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Combatting toxic chemical elements pollution for Sub-Saharan Africa's ecological health

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ABSTRACT

With its booming mining, processing industries, agriculture, and increasing urbanization, sub-Saharan Africa experiences an alarming rise in accumulation of toxic chemical elements in all environmental matrices threatening entire ecology. Most toxic chemical elements are mercury, lead, cadmium, chromium, and arsenic. These toxic chemical elements are known human carcinogens, systemic toxicants and can induce multiple organ damage. The occurrences of toxic chemical elements in Sub-Saharan Africa are amplified by anthropogenic activities such as mining, industrial discharges, and agricultural practices. This study examined the extent of exposure to toxic chemical elements in surface and underground waters, sediments, soils, effluents, food crops, vegetables, aquatic organisms, industrial products, humans, and other animals in Sub-Saharan Africa. Results indicate occurrences of toxic chemical elements in surface and underground waters, sediments, soils, effluents, food crops, vegetables, aquatic organisms, industrial products, humans, and other animals above the recommended threshold. These findings highlight the persistent pollution of water, soil, sediments, food crops, aquatic organisms, and even industrial products, emphasizing the potential for bioaccumulation and exposure through the food chain. This requires interdisciplinary approaches, including updating and enforcing stricter regulations tailored to regional industrial and agricultural practices. Advanced remediation technologies, such as phytoremediation, and bioremediation, should be prioritized to remove toxic chemical elements from affected environments. Additionally, promoting sustainable practices, such as waste recycling programs, can help reduce anthropogenic contributions, strengthen environmental monitoring systems, nurture community awareness, and essentially encourage regional and international collaboration to protect ecosystems and safeguard human health in Sub-Saharan Africa.

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1. Introduction

Toxic chemical element pollution poses a significant environmental threat, impacting ecosystems and human health. Toxic chemical elements such as lead, mercury, and cadmium are toxic even at low concentrations and can accumulate in living organisms [1,2], causing various health issues, including neurological and developmental disorders. For instance, in industrial regions, fish often show elevated levels of toxic chemical elements, that may impair ecological life. A study by Ngure and Geoffrey reported that levels of Pb, Cd, and Ni in soils exceeded the maximum allowable concentrations (MAC) for agricultural soil [3]. Similarly, levels in fish species like *O. niloticus* were above the MAC levels, and in food items were highest in maize > cabbages > potatoes. Human hair showed elevated levels of Ni above MAC values in some analysed samples [3], indicating pollution from mine tailings potentiates the exposure levels. This bioaccumulation may affect aquatic life and can enter the food chain, impacting ecological balance and human health, and may be leading to unsustainability. Sub-Saharan Africa (SSA), is characterized by diverse cultures, languages, and environments [4,5], with rich ecology (Fig. 1).

Toxic chemical element pollution in SSA is attributed to various human activities detailed in Fig. 2, including agricultural practices such as soil amendments with sewage sludge [6,7], application of manure and mineral fertilizers [8,9], and the use of pesticides and fumigants [10,11]. Natural processes, including weathering [12], soil formation [13], water-rock interaction [14], lithogenic and pedogenic processes [15], as well as chemical mechanisms like oxidation, reduction, hydrolysis, hydration, and chelation [16,17], and mining activities which include ore extraction, processing, and tailing and waste rock management have been reported to contribute to chemical element pollution in the region. Toxic chemical element exposure [18–26], may lead to a range of adverse effects, including adverse effects on human health, ecosystem disruption, pollution of water resources, and through food chain [27,28], requiring intervention. This is due to rapid industrialization, and urbanization, in most cases does not include upgrading of wastewater infrastructure, hence partially treated or untreated effluents containing pollutants are released and expose soils, waters, crops, air [29–31], to toxic chemical elements, evidence is detailed in Tables 1–4.

The increased report of pollution in SSA ecosystems may be attributed by the use of contaminated waters for irrigation, and inefficient waste management systems [32–37]. These pollutants infiltrate ecosystems where they persist, gather, and eventually enter the food chain, posing a serious threat to both human and ecological health [36–41]. Data on toxic chemical element pollution in surface and groundwater, soils, sediments, and effluents, detailed in Table 1, food crops and vegetables detailed in Table 2, aquatic organisms [24,42,43], detailed in Table 3, industrial products, human and other organisms detailed in Table 4. The report of toxic chemical elements in aquatic plants, including algae and seaweeds, are valuable biomarkers for monitoring trace elements and assessing environmental pollution [24,42,43]. Their ability to accumulate toxic chemical elements reflects the varying pollution levels in water and sediments, provides insights into spatial distribution patterns. These plants are particularly effective in detecting temporal changes in pollution levels due to their rapid response to shifts in environmental conditions. Studies have shown variations in metal accumulation capacities for aquatic plant species [44,45], making them sensitive indicators of specific pollutants such as cadmium, lead, and mercury. Their role as primary producers in aquatic ecosystems links their health and metal uptake to broader ecosystem stability, highlighting their importance in biomonitoring programs.

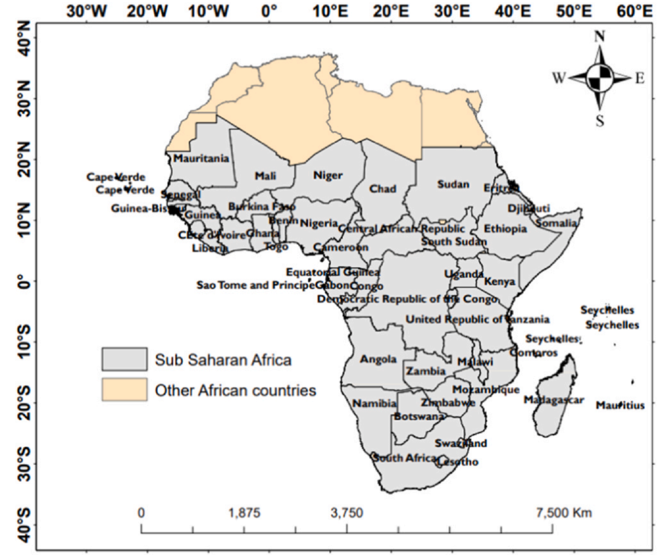

Fig. 1. Presents a map of Sub-Saharan Africa, Base map data Source: OCHA, https://data.humdata.org/dataset/cod-ab-tza. Map created by authors.

