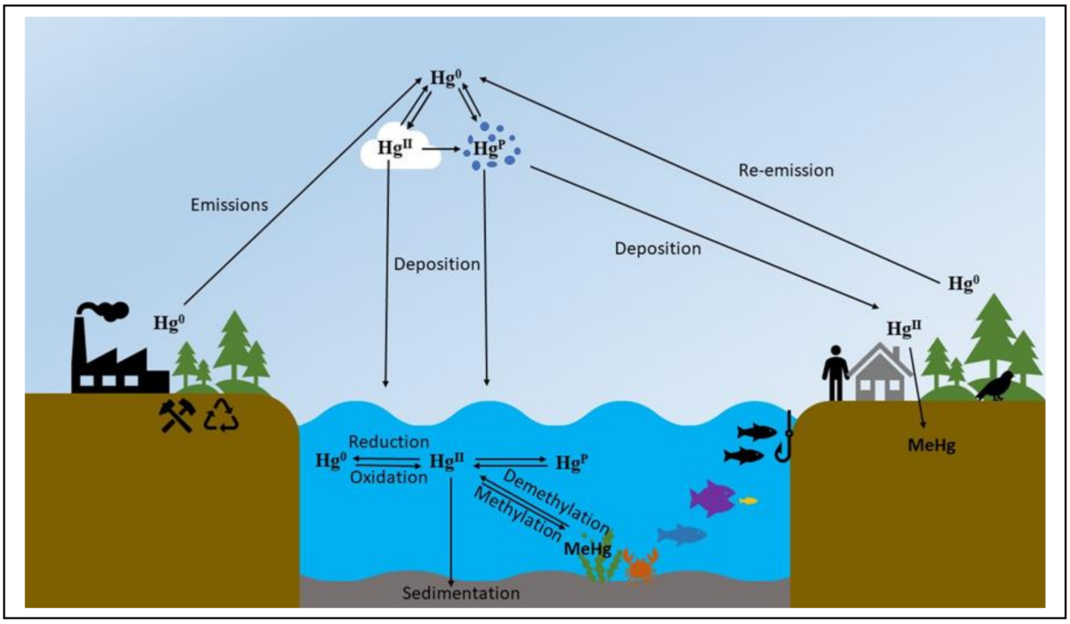
DEPARTMENT OF BIOLOGICAL AND
ENVIRONMENTAL SCIENCE

A STUDY ON THE EFFECTS OF MERCURY IN THE ENVIRONMENT

A focus on atmospheric contributions



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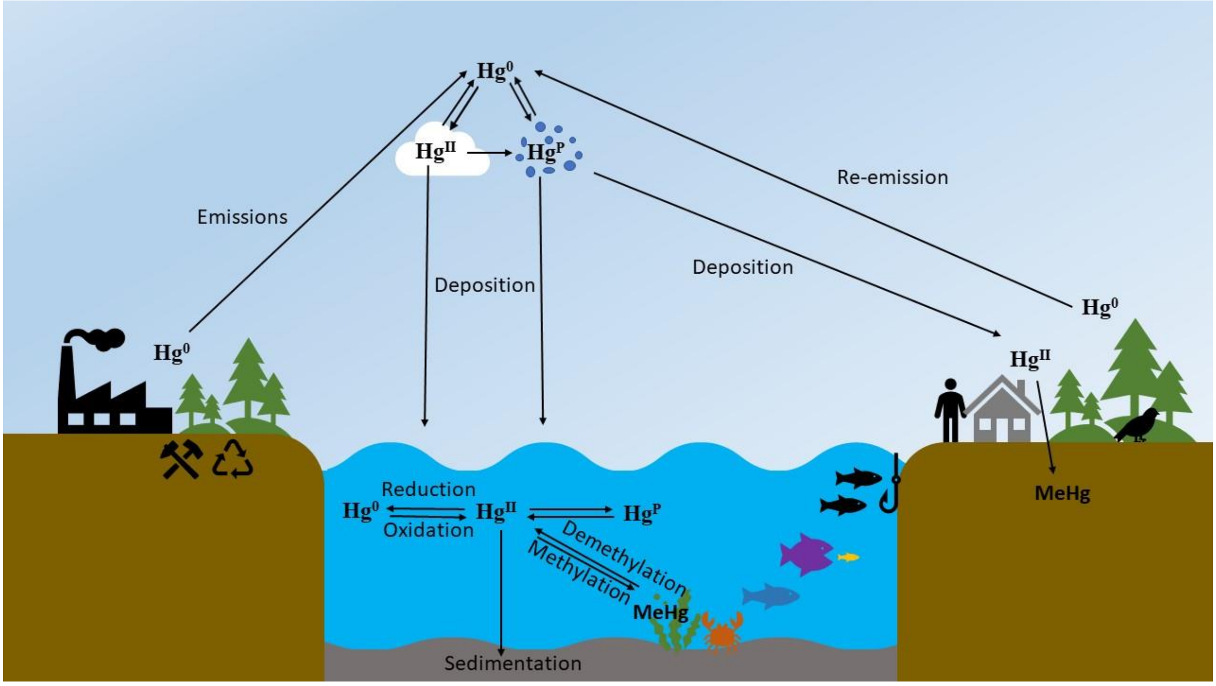
Graphical abstract



