World Journal of Biology Pharmacy and Health Sciences
eISSN: 2582-5542
Cross Ref DOI: 10.30574/wjbphs
Journal homepage: https://wjbphs.com/

(Research Article)

Check for updates

Adverse health effects of heavy metal pollution in the Enugu Area, Southeastern Nigeria

Fagbemi Oluwaseyi Ajibola [1,*], Ikemefuna Nnamdi Onyeyili [2], Maryann Seyram Adabra [3], Chekwube Martin Obianyo [4], David Joseph Ebubechukwu [5], Abdussalam Muhammad Auwal [6] and Edeh Chinenye Justina [7]

[1] *Department of Human Anatomy, Federal University Lokoja, Kogi State, Nigeria.*
[2] *Department of Treatment Care and Support, AIDS Healthcare Foundation Lokoja, Nigeria.*
[3] *School of Nursing and Midwifery, Wisconsin International University College, Accra Ghana.*
[4] *Jiann-Ping Hsu College of Public Health, Georgia Southern University.*
[5] *College of Health Sciences, University of Port Harcourt, Rivers State, Nigeria.*
[6] *Department of Hydrogeological Engineering, University of Miskolc, Hungary.*
[7] *Department of Public Health, National Open University of Nigeria*

World Journal of Biology Pharmacy and Health Sciences, 2024, 20(03), 248–258

Publication history: Received on 22 October 2024; revised on 04 December 2024; accepted on 07 December 2024

Article DOI: https://doi.org/10.30574/wjbphs.2024.20.3.0974

Abstract

Heavy metal pollution in Southeastern Nigeria's Enugu area presents a severe environmental and public health hazard, with specific locations such as Emene Industrial Area, Ngwo Mechanic Village, and Abakpa experiencing particularly high contamination levels. The primary contaminants—lead, cadmium, arsenic, mercury, and chromium—originate from industrial operations, mining activities, and unregulated waste disposal. In Emene Industrial Area, soil and water samples reveal arsenic and manganese levels significantly above safety thresholds, impacting local residents, especially children and pregnant women. Ngwo Mechanic Village exhibits dangerously high concentrations of lead and chromium due to persistent automobile emissions and industrial effluents, leading to respiratory and neurological health risks for workers and nearby communities. Additionally, agricultural zones like Abakpa are impacted by cadmium from fertilizers, resulting in contamination of crops and local water sources, which poses long-term health risks to consumers. This review examines the sources, pathways, and adverse health effects of heavy metal pollution across these high-risk locations in Enugu, while also recommending mitigation strategies, including stricter environmental regulations, sustainable agricultural practices, and community education to reduce exposure and protect public health.

Keywords: heavy metal pollution; Emene Industrial Area; Ngwo Mechanic Village; Abakpa; Enugu; health effects; environmental remediation

1. Introduction

Heavy metal pollution is a major global environmental issue due to its persistence in ecosystems and the serious health risks associated with prolonged exposure. These metals, including lead (Pb), mercury (Hg), cadmium (Cd), arsenic (As), and chromium (Cr), are toxic at low concentrations and can accumulate in living organisms over time [1,2]. Industrialization, urbanization, and modern agricultural practices have contributed significantly to the release of these contaminants into soil, water, and air. In Nigeria, heavy metal pollution has become increasingly pronounced, especially in regions experiencing rapid economic growth and industrial expansion [3]. The Enugu area, located in Southeastern Nigeria, is a prime example of a region grappling with the environmental and health challenges posed by heavy metal contamination [4].

* Corresponding author: Fagbemi Oluwaseyi Ajibola; Email: seyikizz@gmail.com

The region's vulnerability stems from a combination of factors, including extensive mining activities, agricultural chemical use, industrial operations, and inadequate waste management practices. The health effects of heavy metals are well-documented, ranging from neurological and developmental disorders to chronic diseases such as cancer, kidney failure, and cardiovascular complications [3,4]. This review aims to explore the sources and pathways of heavy metal pollution in the Enugu area, identify the health risks posed by such contamination, highlight the vulnerable populations, and suggest mitigation strategies that can reduce exposure and improve public health outcomes.

2. Sources of Heavy Metal Pollution in the Enugu Area

Several anthropogenic activities contribute to the release of heavy metals into the environment in the Enugu area. Understanding these sources is crucial for devising effective control measures.

