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Environmental Contamination by Heavy Metals

Vhahangwele Masindi and Khathutshelo L. Muedi

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Abstract

The environment and its compartments have been severely polluted by heavy metals. This has compromised the ability of the environment to foster life and render its intrinsic values. Heavy metals are known to be naturally occurring compounds, but anthropogenic activities introduce them in large quantities in different environmental compartments. This leads to the environment's ability to foster life being reduced as human, animal, and plant health become threatened. This occurs due to bioaccumulation in the food chains as a result of the nondegradable state of the heavy metals. Remediation of heavy metals requires special attention to protect soil quality, air quality, water quality, human health, animal health, and all spheres as a collection. Developed physical and chemical heavy metal remediation technologies are demanding costs which are not feasible, time-consuming, and release additional waste to the environment. This chapter summarises the problems related to heavy metal pollution and various remediation technologies. A case study in South Africa mines were also used.

Keywords: heavy metals, environment, contamination, legal requirements, pollution

1. Environment

Environment can be referred to the surroundings within which humans exist. These are made up of: the land, the water and the atmosphere of the earth; microorganisms, plant and animal life; any part or combination of the first two items on this list and the interrelationships among and between them and the physical, chemical, aesthetic and cultural properties and conditions of the foregoing that influence human health and well-being. It is also characterised by a number of spheres that influence its behaviour and intrinsic value. The most important sphere of the environment is the biosphere because it harbours the living organisms. This is the sphere where you find living organisms (plants and animals) interacting with each and their nonliving

environment (soil, air and water). In the late centuries, industrialisation and globalisation have impaired pristine environments and their ability to foster life. This has introduced components that compromise the holistic functioning of the environment and its intrinsic values [1].

1.1. Environmental contamination

An environment can be polluted or contaminated. Pollution differs from contamination; however, contaminants can be pollutants, and pose detrimental impact on the environment. From literature, pollution is defined as the introduction by man, directly or indirectly, of substances or energy into the environment resulting in such deleterious effects as harm to living resources, hazards to human health, hindrance to environmental activities and impairment of quality for use of the environment and reduction of amenities. Contamination on the other hand is the presence of elevated concentrations of substances in the environment above the natural background level for the area and for the organism. Environmental pollution can be referred to undesirable and unwanted change in physical, chemical and biological characteristics of air, water and soil which is harmful for living organisms—both animal and plants. Pollution can take the form of chemical substances or energy, such as noise, heat or light [2].

Pollutants, the elements of pollution, can either be foreign substances/energies or naturally occurring contaminants.

1.1.1. *Types of pollutants*

Environmental pollutants continue to be a world concern and one of the great challenges faced by the global society. Pollutants can be naturally occurring compounds or foreign matter which when in contact with the environment cause adverse changes. There are different types of pollutants, namely inorganic, organic and biological. Irrespective of pollutants falling under different categories, they all receive considerable attention due to the impacts they introduce to the environment. The relationship between environmental pollution and world population has become an inarguable directly proportional relationship as it can be seen that the amount of potentially toxic substances released into the environment is increasing with the alarming growth in global population. This issue has led to pollution being a significant problem facing the environment.

1.1.1.1. *Inorganic pollutants*

Industrial, agricultural and domestic wastes contribute to environmental pollution, which cause adverse harm to human and animal health. From such sources, inorganic pollutants are released. Inorganic pollutants are usually substances of mineral origin, with metals, salts and minerals being examples [2]. Studies have reported inorganic pollutants as material found naturally but have been altered by human production to increase their number in the environment. Inorganic substances enter the environment through different anthropogenic activities such as mine drainage, smelting, metallurgical and chemical processes, as well as natural processes. These pollutants are toxic due to the accumulation in the food chains [3].

1.1.1.2. Organic pollutants

Organic pollution can be briefly defined as biodegradable contaminants in an environment. These sources of pollution are naturally found and caused by the environment, but anthropogenic activity has also been contributing to their intensive production to meet the human needs. Some of the common organic pollutants which have been noted to be of special concern are human waste, food waste, polychlorinated biphenyls (PCBs), polybrominated diphenyl ethers (PBDEs), polycyclic aromatic hydrocarbons (PAHs), pesticides, petroleum and organochlorine pesticides (OCPs) [4].

Organic pollutants have gained attention as they have become a major problem in the environment. Properties of organic pollutants, amongst others, such as high lipid solubility, stability, lipophilicity and hydrophobicity have recently made organic pollutants termed persistent. These properties give organic pollutants the ability to easily bioaccumulate in the different spheres of the environment, thus causing toxicological effects [5, 6].

1.1.1.3. Biological pollutants

Biological pollutants are described as pollutants which exist as a result of humanity's actions and impact on the quality of aquatic and terrestrial environment. This type of pollutants include bacteria, viruses, moulds, mildew, animal dander and cat saliva, house dust, mites, cockroaches and pollen. Studies have documented different sources of these pollutants, including pollens originating from plants; viruses transmitted by people and animals; bacteria carried by people, animals, and soil and plant debris [7].