Abstract

Mercury is a metal that can transform between different forms in both the atmosphere and in ecosystems. The transformation as well as properties of the different mercury compounds affect when, how and where the effects will emerge. In this literature study, the current state of knowledge about mercury and how it cycles in the environment is reviewed. Different sources for emissions are explored, atmospheric transformation and chemical properties are described and how mercury then enters ecosystems is expounded. The effects that it causes within different ecosystems are then explained as well as the outcome for human health by ingestion, inhalation, and dermal contact. Lastly, methods to remediate the problem are discussed, whilst also emphasizing what the current problems are and what must be done in the future to mitigate or eliminate effects. A lot of things have happened within the field of knowledge over the last couple of years and actions are taken continually.

Keywords

Mercury, deposition, transformation, remediation, ecosystem impact, human health.

Figure modified from (Gonzalez-Raymat et al., 2017; Gworek et al., 2017; Lyman et al., 2020; Pavithra et al., 2022).

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1. Motivation of interest

Mercury is a widespread element in the different spheres of the Earth and is of importance when talking about the environment and human health. Mercury contributes to climate change and the loss of biodiversity in different ecosystems around the globe (United Nations, 2022). It is on the World Health Organizations (WHO) list of the 10 chemicals causing the most health concerns (World Health Organization, 2017). The interest regarding mercury was first raised in the Japanese city of Minamata in the 1950-60s due to emerging health problems of the citizens. The issues arose due to mercury in industrial wastewater that was led into the bay where the locals were fishing for food (Harada, 1995; United Nations, n.d.-a). In most places the issues with mercury remain on some level and Sweden is one of the countries where the problem is still apparent since there are no water courses or lakes that reach a good chemical status (Naturvårdsverket, n.d.). This means that the levels of toxic compounds, such as mercury, do exceed the limits regulated in HVMFS (2019:25) (Havs- och vattenmyndigheten, 2020) and contributes to the difficulty in reaching one of the 16 national environmental goals, Non-toxic environment (“Giftfri miljö”) in the near future (Naturvårdsverket, n.d.).

Due to mercury being a global environmental problem the Minamata convention was implemented in 2013 and entered into force in 2017 (United Nations, 2023). The convention is the most up to date global agreement that focuses on both human health and the environment. The purpose is to minimize the use and control the trade and supply of mercury whilst also focusing on emissions and building public knowledge. In the convention there are also deadlines put in place for when different types of mercury containing products must be phased out (United Nations, n.d.-a). The Minamata convention is strongly intertwined with the 17 Sustainable Development Goals (SDG: s) that were implemented by the United Nations in 2015. The aim of the SDG:s is to overcome poverty all over the Earth whilst at the same time protecting the planet (United Nations, 2015, n.d.-b).

This area of subject is of interest because of the effects that arise in the environment, both in connection with human health and with the focus on ecosystems. It is of high importance that we know from where problems emerge, what the consequences of emissions and deposition are, and what can be done to mitigate the outcome in the environment. The aim of the study is to review the current state of knowledge within the field to get an overview of the problems. The question about mercury concerns human health and the status of different ecosystems on Earth but is also strongly intertwined with economy, though the last perspective will not be discussed in this thesis.

2. Method

Since this is a literature study, the method is focused on how relevant papers and other references were gathered. The main search tools for finding academic papers that have been used for this thesis are Google Scholar, Scopus as well as "Supersök", which is the search engine of the library at the University of Gothenburg. A large range of search words have been used to gather as much relevant information as possible. Some of the search words used were the following: *mercury, mercury and environment, mercury deposition, mercury methylation and demethylation, mercury and human health, mercury and ecosystems, mercury and fetus, methylmercury, mercury and emissions, mercury and atmospheric transformation.* The Boolean Operators, AND, OR and NOT, were used in some searches to either combine or define the search (Johansson, 2018).

Many of the articles used in the study were not found by searching, instead they were found in other articles, where they were used as references. Some articles were also found by looking at who have cited the article. For other references than scientific articles, Google was used as a search engine to gather more general information and knowledge about the subject. The references found from this method is the World Health Organization, the United Nations, Naturvårdsverket as well as the website for the Minamata convention and some of the search words where; *mercury and environment, Minamata convention, mercury and health, mercury in Swedish waters.*

The selection of articles that has been made has partly been decided after when it was published. Most focus has been to find more recent articles from after 2019, since there may have happened many changes within the area of subject over time. Though, this is not the case for some articles. In some searches made, the release date was not added into the search engine or there were not enough good articles to be used, so the time was elongated. It was also of interest to use articles that had been cited several times before, however this does not apply to all articles. Furthermore, the articles found were also checked to be peer-reviewed.

