published by

EQA - International Journal of Environmental Quality
ISSN 2281-4485 - Vol. 59 (2024): 13-21
Journal homepage: https://eqa.unibo.it/

Lead remediation techniques – Lessons for sustainable remediation of lead-contaminated sites in Zambia's mining towns

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Article info
Received 3/9/2023; received in revised form 10/11/2023; accepted 11/12/2023
DOI: 10.6092/issn.2281-4485/17928

Abstract

Lead (Pb) contamination is a major problem worldwide. Studies have shown that lead pollution in Kabwe, one of the ten most polluted cities in the world, is the result of anthropogenic activities. These activities are mining, smelting, and the disposal of mine tailings from the closed lead-zinc mine. As in most countries adversely affected by lead contamination, Zambia is actively implementing remediation efforts to mitigate the negative consequences of Pb contamination on human, animal, plant, and environmental health. Heavy metals tend to accumulate in the environment, as they are not biodegradable, necessitating remediation. Critical analysis of the current literature review shows numerous remediation techniques, each with advantages and disadvantages. Highly efficient remediation strategies often combine two or more remediation techniques, which are improved and optimized over time. In addition, modern remediation techniques utilize environmentally sustainable genetic resources of living organisms, including microbes such as bacteria and fungi and plants that are tolerant or resistant to heavy metals. Bioremediation has unique advantages over other remediation techniques, making it sustainable for tackling lead contamination in Zambia. Pb toxicity's public health, environmental, and economic costs are too great to allow the status quo to continue.

Keywords
Bioremediation, heavy metals, lead contamination, integrated remediation, microbial remediation, Kabwe

Introduction

Sources of Pb Contamination in Zambian Towns

Lead contamination is an ongoing environmental problem that negatively impacts plant, animal, and human health. Several studies have shown that Zambia's primary sources of Pb contamination are anthropogenic activities (Fig. 1) (Rama, 2021; Bose-O'Reilly, 2018). These include mining and smelting industries and mining waste disposal. Further sources of Pb contamination are the legacy of leaded petrol (Laidlaw *et al.*, 2017) and the use and unregulated disposal of lead acid batteries (Rees *et al.*, 2020). Like all heavy metals, Pb is not biodegradable and accumulates in the environment.

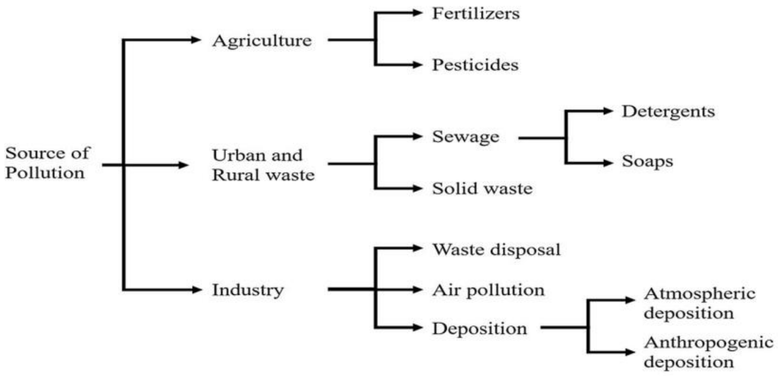

Figure 1
Graphical representation of sources of heavy metal contamination. (Adapted from Dhaliwal et al., 2020)