Toxic elements like lead, mercury, arsenic, and cadmium are naturally occurring in the lithosphere, primarily as a minor component of lead, and copper ores. Its natural concentrations in the Earth's crust typically range from 0.1 to 0.5 mg/kg [46], with an average crustal abundance of about 0.2 mg/kg [47]. However, higher concentrations can occur in specific geological formations, such as sphalerite as an impurity. Mining activities release them, leading to pollution and exposure, impairing ecological health. This pollution is linked to various health issues, including respiratory and musculoskeletal diseases, particularly due to metals like nickel [48–55], copper linked with Alzheimer's and Parkinson’s diseases [20,56], zinc causing stomach cramps, anemia, and changes in cholesterol levels [57], and manganese linked to a parkinsonian-like syndrome called manganism [58–61]. Lead exposure and poisoning from lead-contaminated soil [62], water, and food [63,64], in mining areas like in Zamfara State, Nigeria has been linked to the release of tailing from gold mining [65], leading to the degradation of ecological health.

Similarly, the Copperbelt region in Zambia has experienced significant lead pollution due to mining and smelting activities [66]. A study by Muimba-Kankolongo et al., (2021), reported that drinking water obtained close to mining had median concentrations (μg/L) of all trace elements, and were substantially higher in DRC (n = 20) than in Zambia (n = 18), this being most pronounced for Pb (27 vs 0.08), and Cd (0.7 vs < 0.015) [67]. Compared to control sites, crops obtained near mining exhibited significantly higher concentrations of Pb in Zambia, and of As, Cd, Pb, and U in DRC. Levels of Cd and Pb exceeded international standards in most DRC crops investigated [67], this may impair ecological health. Other scholars reported toxic chemical element pollution as a result of mining activities [68,69].

Although the ores of the Zambian Copperbelt mining district are mined for Cu and Co, several other trace elements (Pb, As, Cd, Hg, Pb,) gradually accumulated in soils and stream sediments [68]. This is due to ore mining and processing activities that release waste rock tailing and dust generated polluting soils, leading to bioaccumulation in crops [68]. A recent study reported that mean concentrations of Pb, and Cd, were 55.22, and 52.45, mg/kg, respectively [70]. Geoaccumulation indices (Igeo) revealed moderate Pb pollution and extreme pollution with Cd (Igeo: 5.12) [70]. Hazard index (HI) values for all elements were below the non-carcinogenic risk threshold for adults, indicating no significant health risk [70]. However, for children, the HI values for Pb and Cd were 3.37, and 1.25, respectively, suggesting a higher risk [70].

Similarly, the mining activities and widespread use of mercury in small-scale gold mining in Ghana, Cameroon, and Tanzania, may lead to environmental pollution and health risks for miners and nearby communities [71–73]. Cadmium pollution is associated with mining activities, particularly in the Limpopo and Mpumalanga provinces in

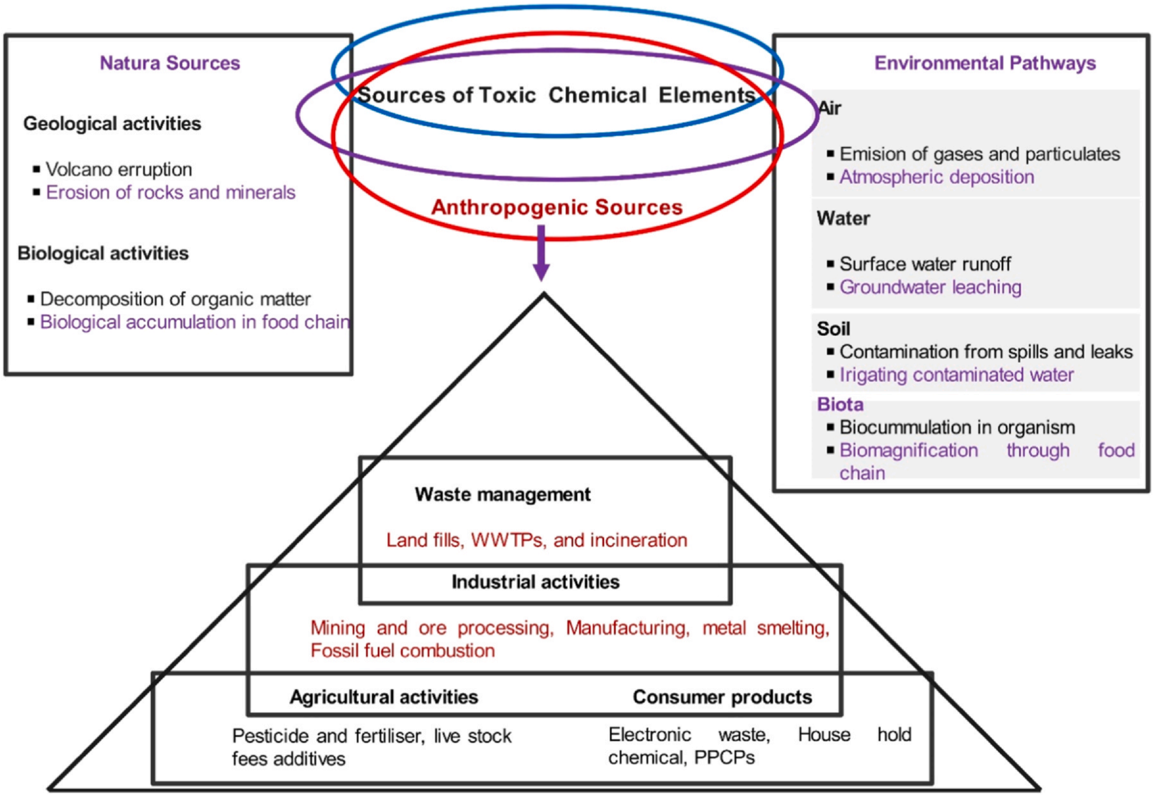

Fig. 2. Brief description of sources of toxic chemical pollution.