To see if the articles found would be of interest to the study, the abstracts and conclusions were primarily read to see if more detailed reading should be of interest and at the start of the literature search, focus was on finding research articles to get a broad knowledge about the subject and for what to search for when conducting the literature study.

3. Sources

Mercury is a heavy metal that is naturally found in the environment, but it can also end up there due to various anthropogenic processes (Pirrone et al., 2010). Mercury is found in the crust of the Earth and the natural sources of mercury include volcanoes and geothermal sources, though soil, vegetation and the oceans are of most importance in the global budget (Holmes et al., 2010). The anthropogenic emissions originate from a broad range of sources with burning of fossil fuels and gold mining, both on a small and artisanal scale, being the largest emitters. It also emerges from manufacturing of metals, production of cement, caustic soda, and other chemicals as well as from the processing of metal ores and incineration of waste. The incinerated waste origin from different sources such as medical, urban, and industrial waste (Mahbub et al., 2017; Pirrone et al., 2010). Mercury has been utilized by humans for a long time and was previously found in various products on the market. However, many of them have now been modernized and no longer include as much or no mercury. Mercury can still be found in households in thermostats, fluorescent light bulbs, thermometers, dental amalgams as well as in other medical products (Ariya et al., 2015). In dental amalgams it was frequently used due to its properties to be in liquid form at room temperature (Gonzalez-Raymat et al., 2017).

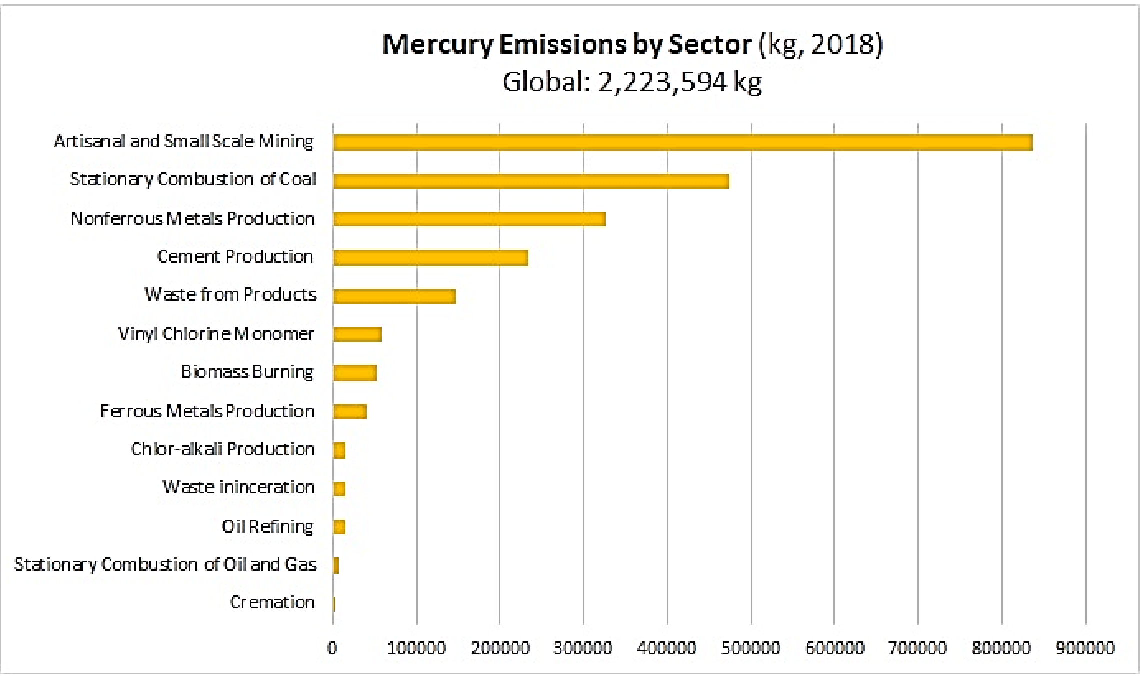

Figure 1. Anthropogenic mercury emissions (United Nations, 2018).

Except for the direct emissions of mercury that are released from the burning of fossil fuels, it can also have an indirect effect on atmospheric mercury later. Nitrogen oxides and sulfur dioxide are also released into the atmosphere and due to their importance in atmospheric chemistry they can have a further impact on mercury in the atmosphere and on the deposition that will occur (Pirrone et al., 2010).

3.1. Quantifications of emissions

Even though natural and anthropogenic emissions are frequently differentiated in literature, the exact quantifications between the two have its difficulties. The quantification of emissions is also challenging due to the re-emissions that occur back from the environment, since the re-emitted mercury originate from both natural and anthropogenic sources (Gworek et al., 2017). However, quantifications of the global mercury budget have been made and by using modelling the total emissions of Hg^0 have been found to be 8300 Mg Hg yr^{-1} (1 Mg = 1×10^6 g = 1 ton) with the anthropogenic emissions making up approximately a fourth, 2050 Mg Hg yr^{-1} (Holmes et al., 2010). Similar estimations say that 5207 Mg Hg yr^{-1} come from natural sources and 2320 Mg Hg yr^{-1} are from anthropogenic sources (Pirrone et al., 2010).