Heavy metals switch from non-bioavailable forms to bioavailable forms depending on conditions like oxygen levels, pH, and the presence of various natural iron oxide compounds (Fe_2O_3/SiO_2/MnO_2), which are naturally efficient scavengers of metal ions (Villa *et al.*, 2018). Lead toxicity also causes DNA damage and is considered carcinogenic (Nakata *et al.*, 2021). Research by Nakata *et al.* (2021), which corroborated the findings of Yabe *et al.* (2020), showed that children in highly contaminated areas of Kabwe have disproportionately elevated Blood Lead Levels (BLLs), with 5 of 291 children tested at three months and three years of age exceeding the 100 g/dL level. This peaks at two years of age. These elevated BLLs far exceed the CDC/ WHO recommended BLL of 5 g/dL (Rees *et al.*, 2020; Yamada *et al.*, 2020). Furthermore, exposure affects children's neurological development and, consequently, their behaviour and cognitive performance, delaying postnatal growth and puberty (Fig. 2) (Kumar *et al.*, 2020). The study by Yohannes *et al.* (2022) on populations with chronic exposure suggests that it amplifies abnormalities in promoter methylation of the ALAD and p16 genes. The ALAD and p16 genes are associated with haem production and tumor suppression, respectively. This may also account for lead's overall toxicity and carcinogenic activity. Over 70 % of Pb is stored in dense bone, which could cause remobilized exposure even after environmental exposure has ceased (Collin *et al.*, 2022; Kumar *et al.*, 2020).

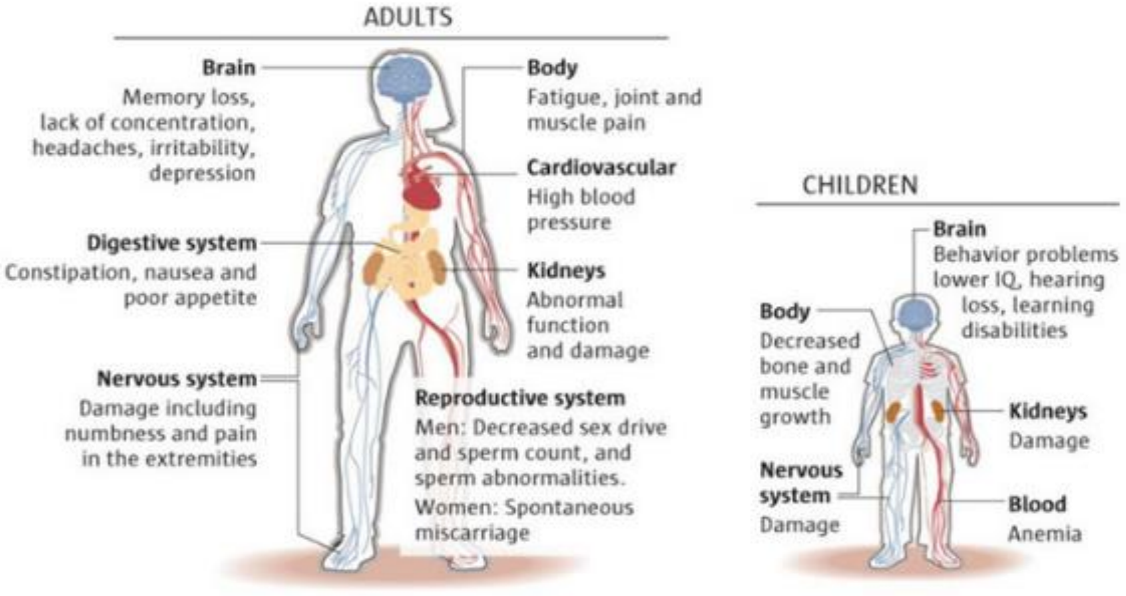

Figure 2. *Effects of lead toxicity on humans (Adapted from Powanga, 2021)*

DOI: 10.6092/issn.2281-4485/17928

Alsafran *et al.* (2023) propose a remediation approach that integrates multiple methods to ensure maximum benefit from bioremediation. Some of the advantages and disadvantages of these techniques are discussed below.

Advantages and Disadvantages of Remediation Techniques

Though there is no universal definition for remediation, we shall use the definition by Landrigan *et al.* (2018), who define remediation as removing contaminants from sediment, soil, and water, reducing exposure to their toxic effects. This definition is espoused by the WHO (2018). Ultimately, remediation aims to restore disrupted ecosystems and their natural functions. Remediation techniques are classified based on several factors, including the type of intervention used, whether immobilization or extraction, where the intervention is located and the kind of technology used (Hesse *et al.*, 2019; Ifon *et al.*, 2019). According to Alsafran *et al.* (2023), factors considered when choosing which remediation technique to use include the availability of personnel, costs, period, and remediation goals. Several factors affect the behaviour of metals in soil, so their remediation presents a unique challenge and requires a different remediation approach when dealing with multiple contaminants (Selvi *et al.*, 2019). In practice, the bioavailability of a contaminant determines how it will be removed from an ecosystem.