South Africa [74], and the Copperbelt region in Zambia [75]. Mining activities and the use of contaminated water sources contributed to arsenic exposure in some areas including South Africa [76], Zimbabwe, and Ghana [71,77].

Environmental challenges including pollution as a result of mining activities has been reported elsewhere [66,74,78]. These elements can have serious health and environmental impacts, including poisoning, cancer, and damage to ecosystems. The vulnerability of these countries is often exacerbated by inadequate regulatory frameworks, limited public awareness, and infrastructure to manage and mitigate pollution. Therefore, this review article aims to highlight the presence of toxic chemical elements in surface, groundwaters, sediments, soils, effluents, food crops, vegetables, aquatic organisms, industrial products, humans, and other animals in sub-Saharan Africa, its sources, fate and ways to combat for ecological health and sustainability of entire ecology.

1.1. Sources, and distribution mapping of toxic chemical elements

In Sub-Saharan Africa, toxic chemical elements [79–84], impact ecological balance, and identifying the pollution sources is essential for developing effective mitigation strategies to promote ecological safety and sustainability. Reports indicate that toxic chemical element pollution in SSA originates from the weathering of rocks and ores in the natural environment [85], tailing from mining and mineral processing activities [82], and waste including effluents and sludge [86]. Previous scholars reported that the weathering of rocks and ores releases toxic chemical elements resulting in pollution [87,88]. Similarly, emissions from industries such as metal smelting, battery manufacturing, and chemical production contribute to toxic chemical elements pollution such as Cr, Cd, Hg, and Pb [89], through emissions of pollutants into the air, soil, waters [90,91], and vegetables and other crops. This may lead to the accumulation of toxic chemical elements especially in areas close to mining or industrial activities and hence pollution. The use of agrochemicals, including fertilizers and pesticides, can introduce toxic chemical elements into the soil and water systems, resulting in groundwater pollution [92]. This may reduce the quality and availability of clean water for ecological uses [93], and hygiene [94,95].

Further, improper application or excessive use of fertilizers and pesticides can lead to metal accumulation, especially in agricultural areas [96], resulting in pollution and related risks to humans and the entire ecology. Similarly, improper waste management aggravates pollution, and waste disposal practices, such as open dumping and uncontrolled incineration, can result in the release of toxic chemical elements from various waste streams [97], including municipal solid waste, electronic waste (e-waste) [98], and industrial waste [79,96,99–101], often contain metals like lead, mercury, and cadmium. The use of contaminated water for drinking, irrigation, production, and livestock rearing can contribute to toxic chemical elements pollution [102,103], and related health effects.

Environmental toxic chemical pollution [90,91,103,160–163], also may be through atmospheric deposition, where emissions from industrial activities and vehicular exhaust can result in the deposition onto soil, water, and vegetation [164,165]. Therefore, understanding the sources of toxic chemical element pollution in SSA is crucial for applying targeted sustainable mitigation techniques such as planting genetically engineered cultivars, remediation by adsorption using adsorbents made from agricultural waste, and phytoremediation, to minimize further pollution. It is possible to address these sources and implement suitable waste management practices, and regulatory measures, to limit the risks brought on by toxic chemical element pollution and protect both human and ecological health.

1.2. Status of toxic chemical element pollution

Toxic chemical element pollution is a significant environmental concern in SSA, posing risks to both human and ecological health. Industrial activities, mining operations, and improper waste management have contributed to the release of toxic chemical elements, and other contaminants of emerging concern in the environment [166–183], resulting in widespread pollution [166–168,180,182,184].

Table 1
Data on toxic chemical elements in surface waters, sediments, soils, underground water, and sewerage effluents in selected SSA countries.

