercury. United States Environ Prot Agency. https://www.epa.gov/mercury/basic-information-about-mercury. Accessed 12 Dec 2022
2. Environmental Protection Agency of the United States (2021) Health effects of exposures to mercury. Environ Prot Agency United States. https://www.epa.gov/mercury/health-effects-exposures-mercury#metallic%0Ahttps://www.epa.gov/mercury/health-effects-exposures-mercury. Accessed 13 Dec 2022
3. Brosset C (1981) The mercury cycle - Preliminary communication. Water Air Soil Pollut. https://www.canada.ca/en/environment-climate-change/services/pollutants/mercury-environment/about/cycle.html. Accessed 12 Dec 2022
4. Proper disposal of mercury-containing products and how to manage a mercury spill | department of environmental conservation. https://dec.vermont.gov/waste-management/solid/product-stewardship/mercury/proper-disposal. Accessed 13 Dec 2022
5. Qu P, Pang M, Wang P et al (2022) Bioaccumulation of mercury along continuous fauna trophic levels in the Yellow River Estuary and adjacent sea indicated by nitrogen stable isotopes. J Hazard Mater 432:128631. https://doi.org/10.1016/j.jhazmat.2022.128631
6. Oken E, Bellinger DC (2008) Fish consumption, methylmercury and child neurodevelopment. Curr Opin Pediatr 20:178–183. https://doi.org/10.1097/MOP.0b013e3282f5614c
7. Bashir I, Lone FA, Bhat RA et al (2020) Concerns and threats of contamination on aquatic ecosystems. Bioremediation Biotechnol 1–26. https://doi.org/10.1007/978-3-030-35691-0_1
8. Zaynab M, Al-Yahyai R, Ameen A et al (2022) Health and environmental effects of heavy metals. J King Saud Univ 34:101653
9. Tchounwou PB, Yedjou CG, Patlolla AK, Sutton DJ (2012) Heavy metal toxicity and the environment. EXS 101:133–164. https://doi.org/10.1007/978-3-7643-8340-4_6
10. Briffa J, Sinagra E, Blundell R (2020) Heavy metal pollution in the environment and their toxicological effects on humans. Heliyon 6:e04691. https://doi.org/10.1016/j.heliyon.2020.e04691
11. Asmatulu E, Andalib MN, Subeshan B, Abedin F (2022) Impact of nanomaterials on human health: a review. Environ Chem Lett 20:2509–2529. https://doi.org/10.1007/s10311-022-01430-z
12. Fernandes Azevedo B, Barros Furieri L, Peçanha FMI et al (2012) Toxic effects of mercury on the cardiovascular and central nervous systems. J Biomed Biotechnol. https://doi.org/10.1155/2012/949048

13. Rafati-Rahimzadeh M, Rafati-Rahimzadeh M, Kazemi S, Moghadamnia AA (2014) Current approaches of the management of mercury poisoning: need of the hour. DARU J Pharm Sci 22:1–10. https://doi.org/10.1186/2008-2231-22-46
14. Mitra S, Chakraborty AJ, Tareq AM et al (2022) Impact of heavy metals on the environment and human health: novel therapeutic insights to counter the toxicity. J King Saud Univ Sci 34:101865. https://doi.org/10.1016/j.jksus.2022.101865
15. Ekawanti A, Krisnayanti BD (2016) Response to "Comment on 'Effect of Mercury Exposure on Renal Function and Hematological Parameters among Artisanal and Small-scale Gold Miners at Sekotong, West Lombok, Indonesia.'" J Heal Pollut 6:104–104. https://doi.org/10.5696/2156-9614-6.10.104
16. Driscoll CT, Mason RP, Chan HM et al (2013) Mercury as a global pollutant: sources, pathways, and effects. Environ Sci Technol 47:4967–4983. https://doi.org/10.1021/es305071v
17. Kirk JL, Lehnherr I, Andersson M et al (2012) Mercury in Arctic marine ecosystems: sources, pathways and exposure. Environ Res 119:64–87. https://doi.org/10.1016/j.envres.2012.08.012
18. Brigham ME, Wentz DA, Aiken GR, Krabbenhoft DP (2009) Mercury cycling in stream ecosystems. 1. Water column chemistry and transport. Environ Sci Technol 43:2720–2725
19. Obrist D, Kirk JL, Zhang L et al (2018) A review of global environmental mercury processes in response to human and natural perturbations: changes of emissions, climate, and land use. Ambio 47:116–140
20. Demarty M, Bilodeau F, Tremblay A (2021) Mercury export from freshwater to estuary: carbocentric science elucidates the fate of a toxic compound in aquatic boreal environments. Front Environ Sci 9:697563
21. Gworek B, Dmuchowski W, Baczewska-Dkabrowska AH (2020) Mercury in the terrestrial environment: a review. Environ Sci Eur 32:1–19
22. Lutter R, Irwin E (2002) Mercury in the environment: a volatile problem. Environment 44:24–40. https://doi.org/10.1080/00139157.2002.10543561