2. Heavy metals

Although there is no specific definition of a heavy metal, literature has defined it as a naturally occurring element having a high atomic weight and high density which is five times greater than that of water [8]. Among all the pollutants, heavy metals have received a paramount attention to environmental chemists due to their toxic nature. Heavy metals are usually present in trace amounts in natural waters but many of them are toxic even at very low concentrations [9]. Metals such as arsenic, lead, cadmium, nickel, mercury, chromium, cobalt, zinc and selenium are highly toxic even in minor quantity. Increasing quantity of heavy metals in our resources is currently an area of greater concern, especially since a large number of industries are discharging their metal containing effluents into fresh water without any adequate treatment [3].

Heavy metals become toxic when they are not metabolised by the body and accumulate in the soft tissues. They may enter the human body through food, water, air or absorption through the skin when they come in contact with humans in agriculture, manufacturing, pharmaceutical, industrial or residential settings. Industrial exposure accounts for a common route of exposure for adults. Ingestion is the most common route of exposure in children. Natural and human activities are contaminating the environment and its resources, they are discharging more than what the environment can handle [9, 10] (**Figure 1**).

2.1. Sources of heavy metals

Heavy metals can emanate from both natural and anthropogenic processes and end up in different environmental compartments (soil, water, air and their interface) (Figure 2).

2.1.1. Natural processes

Many studies have documented different natural sources of heavy metals. Under different and certain environmental conditions, natural emissions of heavy metals occur. Such emissions include volcanic eruptions, sea-salt sprays, forest fires, rock weathering, biogenic sources and wind-borne soil particles. Natural weathering processes can lead to the release of metals from their endemic spheres to different environment compartments. Heavy metals can be found in the form of hydroxides, oxides, sulphides, sulphates, phosphates, silicates and organic compounds. The most common heavy metals are lead (Pb), nickel (Ni), chromium (Cr), cadmium (Cd), arsenic (As), mercury (Hg), zinc (Zn) and copper (Cu). Although the aforementioned heavy metals can be found in traces, they still cause serious health problems to human and other mammals [9].

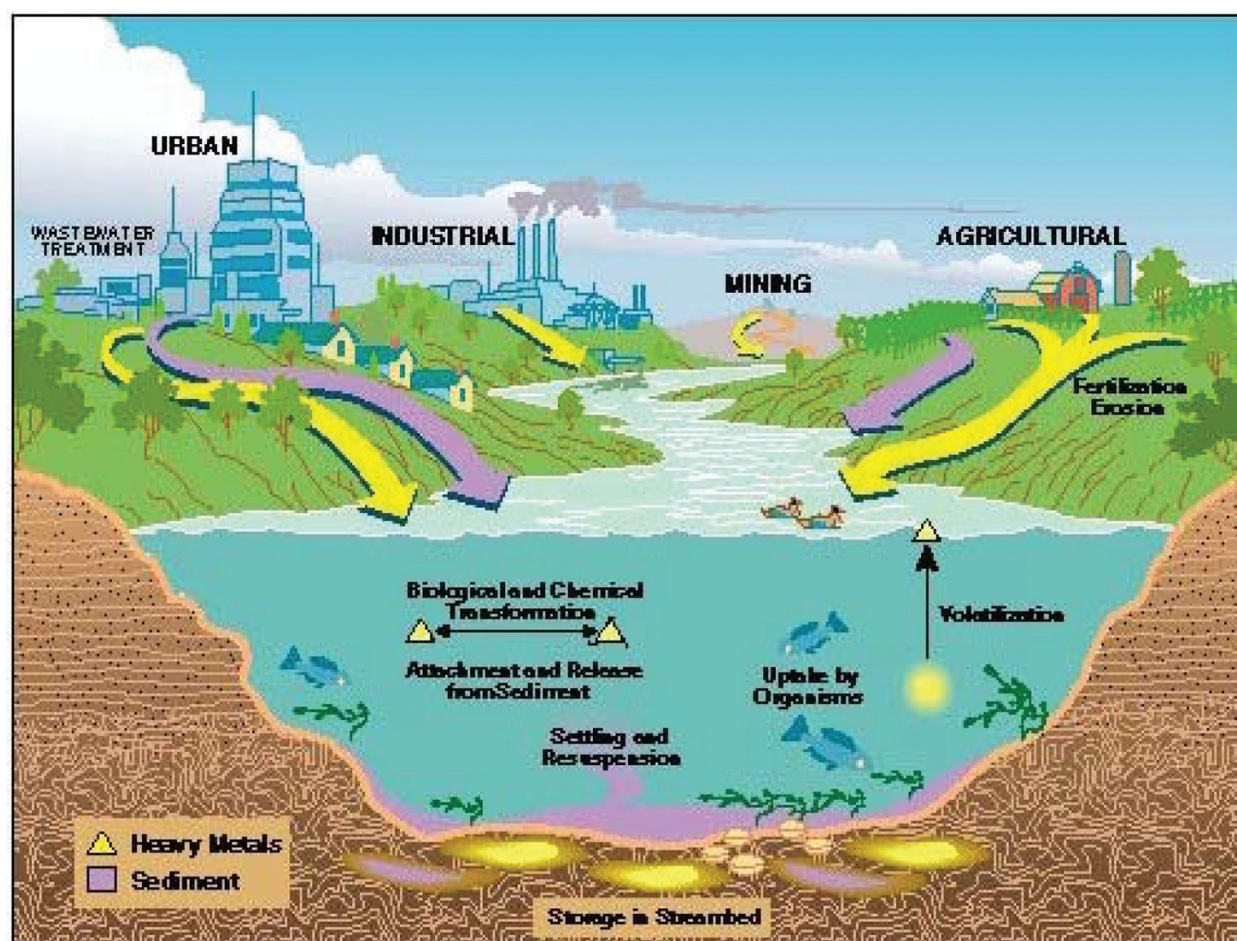


Figure 1. Sources and sinks of heavy metals [11].