- ***Industrial Activities**:* Enugu has a history of coal mining and other industrial activities that release heavy metals into the environment. These include coal mining operations, small-scale manufacturing, and metalwork industries, which discharge untreated industrial effluents containing heavy metals like lead and cadmium into nearby rivers, soil, and the air [5,6]. Over time, these contaminants accumulate, resulting in long-term environmental degradation and increasing exposure risks for the local population. Soil samples from Ada rice fields in Enugu showed lead (Pb) concentrations averaging 4.64 mg/kg, with some samples reaching as high as 7.81 mg/kg. Cadmium (Cd) levels averaged 0.83 mg/kg but were as high as 3.84 mg/kg in certain locations, significantly above permissible levels [7]. Despite existing regulations, the enforcement of environmental standards remains weak, leading to unchecked industrial pollution [7,8].
- ***Agricultural Practices**:* Agrochemicals, including fertilizers, pesticides, and herbicides, are another notable source of heavy metal contamination in Enugu's agricultural sector. Fertilizers often contain trace amounts of heavy metals such as cadmium, arsenic, and lead, while some pesticides contribute mercury and chromium to the soil [9,10]. Heavy metal concentrations found in rice fields around Enugu reflect this: cadmium levels in rice grains reached 1.98 mg/kg, significantly exceeding the WHO permissible limit of 0.1 mg/kg, while zinc (Zn) was detected at levels as high as 229.14 mg/kg. These contaminants leach into groundwater and runoff into streams, heightening risks of metal transfer into crops and the food chain [7].
- ***Waste Disposal**:* Improper waste management in Enugu exacerbates the heavy metal pollution problem. Municipal waste, electronic waste (e-waste), and hazardous industrial waste are often disposed of in open dumpsites [11]. These wastes, particularly e-waste, contain significant amounts of heavy metals, including lead, cadmium, mercury, and chromium, which leach into the soil and water when exposed to the elements. During the rainy season, these metals are carried by runoff into water bodies, further increasing the risk of contamination in areas reliant on surface water for drinking and irrigation [11,12].
- ***Urbanization and Infrastructure Development**:* The rapid urbanization of Enugu, without adequate infrastructure to manage environmental impacts, has contributed to heavy metal pollution. Construction materials, paints, and vehicular emissions release heavy metals such as lead and cadmium into the environment [13]. Soil samples near urban areas have shown lead concentrations of up to 6.88 mg/kg, with an average of 4.50 mg/kg, indicating that urban activities contribute significantly to soil contamination. These metals gradually accumulate in soils and water systems, increasing human exposure, particularly in densely populated urban settings [7].
- ***Groundwater Contamination Sources**:* Groundwater is a vital resource for drinking water in Enugu. However, the region's shallow water table makes it highly susceptible to contamination from nearby pollution sources [14]. Industrial effluents, agricultural runoff, and leachates from dumpsites often seep into groundwater aquifers, carrying heavy metals that make the water unsafe for consumption. In some cases, natural geological formations containing metals like arsenic further contribute to groundwater contamination, compounding the health risks [15-17].

3. Common Heavy Metals Found in the Enugu Area

- ***Lead (Pb):*** Lead contamination is primarily associated with industrial activities, including coal mining and various small-scale manufacturing processes. Lead is also prevalent in paints, e-waste, and construction materials [18]. Detected at concentrations as high as 7.5 mg/kg in rice grains and averaging 4.64 mg/kg in soil, lead levels frequently surpass the WHO's permissible limit of 0.2 mg/kg in food, posing considerable health risks, especially to children, due to potential impacts on cognitive and behavioral development [7].
- ***Mercury (Hg):*** Mercury pollution results from industrial waste and the improper use of mercury-containing pesticides. It is highly toxic, particularly in its methylmercury form, which bioaccumulates in aquatic organisms

[19,20]. Human exposure occurs mainly through fish consumption, leading to neurological and developmental issues, particularly in infants and young children [19].

- ***Cadmium (Cd):*** Cadmium contamination, largely stemming from industrial discharges and the use of phosphate-based fertilizers, is significant in Enugu's soils and crops [21]. Soil samples revealed cadmium concentrations as high as 3.84 mg/kg, with an average of 0.83 mg/kg—surpassing safe levels in 30% of samples. In rice grains, cadmium reached up to 1.98 mg/kg, exceeding WHO's food safety limit, thus posing long-term health risks, particularly to the kidneys, bones, and liver [7].
- ***Arsenic (As):*** Arsenic is naturally present in the earth's crust, but its concentration in the environment is heightened by mining activities and industrial discharges [22]. Chronic exposure to arsenic is linked to skin lesions, cancer, cardiovascular diseases, and diabetes. It is also highly toxic when ingested through contaminated water or food [23].
- ***Chromium (Cr):*** Chromium contamination, notably from metal-related industries and waste, is a concern due to the toxic effects of its hexavalent form (Cr VI). Soil samples in Enugu showed chromium concentrations up to 53.89 mg/kg, with rice grains containing as much as 26.11 mg/kg. Chromium exposure risks include respiratory problems, skin ulcers, and cancer when inhaled or ingested at elevated levels [7].
- ***Zinc (Zn):*** Zinc, although essential for health in trace amounts, can lead to toxicity when accumulated in large quantities [24]. In Enugu, zinc pollution results from fertilizers and industrial emissions, with rice samples showing average concentrations of 65.37 mg/kg, peaking at 229.14 mg/kg. Excessive zinc exposure has been linked to gastrointestinal and immune system issues, presenting health risks to individuals consuming contaminated food over time [7,25].

Table 1 Heavy Metal Concentrations in Enugu and WHO Permissible Limits (modified from Ref [25] with permission)

Heavy Metal	Concentration Range (mg/kg)	WHO Permissible Limit (mg/kg)	Major Sources	Compliance Status
Iron (Fe)	107.8 - 578.7	300	Dumpsites, industrial soils, discarded metal materials	Exceeds in dumpsite and industrial soils
Manganese (Mn)	18.05 - 101.9	20	Dumpsites, industrial soils, mechanic workshops	Exceeds in most samples except control
Arsenic (As)	20.9 - 48.35	40	Agricultural chemicals, industrial waste	Exceeds in animal dungs, dumpsites, and industrial soils
Lead (Pb)	43.8 - 106.6	85	Vehicle exhaust, batteries, industrial waste	Exceeds in dumpsites, industrial, and animal dung soils
Zinc (Zn)	228.9 - 432.2	300	E-waste, agrochemicals, industrial discharge	Exceeds in dumpsite, river bed, and industrial soils
Cadmium (Cd)	0.422 - 2.118	0.8	Phosphate fertilizers, industrial processes	Exceeds in all samples except control
Chromium (Cr)	71.58 - 119.13	100	Paints, batteries, leather tanning waste	Exceeds in several samples
Nickel (Ni)	14.66 - 48.41	35	Mechanic workshops, lubricants, vehicle emissions	Exceeds in mechanic workshop soils
Copper (Cu)	30.17 - 75.34	73	Industrial waste, e-waste, paints	Exceeds only in dumpsite soils