23. Cycle TM, Sampling M, Clean-up M (2014) Mercury in the environment and water supply. https://people.uwec.edu/piercech/Hg/mercury_water/cycling.htm. Accessed 12 Sep 2022
24. Li F, Ma C, Zhang P (2020) Mercury deposition, climate change and anthropogenic activities: a review. Front Earth Sci 8:316
25. Abelsohn A, Gibson BL, Sanborn MD, Weir E (2002) Identifying and managing adverse environmental health effects: 5. Persistent organic pollutants. C Can Med Assoc J 166:1549–1554
26. Tanzim F, Subeshan B, Asmatulu R (2022) Improving the saline water evaporation rates using highly conductive carbonaceous materials under infrared light for improved freshwater production. Desalination 531:115710. https://doi.org/10.1016/j.desal.2022.115710
27. Selin NE (2009) Global biogeochemical cycling of mercury: a review. Annu Rev Environ Resour 34:43–63. https://doi.org/10.1146/annurev.environ.051308.084314
28. United States Environmental Protection Agency Storing, Transporting and Disposing of Mercury | US EPA. https://www.epa.gov/mercury/storing-transporting-and-disposing-mercury. Accessed 12 May 2022
29. USEPA (1996) Land disposal restrictions for hazardous waste. https://www.epa.gov/hw/land-disposal-restrictions-hazardous-waste. Accessed 12 Oct 2022
30. Mercury bearing waste disposal. https://ehs.research.uiowa.edu/mercury-bearing-waste-disposal. Accessed 12 Nov 2022
31. Ahmed T, Mohammed Q, Subeshan B et al (2022) Improving flame retardancy and hydrophobicity of fabrics via graphene inclusion obtained from recycled batteries. Mater Today Proc 71:78–89. https://doi.org/10.1016/j.matpr.2022.07.469
32. Baldé K, D'Angelo E, Forti V et al (2018) Waste Mercury Perspective: 2010–2035 From global to regional. https://collections.unu.edu/view/UNU:6712#viewAttachments. Accessed 12 Dec 2022
33. Takaoka M (2015) Mercury and mercury-containing waste management in Japan. J Mater Cycles Waste Manag 17:665–672. https://doi.org/10.1007/s10163-014-0325-z
34. Utah Department of Environmental Quality. Mercury. https://deq.utah.gov/water-quality/mercury. Accessed 12 Dec 2022
35. Ward DM, Nislow KH, Folt CL (2010) Bioaccumulation syndrome: identifying factors that make some stream food webs prone to elevated mercury bioaccumulation. Ann N Y Acad Sci 1195:62–83
36. Schroeder WH, Munthe J (1998) Atmospheric mercury—an overview. Atmos Environ 32:809–822
37. Rumayor M, Diaz-Somoano M, Lopez-Anton MA, Martinez-Tarazona MR (2013) Mercury compounds characterization by thermal desorption. Talanta 114:318–322. https://doi.org/10.1016/j.talanta.2013.05.059
38. Shedd ES, Scheiner BJ, Lindstrom RE (1975) Recovery of mercury from cinnabar ores by electrooxidation - extraction plant amenability tests. US Department of the Interior, Bureau of Mines
39. Electrical F, Wastes M (1994) Characterization and recovery of mercury by thermal desorption. (**ISSN 1066-5552**)
40. Chalkidis A, Jampaiah D, Aryana A et al (2020) Mercury-bearing wastes: sources, policies and treatment technologies for mercury recovery and safe disposal. J Environ Manage 270:110945. https://doi.org/10.1016/j.jenvman.2020.110945
41. Lee CH, Popuri SR, Peng YH et al (2015) Overview on industrial recycling technologies and management strategies of end-of-life fluorescent lamps in Taiwan and other developed countries. J Mater Cycles Waste Manag 17:312–323. https://doi.org/10.1007/s10163-014-0253-y
42. Back SK, Lee ES, Seo YC, Jang HN (2020) The effect of NaOH for the recovery of elemental mercury from simulated mixture wastes and waste sludge from an industrial process using a thermal desorption process. J Hazard Mater 384:121291. https://doi.org/10.1016/j.jhazmat.2019.121291
43. Esbrí JM, Rivera S, Tejero J, Higueras PL (2021) Feasibility study of fluorescent lamp waste recycling by thermal desorption. Environ Sci Pollut Res 28:61860–61868. https://doi.org/10.1007/s11356-021-16800-3
44. Chang TC, Chen CM, Lee YF, You SJ (2010) Mercury recovery from cold cathode fluorescent lamps using thermal desorption technology. Waste Manag Res 28:455–460. https://doi.org/10.1177/0734242X09335694
45. Anwari RA, Coskun S, Saltan M (2022) Research on recycle of waste fluorescent lamp glasses and use as mineral filler in asphalt mixture. J Mater Cycles Waste Manag. https://doi.org/10.1007/s10163-022-01525-3