Study	Year	Country	Matrix	Results	Implication	References
Water quality of urban rivers investigated	2023	Tanzania	River waters	Poor water quality for Msimbazi River, the quality fluctuated temporally and spatially	Pollution of River waters	[104]
Investigation of toxic chemical elements in surface waters and sediments from Mara	2021		Surface waters and sediments	Higher concentration during dry seasons with 1.56 of Cd, 0.01 of Pb, 17.45 of Hg, 0.01 of Cr, and 30 of As in sediments all in mg/kg Higher levels of lead (4.37 mg/kg), Hg (0.012 mg/kg), Cd (2.25 mg/kg), and As (53 mg/kg). Surface waters had elevated levels of Cd, Pb, Hg, and As.	Pollution of Mara River	[23]
Toxic chemical elements in water and soil was investigated	2018		Surface waters and soil	The waters and soil around the Msimbazi River are contaminated with copper, chromium, and lead	Toxic chemical elements exceeded permissible limits as per WHO and TBS, and potential exposure to ecosystems	[105]
Toxic chemical elements in soil and waters along Msimbazi River valley were investigated	2010		Surface waters	Lead levels of 0.113 and 0.083 mg/L	Above WHO (2004) drinking water limit of 0.01 mg/L, indicating potential ecosystem injury	[106]
			Soil	The highest concentration of Pb 22.85 mg/kg in soil		[106]
The occurrences of toxic chemical elements in sediments investigated.	2003		Sediments	Results indicate the presence of 0.2 Hg and 30.7 Pb in mg/kg	Pollution of Lake Victoria	[107]
Levels, distribution, and environmental risk of toxic chemical elements was assessed.	2019	Kenya	Topsoil	Investigated areas were contaminated with toxic chemical elements including Pb (0.2 to 12.50), As (not detected to 2.28), Cd (0.01 to 0.23), and Hg (not detected to 0.03 mg/kg)	All of the study sites had high levels of As and Pb, which could be hazardous to the ecosystem as a whole.	[108]
Cd, Ni, and Pb levels in Kilimambogo region borehole water was investigated.	2020		Underground water	The mean toxic chemical element levels were found to be 6.4 for Cd, and 42.0 for Pb in ppm. Pb levels were 0.049, 0.012, and 0.0073 for adults and 0.011, 0.028, and 0.0016 for children	The boreholes are polluted with toxic chemical elements	[109]
Toxic chemical elements in tainted water & soil from open drainage channels were investigated.	2020		Tainted water and soil samples from open drainage channels	Wastewater & soil samples metal concentrations ranged from 160.33 to 544.69 ppm	Potential exposure to ecosystems	[110,111]
Investigation of heavy metal in the soil.	2020		Soil	The concentration of Pb, and Cd in soils exceeded the maximum allowable concentrations (MAC) for agricultural soil	Potential exposure to ecosystems	[3]
The presence of harmful elements in the tissues of common fish was investigated.	2003	Uganda	Detrital sediments, plankton, and fish from sites in Lake George	Results found that the mean concentration of heavy metals in three fish species ranked: Pb (2.56) > As (0.48) > Cd (2.33) > 0.05. Among metals measured Cd, showed the highest level in *O. niloticus.*	Potential exposure ecosystems	[112]
Toxic chemical element loading were investigated.	2006		Water and sediment/soil samples	Industries and mining activities are a great contributor to toxic chemical element pollution	Polluted effluents from industries if released into the environment may potentially harm the entire ecology	[113]
Heavy metal in soils and food crops was investigated.	2022		Soils and food crops	The transfer factor results showed elemental intake by the crops in the sequence; Cd > Pb.	Results indicate that elemental levels in the soil were within the standard recognized by the WHO and the EU	[114]
The status of toxic chemical elements in Shashemane city soils was investigated.	2015	Ethiopia	Soil around the open landfill	The result indicated that the levels of 0.08 for Cd, and 0.08 for Pb	Potential exposure to ecosystems	[115–118]
Toxic chemical element levels in groundwater were investigated.	2021	Nigeria	Groundwater	Presence of toxic chemical elements in mg/L, with 0.459 of Pb, and 0.006 of Cd,	Groundwater is polluted, and potential harm to users presents the ecosystem	[117,118]
Levels of heavy metal in soils were investigated.	2020		Soil	The average of pollution factor was higher for Pb	Potential exposure to humans and other organisms	[119]
Levels of toxic chemical elements in sediment samples were investigated.	2010-		Sediments	Toxic chemical elements in sediment ranged from 0.38 to 6619 ppm in dry season and 0.24 to 8144 ppm in wet season	Sediments were contaminated with toxic chemical elements	[120]

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Table 1 (*continued*)