Combining chemical and physical techniques makes remediation faster and more efficient than using only one technique (Fig. 3). Al-Hashimi *et al.* (2021) presented the pump-and-treat (P&T) method as the predominant treatment method for the remediation of groundwater contaminated with organic and inorganic contaminants. Other additives used during P&T include chelating agents, oxidizing/reducing agents, and flocculants. P&T is an integrated and safe method to clean up large volumes of contaminated groundwater (Al-Hashimi *et al.*, 2021). Groundwater treatment is achieved with activated carbon (Nyirenda et al., 2022), ion exchange, or air stripping (Al-Hashimi *et al.*, 2021). Traditional P&T methods pump contaminated groundwater to the surface for treatment (Kuppusamy *et al.*, 2016). The treated water is discharged into the nearest sewer system or pumped into the subsurface. Kisku *et al.* (2015) lamented that P&T is slow and expensive despite being simple. Since P&T is costly when implemented independently, it's now integrated with chemical methods. Stabilization using chemical additives or physicochemical remediation via the freeze/thaw method coupled with chemical washing is integrated P&T. Combined or integrated remediation, using two or more approaches, ensures more effective and sustainable removal of contaminants from groundwater (Kuppusamy *et al.*, 2016). Below is a schematic summary of heavy metal remediation techniques (Selvi *et al.*, 2019).

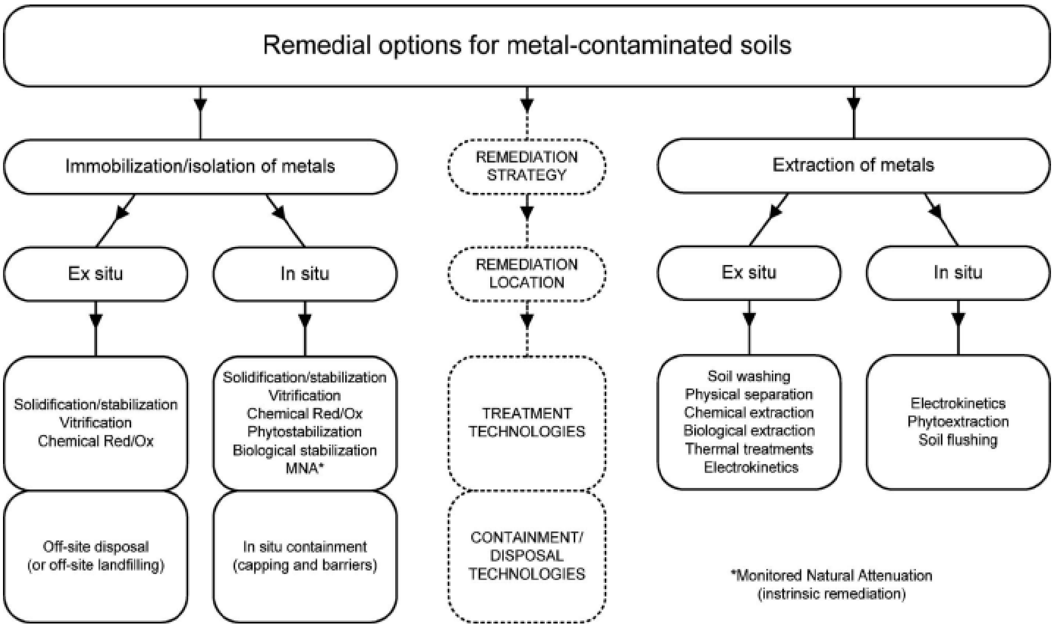

Figure 3
Schematic of heavy metal remediation techniques (Adapted from Dermont et al., 2008)

DOI: 10.6092/issn.2281-4485/17928

Biological remediation approaches offer the most significant potential for sustainably cleaning up environmental contamination. These approaches are less costly and can be carried out *in situ* without further degrading the environment as conventional physical and chemical processes do (Ayangbenro & Babalola, 2017; Grifoni *et al.*, 2022).