4. Mercury compounds

In the environment mercury can exist in three forms: elemental, organic and inorganic (Guzzi & La Porta, 2008) and in the atmosphere it is mainly found in two phases. In the gaseous phase it occurs in its elemental state as Hg^0 as well as in the divalent, oxidized state as Hg^{II} and the latter is most often found in species like $HgCl_2$, HgO and $Hg(OH)_2$ (Gworek et al., 2017). It can also be found in particulate phase as Hg^P (Amos et al., 2012; Lindberg et al., 2007). Hg^P can be formed when Hg^{II}, found in different species, absorbs to particles in the atmosphere and it can also enter the atmosphere in sea salt, soot and dust particles (Poissant et al., 2005). The form of mercury that dominates the emissions into the atmosphere is the elemental state, both from natural and anthropogenic sources (Sommar et al., 2020) and except the most common forms of mercury in the atmosphere, it can also exist in organic form as methyl compounds. Dimethylmercury ($(CH_3)_2Hg$) is the most common but still, organic compounds only make up a maximum of 1% of atmospheric mercury (Gworek et al., 2017), however in ecosystems its presence is of much more importance (Chen et al., 2020).

4.1. Chemical properties of Hg^0 and Hg^{II}

To get a better understanding of why the different mercury states behave in certain ways and have different impact on the environment, it is of importance to understand their chemical properties.

In its elemental form, also known as the metal form, mercury is liquid at room temperature, which differentiates it from other heavy metals. The reasoning behind this is due to its low melting point which is partly because of the electron configuration of the compound (Gonzalez-Raymat et al., 2017). The different states of mercury have different solubility and chemical reactivity (Saiz-Lopez et al., 2018). Hg^0 is also relatively inert and not very water soluble (Horowitz et al., 2017). It also has a high vapor pressure and low volatility due to lanthanide contraction and the relativistic effects, which enables it to have a long atmospheric lifetime (Gonzalez-Raymat et al., 2017). Hg^{II} on the other hand is more reactive and water soluble than the elemental form which causes it to have a shorter atmospheric lifetime and thus it is deposited more quickly (Lin et al., 2006).

4.2. Atmospheric lifetimes

Hg^0 is the most stable form of mercury and has a lifetime of somewhere between 0,5 - 2 years in the atmosphere (Gworek et al., 2017; Wängberg et al., 2001). The relatively long atmospheric residence time allows it to travel long distances which makes it a global issue (Wängberg et al., 2001). The lifetime of Hg^{II} and Hg^P ranges from only a couple of hours up to a few days. The reason for the highly differing atmospheric lifetimes of mercury states is because the chemical properties of the compounds are different (Gworek et al., 2017; Saiz-Lopez et al., 2018). The shorter lifetime, and therefore inability to travel far distances, of Hg^{II} makes it more important on a local level (Lin et al., 2006). A factor that has an impact on the concentration of mercury in the atmosphere is the volatility of the compound and therefore the temperature of the air plays an important role (Gworek et al., 2017). The lifetime of Hg^P is dependent on the size of the particles, since this affects deposition (Lynam & Keeler, 2005).

5. Atmospheric removal of mercury

There are several ways that mercury can be removed from the atmosphere, and the course of action differs between the different states of mercury.

5.1. Deposition mechanisms

Mercury can leave the atmosphere in different ways through different removal mechanisms, with the main deposition mechanisms being dry and wet deposition. Especially for Hg^{II} dry and wet deposition are effective removal mechanisms, though it can also be reduced back to its elemental form. It is therefore the redox chemistry that determines the deposition of mercury globally (Horowitz et al., 2017). The reason for wet deposition to be effective for Hg^{II} depends on the high water solubility of the compound (Amos et al., 2012) and the process for Hg^0 is slow due to its water insolubility, compared to Hg^{II} (Horowitz et al., 2017). The small fraction of deposition of Hg^0 that occur, is highly dependent on its atmospheric concentration (Zhang et al., 2009). The deposition of mercury is not frequent over the year and tend to peak in the spring (Angot et al., 2016).

Dry deposition of mercury mainly occurs through gravitational settling and surface sorption (Gonzalez-Raymat et al., 2017) and after it has occurred and mercury has ended up in canopy or on other types of vegetation. After that different processes can take place and two of them are litterfall and throughfall. Litterfall occurs in canopy of trees and is when uptake takes place in the bark of trees, cuticles and stomata in leaves or the soil that is underneath. The mercury can enter different parts of the tree and thus it can either go into the stems, roots and branches or be re-emitted into the atmosphere (Wright et al., 2016). Throughfall is when the mercury that has ended up in a vegetation canopy by dry deposition is washed off by precipitation (Risch et al., 2012; Wright et al., 2016). In different ecosystems the fraction between dry and wet deposition can differ (Risch et al., 2012). Most of the deposition of Hg^{II} happens over the oceans around the globe which can be connected to the amounts of bromine that arise from the oceans in sea salt aerosols and due to their importance for oxidation of Hg^0 (Horowitz et al., 2017).