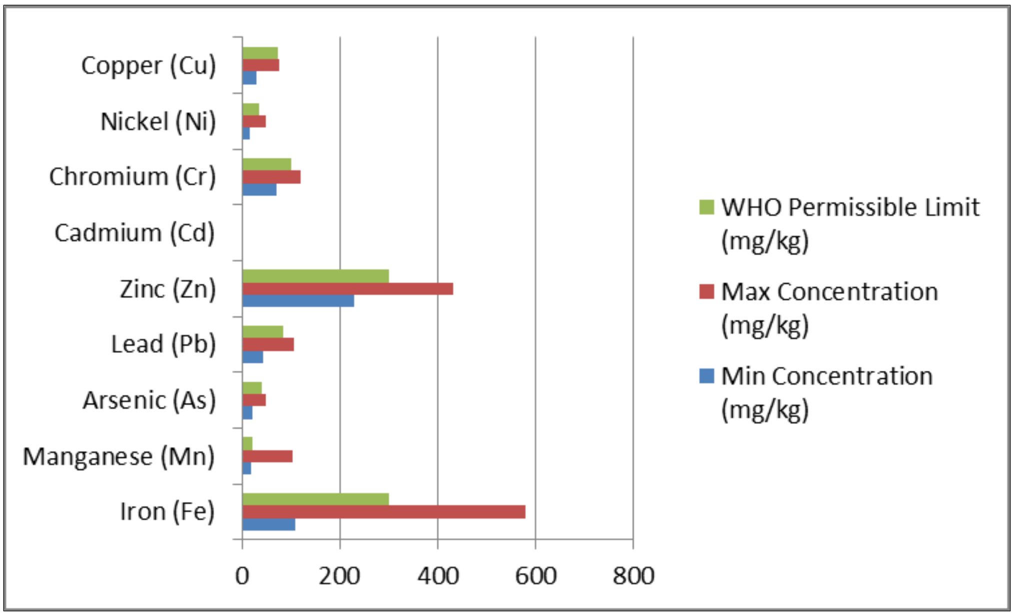

Figure 1 Heavy Metal Concentrations in soils along Awka- Enugu Road, Enugu State [25]

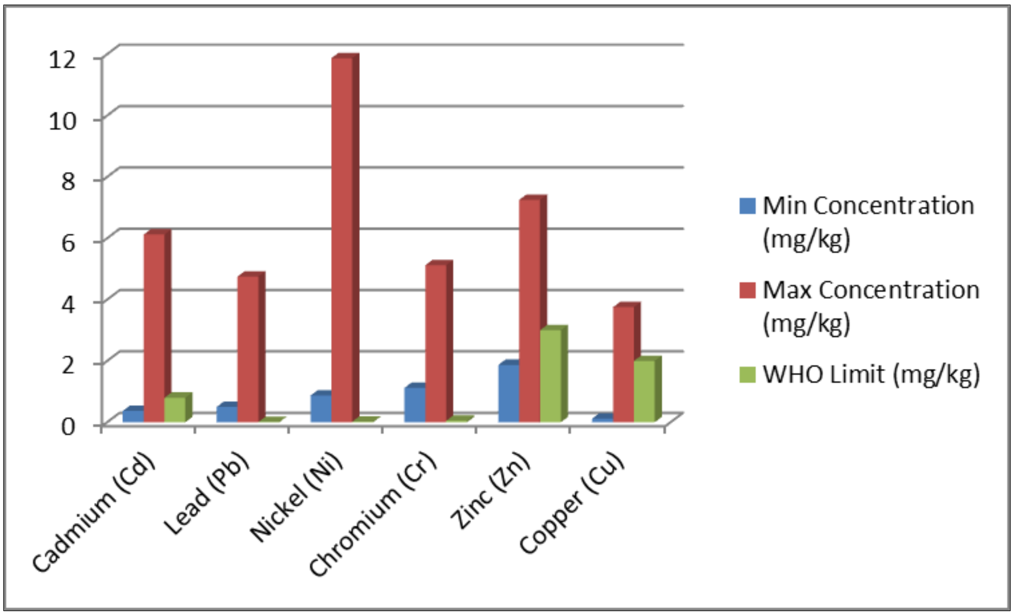

Figure 2 Heavy Metal Concentrations in Ngwo, Nsude, Abor Areas of Enugu State [26]

4. Pathways of Human Exposure to Heavy Metals

Heavy metals enter the human body through various environmental media, presenting varying levels of risk depending on the frequency and intensity of exposure. According to Saif et al. [27], one of the most common routes is ingestion, primarily through contaminated food and water. Crops grown in metal-polluted soils absorb these toxic elements, which then accumulate in their edible parts. Similarly, water sources, whether surface water or groundwater, often carry heavy metals, making them a significant ingestion risk. This issue is particularly pressing in the Enugu area, where widespread water contamination exacerbates the problem, and locally grown agricultural products are commonly consumed, heightening the exposure risk [27,28].

Inhalation also serves as a critical pathway for heavy metal entry into the body, especially in urban areas like Enugu. From the notable studies conducted by Chukwu [29] and Ogbeide et al. [30], it is clear that airborne particles from industrial emissions, vehicle exhaust, and dust from construction sites introduce these metals into the respiratory system. Once inhaled, these particles can lodge in the lungs and enter the bloodstream, causing respiratory and systemic health issues. The concentration of vehicular emissions and industrial activities in urban centers makes this exposure route a significant public health concern [29,30].

Although less frequent, dermal contact with contaminated soil or water represents another avenue for heavy metal absorption. This exposure is particularly relevant to individuals working in agriculture or construction, where direct contact with polluted environments is a daily occurrence. Through prolonged interaction with contaminated soils and water, these workers face risks of heavy metal absorption through the skin [30,31].

Beyond direct exposure, heavy metals also pose significant risks through bioaccumulation and biomagnification in food chains. Aquatic ecosystems, for instance, are often affected when fish accumulate mercury from contaminated water bodies [32]. Humans consuming such fish experience heightened exposure levels due to the magnification of metal concentrations up the food chain. Even low environmental concentrations of heavy metals can lead to severe long-term health risks for top predators, including humans, emphasizing the insidious nature of this form of exposure [32-34].