46. Shen F, Liu J, Wu D et al (2019) Development of O 2 and NO Co-doped porous carbon as a high-capacity mercury sorbent. Environ Sci Technol 53:1725–1731. https://doi.org/10.1021/acs.est.8b05777
47. Lee C-S, Fisher NS (2017) Bioaccumulation of methylmercury in a marine diatom and the influence of dissolved organic matter. Mar Chem 197:70–79
48. Yang W, Wang Z, Liu Y (2020) Review on magnetic adsorbents for removal of elemental mercury from flue gas. Energy Fuels 34:13473–13490. https://doi.org/10.1021/acs.energyfuels.0c02931
49. Yang Z, Li H, Liao C et al (2018) Magnetic rattle-type Fe3O4@CuS nanoparticles as recyclable sorbents for mercury capture from coal combustion flue gas. ACS Appl Nano Mater 1:4726–4736. https://doi.org/10.1021/acsanm.8b00948

50. Zhang LX, Zhang AC, Zhu QF et al (2018) Effects of experimental parameters on Hg0 removal over magnetic AgI-BiOI/CoFe2O4 photocatalysts using wet process. Ranliao Huaxue Xuebao/J Fuel Chem Technol 46:365–374. https://doi.org/10.1016/s1872-5813(18)30016-1
51. Yang J, Zhao Y, Liang S et al (2018) Magnetic iron–manganese binary oxide supported on carbon nanofiber (Fe3−xMnxO4/CNF) for efficient removal of Hg0 from coal combustion flue gas. Chem Eng J 334:216–224. https://doi.org/10.1016/j.cej.2017.10.004
52. Cao T, Zhou Z, Chen Q et al (2017) Magnetically responsive catalytic sorbent for removal of Hg0 and NO. Fuel Process Technol 160:158–169. https://doi.org/10.1016/j.fuproc.2017.02.022
53. Safari E, Ansari M, Ghazban F (2017) Preliminary assessment of cement kiln dust in solidification and stabilization of mercury containing waste from a chlor-alkali unit. J Mater Cycles Waste Manag 19:406–412. https://doi.org/10.1007/s10163-015-0437-0
54. Hadi P, To MH, Hui CW et al (2015) Aqueous mercury adsorption by activated carbons. Water Res 73:37–55. https://doi.org/10.1016/j.watres.2015.01.018
55. Gupta K, Joshi P, Gusain R, Khatri OP (2021) Recent advances in adsorptive removal of heavy metal and metalloid ions by metal oxide-based nanomaterials. Coord Chem Rev 445:214100. https://doi.org/10.1016/j.ccr.2021.214100
56. Ugwu EI, Othmani A, Nnaji CC (2022) A review on zeolites as cost-effective adsorbents for removal of heavy metals from aqueous environment. Int J Environ Sci Technol 19:8061–8084. https://doi.org/10.1007/s13762-021-03560-3
57. Anna M, Andrey F, Eugenia V (2022) Comparison of the performance of different methods to stabilize mercury-containing waste. J Mater Cycles Waste Manag 24:1134–1139. https://doi.org/10.1007/s10163-022-01386-w
58. Liu J, Valsaraj KT, Devai I, DeLaune RD (2008) Immobilization of aqueous Hg(II) by mackinawite (FeS). J Hazard Mater 157:432–440. https://doi.org/10.1016/j.jhazmat.2008.01.006
59. Salcedo ODC, Vargas DP, Giraldo L, Moreno-Piraján JC (2021) Study of mercury [Hg(II)] Adsorption from aqueous solution on functionalized activated carbon. ACS Omega 6:11849–11856. https://doi.org/10.1021/acsomega.0c06084
60. Zou C, Liang J, Jiang W et al (2018) Adsorption behavior of magnetic bentonite for removing Hg(II) from aqueous solutions. RSC Adv 8:27587–27595. https://doi.org/10.1039/c8ra05247f
61. Zhou Y, Luan L, Tang B et al (2020) Fabrication of Schiff base decorated PAMAM dendrimer/magnetic Fe3O4 for selective removal of aqueous Hg(II). Chem Eng J 398:125651. https://doi.org/10.1016/j.cej.2020.125651
62. Zhao J, Niu Y, Ren B et al (2018) Synthesis of Schiff base functionalized superparamagnetic Fe3O4 composites for effective removal of Pb(II) and Cd(II) from aqueous solution. Chem Eng J 347:574–584. https://doi.org/10.1016/j.cej.2018.04.151
63. Niu Y, Qu R, Chen H et al (2014) Synthesis of silica gel supported salicylaldehyde modified PAMAM dendrimers for the effective removal of Hg(II) from aqueous solution. J Hazard Mater 278:267–278. https://doi.org/10.1016/j.jhazmat.2014.06.012
64. Zunita M (2021) Graphene oxide-based nanofiltration for Hg removal from wastewater: a mini review. Membranes (Basel) 11:269. https://doi.org/10.3390/membranes11040269
65. Gao W, Majumder M, Alemany LB et al (2011) Engineered graphite oxide materials for application in water purification. ACS Appl Mater Interfaces 3:1821–1826. https://doi.org/10.1021/am200300u