Study	Year	Country	Matrix	Results	Implication	References
Levels of heavy metals of drinking water sources were investigated.	2022		Drinking water sources (borehole, well, sachet water, harvested rain, and stream water)	The acceptable limits suggested by international authorities were not met for both groups, the CDI indices in the stream, well, sachet, and borehole water samples were Cd > Hg > Pb.	Potential exposure and injury to humans and other organisms	[121]
Levels of heavy metal in paint dust were investigated.	2019		Paint dust	The highest concentrations of Cd (3.58 mg/kg) and (3.36) and higher than levels in workshops A, B, C, E, G, and H.	Potential occupational exposure	[122]
Levels of heavy metal in welding fumes were investigated.	2021		Metal welding fumes	Exposure to metal welding fumes has caused damages that have translated into lesions and several pathologies in the kidney, lungs, liver, and heart tissues of the test animals.	Regulation and control should be imposed on exposure to welding fumes by metal workers.	[123]
Content of heavy metal in paint fumes	2022		Paint fumes	Chronic exposure to paint fumes in automobile artisans may impair renal, and liver function, and induce oxidative stress and toxicity.	The use of protective equipment by artisans will reduce occupational hazards and toxicity due to heavy metal exposure.	[124]
Levels of toxic chemical elements in surface waters were investigated.	2005	South Africa	Surface waters	Presence of Cd ranging from 1.6 to 9.3, Pb from 10.5 to 20.1 $\mu g\,l^{-1}$	Potential exposure to ecosystems through food web	[125]
Levels of toxic chemical elements in surface and ground waters were investigated.	2021		Surface and groundwaters	Chemical elements like Mn, Zn, Cu, Fe, Ni, and Ba, express statistically significant values ($p < 0.05$).	Pollution of surface and groundwater, potential exposure, and harm to ecosystems	[126]
Assessment of toxic chemical elements in sediment, water, and tissues.	2012	Senegal	Sediment, water, and tissues (liver)	Presence of toxic chemical elements	Potential pollution, and exposure through the food chain	[127]
Levels of toxic chemical elements in mine waste and sediments were investigated.	2019	Zambia	Mine waste sediments	Higher levels of toxic chemical elements in mine waste sediments than the forest soil	Mining activities contributes to the toxic chemical element's pollution	[128]
Toxic chemical elements in sediment and tilapia fish were investigated.	2016		Sediments, tilapia fish	Presence of 36.2 mg/kg of Pb at Kafue Town,	Potential exposure through the food chain	[129]
Levels of toxic chemical elements in coal and gangue investigated.	2022		Coal and coal gangue	The mean levels were Cd from 0.38 to 1.11 and Pb from 13.96 to 46.02 mg/kg.	Potential exposure through the food chain	[130]
Levels of toxic chemical elements in soil from abandoned mining areas were investigated.	2001	Togo	Soil samples taken from mining areas	Cd levels from 0.2 to 43 ppm, Pb from 15 to 115 ppm	The mining activities contribute to toxic chemical element pollution	[131]
Levels of toxic chemical elements in aquatics were investigated.	2021		Surface sediments from Mono River Estuary	Presence of 4.67 of Pb $>$ 0.038 of Hg in sediments and 2.42 of Pb $>$ 0.034 of Hg, all in µg/g dw.	Toxic chemical elements pollution of aquatic ecosystems	[132]
Levels of toxic chemical elements in surface water and sediments were investigated.	2011		Surface waters and sediments	The presence of toxic chemical elements in surface sediments ranged from 0.130 to 0.829 mg/kg for As, from 0.016 to 0.121 mg/kg for Cd, and from 3 to7 mg/kg for Pb	Toxic chemical elements pollution of aquatic ecosystems	[132]
Levels of heavy metal in Geophagic clay were investigated.	2016	Ghana	Geophagic clay	The clay samples were found to contain toxic metals such as As and Pb. There were isolated cases of the presence of Hg and all samples had Cd levels below detection.	The levels of heavy metals in geophagic clay consumed were high compared to the Permitted Maximum Tolerable Daily Intake (PMTDI) by (WHO/FAO)	[133]
Levels of toxic chemical elements near-surface soils ~ 0–15 cm was investigated.	2012		Soils from an industrial cluster	The soil contained Pb from 133.7 to 571.3 $mgkg^{-1}$, Cd from 6.9 to 13.2 $mgkg^{-1}$, Hg from 5.5 to 10.4 mg/kg, and As from 2.3 to 18.6 $mgkg^{-1}$	Toxic chemical element contamination	[134]
Levels of toxic chemical elements in the environment were investigated.	2014		Soil and waters	Soil had 95.13 mg/Kg of Pb, and 190.27 mg/L in water; while Mercury was 140.87 ug/Kg in soil and 211.31 mg/L in water.	Toxic chemical elements pollution	[135]
Levels of toxic chemical elements in all environmental compartments of the swamps were investigated.	2010	Rwanda	Water and sediment	The sediment amasses toxic chemical elements with up to 4.2 mg/kg of Cd, and 58.3 mg/kg of Pb, followed by the roots of C. papyrus with up to 4.2 mg/kg of Cd, and 56.1 mg/kg of Pb.	Toxic chemical elements pollution	[99]

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Table 1 (*continued*)

Study	Year	Country	Matrix	Results	Implication	References
Levels of toxic chemical elements pollution in lake water investigated.	2012		Surface water near industrial mines	The mean Cd level of 0.026 mg/L, and Pb level of 0.292 mg/L		[136]
Toxic chemical elements in surface water were investigated.	2020		Surface water	Presence of Pb from 8.81 to 37.44 µg/l, and Cd from 5.01 to 14.01 µg/l		[100]
Assessment of toxic chemical elements in river water	2016	Namibia	Surface water	Presence of 0.047 mg/l of As	Toxic chemical elements pollution	[137]
Toxic chemical elements status of surface soils	2023		Surface soil dusts	Presence of 0.33 mg/kg of Cd	Lower levels than their WHO's maximum permissible levels	[138]
Levels and distribution of toxic chemical elements in shore sediment investigated.	2016		Shore sediments	Toxic chemical elements ranged from 2.1 to 6.1 mg/kg for As, from 0.5 to 3.0 mg/kg for Pb	Toxic chemical elements pollution	[139]
Assessment of toxic chemical elements in environmental samples investigated.	2022	Mozambique	Surface soils, river sediments, surface waters and groundwater	Presence of As ranging from 0.3 to 10.9 µg/L, and Pb from 1.3 to10.8 µg /L	pollution of aquatic ecosystem	[140]
Evaluation of toxic chemical elements contamination in surface water	2022	Democratic Republic of Congo (DRC)	Surface waters	The levels of metals varied depending on the feed concentration. Interestingly, the NF membranes rejected Cd ions by 92.3 %.	Toxic chemical elements pollution	[141]
Investigation of toxic chemical elements in agricultural soil, irrigation water, and vegetables	2023		Agricultural soil, and irrigation water	Presence of 236 Cd in mg/kg	Higher than the WHO thresholds of 100 mg/kg for Cu and 2 mg/kg for Cd), indicating pollution	[142]
Evaluation of accumulation of toxic chemical elements in waters	2012	South Sudan	Water samples from streams in Juba, Central Equatoria state	Levels of Cd ranged from 0.86 mg/l to 1.92 mg/l, and Pb from 0.29 mg/l to 0.95 mg/l	Potential exposure to ecosystems	[143]
Evaluation of ecological risks caused by toxic chemical elements	2020	Malawi	Agricultural soils of the Lake Chilwa catchment	Levels of toxic chemical elements were in the order: Pb $>$ As. Strong correlations amongst detected toxic chemical elements suggest similar sources.		[144]
Assessment of biological, physical, and chemical pollutants in surface waters	2012		Water from the Mudi River	Levels of Pb ranged from 0.21 to 0.93 mg/l, Cd from 0.00 to 0.02 mg/l	Higher levels than the European Commission Standards of 1994 for aquatic life	[145]
Assessment of heavy metal pollution of agricultural soils	2022		Agricultural soil	Results indicated that mean soil As (2.2 mg As kg − 1), Cd (0.044 mg Cd kg − 1), Pb (11 mg Pb kg − 1) concentrations were at least three times lower than the respective guidelines and MAL recommended by WHO, UK CLEA, and CEQS	The values obtained in this study were also within the normally reported metal(loid) for unpolluted agricultural soils	[146]
Assessment of heavy metal pollution of Lake Chilwa Catchment	2019		Surface waters	Detection of Pb (BDL–49.94 µg/L) and Cd (BDL–0.53 µg/L).	Potential exposure to aquatic ecosystem	[147]
Assessment of levels and spatial distribution of toxic chemical elements	2019		Surface waters	Presence of Pb from BDL to 49.94 µg/L and Cd from BDL to 0.53 µg/L	Potential exposure to the ecosystem	[147]
Evaluation of toxic chemical elements concentration in soils	2022	Cameroon	Soils from Pawara gold mines	The presence of 1590 mg/kg of Hg and 12,274 mg/kg of Pb	The high degree of pollution	[148]
Analysis of toxic chemical elements in soil and groundwater	2015		Groundwater and soil samples from the Ntemi watershed in Yaoundé	Presence of Pb ranging from 0.13 to 0.19	Levels of toxic chemical elements were higher than those of WHO limits, which implies pollution	[149]
Evaluation of toxic chemical elements in soils	2013		Soils	The presence of Pb from 8 to 130, in wt%	Pollution to toxic chemical elements, potential exposure, and harm to ecosystems	[150]
Assessment of heavy metal in soils	2023	Botswana	Soils	The results showed that areas (0.1–2 km) nearer to the dumpsite, especially in the leeward direction had a higher pollution factor for 3.10–3.17 for Pb.	Potential for exposure to human and other organisms	[151]
Assessment of toxic chemical elements from street dust	2005	Angola	Street dust	The only distinct anthropogenic fingerprint in the composition of Luanda's street dust is the association Pb–Cd	Exposure to toxic chemical elements	[52]
Assessment of heavy metal levels in sediments	2020	Lesotho	Sediments	The mean levels of As and Pb in sediment were 2.34; and 0.29 mg/kg respectively. The magnitude of As and Pb by location in the reservoir varied spatially	Measures should be taken to minimize the risk of health adverse effects	[152]