5. Health Risks Associated with Heavy Metal Exposure

The health effects of heavy metal exposure are both diverse and severe, particularly when exposure is chronic. The risks associated with heavy metals depend on several factors, including the specific metal involved, the level and duration of exposure, and individual factors such as age, health status, and occupation [35,36]. These variables contribute to a wide range of health complications, making heavy metal exposure a significant public health concern [36].

Neurological disorders are among the most concerning outcomes of heavy metal exposure, with lead and mercury being particularly neurotoxic. From the findings of Rehman et al [37], these metals can cause profound damage to the nervous system, with effects that vary across different age groups. In children, exposure can result in developmental delays, reduced IQ, learning disabilities, and behavioral problems, undermining cognitive and emotional development [38]. Adults exposed to these metals over time may experience memory loss, depression, and cognitive decline, highlighting the pervasive and lasting impact of these substances on neurological health [38,39].

Kidney and liver damage also feature prominently among the adverse effects of heavy metals, particularly with cadmium and mercury, which have a propensity to accumulate in these organs [40]. Over time, this accumulation can lead to impaired kidney function, nephropathy, and, in severe cases, kidney failure. Similarly, the liver, as the body's primary detoxifying organ, bears significant harm from prolonged exposure to metals like arsenic. This damage can manifest as liver fibrosis or even cirrhosis, emphasizing the critical role of these organs in mediating the toxic effects of heavy metals [35,39,40].

Reproductive and developmental health is another area profoundly affected by heavy metal exposure [41]. Lead and mercury pose significant risks, particularly to women of childbearing age and pregnant women. Lead exposure during pregnancy is linked to miscarriage, preterm birth, and low birth weight, while mercury exposure can impair fetal brain development, leading to cognitive and motor skill deficits. These effects not only jeopardize maternal health but also have long-term implications for offspring [41-43].

The carcinogenic potential of heavy metals further emphasizes their hazardous nature. Metals such as arsenic, cadmium, and hexavalent chromium are classified as carcinogens, with chronic exposure associated with cancers of the lung, bladder, skin, and kidney. Arsenic, notably, has a strong link to skin cancer and internal cancers when ingested through contaminated drinking water, representing a significant risk for populations exposed to such contamination [36,44,45].

Cardiovascular diseases are another major concern linked to heavy metal exposure, particularly from lead and cadmium. These metals are associated with increased risks of hypertension, atherosclerosis, and other cardiovascular conditions. Their impact on cardiovascular health is mediated through oxidative stress, inflammation, and damage to the endothelial cells lining blood vessels, which disrupt normal cardiovascular function and elevate disease risk [46,47].

Finally, heavy metals can act as endocrine disruptors, interfering with the body’s hormonal balance. According to Balali-Mood et al. [44], cadmium and mercury, for instance, mimic or disrupt hormone function, leading to reproductive health issues, metabolic disorders, and an increased risk of diseases such as diabetes. The disruption of hormonal systems further amplifies the systemic impact of heavy metal exposure, affecting multiple aspects of human health [44,48].

In essence, the effects of heavy metal exposure are extensive, affecting nearly every major organ system. From neurological and reproductive damage to carcinogenic and cardiovascular risks, the consequences highlight the critical need for preventive measures and interventions to reduce exposure and mitigate the associated health burdens.

Table 2 Potential Adverse Health Effects of Heavy Metals Found in Enugu (Adapted from Ref [25])

Heavy Metal	Concentration Range (mg/kg)	Potential Health Effects
Iron (Fe)	107.8 - 578.7	Gastrointestinal distress, liver damage with chronic exposure
Manganese (Mn)	18.05 - 101.9	Neurological effects, behavioral changes, respiratory issues
Arsenic (As)	20.9 - 48.35	Skin lesions, cancer, cardiovascular diseases
Lead (Pb)	43.8 - 106.6	Cognitive impairment, developmental delays in children, kidney damage
Zinc (Zn)	228.9 - 432.2	Gastrointestinal issues, immune dysfunction
Cadmium (Cd)	0.422 - 2.118	Kidney damage, bone degradation, cancer risk
Chromium (Cr)	71.58 - 119.13	Respiratory issues, skin ulcers, potential carcinogen (Cr VI)
Nickel (Ni)	14.66 - 48.41	Respiratory problems, skin allergies, potential carcinogen
Copper (Cu)	30.17 - 75.34	Liver and kidney damage, gastrointestinal irritation

Table 3 Average Heavy Metal Concentrations and Sources in some parts of Enugu (Adapted from Ref [26])

Heavy Metal	Average Concentration (mg/kg)	Potential Health Effects	Major Sources	Vulnerable Locations in Enugu
Cadmium (Cd)	2.18	Kidney damage, osteoporosis, cancer risk	Automobile emissions, roadside dust, mechanic workshops	High levels observed at Obioma, Nsude
Lead (Pb)	2.59	Cognitive impairment, developmental delays, kidney damage	Automobile workshops, road dust, industrial discharge	Notably high at Ngwo, Abor, and areas near workshops
Nickel (Ni)	6.11	Respiratory problems, skin allergies, carcinogenic	Vehicle emissions, roadside dust, industrial discharge	Concentrated in roadside dust in Ngwo, Nsude
Chromium (Cr)	1.99	Respiratory issues, skin ulcers, potential carcinogen (Cr VI)	Roadside dust, industrial activities, road surfaces	Observed in Ngwo and Nsude
Zinc (Zn)	4.41	Gastrointestinal issues, immune dysfunction	Vehicular emissions, e-waste, roadside dust	Abor, areas near roadsides
Copper (Cu)	1.44	Liver and kidney damage, gastrointestinal irritation	Automobile emissions, industrial waste	Within limits, minimal risk across sites

6. Vulnerable Populations

Certain groups within the Enugu population are more vulnerable to the health risks associated with heavy metal pollution due to factors such as age, occupation, and socioeconomic status. Soil analyses from sites around Enugu, including areas like Ogui, Emene, and Ngwo, have revealed heavy metal levels surpassing WHO guidelines, underscoring the heightened health risks, particularly for certain exposed groups [25,26].