5.2. Removal of Hg^0

Hg^0 can be transformed into Hg^{II} and back by redox chemistry. Hg^0 can also be in particulate phase. Hg^{II} can absorb to particles and thus be transformed into Hg^P, but not the other way around (Gonzalez-Raymat et al., 2017). It is only permanently removed from the environment once it has been embedded into mineral soils where it can stay for a very long time (Gworek, 2020).

Hg^0 can be removed by oxidation of the atmospheric oxidants ozone (O_3), nitrate radical (NO_3) or hydroxyl radical (OH) (Gworek et al., 2017). But the oxidation by OH and O_3 have been shown to be slow and not the main pathways for oxidation of mercury (Calvert & Lindberg, 2005). Instead, atomic halogens are important for atmospheric oxidation of mercury. Out of the halogens, Bromine (Br) has been found to be a more likely oxidant than for instance chlorine (Cl) and the halogens are abundant in areas close to or over oceans since they are found in sea salt aerosols that origin from the ocean (Ariya et al., 2002).

5.2.1. Reaction with bromine

The following reactions show the oxidation of elemental mercury to form divalent mercury using bromine (Holmes et al., 2010; Seigneur & Lohman, 2008):

$$Hg^0 + Br \xrightarrow{M} HgBr$$

$$HgBr + X \xrightarrow{M} Hg^{II}$$

X can be any oxidant; Br, BrO, Br^2, OH, O_3, HO_2 or NO_2, although Br has been found to be of most importance (Holmes et al., 2010; Horowitz et al., 2017; Seigneur & Lohman, 2008). The oxidation of mercury with bromine is also of importance from another perspective than the deposition of inorganic mercury from the atmosphere, since it causes ozone depletion (Wang et al., 2019).

6. Effects on ecosystems

The fate of all mercury in the atmosphere is in different ecosystems on Earth, where it will end up after deposition, and this can take some time due to different atmospheric processes (Lyman et al., 2020), as mentioned in previous section. Despite the focus in this thesis being on the atmospheric contributions and deposition, it is worth mentioning that mercury can also enter ecosystems through transport from rivers or by runoff from different surfaces (Chen et al., 2020). The major source of mercury to both aquatic and terrestrial ecosystems is atmospheric deposition, where it is mainly deposited in inorganic form (Nie et al., 2023). For mercury to be bioavailable it must be in organic form, often in the form of methylmercury (Chen et al., 2020), which is the major type of organic mercury in ecosystems (Rice et al., 2014).

6.1. Methylmercury

Although there is some methylmercury in the atmosphere, it is mainly formed within ecosystems by transformation of inorganic mercury by anaerobic microbes under oxygen-limited conditions (Bravo & Cosio, 2020; Zheng et al., 2023) and is thus dependent on the supply of inorganic mercury from the atmosphere (Ariya et al., 2015). The process is called methylation and it is the primary source of methylmercury in aquatic systems (Kalisinska et al., 2021; Li & Cai, 2013).

$$Hg^{II} + CH_3{}^{-} \rightarrow CH_3Hg^{+}$$

It takes place in the sediment, damp soils and bodies of water (Kalisinska et al., 2021) and can occur in both fresh and marine water periphyton (Li & Cai, 2013). Since the methylmercury is bioavailable it can then be bioaccumulated and biomagnified in the food web (Chen et al., 2020) and the ability of methylmercury to be bioaccumulated and biomagnified depends on its low water solubility and thus rather high lipid solubility (Rice et al., 2014). The amount of bioavailable methylmercury in the food chain has been found to be at its highest on lower trophic levels (Rolfhus & Fitzgerald, 1995), thus it also plays an important role in how species on other trophic levels are exposed (Evers et al., 2011).

The process of demethylation is the opposite of methylation when mercury is released from the methyl group (Al-Sulaiti et al., 2022; Li & Cai, 2013).

$$CH_3Hg^{+} \rightarrow Hg^{II} + CH_3{}^{-}$$

Demethylation and methylation occur in the same sites, though methylation should occur more than demethylation. Thus, in both sediment and periphyton, it affects the net production of methyl mercury (Li & Cai, 2013). The processes for methylation and demethylation are not only bacterial but can also occur from UV-radiation (Al-Sulaiti et al., 2022).

After uptake of methylmercury has occurred, mainly from ingestion, it can enter the bloodstream which causes a quick spread into different parts of the body and thus several organs (López-Berenguer et al., 2020). Methylmercury cysteine (MeHg-Cys) is a compound that can be formed in the body when MeHg that has been ingested interacts with cysteine from broken down proteins (Manceau et al., 2021). MeHg-Cys have been shown to increase how much MeHg that can enter tissues in the body, and thus the organs (Roos et al., 2010). In the body, methylmercury has a lifetime of 39-70 days, though this is dependent on the body (Rice et al., 2014).