Bioremediation approaches are cost-effective and environmentally friendly compared to chemical and physical ones. It minimizes the potential human health and environmental hazards associated with handling and transporting contaminated waste. Furthermore, microorganisms and plants can accumulate, sequester, or immobilize toxicants, reducing their bioavailability and rendering them less harmful. Bioremediation also has disadvantages. Megharaj *et al.* (2014) advocate extensive site characterization, particularly in the case of microbial remediation. This is because microbial acclimatization to soil physiochemical parameters is necessary, which may not develop for recalcitrant toxicants. In addition, biological processes are particular, so all site factors need to be considered. These site factors include the presence of metabolically active microbial ecosystems, appropriate environmental growth conditions, and appropriate levels of nutrients and pollutants. Soil physiochemical parameters, such as clay or humic compounds and pH, affect the effectiveness of biological interventions. Contamination hotspots in Kabwe have multi-element heavy metal contamination, including Cd, Pb, and Zn (Mwilola *et al.*, 2020). Each of these metals has different physiochemical properties, and one remediation method will not necessarily remove all metals to the same degree, as Mwilola *et al.* (2020) illustrated. This means more research is needed to develop bioremediation techniques that are appropriate for sites with complex mixtures of contaminants, such as multi-element contamination, which is unevenly distributed in the environment. Inadequate understanding of the toxicant degradation capabilities of microbial communities in the field and poor knowledge of metabolic cooperation networks among microbial communities are limiting factors to sustainable bioremediation. Perhaps in response to these disadvantages, research into contemporary remediation techniques, such as enzyme-based approaches and physiochemical and physiobiological ones in treating contaminated ecosystems, is gaining ground.

Optimization of Remediation of Contaminated Soil

The literature shows that extensive research has been conducted on the hazards of Pb contamination on humans, plants, animals, and microbial communities (Dermont *et al.*, 2008). The factors that require optimization during bioremediation include physiochemical factors like pH, soil type, and electron acceptors/ donors. Additional physiochemical factors of importance are particle size and ionic or particle form, as is the concentration of contaminants (Muttaleb & Ali, 2022). The presence of microbial populations, the availability of contaminants to the microbial population as a carbon source, and nutrients for biological systems should also be considered (Chu, 2018).

Large-scale Remediation of Contaminated Sites

Despite the complex nature of Pb contamination, there are cases of successful large-scale remediation and restoration of contaminated sites. The US EPA has published extensively on large-scale remediation of Pb-contaminated sites, called superfund sites. The Bunker Hill Superfund Site is one such example, which was highly contaminated with several heavy metals, including Pb, Zn, and Ag, after over one hundred years of mining and smelting over an expansive area that included 18,000 acres of waterfowl habitat (US EPA, 2015). Another successful story of ecological revitalization is the Anaconda Superfund Site, which ceased operations in 1980 (US EPA, 2016). This massive 192,000 acres of varied, rugged terrain presented significant challenges in designing and implementing remedial measures. Its smelting plants at the Anaconda Smelter released tons of As, Cu, S, Pb, and Zn daily. The Palmerton Superfund Site is an over two thousand-acre site that operated Zn smelters until December 1980 (US EPA, 2011). Smelting activities at the site released large quantities of Zn, Pb, Cd, and SO_2. This is in addition to defoliating more than 2,000 acres near one of its two smelters. Process tailings and plant waste were disposed of at a slag bank at a four-kilometer-long, 255-acre dumpsite. By 2011, after over 10 years of remediation activity, 850 acres of land at the Palmerton Superfund Site were reclaimed. These superfund sites show that ecological remediation and reclamation are achievable using integrated remediation approaches. Unfortunately, similar successful remediation initiatives have not reached the African continent. This review paper analyses sources of large-scale lead contamination in Zambia towns and proposes possible remediation techniques based on case studies from other countries.