- **Children:** Children are particularly vulnerable to the toxic effects of heavy metals, especially lead and manganese. Soil samples collected from dumpsites around Ogui showed lead (Pb) concentrations reaching 106.6 mg/kg in the rainy season, well above the WHO limit of 85 mg/kg. These levels are especially dangerous for children, whose developing bodies and nervous systems are more susceptible to lead poisoning, which can result in irreversible cognitive and developmental issues. Additionally, because children often play outdoors in these areas, they are more likely to ingest or have skin contact with contaminated soil and dust, increasing their risk of exposure through dermal and oral routes [25].
- **Pregnant Women:** Pregnant women in Enugu, particularly those living near sites with high levels of arsenic and lead, are at elevated risk for complications associated with heavy metal exposure. The Emene industrial zone, where arsenic (As) levels in soils near waste dumps reached 48.35 mg/kg, presents a significant risk [25]. This concentration exceeds the WHO limit of 40 mg/kg, and arsenic exposure during pregnancy can lead to miscarriage, stillbirth, and developmental abnormalities in infants. Furthermore, lead levels near the Ngwo mechanic village often surpass safe limits, compounding the risks for pregnant women residing in this area. This underscores the urgent need for intervention to reduce exposure for these vulnerable individuals [25,43].
- **Agricultural Workers:** Farmers and agricultural workers, particularly in the Abakpa and Emene agricultural zones, face high exposure risks due to their regular contact with contaminated soil and water. The study reports cadmium (Cd) levels in Emene's agricultural soils as high as 2.118 mg/kg, surpassing the WHO's permissible limit of 0.8 mg/kg [25]. This heightened cadmium exposure is especially concerning, as cadmium in phosphate-based fertilizers poses significant health risks for these workers, who may experience kidney damage, skeletal issues, and other chronic health effects through inhalation, ingestion, and skin contact. The high levels in these zones highlight the need for safer agricultural practices and protective measures for workers [25,26].
- **Residents near Industrial Sites:** Communities living near Enugu's major industrial hubs, such as the Emene and Ogui industrial areas, are at elevated risk from both airborne and waterborne heavy metal contamination. For example, from the findings of Chibuike et al. [25], manganese (Mn) concentrations in soil in Emene averaged 83.5 mg/kg during the rainy season, which is over four times the WHO limit of 20 mg/kg. Chronic manganese exposure is linked to neurotoxic effects, including memory loss and behavioral changes, particularly in adults. Furthermore, residents in the industrially dense Ngwo region are also at risk due to high levels of chromium and lead in the soil and nearby water bodies, where lack of adequate environmental regulations and waste management exacerbates the contamination. This situation calls for stronger environmental policies and community protection efforts to mitigate exposure for residents in these areas [25].

7. Environmental and Public Health Monitoring

Effective monitoring of heavy metal pollution and its impact on public health is crucial to addressing the growing environmental challenges in Enugu. However, the current efforts face numerous obstacles that limit their effectiveness and impede progress in mitigating the risks associated with heavy metal contamination [13,30].

Environmental monitoring in the Enugu area is sporadic and often lacks the depth and consistency needed to fully understand the scale of heavy metal pollution. While some governmental and non-governmental organizations conduct periodic assessments of water, soil, and air quality, these efforts are frequently limited in scope and frequency. This piecemeal approach fails to provide the comprehensive data necessary to assess pollution trends accurately or to identify contamination hotspots. More systematic and frequent monitoring initiatives are required to address these deficiencies and support targeted interventions [49,50].

In addition to the inadequacies in monitoring, gaps in environmental regulations and their enforcement exacerbate the problem. Although Nigeria has established laws aimed at controlling industrial emissions and waste disposal, enforcement remains weak. Many industries continue to operate without implementing proper pollution control measures, and illegal dumping of hazardous waste is a widespread practice. Strengthening the enforcement of existing laws, coupled with the introduction of stricter penalties for non-compliance, is essential to curbing these practices and reducing the prevalence of heavy metal pollution [51,52].

Moreover, there is a pressing need to enhance surveillance efforts. Comprehensive environmental monitoring programs must be implemented to identify the sources of heavy metal contamination and evaluate the success of mitigation strategies. Equally important is the establishment of robust public health surveillance systems to track the incidence of health conditions linked to heavy metal exposure, such as cancer, kidney disease, and developmental disorders. These measures will not only provide a clearer picture of the pollution problem but also guide evidence-based policy decisions to protect the health and well-being of affected populations [35,53].

8. Mitigation and Remediation Strategies

Mitigating the health risks associated with heavy metal pollution necessitates a coordinated approach that encompasses environmental remediation, public health interventions, and community education [54]. A critical component of this strategy is strengthening waste management and industrial regulations; stricter enforcement of regulations on industrial emissions and waste disposal is essential. Industries must be mandated to treat their effluents prior to discharge and to adopt cleaner production technologies to minimize the release of heavy metals into the environment. Additionally, enhanced waste management systems are needed to prevent the leaching of heavy metals from open dumpsites into soil and water bodies [54,55].