66. Kazemi A, Bahramifar N, Heydari A, Olsen SI (2019) Synthesis and sustainable assessment of thiol-functionalization of magnetic graphene oxide and superparamagnetic Fe3O4@SiO2 for Hg(II) removal from aqueous solution and petrochemical wastewater. J Taiwan Inst Chem Eng 95:78–93. https://doi.org/10.1016/j.jtice.2018.10.002
67. Tene T, Arias Arias F, Guevara M et al (2022) Removal of mercury(II) from aqueous solution by partially reduced graphene oxide. Sci Rep 12:1–12. https://doi.org/10.1038/s41598-022-10259-z
68. Ge H, Du J (2020) Selective adsorption of Pb(II) and Hg(II) on melamine-grafted chitosan. Int J Biol Macromol 162:1880–1887
69. Wang J, Deng B, Chen H et al (2009) Removal of aqueous Hg(II) by polyaniline: Sorption characteristics and mechanisms. Environ Sci Technol 43:5223–5228. https://doi.org/10.1021/es803710k
70. Rani L, Srivastav AL, Kaushal J (2021) Bioremediation: an effective approach of mercury removal from the aqueous solutions. Chemosphere 280:130654. https://doi.org/10.1016/j.chemosphere.2021.130654
71. Chaudhuri S, Sigmund G, Bone SE et al (2022) Mercury removal from contaminated water by wood-based biochar depends on natural organic matter and ionic composition. Environ Sci Technol 56:11354–11362. https://doi.org/10.1021/acs.est.2c01554
72. Raina SA, Van EB, Alonzo DE et al (2015) Trends in the precipitation and crystallization behavior of supersaturated aqueous solutions of poorly water-soluble drugs assessed using synchrotron radiation. J Pharm Sci 104:1981–1992. https://doi.org/10.1002/jps.24423
73. Kang HY, Schoenung JM (2005) Electronic waste recycling: a review of U.S. infrastructure and technology options. Resour Conserv Recycl 45:368–400. https://doi.org/10.1016/j.resconrec.2005.06.001
74. Pohl A (2020) Removal of heavy metal ions from water and wastewaters by sulfur-containing precipitation agents. Water Air Soil Pollut 231:1–17. https://doi.org/10.1007/s11270-020-04863-w
75. Rajasulochana P, Preethy V (2016) Comparison on efficiency of various techniques in treatment of waste and sewage water – a comprehensive review. Resour Technol 2:175–184. https://doi.org/10.1016/j.reffit.2016.09.004
76. Das TK, Poater A (2021) Review on the use of heavy metal deposits from water treatmentwaste towards catalytic chemical syntheses. Int J Mol Sci 22:13383. https://doi.org/10.3390/ijms222413383
77. Rojas LA, Yáñez C, González M et al (2014) Characterization of the metabolically modified heavy metal-resistant *Cupriavidus metallidurans* strain MSR33 generated for mercury bioremediation. Heavy Met Contam Water Soil Anal Assess Remediat Strateg 2011:305–327. https://doi.org/10.1201/b16566
78. Zhuang JM, Walsh T, Lam T (2003) A new technology for the treatment of mercury contaminated water and soils. Environ Technol (United Kingdom) 24:897–902. https://doi.org/10.1080/09593330309385626
79. Blue LY, Jana P, Atwood DA (2010) Aqueous mercury precipitation with the synthetic dithiolate, BDTH2. Fuel 89:1326–1330. https://doi.org/10.1016/j.fuel.2009.10.031
80. Vardhan KH, Kumar PS, Panda RC (2019) A review on heavy metal pollution, toxicity and remedial measures: current trends and future perspectives. J Mol Liq 290:111197. https://doi.org/10.1016/j.molliq.2019.111197
81. Pang FM, Teng SP, Teng TT, Mohd Omar AK (2009) Heavy metals removal by hydroxide precipitation and coagulation-flocculation methods from aqueous solutions. Water Qual Res J Canada 44:174–182. https://doi.org/10.2166/wqrj.2009.019
82. Vidu R, Matei E, Predescu AM et al (2020) Removal of heavy metals from wastewaters: a challenge from current treatment methods to nanotechnology applications. Toxics 8:1–37. https://doi.org/10.3390/toxics8040101

83. Prokkola H, Nurmesniemi ET, Lassi U (2020) Removal of metals by sulphide precipitation using na2s and hs−-solution. ChemEngineering 4:1–10. https://doi.org/10.3390/chemengineering4030051
84. Qasem NAA, Mohammed RH, Lawal DU (2021) Author Correction: removal of heavy metal ions from wastewater: a comprehensive and critical review (npj Clean Water, (2021), 4, 1, (36), 10.1038/s41545-021-00127-0). npj Clean Water 4:1–15. https://doi.org/10.1038/s41545-021-00144-z