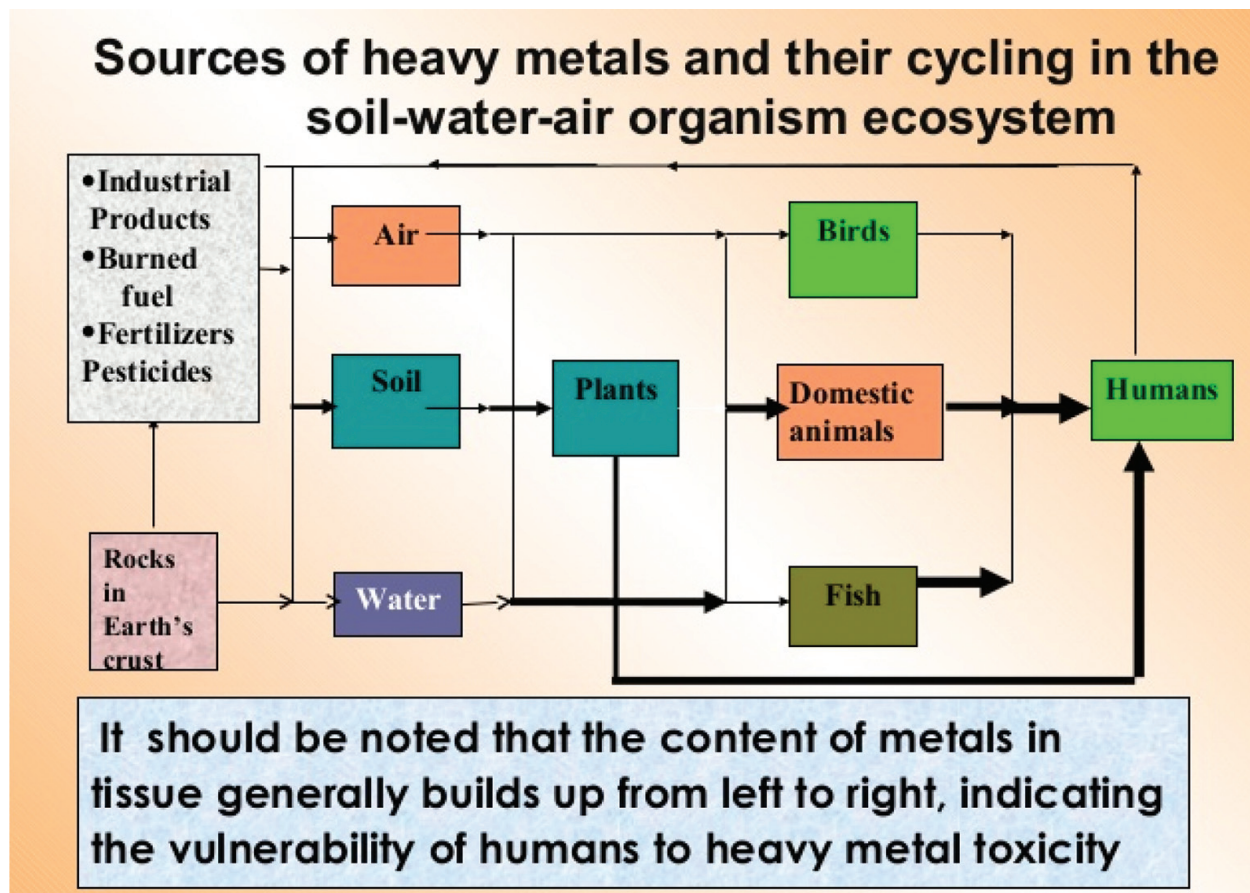


Figure 2. Sources of heavy metals and their cycle in the environment [12].

2.1.2. Anthropogenic processes

Industries, agriculture, wastewater, mining and metallurgical processes, and runoffs also lead to the release of pollutants to different environmental compartments. Anthropogenic processes of heavy metals have been noted to go beyond the natural fluxes for some metals. Metals naturally emitted in wind-blown dusts are mostly from industrial areas. Some important anthropogenic sources which significantly contribute to the heavy metal contamination in the environment include automobile exhaust which releases lead; smelting which releases arsenic, copper and zinc; insecticides which release arsenic and burning of fossil fuels which release nickel, vanadium, mercury, selenium and tin. Human activities have been found to contribute more to environmental pollution due to the everyday manufacturing of goods to meet the demands of the large population [10].

2.2. Environmental impacts of heavy metals

The presence of heavy metals in the environment leads to a number of adverse impacts. Such impacts affect all spheres of the environment, that is, hydrosphere, lithosphere, biosphere and

atmosphere. Until the impacts are dealt with, health and mortality problems break out, as well as the disturbance of food chains. **Figure 3** summarises the health impacts of heavy metals.