Promoting sustainable agricultural practices is another vital strategy. Reducing the use of chemical fertilizers and pesticides in agriculture can substantially decrease heavy metal contamination in soils and water. Encouraging organic farming methods and less toxic alternatives, along with implementing soil testing and monitoring programs, can help farmers identify and mitigate contamination in their fields [56,57]. Public awareness and education campaigns are crucial for instilling behavioral changes at the community level; these initiatives should focus on educating residents about the dangers of heavy metal pollution, sources of exposure, and protective measures they can take for their families [58]. Furthermore, several technologies are available for the remediation of heavy metal-contaminated environments, including phytoremediation, which utilizes plants to absorb and detoxify heavy metals, and bioremediation techniques that employ microorganisms to treat polluted water and soil. These cost-effective and environmentally friendly methods are well-suited for large-scale application in affected areas such as Enugu [59,60]

9. Conclusion

Heavy metal pollution in the Enugu area underscores the urgent need for a comprehensive, multi-faceted approach to environmental health management. Persistent contamination from industrial, agricultural, and urban sources exacerbates health risks for vulnerable populations, particularly in poorly regulated settings. Effective mitigation will require coordinated efforts between government agencies, industry stakeholders, and local communities, emphasizing stricter enforcement of environmental standards, improved waste management, and adoption of clean technologies. Additionally, educating communities on the health risks associated with heavy metal exposure and promoting sustainable agricultural practices will be crucial in reducing long-term risks. As environmental degradation and health risks continue to rise, addressing heavy metal pollution in Enugu will not only safeguard public health but also support sustainable economic development in the region.

Compliance with ethical standards

Acknowledgement

The authors wish to acknowledge the collaborative effort of all contributing scholars and colleagues who jointly authored and edited this review paper. This work was conducted entirely through the intellectual and academic contributions of the authoring team, without external funding or assistance from any individual, institution, or organization

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Ali, H., Khan, E., & Ilahi, I. (2019). Environmental chemistry and ecotoxicology of hazardous heavy metals: environmental persistence, toxicity, and bioaccumulation. *Journal of chemistry*, *2019*(1), 6730305.

[2] Mishra, S., Bharagava, R. N., More, N., Yadav, A., Zainith, S., Mani, S., & Chowdhary, P. (2019). Heavy metal contamination: an alarming threat to environment and human health. *Environmental biotechnology: For sustainable future*, 103-125.

[3] Nkwunonwo, U. C., Odika, P. O., & Onyia, N. I. (2020). A review of the health implications of heavy metals in food chain in Nigeria. *The Scientific World Journal*, *2020*(1), 6594109.

[4] Mama, C. N., Nnaji, C. C., Nnam, J. P., & Opata, O. C. (2021). Environmental burden of unprocessed solid waste handling in Enugu State, Nigeria. *Environmental Science and Pollution Research*, *28*, 19439-19457.

[5] Nzereogu, S. K., Asekun, F. O., Lawal, T. D., Oladeinde, J. O., Ayoade, A. M., & Udo, D. I. Environmental Health Risks of Coal Mine Leachates in Enugu Metropolis: A Brief.

[6] Ifediegwu, S. I., Ozoko, D. C., & Aganigbo, I. C. (2021). Multivariate statistical and GIS methods for the assessment of heavy metal toxicity in Ekulu River, Southeastern, Nigeria. *International Journal of Energy and Water Resources*, 1-14.

[7] Ihedioha, J. N., Ujam, O. T., Nwuche, C. O., Ekere, N. R., & Chime, C. C. (2016). Assessment of heavy metal contamination of rice grains (Oryza sativa) and soil from Ada field, Enugu, Nigeria: Estimating the human healtrisk. *Human and Ecological Risk Assessment: An International Journal*, *22*(8), 1665-1677.

[8] Ugbede, F. O., Osahon, O. D., Akpolile, A. F., & Oladele, B. B. (2021). Assessment of heavy metals concentrations, soil-to-plant transfer factor and potential health risk in soil and rice samples from Ezillo rice fields in Ebonyi State, Nigeria. *Environmental Nanotechnology, Monitoring & Management*, *16*, 100503.

[9] Omeje, K. O., Ezema, B. O., Okonkwo, F., Onyishi, N. C., Ozioko, J., Rasaq, W. A., ... & Okpala, C. O. R. (2021). Quantification of heavy metals and pesticide residues in widely consumed Nigerian food crops using atomic absorption spectroscopy (AAS) and gas chromatography (GC). *Toxins*, *13*(12), 870.

[10] Apeh, A. C., Apeh, C. C., Ukwuaba, S. I., Agbugba, I. K., & Onyeaka, H. (2024). Exploring data sources and farmers' perceptions regarding agrochemical use and food safety in Nigeria. *JSFA Reports*, *4*(8), 304-315.

[11] Eze, V. C., Maduka, T. O., Iheme, C. I., Chiedozie, A. C., Abugu, H. O., Egbueri, J. C., ... & Abba, S. I. (2024). Polychlorinated biphenyls in soils around a poorly-managed dumpsite in SE Nigeria: contamination status, exposure risks, source identification and pathways for environmental sustainability. *International Journal of Environmental Analytical Chemistry*, 1-27.

[12] Chakraborty, S. C., Qamruzzaman, M., Zaman, M. W. U., Alam, M. M., Hossain, M. D., Pramanik, B. K., ... & Moni, M. A. (2022). Metals in e-waste: Occurrence, fate, impacts and remediation technologies. *Process Safety and Environmental Protection*, *162*, 230-252.

[13] Ogbeide, O., & Henry, B. (2024). Addressing Heavy Metal Pollution in Nigeria: Evaluating Policies, Assessing Impacts, and Enhancing Remediation Strategies. *Journal of Applied Sciences and Environmental Management*, *28*(4), 1007-1051.

[14] Nnaemeka-Okeke, R. C., & Okeke, F. O. (2024). Assessing the influence of seasonal precipitation patterns on groundwater quality in the coal rich environment of Enugu, Nigeria. *Discover Applied Sciences*, *6*(4), 208.