85. Elgarahy AM, Elwakeel KZ, Mohammad SH, Elshoubaky GA (2021) A critical review of biosorption of dyes, heavy metals and metalloids from wastewater as an efficient and green process. Clean Eng Technol 4:100209. https://doi.org/10.1016/j.clet.2021.100209
86. Vijayan PP, Chithra PG, Krishna SVA et al (2022) Development and current trends on ion exchange materials. Sep Purif Rev. https://doi.org/10.1080/15422119.2022.2149413
87. Gupta A, Sharma V, Sharma K et al (2021) A review of adsorbents for heavy metal decontamination: growing approach to wastewater treatment. Materials (Basel) 14:4702. https://doi.org/10.3390/ma14164702
88. Verbych S, Hilal N, Sorokin G, Leaper M (2004) Ion exchange extraction of heavy metal ions from wastewater. Sep Sci Technol 39:2031–2040. https://doi.org/10.1081/SS-120039317
89. Czupryński P, Płotka M, Glamowski P et al (2022) An assessment of an ion exchange resin system for the removal and recovery of Ni, Hg, and Cr from wet flue gas desulphurization wastewater—a pilot study. RSC Adv 12:5145–5156. https://doi.org/10.1039/d1ra09426b
90. Monteagudo JM, Ortiz MJ (2000) Removal of inorganic mercury from mine waste water by ion exchange. J Chem Technol Biotechnol 75:767–772. https://doi.org/10.1002/1097-4660(200009)75:9%3c767::AID-JCTB281%3e3.0.CO;2-1
91. Qu Z, Yan L, Li L et al (2014) Ultraeffective ZnS nanocrystals sorbent for mercury(II) removal based on size-dependent cation exchange. ACS Appl Mater Interfaces 6:18026–18032. https://doi.org/10.1021/am504896w
92. Smith AM, Nie S (2011) Bright and compact alloyed quantum dots with broadly tunable near-infrared absorption and fluorescence spectra through mercury cation exchange. J Am Chem Soc 133:24–26. https://doi.org/10.1021/ja108482a
93. Moradi G, Zinadini S, Rajabi L (2020) Development of the tetrathioterephthalate filler incorporated PES nanofiltration membrane with efficient heavy metal ions rejection and superior antifouling properties. J Environ Chem Eng 8:104431. https://doi.org/10.1016/j.jece.2020.104431
94. Cevallos-Mendoza J, Amorim CG, Rodríguez-Díaz JM, da Montenegro MCBSM (2022) Removal of contaminants from water by membrane filtration: a review. Membranes (Basel) 12:570. https://doi.org/10.3390/membranes12060570
95. Khulbe KC, Matsuura T (2018) Removal of heavy metals and pollutants by membrane adsorption techniques. Appl Water Sci 8:1–30. https://doi.org/10.1007/s13201-018-0661-6
96. Rakib M, Baddam Y, Subeshan B et al (2022) Fabrication of spirulina based activated carbons for wastewater treatment. Environ Technol (United Kingdom). https://doi.org/10.1080/09593330.2022.2138557
97. Oyarce E, Roa K, Boulett A et al (2021) Removal of dyes by polymer-enhanced ultrafiltration: an overview. Polymers (Basel) 13:3450. https://doi.org/10.3390/polym13193450
98. Hakami MW, Alkhudhiri A, Al-Batty S et al (2020) Ceramic microfiltration membranes in wastewater treatment: filtration behavior, fouling and prevention. Membranes (Basel) 10:1–34. https://doi.org/10.3390/membranes10090248
99. AJ S, R T, Yimam A (2018) Magnetic hetero-structures as prospective sorbents to aid arsenic elimination from life water streams. Water Sci 32:151–170. https://doi.org/10.1016/j.wsj.2017.05.001
100. Oehmen A, Vergel D, Fradinho J et al (2014) Mercury removal from water streams through the ion exchange membrane bioreactor concept. J Hazard Mater 264:65–70. https://doi.org/10.1016/j.jhazmat.2013.10.067
101. Bessbousse H, Rhlalou T, Verchère JF, Lebrun L (2010) Mercury removal from wastewater using a poly(vinylalcohol)/poly(vinylimidazole) complexing membrane. Chem Eng J 164:37–48. https://doi.org/10.1016/j.cej.2010.08.004
102. Urgun-Demirtas M, Benda PL, Gillenwater PS et al (2012) Achieving very low mercury levels in refinery wastewater by membrane filtration. J Hazard Mater 215–216:98–107. https://doi.org/10.1016/j.jhazmat.2012.02.040
103. Yu X, Liu W, Deng X et al (2018) Gold nanocluster embedded bovine serum albumin nanofibers-graphene hybrid membranes for the efficient detection and separation of mercury ion. Chem Eng J 335:176–184. https://doi.org/10.1016/j.cej.2017.10.148
104. Aguado J, Arsuaga JM, Arencibia A (2008) Influence of synthesis conditions on mercury adsorption capacity of propylthiol functionalized SBA-15 obtained by co-condensation. Microporous Mesoporous Mater 109:513–524. https://doi.org/10.1016/j.micromeso.2007.05.061