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Table 1 (*continued*)

Study	Year	Country	Matrix	Results	Implication	References
Evaluation of the translocation of metals	2012	Gabon	Agricultural soils	Al concentrations ranging from 239 to 1222 mg/kg, Cd less than 0.3 mg/kg, and Pb less than 2.36 mg/kg,	Measures should be taken for ecological safety	[153]
Evaluation of the coastal pollution and potential biomonitors of metals	2006	Mauritanius	Seawater and sediments from the coast	Maximum concentrations of 0.247 mg/l for Pb, and 0.232 mg/l for Cd. Maximum concentrations of Cd, and Pb at low tide along the sewage-affected shoreline	pollution of toxic chemical elements, potential exposure, and harm to ecosystems through the food chain	[154]
Evaluation of harmful chemical element pollution in marine sediments	2022		Marine sediments	Potential pollution because of quantifiable levels of toxic chemical elements	Threats to the aquatic ecosystem.	[155]
Assessment of toxic chemical elements content in Mauritania	2022		Sewage discharges from health structure	4.625 g/L As, 3.800 g/L Pb, 0.05 g/L cyanide, 0.013 g/L and LD- 0.000000012 g/L Pb		[156]
Toxic chemical components in sediment, zooplankton, and epibenthic invertebrates investigated	1993		Sediment,	Presence of 12 to 55 for Pb, and 4 to 10 for Cd.	Marine ecosystems in various climatological zones have lower quantities of harmful chemical components.	[157]
Evaluation of the presence of hazardous chemicals	2019	Burkina-Faso	Irrigated water, soil	Toxic chemical elements in mg·Kg^{-1} ranged from 1.32 to 1.69 Pb	The concentration was higher than the WHO maximum limit permissible (ML) in vegetables	[158]
Assessment of heavy metal in soils	2023		Agricultural soils	Concentrations of Hg, and As, were found to be higher than average continental crust values. In addition, the concentrations of Hg and As exceed South African standards, while Hg also exceeds the standards set by WHO and FAO.	Studied area was highly enriched in mercury	[159]

Detailed reports of toxic chemical element pollution in surface waters, sediments, soils, underground water, sewerages, and effluents in selected SSA countries are presented in Table 1. Details of toxic chemical elements pollution of food crops, and vegetables in selected SSA countries are presented in Table 2. Reports of toxic chemical exposure of aquatic organisms in selected SSA countries are presented in Table 3.

The data on toxic chemical elements in industrial products, and exposure to humans in selected SSA countries are presented in Table 4. These results indicate the potential for occupational, environmental exposure and through food chains, requiring intervention for ecological safety. Similarly, the reported total elemental contents of some trace elements in uncontaminated mineral soils range from 1–100 ug/l and methods used for obtaining these data differ widely and thus it is difficult to determine adequate mean contents of elements in soil matrices, see variations in reported values detailed in Table 1, and for other matrices Tables 2–4. Contents of trace elements in soils from natural as well as from polluted sites often show great variability, the heterogeneity of soils, especially at the microscales, also creates real problems in representative sampling that have serious impacts on the reproducibility and comparability of the analytical data.

1.3. *Anthropogenic loading and fate*

Mining activities is vital for the region's economy [185,186]. But improper mining practices, such as the use of mercury in artisanal gold mining, can lead to the release of toxic substances into water bodies, soil, and even air [39,187,188], creating harm to the entire ecology [39,186–190]. Roy and colleagues, reported higher quantities of chemical elements including Cd, and Pb, than background levels [191]. The levels of chemical elements vary greatly between towns, nations, continents, and eras. The main sources of soil metal content such as Pb and Cd pollution are anthropogenic with ore-like mixtures from mine tailing waste, smelter emissions, fertilizers, and other products manufacturing [191,192].