6.2. Terrestrial environments

Terrestrial environments, more specifically this applies for low mercury containing soils, are of importance for atmospheric mercury since those ecosystems can function as both sinks and sources. This can be connected to the re-emissions of mercury that occur from ecosystems to the atmosphere after deposition (Gustin et al., 2008).

Plants have been shown to be very important for the uptake of mercury and further the biogeochemical cycling of the element (Gworek, 2020) and different species and types of plants take up mercury in different ways, some take up from atmospheric deposition (Boening, 2000) and some from the soil. Oxidative stress has been seen to be induced by mercury uptake which can cause damage to cells, and eventually lead to disturbances in the production of chlorophyll and cause growth retardation of both shoots and roots (Mahbub et al., 2017; Shahid et al., 2020). Reduced production of chlorophyll can lead to changing rates of photosynthesis, which is crucial both for the plant itself but also for other species that use its services (Shahid et al., 2020). Other biological effects include changes in the permeability of cell membranes within the plants and changing mitochondrial activity (Mahbub et al., 2017).

There are many species of microorganisms that are sensitive to mercury in soils and the presence of the metal can cause the communities to change. It can also cause changes in the nitrification process, the activity of enzymes and the respiration that takes place within the soil (Mahbub et al., 2017). However, some species have built up a resistance against mercury through different mechanisms such as chelation and efflux pumps (Boening, 2000). If there is much mercury in the soil it can have a negative effect on the viability of the ecosystem (Shahid et al., 2020).

Methylmercury has been shown to cause significant negative effects on bird populations that consume fish that have accumulated mercury in its tissue. Higher methylmercury levels in the birds can affect how many eggs that will be hatched successfully, embryo viability and the behavior of the chicks. Slower growing rates is also an effect, though the effects that mercury has on birds differ between species (Kenow et al., 2011). In terrestrial mammals the neurotoxicological effects are of high concern since the blood-brain barrier can be crossed by methylmercury (Scheuhammer et al., 2015). Reproduction is also affected, partly through decreasing litter sizes (Yang et al., 2020). It can interrupt biological processes (Kalisinska et al., 2021) whilst also affecting the visual system as well as emotional and cognitive activities (Yang et al., 2020). Contamination of mercury can also change the physical capacity of mammals, for example changing their ability to swim (Yang et al., 2020).

6.3. Aquatic environments

In marine environments there are two different types of methylated mercury, monomethyl mercury and dimethyl mercury, however monomethyl mercury is unique to be biomagnified. The largest source of mercury in the oceans originates from the atmosphere and has been deposited (Zhang et al., 2020). The pathway for exposure in aquatic organisms such as fish is through ingestion, the gills or the scales on the skin (Morcillo et al., 2017). Some aquatic species tend to accumulate higher concentrations of methylmercury than others, and these are often found in the higher trophic levels because of the biomagnification that has occurred in the food web. Among these species are tilefish and king mackerel, as well as several shark species (Rice et al., 2014). Benthic macroinvertebrates and the structure within their community are important for the availability of methylmercury to predators on higher trophic levels in urban aquatic systems (Goto & Wallace, 2009).

Health effects that result from mercury in fish are changes within the immune system, cardiomyopathy, problems for the gills to correctly perform gas-exchange, which can make them more energy consuming and also cause issues in the frequency of ventilation (Morcillo et al., 2017). Oxidative stress can be induced, causing cell damage (Scheuhammer et al., 2015). Tissues can also become damaged and reproductive issues can emerge by changing fecundity and spawning (Morcillo et al., 2017; Scheuhammer et al., 2015). Mercury can also cause problems in the nervous system, digestive system, and blood system. Though all of these issues can occur, the effects differ highly between different species of fish, the concentration and time for exposure and the conditions of the environment (Morcillo et al., 2017). Even though methyl mercury is the mercury compound that is bioaccumulated the most, both inorganic and organic mercury compounds have been found inside the brain of fish. Though this occurred it was also shown that compensatory mechanisms can be used which can reduce the risks of lipid peroxidative damage (Mieiro et al., 2011). The bioaccumulation potential in fish can be affected by other parameters than environmental ones and the presence of microplastics is one of these (Barboza et al., 2018).

7. Effects on human health

Mercury is a heavy metal that is toxic in all its forms (Al-Sulaiti et al., 2022) and non-essential for the survival for humans (Park & Zheng, 2012), thus it constitutes a threat to human health if ingested, inhaled or through dermal contact. There are several organs in the body that can be affected negatively by mercury and below the effects discussed in scientific research are described.

There are a few different ways of exposure of mercury for humans; mercury vapor, products that have been contaminated by mercury as well as the consumption of food from oceans, which includes both fish, mammals and seafood (Rice et al., 2014). In mining areas people are exposed to both inorganic and organic mercury by inhalation (Zhang et al., 2020). Though, the main way of exposure is methylmercury that has accumulated in aquatic organisms which causes people that heavily depend on fish and seafood to suffer a larger risk (Evers et al., 2011). In areas where people are not dependent on food from aquatic systems, the same problems have emerged. It has been shown that consumption of rice is an important way of exposure away from the coast, both in organic and inorganic form (Basu et al., 2023; Zhang et al., 2020).