105. Vieira RS, Guibal E, Silva EA, Beppu MM (2007) Adsorption and desorption of binary mixtures of copper and mercury ions on natural and crosslinked chitosan membranes. Adsorption 13:603–611. https://doi.org/10.1007/s10450-007-9050-4
106. López-Muñoz MJ, Aguado J, van Grieken R, Marugán J (2009) Simultaneous photocatalytic reduction of silver and oxidation of cyanide from dicyanoargentate solutions. Appl Catal B Environ 86:53–62. https://doi.org/10.1016/j.apcatb.2008.07.022
107. López-Muñoz MJ, Aguado J, Arencibia A, Pascual R (2011) Mercury removal from aqueous solutions of HgCl2 by heterogeneous photocatalysis with TiO2. Appl Catal B Environ 104:220–228. https://doi.org/10.1016/j.apcatb.2011.03.029
108. US EPA (2018) Recycling and disposal of CFLs and other bulbs that contain mercury. https://www.epa.gov/cfl/recycling-and-disposal-cfls-and-other-bulbs-contain-mercury. Accessed 13 Dec 2022
109. Bussi J, Cabrera MN, Chiazzaro J et al (2010) The recovery and recycling of mercury from fluorescent lamps using photocatalytic techniques. J Chem Technol Biotechnol 85:478–484. https://doi.org/10.1002/jctb.2313
110. Coskun S, Cirlengic M, Ozgur C et al (2013) The mercury recovery from the spent fluorescent lamps using chemical leaching and heterogeneous photocatalytic reduction. In: Sardinia 2013, 14th International waste management and landfill symposium
111. Byrne HE, Mazyck DW (2009) Removal of trace level aqueous mercury by adsorption and photocatalysis on silica-titania composites. J Hazard Mater 170:915–919. https://doi.org/10.1016/j.jhazmat.2009.05.055
112. Yang J, Li Q, Li M et al (2020) In situ decoration of selenide on copper foam for the efficient immobilization of gaseous elemental mercury. Environ Sci Technol 54:2022–2030. https://doi.org/10.1021/acs.est.9b07057
113. Perumal S, Atchudan R, Yoon DH et al (2019) Spherical chitosan/gelatin hydrogel particles for removal of multiple heavy metal ions from wastewater. Ind Eng Chem Res 58:9900–9907. https://doi.org/10.1021/acs.iecr.9b01298
114. Qu Z, Fang L, Chen D et al (2017) Effective and regenerable Ag/graphene adsorbent for Hg(II) removal from aqueous solution. Fuel 203:128–134. https://doi.org/10.1016/j.fuel.2017.04.105
115. Abadast F, Mouradzadegun A, Ganjali MR (2017) Rational design, fabrication and characterization of a thiol-rich 3D-porous hypercrosslink polymer as a new engineered Hg2+ sorbent:

enhanced selectivity and uptake. New J Chem 41:5458–5466. https://doi.org/10.1039/c7nj00663b

116. Amara-Rekkab A, Didi MA (2016) Design optimization of extraction procedure for mercury (II) using Chelex 100 resin. Desalin Water Treat 57:6950–6958. https://doi.org/10.1080/19443994.2015.1012745
117. Bhalara PD, Balasubramanian K, Banerjee BS (2015) Spider-web textured electrospun composite of graphene for sorption of Hg(II) ions. Mater Focus 4:154–163. https://doi.org/10.1166/mat.2015.1232
118. Liu C, Yang S, Zhang C et al (2017) MoS2 nanosheets with widened interlayer spacing for high-efficiency removal of mercury in fule gas. 14th Int Symp East Asian Resour Recycl Technol EARTH 26:5542–5549
119. Ganguly M, Dib S, Ariya PA (2018) Fast, cost-effective and energy efficient mercury removal-recycling technology. Sci Rep 8:1–10. https://doi.org/10.1038/s41598-018-34172-6
120. Bejan A, Doroftei F, Cheng X, Marin L (2020) Phenothiazine-chitosan based eco-adsorbents: a special design for mercury removal and fast naked eye detection. Int J Biol Macromol 162:1839–1848. https://doi.org/10.1016/j.ijbiomac.2020.07.232
121. Alijani H, Shariatinia Z (2018) Synthesis of high growth rate SWCNTs and their magnetite cobalt sulfide nanohybrid as super-adsorbent for mercury removal. Chem Eng Res Des 129:132–149. https://doi.org/10.1016/j.cherd.2017.11.014
122. Lin G, Wang S, Zhang L et al (2018) Selective and high efficient removal of Hg2+ onto the functionalized corn bract by hypophosphorous acid. J Clean Prod 192:639–646. https://doi.org/10.1016/j.jclepro.2018.05.043
123. Chandra V, Kim KS (2011) Highly selective adsorption of Hg2+ by a polypyrrole–reduced graphene oxide composite. Chem Commun 47:3942–3944. https://doi.org/10.1039/c1cc00005e