DOI: 10.6092/issn.2281-4485/17928

Methodology

This review presents a literature search of remediation techniques worldwide. It also draws on media articles that highlight remediation techniques. A database search of Academia, Google Scholar, ResearchGate, the Researcher, and Semantic Scholar was performed with the key terms 'bioremediation,' 'conventional remediation,' 'integrated remediation,' 'lead contamination,' 'microbial remediation,' 'phytoremediation' and 'Zambia.' Author versions/ pre-prints relevant to the subject under discussion were included in the review. Relevant additional literature was obtained through back-searching references. Only articles published from 2013 onwards were reviewed to ensure the presentation of current information. However, a few articles published before 2013 were included due to their importance in reporting the first set of empirical studies.

Results

The literature shows that Pb contamination and its effects have been studied extensively in Kabwe and the African continent. Ishizuka (2020) provided evidence that Pb contamination is most significant in areas of Kabwe close to the Pb-Zn mine. The literature also shows that ornamental plants and food crops accumulate heavy metals over time, stored in roots or above-ground tissue. Dietary Pb intake occurs once these plants and meat are consumed. The literature also shows that incidental ingestion of particulate Pb occurs and is particularly problematic during the dry season (Onakpa *et al.*, 2018). This is especially true for children exposed to playgrounds. Data from an econometric analysis by Yamada *et al.* (2020) suggests that over 90% of the population of Kabwe is exposed to Pb. The effects of both acute and chronic exposure to the metal are extensively documented. In any case, Pb has no known beneficial or biological impact on living organisms. The literature also highlights the several remediation techniques used to remediate Pb from hotspots worldwide. The literature also indicates the need to understand and use the affordances of natural metabolic processes, which enable living organisms like microorganisms and green plants to thrive in Pb-contaminated areas.

Discussion

As earlier alluded to, biological approaches to remediation appear to offer the most significant potential for sustainably cleaning up environmental contamination. They are less costly and can be carried out without causing secondary contamination associated with conventional physical and chemical approaches (Ayangbenro and Babalola, 2017; Grifoni *et al.*, 2022). Microbes occur in virtually every habitat and ecological niche on the planet, and their ubiquity in natural and artificial habitats is well documented. These habitats include high saline mangrove forests, elevated heavy metal concentrations, and a range of environmental pH and temperatures (Atigh *et al.*, 2020; Chakdar *et al.*, 2022). According to Alsafran *et al.* (2023), bioremediation takes advantage of natural microbial metabolic processes performed by microbes to reduce the adverse effects of contamination. Ayangbenro and Babalola (2017) reviewed the applicability of growing algal, bacterial, and fungal cells for removing heavy metals from the environment. Bioremediation using growing microbes is a viable alternative to pure biosorption removal of metal contaminants from complex industrial effluents such as those associated with mineral processing. Microbial remediation is a natural process with multiple benefits, such as low energy requirements, low operating costs, limited environmental and health risks, and possibly recovery of heavy metals. The literature suggests that anaerobic microorganisms are less commonly used for metal remediation than aerobes. It is recommended that in any environment where microbial activity occurs, there is a transition from aerobic to anaerobic conditions (ultimately methanogenic) with an associated change in the redox status of the system (Igiri *et al.*, 2018). For more extensive discussions of heavy metal resistance mechanisms in microbes, see reviews by (Chakdar *et al.* 2022; Igiri *et al.*, 2018). Literature analysis shows that bioremediation, through optimizing microbial enzymes or metal transporters, is viable for cleaning up Zambian Towns.