7.1. Effects of methylmercury

The way methylmercury mainly causes issues in the human body is by interacting with proteins that are thiol based -SH (Guzzi & La Porta, 2008) and in that way entering tissues all over the body (Roos et al., 2010). It can cause autoimmune diseases (Bjørklund et al., 2017) and is immunotoxic even at low concentrations, and the effects occur due to that the T-cell function is decreased (Shenker et al., 1992). It also causes neurotoxicity and thus affects the nervous system which can further cause oxidative stress as well as neuroinflammation (Bjørklund et al., 2017). If methylmercury reaches the central nervous system, it can damage the blood brain barrier and make it easier for other toxic metals to penetrate to the brain (Rice et al., 2014). Since it can cross the blood-brain barrier it also causes the breakdown of phospholipid membranes and changes to the metabolism of amino acids (Bjørklund et al., 2017). Negative effects on the cardiovascular system can be caused and there is an increased risk of cardiomyopathy (Gworek, 2020; Rice et al., 2014).

Even at low concentrations it has been shown that methylmercury can have an impact on the endocrine system. It disrupts the pancreas as well as the thyroid, pituitary and adrenal glands and there are some hormones that seem to be the more affected than others and these are insulin, adrenaline, estrogen and testosterone (Rice et al., 2014). Therefore, it can also cause effects on the reproductive system in both women (Rattan et al., 2017) and men (Chowdhury et al., 1989). In women these hormone changes can cause ovarian dysfunction as well as decreased numbers of eggs, oocytes and follicle count, which increase the risk of pre-term birth (Henriques et al., 2019; Rice et al., 2014). In men it has been shown to decrease both sperm motility and the number of motile sperm whilst also decreasing the sperm swimming speed and total sperm count (Chowdhury et al., 1989). The risk of DNA damage also increases and the issues that emerge in both men and women contribute to an increased risk of abortion of a fetus (Henriques et al., 2019).

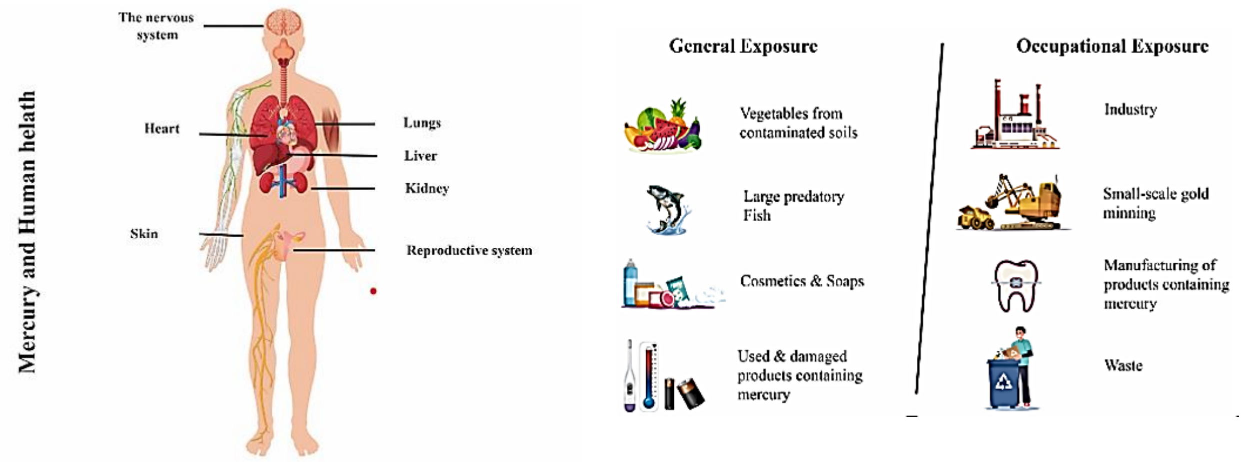

Figure 2. The health effects of mercury exposure for humans (Pavithra et al., 2022).

Other physical effects of mercury are chest and abdominal pain, kidney damage, ulcers, bloody diarrhea, and inflammatory bowel disease as well as effects on the renal and digestive systems. Tremors in different parts of the body can also be induced. It can also cause more psychological conditions such as hallucination, depression, paranoia and memory loss (Rice et al., 2014).

7.2. Effects of elemental and inorganic mercury

Elemental mercury enters the body via inhalation and has close to zero bioavailability. It mostly causes adverse effects on the brain and the kidneys, but it can also enter the blood brain barrier since it is lipid soluble (Park & Zheng, 2012). Inhalation of mercury can cause effects on the visual system and the respiratory system, more specifically the lungs (Bjørklund et al., 2017). Inorganic mercury enters the body through ingestion and is water soluble and bioavailable. It is an irritant that can be accumulated in the kidneys whilst also causing gastrointestinal symptoms (Park & Zheng, 2012).