124. Movahedi F, Masrouri H, Tayyebi H (2018) Highly efficient adsorption behavior of benzoylthiourea functionalized graphene oxide with respect to the removal of Hg(II) from aqueous solutions: isothermal, kinetic and thermodynamic studies. Res Chem Intermed 44:5419–5438. https://doi.org/10.1007/s11164-018-3431-z
125. Zarei S, Niad M, Raanaei H (2018) The removal of mercury ion pollution by using Fe3O4-nanocellulose: synthesis, characterizations and DFT studies. J Hazard Mater 344:258–273. https://doi.org/10.1016/j.jhazmat.2017.10.009
126. Cibotaru S, Ailincai D, Andreica B-I et al (2022) TEGylated phenothiazine-imine-chitosan materials as a promising framework for mercury recovery. Gels 8:692. https://doi.org/10.3390/gels8110692
127. Ravi S, Ahn WS (2018) Facile synthesis of a mesoporous organic polymer grafted with 2-aminoethanethiol for Hg2+ removal. Microporous Mesoporous Mater 271:59–67. https://doi.org/10.1016/j.micromeso.2018.05.038
128. Sobhanardakani S, Zandipak R (2017) Synthesis and application of TiO2/SiO2/Fe3O4 nanoparticles as novel adsorbent for removal of Cd(II), Hg(II) and Ni(II) ions from water samples. Clean Technol Environ Policy 19:1913–1925. https://doi.org/10.1007/s10098-017-1374-5
129. Geng B, Wang H, Wu S et al (2017) Surface-tailored nanocellulose aerogels with thiol-functional moieties for highly efficient and selective removal of Hg(II) ions from water. ACS Sustain Chem Eng 5:11715–11726. https://doi.org/10.1021/acssuschemeng.7b03188
130. Sheela T, Nayaka YA, Viswanatha R et al (2012) Kinetics and thermodynamics studies on the adsorption of Zn(II), Cd(II) and Hg(II) from aqueous solution using zinc oxide nanoparticles. Powder Technol 217:163–170. https://doi.org/10.1016/j.powtec.2011.10.023
131. Huang L, Peng C, Cheng Q et al (2017) Thiol-functionalized magnetic porous organic polymers for highly efficient removal of mercury. Ind Eng Chem Res 56:13696–13703. https://doi.org/10.1021/acs.iecr.7b03093
132. Zhu H, Shen Y, Wang Q et al (2017) Highly promoted removal of Hg(II) with magnetic CoFe2O4@SiO2 core-shell nanoparticles modified by thiol groups. RSC Adv 7:39204–39215. https://doi.org/10.1039/c7ra06163c
133. Daneshmand M, Outokesh M, Akbari A et al (2018) Synthesis of “L-cysteine–graphene oxide” hybrid by new methods and elucidation of its uptake properties for Hg(II) ion. Sep Sci Technol 53:843–855. https://doi.org/10.1080/01496395.2017.1418889
134. Ifthikar J, Jiao X, Ngambia A et al (2018) Facile one-pot synthesis of sustainable carboxymethyl chitosan – sewage sludge biochar for effective heavy metal chelation and regeneration. Bioresour Technol 262:22–31. https://doi.org/10.1016/j.biortech.2018.04.053
135. Tadjarodi A, Moazen Ferdowsi S, Zare-Dorabei R, Barzin A (2016) Highly efficient ultrasonic-assisted removal of Hg(II) ions on graphene oxide modified with 2-pyridinecarboxaldehyde thiosemicarbazone: adsorption isotherms and kinetics studies. Ultrason Sonochem 33:118–128. https://doi.org/10.1016/j.ultsonch.2016.04.030
136. Saman N, Johari K, Song ST et al (2017) High removal efficacy of Hg(II) and MeHg(II) ions from aqueous solution by organoalkoxysilane-grafted lignocellulosic waste biomass. Chemosphere 171:19–30. https://doi.org/10.1016/j.chemosphere.2016.12.049
137. Kyzas GZ, Travlou NA, Deliyanni EA (2014) The role of chitosan as nanofiller of graphite oxide for the removal of toxic mercury ions. Colloids Surfaces B Biointerfaces 113:467–476. https://doi.org/10.1016/j.colsurfb.2013.07.055
138. Shan C, Ma Z, Tong M, Ni J (2015) Removal of Hg(II) by poly(1-vinylimidazole)-grafted Fe3O4 at SiO2 magnetic nanoparticles. Water Res 69:252–260. https://doi.org/10.1016/j.watres.2014.11.030
139. Khazaei M, Nasseri S, Ganjali MR et al (2018) Selective removal of mercury(II) from water using a 2,2-dithiodisalicylic acid-functionalized graphene oxide nanocomposite: Kinetic, thermodynamic, and reusability studies. J Mol Liq 265:189–198. https://doi.org/10.1016/j.molliq.2018.05.048
140. Cui L, Wang Y, Gao L et al (2015) EDTA functionalized magnetic graphene oxide for removal of Pb(II), Hg(II) and Cu(II) in water treatment: adsorption mechanism and separation property. Chem Eng J 281:1–10. https://doi.org/10.1016/j.cej.2015.06.043