[15] Ezeala, H. I., Okeke, O. C., Amadi, C. C., Irefin, M. O., Okeukwu, E. K., Dikeogu, T. C., & Akoma, C. D. (2023). INDUSTRIAL WASTES: REVIEW OF SOURCES, HAZARDS AND MITIGATION. *Engineering Research journal*, *3*(9), 1-26.

[16] Brindha, K., & Schneider, M. (2019). Impact of urbanization on groundwater quality. *GIS and geostatistical techniques for groundwater science*, *2019*, 179-196.

[17] Raju, N. J. (2022). Arsenic in the geo-environment: A review of sources, geochemical processes, toxicity and removal technologies. *Environmental research*, *203*, 111782.

[18] Zhang, Y., Hou, D., O'Connor, D., Shen, Z., Shi, P., Ok, Y. S., ... & Luo, M. (2019). Lead contamination in Chinese surface soils: Source identification, spatial-temporal distribution and associated health risks. *Critical Reviews in Environmental Science and Technology*, *49*(15), 1386-1423.

[19] Kumar, V., Umesh, M., Shanmugam, M. K., Chakraborty, P., Duhan, L., Gummadi, S. N., ... & Dasarahally Huligowda, L. K. (2023). A retrospection on mercury contamination, bioaccumulation, and toxicity in diverse environments: current insights and future prospects. *Sustainability*, *15*(18), 13292.

[20] Zafar, A., Javed, S., Akram, N., & Naqvi, S. A. R. (2024). Health Risks of Mercury. In *Mercury Toxicity Mitigation: Sustainable Nexus Approach* (pp. 67-92). Cham: Springer Nature Switzerland.

[21] Ezeofor, C. C., Ihedioha, J. N., T. Ujam, O., Ekere, N. R., & Nwuche, C. O. (2019). Human health risk assessment of potential toxic elements in paddy soil and rice (Oryza sativa) from Ugbawka fields, Enugu, Nigeria. *Open Chemistry*, *17*(1), 1050-1060.

[22] Rae, I. D. (2020). Arsenic: its chemistry, its occurrence in the earth and its release into industry and the environment. *ChemTexts*, *6*(4), 25.

[23] Rahaman, M. S., Rahman, M. M., Mise, N., Sikder, M. T., Ichihara, G., Uddin, M. K., ... & Ichihara, S. (2021). Environmental arsenic exposure and its contribution to human diseases, toxicity mechanism and management. *Environmental Pollution*, *289*, 117940.

[24] Kaur, K., Gupta, R., Saraf, S. A., & Saraf, S. K. (2014). Zinc: the metal of life. *Comprehensive Reviews in Food Science and Food Safety*, *13*(4), 358-376.

[25] Chibuike, I. E., Chukwuemeka, O. D., & Chukwudi, E. C. (2019). Heavy metal geochemistry of soils in selected industrial and farmlands of Enugu state: a preliminary investigation. *Sci Res J*, *7*, 15-26

[26] Ezemokwe, D., Ichu, C., Okoro, J., & Opara, A. (2017). Evaluation of heavy metal contamination of soils alongside Awka-Enugu road, southeastern Nigeria. *Asian Journal of Environment & Ecology*, *4*(1), 1-11

[27] Saif, S., Khan, M. S., Zaidi, A., Rizvi, A., & Shahid, M. (2017). Metal toxicity to certain vegetables and bioremediation of metal-polluted soils. *Microbial Strategies for Vegetable Production*, 167-196.

[28] Sandeep, G., Vijayalatha, K. R., & Anitha, T. (2019). Heavy metals and its impact in vegetable crops. *Int J Chem Stud*, *7*(1), 1612-21.

[29] Chukwu, T. M. (2023). *Assessment of air quality in urban settings in Nigeria: a comparison of perceptual indicators, causes and management in Abuja and Enugu* (Doctoral dissertation, University of Surrey).

[30] Egbueri, J. C., Agbasi, J. C., Ezugwu, A. L., Omeka, M. E., Ucheana, I. A., Aralu, C. C., & Abugu, H. O. (2024). Metal (loid) s, nitrate, polycyclic aromatic hydrocarbons, and radioactive contaminants in Nigerian water resources: state-of-the-art of their ecological and health risk assessments. *Environment, Development and Sustainability*, 1-50.

[31] Wang, Z., Luo, P., Zha, X., Xu, C., Kang, S., Zhou, M., ... & Wang, Y. (2022). Overview assessment of risk evaluation and treatment technologies for heavy metal pollution of water and soil. *Journal of Cleaner Production*, *379*, 134043.

[32] Kumar, S., Prasad, S., Yadav, K. K., Shrivastava, M., Gupta, N., Nagar, S., ... & Malav, L. C. (2019). Hazardous heavy metals contamination of vegetables and food chain: Role of sustainable remediation approaches-A review. *Environmental research*, *179*, 108792.

[33] Edo, G. I., Samuel, P. O., Oloni, G. O., Ezekiel, G. O., Ikpekoro, V. O., Obasohan, P., ... & Agbo, J. J. (2024). Environmental persistence, bioaccumulation, and ecotoxicology of heavy metals. *Chemistry and Ecology*, *40*(3), 322-349.

[34] Chapman, P. M., Wang, F., Janssen, C. R., Goulet, R. R., & Kamunde, C. N. (2003). Conducting ecological risk assessments of inorganic metals and metalloids: current status. *Human and ecological risk assessment*, *9*(4), 641-697.

[35] Rehman, K., Fatima, F., Waheed, I., & Akash, M. S. H. (2018). Prevalence of exposure of heavy metals and their impact on health consequences. *Journal of cellular biochemistry*, *119*(1), 157-184.

[36] Anyanwu, B. O., Ezejiofor, A. N., Igweze, Z. N., & Orisakwe, O. E. (2018). Heavy metal mixture exposure and effects in developing nations: an update. *Toxics*, *6*(4), 65.