2.3. Effect of heavy metals contamination

Heavy metals contamination is becoming a serious issue of concern around the world as it has gained momentum due to the increase in the use and processing of heavy metals during various activities to meet the needs of the rapidly growing population. Soil, water and air are the major environmental compartments which are affected by heavy metals pollution.

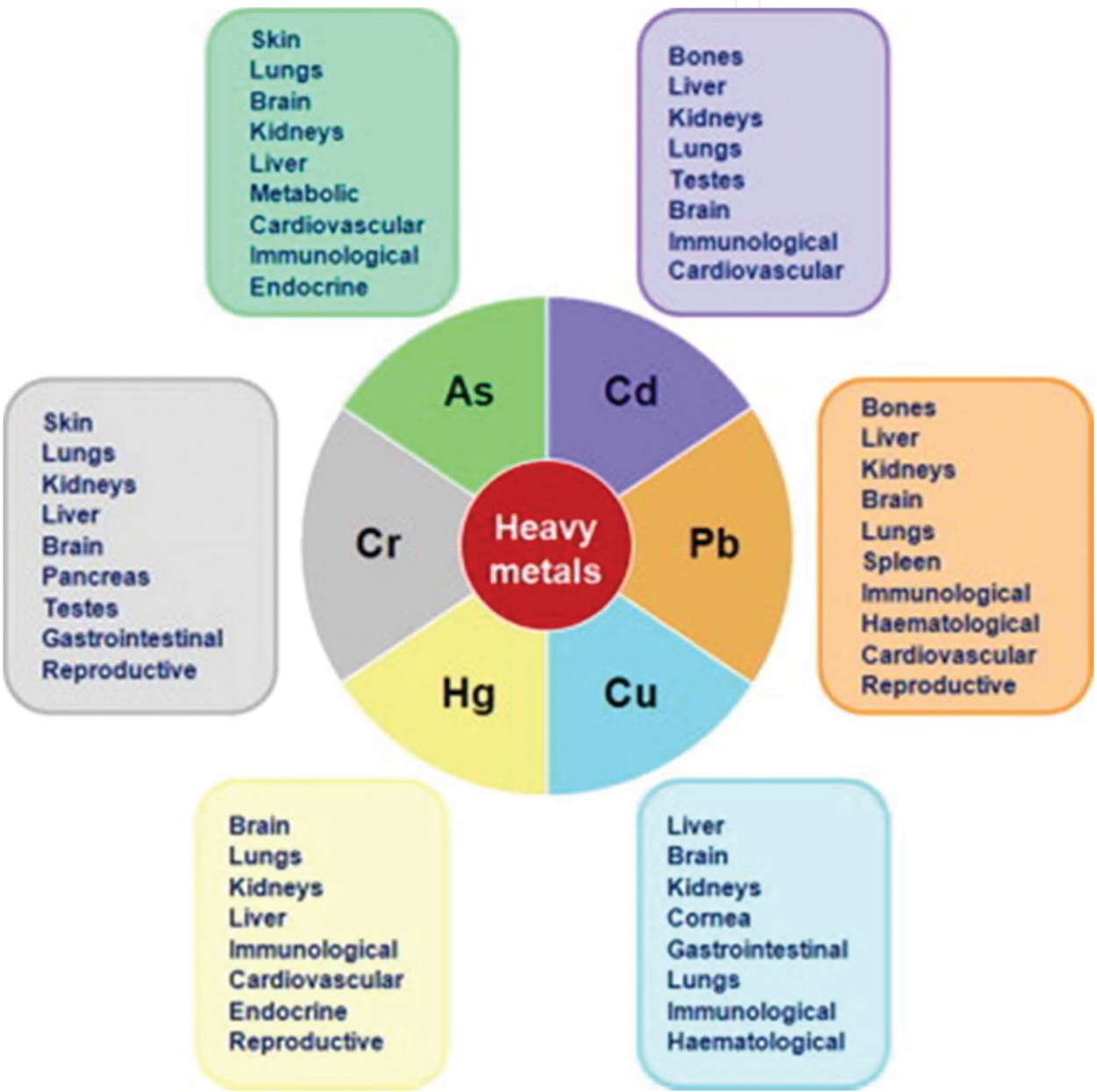


Figure 3. Impacts of heavy metals on the environment [13].

2.3.1. *Effect on soil*

Emissions from activities and sources such as industrial activities, mine tailings, disposal of high metal wastes, leaded gasoline and paints, land application of fertilisers, animal manures, sewage sludge, pesticides, wastewater irrigation, coal combustion residues and spillage of petrochemicals lead to soil contamination by heavy metals. Soils have been noted to be the major sinks for heavy metals released into the environment by aforementioned anthropogenic activities. Most heavy metals do not undergo microbial or chemical degradation because they are nondegradable, and consequently their total concentrations last for a long time after being released to the environment [5, 14].

The presence of heavy metals in soils is a serious issue due to its residence in food chains, thus destroying the entire ecosystem. As much as organic pollutants can be biodegradable, their biodegradation rate, however, is decreased by the presence of heavy metals in the environment, and this in turn doubles the environmental pollution, that is, organic pollutants and heavy metals thus present. There are various ways through which heavy metals present risks to humans, animals, plants and ecosystems as a whole. Such ways include direct ingestion, absorption by plants, food chains, consumption of contaminated water and alteration of soil pH, porosity, colour and its natural chemistry which in turn impact on the soil quality [15].