141. Hadavifar M, Bahramifar N, Younesi H et al (2016) Removal of mercury(II) and cadmium(II) ions from synthetic wastewater by a newly synthesized amino and thiolated multi-walled carbon nanotubes. J Taiwan Inst Chem Eng 67:397–405. https://doi.org/10.1016/j.jtice.2016.08.029
142. de Brião GV, de Andrade JR, da Silva MGC, Vieira MGA (2020) Removal of toxic metals from water using chitosan-based magnetic adsorbents. A review. Environ Chem Lett 18:1145–1168. https://doi.org/10.1007/s10311-020-01003-y
143. Zhang S, Zhang Y, Liu J et al (2013) Thiol modified Fe3O4@SiO2 as a robust, high effective, and recycling magnetic sorbent for mercury removal. Chem Eng J 226:30–38. https://doi.org/10.1016/j.cej.2013.04.060
144. Sun M, Cheng G, Ge X et al (2018) Aqueous Hg(II) immobilization by chitosan stabilized magnetic iron sulfide nanoparticles. Sci Total Environ 621:1074–1083. https://doi.org/10.1016/j.scitotenv.2017.10.119
145. Xiong YY, Li JQ, Le GL et al (2017) Using MOF-74 for Hg2+ removal from ultra-low concentration aqueous solution. J Solid State Chem 246:16–22. https://doi.org/10.1016/j.jssc.2016.10.018

146. Wang M, Li Y, Zhao D et al (2020) Immobilization of mercury by iron sulfide nanoparticles alters mercury speciation and microbial methylation in contaminated groundwater. Chem Eng J 381:122664. https://doi.org/10.1016/j.cej.2019.122664
147. Wang L, Wang M, Li Z, Gong Y (2020) Enhanced removal of trace mercury from surface water using a novel Mg2Al layered double hydroxide supported iron sulfide composite. Chem Eng J 393:124635. https://doi.org/10.1016/j.cej.2020.124635
148. Sun Y, Liu Y, Lou Z et al (2018) Enhanced performance for Hg(II) removal using biomaterial (CMC/gelatin/starch) stabilized FeS nanoparticles: stabilization effects and removal mechanism. Chem Eng J 344:616–624. https://doi.org/10.1016/j.cej.2018.03.126
149. Azari A, Gharibi H, Kakavandi B et al (2017) Magnetic adsorption separation process: an alternative method of mercury extracting from aqueous solution using modified chitosan coated Fe3O4 nanocomposites. J Chem Technol Biotechnol 92:188–200. https://doi.org/10.1002/jctb.4990
150. Fang L, Li L, Qu Z et al (2018) A novel method for the sequential removal and separation of multiple heavy metals from wastewater. J Hazard Mater 342:617–624. https://doi.org/10.1016/j.jhazmat.2017.08.072
151. Ray C, Sarkar S, Dutta S et al (2015) Evolution of tubular copper sulfide nanostructures from copper(I)-metal organic precursor: a superior platform for the removal of Hg(II) and Pb(II) ions. RSC Adv 5:12446–12453. https://doi.org/10.1039/c4ra09999k
152. Xiong Y, Su L, Yang H et al (2015) Fabrication of copper sulfide using a Cu-based metal organic framework for the colorimetric determination and the efficient removal of Hg2+ in aqueous solutions. New J Chem 39:9221–9227. https://doi.org/10.1039/c5nj01348h
153. Czarna D, Baran P, Kunecki P et al (2016) Synthetic zeolites as potential sorbents of mercury from wastewater occurring during wet FGD processes of flue gas. J Clean Prod 172:2636–2645. https://doi.org/10.1016/j.jclepro.2017.11.147
154. Chen Y, Guo X, Wu F (2020) Development and evaluation of magnetic iron-carbon sorbents for mercury removal in coal combustion flue gas. J Energy Inst 93:1615–1623. https://doi.org/10.1016/j.joei.2020.01.023
155. Lee WR, Eom Y, Lee TG (2017) Mercury recovery from mercury-containing wastes using a vacuum thermal desorption system. Waste Manag 60:546–551. https://doi.org/10.1016/j.wasman.2016.12.017
156. Tunsu C, Wickman B (2018) Effective removal of mercury from aqueous streams via electrochemical alloy formation on platinum. Nat Commun 9:1–9. https://doi.org/10.1038/s41467-018-07300-z
157. EcoCycle (2019) 5 Benefits of Recycling E-Waste. https://ecocycle.com.au/lighting-and-electrical/5-benefits-of-recycling-e-waste/. Accessed 12 Nov 2022
158. DeFoe D (2013) Understanding Mercury Waste & Mercury Recycling Process. https://retrofitcompanies.com/understanding-mercury-waste-mercury-recycling-process/. Accessed 13 Dec 2022
159. World Health Organization (2021) Mercury and human health. World Heal Organ. https://www.grida.no/resources/7778. Accessed 13 Dec 2022
160. Fthenakis V Overview of Hazards. https://drs.illinois.edu/Page/SafetyLibrary/Mercury. Accessed 13 Dec 2022