[37] Rehman, Q., Rehman, K., & Akash, M. S. H. (2021). Heavy metals and neurological disorders: from exposure to preventive interventions. In *Environmental contaminants and neurological disorders* (pp. 69-87). Cham: Springer International Publishing.

[38] Koger, S. M., Schettler, T., & Weiss, B. (2005). Environmental toxicants and developmental disabilities: a challenge for psychologists. *American Psychologist*, *60*(3), 243.

[39] Vielee, S. T., & Wise Jr, J. P. (2023). Among Gerontogens, heavy metals are a class of their own: A review of the evidence for cellular senescence. *Brain Sciences*, *13*(3), 500.

[40] Matović, V., Buha, A., Đukić-Ćosić, D., & Bulat, Z. (2015). Insight into the oxidative stress induced by lead and/or cadmium in blood, liver and kidneys. *Food and Chemical Toxicology*, *78*, 130-140.

[41] Dutta, S., Gorain, B., Choudhury, H., Roychoudhury, S., & Sengupta, P. (2022). Environmental and occupational exposure of metals and female reproductive health. *Environmental Science and Pollution Research*, *29*(41), 62067-62092.

[42] Amadi, C. N., Igweze, Z. N., & Orisakwe, O. E. (2017). Heavy metals in miscarriages and stillbirths in developing nations. *Middle East Fertility Society Journal*, *22*(2), 91-100.

[43] Lei, H. L., Wei, H. J., Ho, H. Y., Liao, K. W., & Chien, L. C. (2015). Relationship between risk factors for infertility in women and lead, cadmium, and arsenic blood levels: a cross-sectional study from Taiwan. *BMC Public Health*, *15*, 1-11.

[44] Balali-Mood, M., Naseri, K., Tahergorabi, Z., Khazdair, M. R., & Sadeghi, M. (2021). Toxic mechanisms of five heavy metals: mercury, lead, chromium, cadmium, and arsenic. *Frontiers in pharmacology*, *12*, 643972.

[45] Cocârţă, D. M., Neamţu, S., & Reşetar Deac, A. M. (2016). Carcinogenic risk evaluation for human health risk assessment from soils contaminated with heavy metals. *International Journal of Environmental Science and Technology*, *13*, 2025-2036.

[46] Alissa, E. M., & Ferns, G. A. (2011). Heavy metal poisoning and cardiovascular disease. *Journal of toxicology*, *2011*(1), 870125.

[47] Yang, A. M., Lo, K., Zheng, T. Z., Yang, J. L., Bai, Y. N., Feng, Y. Q., ... & Liu, S. M. (2020). Environmental heavy metals and cardiovascular diseases: Status and future direction. *Chronic diseases and translational medicine*, *6*(04), 251-259.

[48] Liu, D., Shi, Q., Liu, C., Sun, Q., & Zeng, X. (2023). Effects of endocrine-disrupting heavy metals on human health. *Toxics*, *11*(4), 322.

[49] Omeka, M. E., Ezugwu, A. L., Agbasi, J. C., Egbueri, J. C., Abugu, H. O., Aralu, C. C., & Ucheana, I. A. (2024). A review of the status, challenges, trends, and prospects of groundwater quality assessment in Nigeria: an evidence-based meta-analysis approach. *Environmental Science and Pollution Research*, *31*(15), 22284-22307.

[50] Umeobi, E. C., Azuka, C. V., Ofem, K. I., John, K., Nemeček, K., Jidere, C. M., & Ezeaku, P. I. (2024). Evaluation of potentially toxic elements in soils developed on limestone and lead-zinc mine sites in parts of southeastern Nigeria. *Heliyon*, *10*(7).

[51] Ambituuni, A., Amezaga, J., & Emeseh, E. (2014). Analysis of safety and environmental regulations for downstream petroleum industry operations in Nigeria: Problems and prospects. *Environmental Development*, *9*, 43-60.

[52] Sridhar, M., Oluborode, J. A., & Zacchaeus, U. (2017). Waste management policy and implementation in Nigeria. *International Journal of Advanced Education and Research, 3, 23*, *35*.

[53] Planchart, A., Green, A., Hoyo, C., & Mattingly, C. J. (2018). Heavy metal exposure and metabolic syndrome: evidence from human and model system studies. *Current environmental health reports*, *5*, 110-124.

[54] Chen, S., & Ding, Y. (2023). Tackling heavy metal pollution: evaluating governance models and frameworks. *Sustainability*, *15*(22), 15863.

[55] Selvam, R., Kalaiyarasi, G., & Saritha, B. (2024). Heavy Metal Contamination in Soils: Risks and Remediation. *Soil Fertility and Plant Nutrition*, 141.

[56] Alengebawy, A., Abdelkhalek, S. T., Qureshi, S. R., & Wang, M. Q. (2021). Heavy metals and pesticides toxicity in agricultural soil and plants: Ecological risks and human health implications. *Toxics*, *9*(3), 42.

[57] Lin, H., Wang, Z., Liu, C., & Dong, Y. (2022). Technologies for removing heavy metal from contaminated soils on farmland: A review. *Chemosphere*, *305*, 135457.

[58] Zhou, H., Chen, Y., Liu, Y., Wang, Q., & Liang, Y. (2022). Farmers' adaptation to heavy metal pollution in farmland in mining areas: The effects of farmers' perceptions, knowledge and characteristics. *Journal of Cleaner Production*, *365*, 132678.

[59] Nedjimi, B. (2021). Phytoremediation: a sustainable environmental technology for heavy metals decontamination. *SN Applied Sciences*, *3*(3), 286.

[60] Yaashikaa, P. R., Kumar, P. S., Jeevanantham, S., & Saravanan, R. (2022). A review on bioremediation approach for heavy metal detoxification and accumulation in plants. *Environmental Pollution*, *301*, 119035.