2.3.2. *Effects on water*

Although there are many sources of water contamination, industrialisation and urbanisation are two of the culprits for the increased level of heavy metal water contamination. Heavy metals are transported by runoff from industries, municipalities and urban areas. Most of these metals end up accumulating in the soil and sediments of water bodies [15].

Heavy metals can be found in traces in water sources and still be very toxic and impose serious health problems to humans and other ecosystems. This is because the toxicity level of a metal depends on factors such as the organisms which are exposed to it, its nature, its biological role and the period at which the organisms are exposed to the metal. Food chains and food webs symbolise the relationships amongst organisms. Therefore, the contamination of water by heavy metals actually affects all organisms. Humans, an example of organisms feeding at the highest level, are more prone to serious health problems because the concentrations of heavy metals increase in the food chain [16].

2.3.3. *Effects on air*

Industrialisation and urbanisation, due to rapid world population growth, have recently made air pollution as a major environmental problem around the world. The air pollution was reported to have been accelerated by dust and particulate matters (PMs) particularly fine particles such as PM_{2.5} and PM₁₀ which are released through natural and anthropogenic processes. Natural processes which release particulate matters into air include dust storms, soil erosion, volcanic eruptions and rock weathering, while anthropogenic activities are more industrial and transportation related [17].

Particulate matters are important and require special attention as they can lead to serious health problems such as skin and eyes irritation, respiratory infections, premature mortality and cardiovascular diseases. These pollutants also cause deterioration of infrastructure,

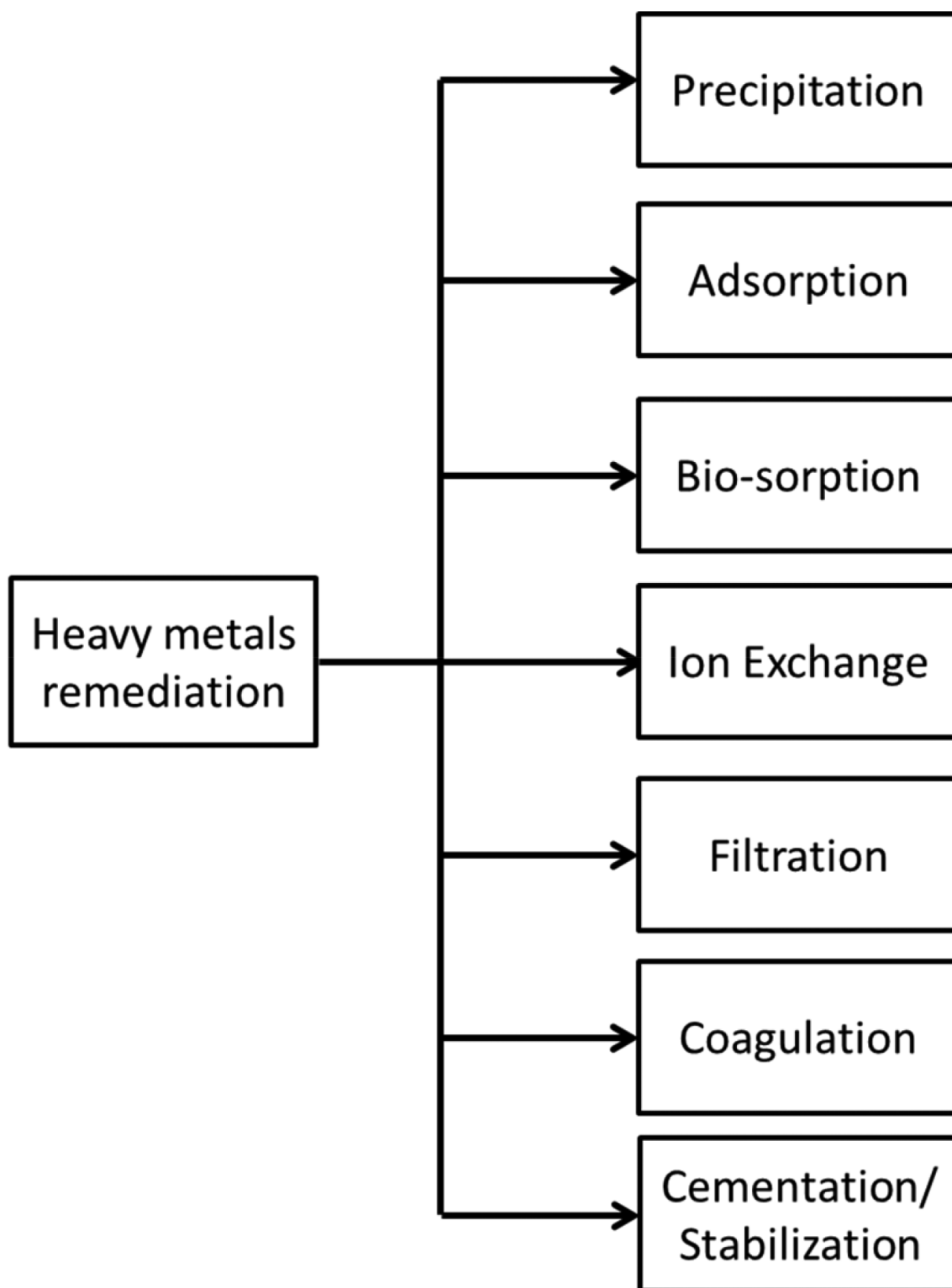


Figure 4. Mechanisms for the removal of heavy metals [20].

corrosion, formation of acid rain, eutrophication and haze [9]. Amongst others, heavy metals such as group 1 metals (Cu, Cd, Pb), group 2 metals (Cr, Mn, Ni, V and Zn) and group 3 metals (Na, K, Ca, Ti, Al, Mg, Fe) originate from industrial areas, traffic and natural sources, respectively [17, 18].