In the SSA, reports of pollution of surface waters [113,125,132], groundwater [109–111,115–118,193], effluents [156], sediments [120,126–131,194], soils [154,155,195], including agricultural lands [153,196], vegetations [197], aquatic organism [112,198–200], irrigated water [141–143,157,158,201], and other matrices [134–140,202–205], are available. To protect the environment, the United Nations Environmental Program (UNEP) and the United States Environmental Protection Agency (USEPA) have implemented a few laws and regulations. In SSA, toxic chemical element pollution has a wide-ranging impact. Communities living close to polluted sites are more likely to be exposed, especially those engaged in small-scale mining or residing in industrial zones [36,206]. Furthermore, as metals build up in fish and other species, contaminated water bodies can lead to a decline in aquatic biodiversity [39,207–210]. Along with upsetting ecosystems' natural balance, this has an impact on communities that depend on agriculture and fishing for their livelihoods.

2. Toxic chemical elements pollution and ecological health

Toxic chemical element pollution has profound effects on ecosystems [190,208,228,229], disrupting ecological balance, posing threats to biodiversity, ecosystem functioning, and overall environmental health resulting to a non-resilient environment. The SSA environment, with its diverse and delicate ecosystems, is particularly vulnerable to the ecological impacts [230–234]. This is due to detrimental effects on plant and animal species, leading to reduced biodiversity. Some metals such as lead inhibit seed germination, impair plant growth, and disrupt photosynthesis [210], affecting the composition and structure of plant communities. Polluted soils can experience reduced microbial activity, altered nutrient cycling, and decreased plant productivity [235]. In aquatic ecosystems, toxic chemical elements can accumulate in organisms, leading to population declines and alterations in species

Table 2

Data of toxic chemical elements on food crops, and vegetables in selected SSA countries, indicating the potential of exposure through food chains.

Study	Year	Country	Matrix	Results	Implication	References
Trace metal levels in *Spinacia oleracea* planted in dump sites soils were investigated	**2013**	South Africa	Vegetables	The trend in trace metal accumulation from the leaves was in the order Pb > Cd.	Potential for exposure through the food chain	[211]
Evaluation of toxic chemical elements in medicinal plants	2014		Medical plants	*Bulbine natalensis* and *Alepidea amatymbica* demonstrated high levels of As and Hg mg/kg, with	Levels of As and Hg above the WHO permissible limits	[101]
Investigation of heavy metal content in vegetables and fruits	2020		Vegetables and fruits	Heavy metal concentrations in fruits and vegetables ranged from 0.23 to 2.94 mg·kg^{-1} for Cd	The results indicated that Cd concentrations in fruits, and vegetables exceeded the maximum acceptable levels proposed by FAO/WHO	[212]
Assessment of heavy metal in spices	2023		Spices	The following elements were present in quantifiable levels Pb, Cd, and As.	pollution of food crops, Potential exposure to ecosystems through the food web	[28]
Investigation of heavy metal content in cocoyam crops	2020	Tanzania, Kenya, and Uganda	cocoyam crops	The mean heavy metals concentration in cocoyam samples was above the maximum permissible limits of 0.1 mg/kg for Hg, As, and Pb established by FAO/WHO (1995) and EU (2004; 2006).	Unsafe for human consumption.	[213]
Examination of potentially harmful chemical components in green vegetables	1999	Tanzania	Green vegetables	Reported cadmium levels ranging 0.01 to 0.06, copper from 0.25 to1.60, lead from 0.19 to 0.66, and zinc from 1.48 to 4.93 in mg/100 g	Potential exposure through the food web	[214]
Examination of potentially harmful chemicals in plants	2021		Plants	The total HM concentration in plant samples was (in mg/kg) was Cd (4.3–17.46), and Pb (0.01–28.25)		[215]
Examination of potentially harmful chemical components in crops	2023		Food crops	Mercury levels in some crops near the Shenda gold mine exceed safety limits, posing health risks to consumers		[216]
Investigation of pollution of vegetables	2020	Kenya	Vegetables	In spinach, mean concentrations of Pb, exceeded WHO permissible limits, while Cd was within safe levels. In kale, Pb remained within recommended thresholds for human consumption	The presence of Pb in vegetables signifies health hazards through food chain	[217]
Investigation of pollution of crops	2020		Crops	Concentration levels in food items were highest in maize, cabbages, and potatoes, in that order	Potential exposure through the food web	[3]
Investigation of pollution of crops	2023		Crops	Elements that were above allowable limits (mg/kg) in the crops were Cd (1.7 - 4.49), and Cd (1.76 = 5.27) in Kales and Cd (1.17 −3.51), in tomatoes.		[218]
Assessment of heavy metal in soils and food crops	2022		food crops	The transfer factor results showed elemental intake by the crops in the sequence; Cd > Pb. Organization (WHO) and European Union (EU).	Potential, exposure through the food chain	[114]
Investigation of the levels of toxic chemical elements in cultivated vegetables	2023	Ethiopia	Vegetable crops	Vegetables contaminated with toxic chemical components with 17.76 mg/kg of Pb, and 0.25 mg/kg of Cd.		[219]
Assessment of horticultural crops	2023		Horticultural crops	Presence of Pb (BDL–17.00) in vegetables	Pb levels in all vegetables surpassed the maximum allowable limits set by the joint FAO/WHO committee	[220]
Investigation of toxic chemical elements in groundwater	2021	Nigeria	Groundwater	The presence of toxic chemical elements in mg/L, with 0.459 of Pb, and 0.006 of Cd	Groundwater is polluted	[117,118]
Investigation of heavy metal pollution in vegetables	2022	Senegal	Vegetables	Vegetables had high levels of Pb in many of the studied foodstuffs. The levels measured reached up to and 3.4 mg/kg for Pb.	Levels of heavy metal exceeding the threshold values set by the FAO/WHO	[221]
Assessment of heavy metal in food crops	2021	Ghana	Food crops	Unprocessed samples contained higher Pb and As levels than those from Obuasi, exceeding WHO permissible limits.	Potential for exposure through the food chain	[222]
Assessment of toxic chemical elements in water, and vegetables	2018	Mozambique	vegetables	Iron exceeded the recommended guidelines in water samples	Toxic chemical elements pollution	[205]
Investigation of toxic chemical elements	2023	DRC	Vegetables, agricultural soil, irrigation water	Presence of 236 Cd in mg/kg	Higher than the WHO thresholds of 2 mg/kg for Cd, indicating pollution	[142]