7.3. Age groups of higher concern

Even though all humans are affected by mercury contamination, some age groups have been shown to be more sensitive than others. Amongst the most sensitive groups are fetuses and young children. There is a direct correlation between mercury levels in placental blood and tissue and the level in the blood and tissue of the umbilical cord, connecting the fetus to the mother. This means that the fetus is exposed to the approximately same levels as the mother (Al-Saleh et al., 2011; Hadavifar et al., 2020). What then makes fetuses so sensitive to even low concentrations of mercury in their blood is because in the development stage in the uterus, the cells are divided frequently and this can disrupt development of the brain (Clarkson et al., 2003; Hadavifar et al., 2020). The effects that can be shown in fetuses that have been exposed to mercury are therefore brain damage as well as effects on the nervous system and potential effects on their cognitive development. It can therefore have a crucial chronicle effect on the infant that will follow them through their life (Al-Saleh et al., 2011; Hadavifar et al., 2020). Mercury exposure to the mother has also been shown have significant impacts for infants during their first year by increasing the risk of respiratory infections and symptoms (Emeny et al., 2019).

8. Future outlook

The environmental problems posed by mercury in the environment are of high importance, and even though efforts to reduce the emissions are made through political instruments like The Minamata Convention, the problems will remain for a long period of time. Therefore, there is a need for the implementation of remediation techniques for areas that have been contaminated with mercury. There are different ways to approach mercury contamination after it has been deposited to the environment and the different methods that are available use different properties; thermal, biological, chemical and physical (Eckley et al., 2020). The cost of a technique depends mainly on two factors, the site where the remediation will take place as well as what technique is being used. For contaminated soils there are both in-situ and ex-situ remediation techniques and they include everything from soil flushing and surface capping to vitrification and solidification (Liu et al., 2020).

In scientific literature there are many articles about different ways to remediate mercury and other heavy metals from different materia such as soil, sediment, waste and water in the environment (Eckley et al., 2020; Liu et al., 2018). Some techniques that are being brought up are still in the research stage whilst others are on the market, amongst the techniques there are both in situ and ex situ methods. All techniques seem to have both positive and negative sides, one might be inexpensive but have a low efficiency or high cost but is very effective and remove substantial amounts without interrupting the environment (Liu et al., 2018). Several of the techniques on the market also need high temperatures and take much time to perform (Liu et al., 2022).

Since there are so many techniques available, two promising ones, nanotechnology and phytoremediation, have been selected to be discussed in more detail. Both techniques are emerging on the market for mercury remediation in the environment and seem to have a bright future, though there are still some uncertainties that need clarification for them to be as attractive as possible.

8.1. Nanotechnology

Nanotechnology has increased in the research field almost exponentially over the last 20 years and in 2020 there were over 4000 publications made about the technique (Inobeme et al., 2023). The technique is supposed to be quick, have a low cost and also have a small impact on the environment (Liu et al., 2022). Another positive perspective is that nanotechnology based techniques work for soil, water and sediments which makes it useful in more settings than only one (Eckley et al., 2020).

There are different types of nanomaterials used regarding the remediation of mercury from the environment and the differences can be based on their dimensions or whether they are based on organic or inorganic materials. There are several carbon-based materials such as two-dimensional graphene and carbon nanotubes and in addition to those there are for example silica- and polymer-based nanomaterials, metal nanoparticles and magnetic nanocomposites (Inobeme et al., 2023). Even though there are many methods available, there is still much that is needs to be done within the field and even more environmentally friendly, less costly and more efficient techniques are of importance (Liu et al., 2022).

8.2. Phytoremediation

Phytoremediation is a technique that uses the properties of plants to remove heavy metals, including mercury, from the soils in ecosystems (Ansari et al., 2021; Eckley et al., 2020). There are different factors that are of importance for phytoremediation, both the properties of the soil and the heavy metals, but most importantly what plant is being used (Zhao et al., 2019). There are plants used to remove several other heavy metals from the environment, but there is still no plant that is considered to be efficient to remove mercury. However, studies are being done to find a species that will fill the gap (Ansari et al., 2021; Liu et al., 2022). The Indian mustard plant has been examined and one of its genotypes has been shown to have the ability to remediate mercury in soil (Ansari et al., 2021). For the future it has been found that phytoremediation combined with the agriculture of crops may be of importance and needs further research to answer the questions that still need answers (Liu et al., 2022; Zhao et al., 2019).

Conclusion

It can be concluded that the effects that follow due to mercury contamination in ecosystems and human health are severe. Due to the ability of organic mercury to be bioaccumulated and biomagnified it can cause issues within the food web that disrupt important species from developing as they should, and it can even cause some species to go extinct, decreasing biodiversity in ecosystems. For us humans the effects of mercury in the body are compelling and the results can be devastating. The health effects that can transpire from mercury contamination are of a broad spectrum and can follow people from before birth till the day they die. Even though the problem is still very much an issue, there is hope for the future. There are remediation techniques that are used today and that work well removing mercury from the environment, but they all come with disadvantages. Some are too expensive, and others cause harm to the environment. That said, newer techniques are researched all the time to contribute with even better, more affordable, and less invasive techniques.

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