2.4. Mechanisms of remediating heavy metals

Treatment processes for acid mine water typically generate high-density sludge that is heterogeneous due to variety of metals, metalloids and anionic components, and this makes it difficult to dispose the sludge [19]. Recent researches have therefore focused on the recovery of chemical species from acid mine drainage (AMD) and secondary sludge. This is aimed at recovering valuable resources and also enabling easier and safer disposal of the treated sludge, hence reducing their environmental footprints. Disposal of metal laden waste to landfills and waste retention ponds/heaps lead to secondary pollution of surface and subsurface water resources. It may also lead to soil contamination, hence affecting their productivity [19].

In order to protect the human health, plants, animals, soil and all the compartments of the environment, proper and careful attention should be given to remediation technologies of heavy metals. Most physical and chemical heavy metal remediation technologies require handling of large amounts of sludge, destroy surrounding ecosystems and are very expensive [19] (**Figure 4**).

2.4.1. Precipitation

A variety of alkaline chemical reagents have been used over the years for neutralisation of acid mine drainage (AMD) in order to increase the pH and consequently precipitate and recover the metals. The most common alkaline reagents used for sequential recovery of minerals resources from AMD are limestone (CaCO_3), caustic soda (NaOH), soda ash (Na_2CO_3), quicklime (CaO), slaked lime (Ca(OH)_2) and magnesium hydroxide (Mg(OH)_2) [21]. Some processes have recovered metals at varying pH regimes (**Table 1**) and synthesised commercially valuable materials such as pigments and magnetite [22]. Some minerals are recovered and sold to metallurgical industries, hence off-setting the treatment costs [19].

2.4.2. Adsorption

Adsorption occurs when an adsorbate adheres to the surface of an adsorbent. Due to reversibility and desorption capabilities, adsorption is regarded the most effective and economically

Metal ion	pH	Metal ion	pH	Metal ion	pH
Al^{3+}	4.1	Hg^{2+}	7.3	Cd^{2+}	6.7
Fe^{3+}	3.5	Na^+	6.7	Fe^{2+}	5.5
Mn^{2+}	8.5	Pb^{2+}	6.0	Cu^{2+}	5.3
Cr^{3+}	5.3	Zn^{2+}	7.0		

Table 1. pH values at which metals in AMD precipitate [21].

viable option for the removal of metals from aqueous solution. Although efficient, adsorption is not effective with very concentrated solution as the adsorbent easily gets saturated with the adsorbate. It is only feasible for very dilute solutions, is labour intensive because it requires frequent regeneration and it is not selective in terms of metal attenuation [21]. Adsorption is therefore not applied in a large scale of metal remediation.

2.4.3. *Ion exchange*

Ion exchange is the exchange of ions between two or more electrolyte solutions. It can also refer to exchange of ions on a solid substrate to soil solution. High cation exchange capacity clay and resins are commonly used for the uptake of metals from aqueous solutions. However, this method requires high labour and is limited to certain concentration of metals in the solution. This system also operates under specific temperature and pH. Natural and synthetic clays, zeolites and synthetic resins have been used for removal and attenuation of metals from wastewater [19, 23].

2.4.4. *Biosorption*

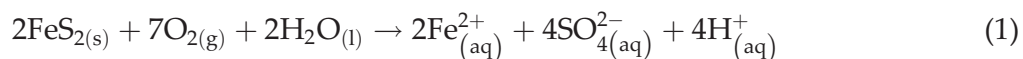
Biosorption refers to the removal of pollutants from water systems using biological materials, and it entails the absorption, adsorption, ion exchange, surface complexation and precipitation. Biosorbents have an advantage of accessibility, efficiency and capacity. This process is readily and easily available. Regeneration is easy, hence making it very favourable. However, when the concentration of the feed solution is very high, the process easily reaches a breakthrough, thus limiting further pollutant removal [24].

2.4.5. *Membrane technologies*

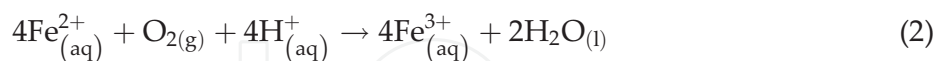
The use of membrane technologies for the recovery of acid mine drainage is very effective for water that has high concentration of pollutants. It uses the concentration gradients phenomenon or the opposite which is reverse osmosis. There are different types of membranes that are used for mine water treatment including: ultrafiltration, nano-filtration, reverse osmosis, microfiltration and particle filtration [19, 25, 26].