Lead Remediation in Zambian Towns

The extractive industries are, by nature, destructive of the environment and release waste, which is generally toxic. Mining waste is a constant hazard and a recurring source of environmental degradation. According to Kříbek *et al.* (2019), Kabwe and Central Province are among Africa's most contaminated districts/provinces due to the mining and smelting of local Pb-Zn ores. Ettler *et al.* (2020) demonstrated that even by conservative estimates, the fine dust particles from the ISF and Waelz slag deposits in Kabwe pose a health risk for the local population. They propose covering the slag

DOI: 10.6092/issn.2281-4485/17928

deposits to limit dust dispersion and fencing them off to restrict access by locals; here, we propose using bioremediation to clean up these areas. Sikaundi (2013) presents dire statistics on the post-mining state of the Copperbelt Province of Zambia:

1. 9,125 hectares of land contains an estimated 791 million tonnes of tailings dams.
2. 20,646 hectares of land have 1899 million tonnes of overburden.
3. Three hundred eighty-eight hectares contain 77 million tonnes of waste rock.
4. 279 hectares of land have 40 million tonnes of slag.

The literature suggests that there could be a public health crisis in Kabwe (Yamada *et al.*, 2020; Yohannes *et al.*, 2020) and the Copperbelt (Muimba-Kankolongo *et al.*, 2022) due to high levels of lead contamination. Moreover, the proper lessons aren't learned from the country's mining and mining waste management legacy. In that case, this crisis will be replicated in areas with new mines, such as the 'New' Copperbelt. Evidence suggests this might already be happening (Chansa, 2021). Other studies have confirmed that flora and fauna in areas with closed or active mines have accumulated high metal concentrations in their tissues (Nakata *et al.*, 2021; Zyambo *et al.*, 2022). The literature highlights the need for remediation in areas with closed or active mines. Consequently, the challenge ahead is sustainable remediation and restoration of environments contaminated with mining and smelting waste, such as slag, leach residues, and tailings (Ettler *et al.*, 2020). Growing societal awareness of the impacts of mining activities requires ever more sustainable practices. This makes environmental remediation through multiple techniques essential to ensure its removal sustainably (Landrigan *et al.*, 2018).

The commitment to heavy metal remediation in Zambia's mining towns made through ZMERIP, a World Bank-funded remediation project, is underway. When launched in January 2015, ZMERIP had an overall approved budget of US$50 million (MMMD, 2018; The World Bank, 2019). According to (MMMD, 2018), ZMERIP had a projected five-year lifespan and was scheduled for completion in 2022. (The World Bank, 2019) estimated the cost of cleaning up contamination hotspots alone and improving environmental infrastructure to be US$29.60 million. These costs do not include other project components, like reducing the health risks of mining and smelting through localized interventions. Estimates show that these would require an additional US$18.50 million to complete (The World Bank, 2019). This brought the proposed total cost of various remediation and related activities to US$65.6 million. Conventional remediation is costly and takes a long time to achieve satisfactory results. The World Bank notes that progress on remediation in Kabwe is slow, with overall implementation progress rated as moderately unsatisfactory to moderately acceptable between 2019 and 2021 (The World Bank, 2019). It is clear from these figures that the remediation techniques employed are not working, and more environmentally sustainable techniques need to be introduced urgently.

Conclusion

Lead contamination is a problem worldwide, primarily due to anthropogenic activities like mining and smelting. Several techniques are available for removing lead from the environment, with varying degrees of sustainability. Among these, bioremediation is a viable alternative to removing Pb and other heavy metals from environments similar to Kabwe. It provides sustainable routes to remediating contaminated sites, previously thought beyond restoration. Challenges hinder effective bioremediation implementation and use in restoring contaminated sites. However, bioremediation appears to be the most favourable, effective, and ecologically friendly method of cleaning up environmental contaminants worldwide. The commissioning of new mines in the country means that anthropogenic contamination of the environment and resulting ecological degradation from new and legacy mining is a reality the country will continue to face. Kabwe can benefit ecologically from adopting some of the bioremediation techniques highlighted in the paper to ensure sustainable ecological remediation. Finally, Pb toxicity's public health, environmental, and economic costs are too great to allow the status quo to continue

Acknowledgment

The authors thank their colleagues at Mukuba University, Copperbelt University, Levy Mwanawasa Medical University, and Mzuzu University for their moral support while preparing the manuscripts.

Funding sources

This work has no external source of funding. The authors contributed equally to compiling articles for the manuscript's review, drafting, and editing.

Conflict of interest

The authors declare that there are no conflicts of interest.

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