3. Case study of South Africa acid mine drainage

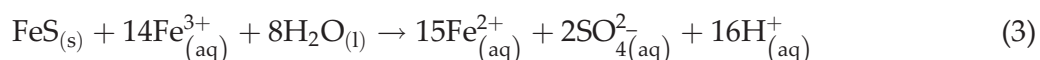
South Africa is well endowed by mineral reserves and this has triggered its immense dependence on mineral resources for gross domestic product and economy. However, the legacy of coal and gold mining has left in its wake serious environmental problems. The major problem is acid mine drainage. Acid mine drainage (AMD) is formed from the hydro-geochemical weathering of sulphide-bearing rocks (pyrite, arsenopyrite and marcasite) in contact with water and oxygen [23, 27]. This reaction is also catalysed by iron (Fe) and sulphur-oxidising microorganisms [28, 29]. In a nutshell, the formation of AMD can be summarised as follows [19, 23, 30, 31]:



The oxidation of sulphide to sulphate solubilises the ferrous iron (Fe(II)), which is subsequently oxidised to ferric iron (Fe(III)):



Either these reactions can occur spontaneously or can be catalysed by microorganisms (sulphur- and iron-oxidising bacteria) that derive energy from the oxidation reaction [26]. The ferric cations produced can also oxidise additional pyrite into ferrous ions:



The net effect of these reactions is to produce H^{+} and maintain the solubility of the ferric iron [32]. Because of the high acidity and elevated concentration of toxic and hazardous metals, AMD has been a prime issue of environmental concern that has globally raised public concern [33].

The discharge of metalliferous drainage from mining activities has rendered the environment unfit to foster life [22]. Pragmatic approaches need to be developed to counter for this mining legacy that is perpetually degrading the environment and its precious resources [21]. Researches and piloted studies have indicated that active and passive approaches can be successfully adopted to treat acid mine drainage and remove potentially toxic chemical species [23, 31]. The presence of Al, Fe, Mn and sulphates is a prime concern in addition to the trace of Cu, Ni, Pb and Zn [29]. Metalloids of As and earth alkali metal (Ca and Mg) are also present in significant levels [33]. Several studies have shown the feasibility of treating acid mine drainage to acceptable levels as prescribed by different water quality guidelines, but the resultant sludge has been an issue of public concern due to its heterogeneous and complex nature loaded with metal species [23, 34].

Based on that evidence, research studies have been firmly embedded on the recovery of valuable minerals from AMD [19, 23]. There are several mechanisms used for the recovery of chemical components from AMD including: precipitation [35], adsorption [36], biosorption [24], ion exchange [19, 25, 26], desalination [37] and membrane filtration [38, 39]. Out of those techniques, precipitation has been the promising technology due to the ability to handle large volumes of water with very little dosage [35]. Adsorption and ion exchange have a challenge of poor efficiency at elevated concentrations and quick rate of saturation. Membrane technologies have the problem of generating brine that creates another environmental liability. Desalination has a problem of producing salts that has impurities, hence making them unsuitable for utilisation. Freeze desalination has been the promising technology, but it has never been tried in a large scale [19, 23, 34].

3.1. Impacts of heavy metals in South Africa

South Africa's geology is rich in coal and mineral reserves which contain key metals such as gold, platinum and copper. The significant volume of mineral and coal reserves has made

mining serve as a backbone in the development and growth of the country's economy. This is evident from the massive number of mines found around the country. However, mining has been noted to cause inimical impacts to the human health, organisms and environment as a whole, with water resources being the most common victim of the pollution [40].

The mining of coal and gold for multilateral uses exposes pyrite to oxidising agents. Iron hydroxide and sulphuric acid are toxic chemical species to living organisms when introduced into water resources (both surface and underground). This deteriorates the natural form of the water bodies and its ability to foster life. Acid mine drainage has very low pH of about <1.4 to >3 [41, 42]; high TDS, EC and other metals in toxic concentration. Previous studies documented the following concentrations in AMD: < 75 ppm to >47,800 acidity; <3560 to >41,700 SO₄²⁻ ppm; <460 to >12,270 ppm total Fe; <17,400 to 37,700 µg/L Zn; <270 to >13,000 µg/L Cu; <520 to >1500 µg/L Co; <75 to >360 µg/L Ni; <8 to >30 µg/L Pb and 6 to 30 µg/L Cd [41–44].

However, the above-mentioned concentrations depend on the pH of the AMD—concentrations decrease when pH increases. When exposed to such conditions, mortality and diseases are most likely to occur in organisms, as well as other health [45]. In addition, AMD destroys ecosystems of organisms and also negatively impacts on the economy of the country. Heavy metals in active and abandoned mines in South Africa have impacted both surface and underground water.

Parameter	Gold AMD*	Coal AMD**	Neutral drainage†	DWS industrial	DWS irrigation
pH	2.3	2.5	6.5	5.0–10.0	6.5–8.4
EC	22,713	13,980	500	0–250	>540
Na	248.4	70.5	20.1	—	430–460
K	21.6	34.2	29.1	—	—
Mg	2.3	398.9	861.8	—	—
Ca	710.8	598.7	537.5	—	—
Al	134.4	473.9	0.01	—	5.0–20
Fe	1243	8158.2	0.07	0.0–10	5.0–20
Mn	91.5	88.2	25.0	0.0–10.0	0.02–10.0
Cu	7.8	—	—	—	0.2–5.0
Zn	7.9	8.36	0.16	—	1.0–5.0
Pb	6.3	—	—	—	0.2–2.0
Co	41.3	1.89	0.29	—	0.05–5.0
Ni	16.6	2.97	0.21	—	0.2–2.0
SO ₄ ²⁻	4635	42,862	4603	0–500	—

*Gold mining AMD [44].

**Coalmining AMD.

†Neutral drainage water [40, 42, 45, 47–51].

Table 2. The relevant criteria for discharge of acidic and sulphate-rich water as compared to DWS water quality guidelines.

3.2. Legal requirements of water quality

The National Environmental Management Act (NEMA) 108 of 1998, stipulates that everyone has the right to live in an environment which is safe and unlikely to pose any deleterious effects to their health. The legislative requirements for industrial effluents are primarily governed by the Department of Water Affairs DWS Water Quality Guidelines [46]. This purpose requires that any person who uses water for industrial purposes shall purify or otherwise treat such water in accordance with requirements of DWA [41, 46–48]. The relevant criteria for discharge of acidic and sulphate-rich water are given in **Table 2**.

As shown in **Table 2**, mine effluents in South Africa are dominated by dissolved Fe, Al, Mn, Ca, Na, Mg and traces of Cu, Co, Zn, Pb and Ni. These concentrations are far above the legal requirements.

4. Deleterious effects of acid mine drainage on terrestrial and aquatic ecosystems

The introduction of effluents from mining activities into receiving streams can severely impact aquatic ecosystems through habitat destruction and impairment of water quality. This will eventually lead to reduction in biodiversity of a given aquatic ecosystem and its ability to sustain life. The severity and extent of damage depends on a variety of factors including the frequency of influx, volume and chemistry of the drainage and the buffering capacity of the receiving stream [22, 52–58].

4.1. Acidity

When metals in AMD are hydrolysed, they lower the pH of the water making it unsuitable for aquatic organisms to thrive [52]. AMD is highly acidic (pH 2–4), and this promotes the dissolution of toxic metals [44]. Those toxic species exert hazardous effects on terrestrial and aquatic organisms [23]. Also, if the water is highly acidic, only acidophile microorganisms will thrive on such water with the rest of aquatic organisms migrating to other regions which are conducive to their survival. Many streams contaminated with AMD are largely devoid of life for a long way downstream. To some aquatic organisms, if the pH range falls below the tolerance range, probability of death is very high due to respiratory and osmoregulation failure. Acidic conditions are dominated by H^+ which is adsorbed and pumps out Na from the body which is important in regulating body fluids [23, 52, 53, 56–65].

4.2. Toxic chemical species

Exposure of aquatic and terrestrial organisms to potentially toxic metals and metalloids can have devastating impacts to living organisms [44, 66, 67]. Toxic chemical species present in AMD have been reported to be toxic to aquatic and terrestrial organisms. They are associated with numerous diseases including cancers. Some of these chemical species may accumulate

Element	DWA limit	Ecological impacts of AMD
Al	<0.5 mg/L	Prolonged exposure to aluminium has been implicated in chronic neurological disorders such as <i>dialysis dementia</i> and Alzheimer's disease. Severe aesthetic effects (discolouration) occur in the presence of iron or manganese
Fe	<1 mg/L	Severe aesthetic effects (taste) and effects on plumbing (slimy coatings). Slight iron overload possible in some individuals. Chronic health effects in young children and sensitive individuals in the range of 10–20 mg/L, and occasional acute effects towards the upper end of this range
Mn	<0.2 mg/L	Very severe, aesthetically unacceptable staining. Domestic use unlikely due to adverse aesthetic effects. Some chance of manganese toxicity under unusual conditions
Cu	<1 mg/L	Gastrointestinal irritation, nausea and vomiting. Severe taste and staining problems. Severe poisoning with possible fatalities. Severe taste and staining problems
Mg	<200 mg/L	Water aesthetically unacceptable because of bitter taste users if sulphate present. Increased scaling problems. Diarrhoea in most new consumers
Zn	<5 mg/L	Bitter taste; milky appearance. Acute toxicity with gastrointestinal irritation, nausea and vomiting. Severe, acute toxicity with electrolyte disturbances and possible renal damage

Table 3. Effects of selected AMD metals on the health of living organisms.

and be biomagnified in living organisms, hence threatening the life of higher trophic organisms such as birds [68]. Lead causes blood disorders, kidney damage, miscarriages and reproductive disorders and is linked to various cancers. The exposure of living organisms to toxic chemical species in AMD can also lead to nausea, diarrhoea, liver and kidney damage, dermatitis, internal haemorrhage and respiratory problems. Epidemiological studies have shown a significant increase in the risk of lung, bladder, skin, liver and other cancers on exposure to these chemical species. Effects of Al, Fe, Mn, Cu, Mg and Zn on the health of living organisms are summarised in **Table 3** [44, 56, 67].

Author details

Vhahangwele Masindi^{1,2*} and Khathutshelo L. Muedi¹

*Address all correspondence to: masindivhahangwele@gmail.com

1 Council for Scientific and Industrial Research (CSIR), Built Environment (BE), Hydraulic Infrastructure Engineering (HIE), Pretoria, South Africa

2 Department of Environmental Sciences, School of Agriculture and Environmental Sciences, University of South Africa (UNISA), Florida, South Africa

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