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Table 2 (*continued*)

Study	Year	Country	Matrix	Results	Implication	References
Evaluation of accumulation of toxic chemical elements in waters	2012	South Sudan	Surface water	Levels of Cd ranged from 0.86 mg/l to 1.92 mg/l, and Pb from 0.29 mg/l to 0.95 mg/l	Potential exposure to ecosystems	[143]
Assessment of toxic metal(loids in medicinal herbs	2023	Malawi	Medicinal herbs	Results showed significant variation in metal(loid) concentrations among medicinal herbs. Azadirachta indica had the highest mean As and Cd levels	The mean concentrations of As, Cd, and Pb below the MCL set by the WHO	[223]
Evaluation of accumulation of toxic chemical elements in plants	2021	Cameroon	Plants growing in fly ash dump site	Accumulation of Pb in plants	Potential pollution	[51]
Evaluation of the translocation of metals	2012	Gabon	Roots and leafy vegetables	Cd less than 0.3 mg/kg, Pb less than 2.36 mg/kg,	Measures should be taken for ecological safety	[153]
Evaluation of the presence of hazardous chemicals in the varieties of lettuce	2019	Burkina-Faso	Lettuce varieties, wastewater, soils	Toxic chemical elements are present at higher concentrations in soil than in wastewater and vegetables. Soil had 1.32–1.69 mg/kg for Pb	The concentration was higher than the WHO maximum limit permissible (ML) in vegetables	[158]
Assessment of heavy metal in vegetation	2019		Vegetables	Heavy metal concentrations in vegetables ranged from 0.0098–2.66 mg/kg for Hg, 0.01–1.146 mg/kg for Pb, 0.016–1.72 mg/kg for Cd, and 0.012–1.885 mg/kg for As. The relative abundance followed the sequence: Cd $>$ Pb $>$ As $>$ Hg.	Levels exceeded the lawful maximum concentration (CMR) limits set in France	[224]
Assessment of heavy metal in vegetation	2023	Botswana	vegetations	The main contaminant was As	Proper management of the site is recommended	[225]
Assessment of heavy metal in vegetation	2021	Uganda	Vegetables	Those of non-essential metals were significantly higher and followed the pattern Cd $>$ Pb	Higher levels may lead to exposure through the food chain	[226]
	2022		Food crops	The transfer factor was higher in: Cd $>$ Pb	Below the daily threshold values endorsed by WHO/FAO.	[227]

distribution [209]. The persistence of toxic chemical elements in soil can lead to long-term pollution and hinder ecological restoration efforts. Reports indicate that lead, mercury, and arsenic are neurotoxic and can impair neurological development, especially in children leading to cognitive deficits, decreased IQ, learning disabilities, and behavioral disorders [233,236,237]. Similarly, metals like cadmium and lead, when inhaled, can damage the lungs and compromise respiratory function [238]. Further the inhalation of airborne toxic chemical elements particles or gases can cause respiratory problems such as asthma, bronchitis, and other respiratory infections [238].

Cabral *et al.* reported glomerular dysfunction in exposed subjects, and supported evidence of necrosis of proximal and distal tubule epithelial cells as specific biomarkers in the urine for renal dysfunction and damages [239]. These metals can cross the placenta and disrupt normal growth, potentially leading to birth defects, developmental delays, and lifelong disabilities [240]. Toxic chemical elements, including arsenic, cadmium, and chromium, have carcinogenic properties and are associated with increased cancer risks, requiring intervention to ensure ecological health. These elements are linked to cardiovascular diseases [241,242], and metals like mercury and lead can particularly affect the gastrointestinal system [238], indicating the need for proper management of these toxic chemical elements to ensure ecological health.

In most cases, environmental exposure involves multiple toxic chemical elements, rather than individual toxicants. Shezi and Coallegues reported toxic chemical elements pollution along Kuils River, where soil sample was found with quantifiable amounts of As 16 mg/kg, Pb 30 mg/kg [260], with health index (HI) for non-carcinogenicity showing oral route is the main contributor [260], with the accumulative risk of carcinogenicity exceeding the maximum acceptable level of 0.01 mg/L, according to USEPA. A similar study from Lake Victoria, Uganda by Baguma and Coallegues reported the presence of Pb from 40 to 44 mg/kg, and Cd from 3 to 3.5 mg/kg [261], indicating potential for pollution. This may lead to the biomagnification of these toxic elements to the next trophic level [262], indicating potential dangers through the food chain. Further studies indicate elevated levels of Pb in blood samples [263–265], and these results potential for occupational and environmental exposure, to Pb in particular.

A study by Kapatwa et al. [76], reported statistically significant differences in the distribution of arsenic in water, soil, and blood among investigated sites [76]. The median drinking water arsenic levels in the high-exposure village were 1.75 µg/L (range = 0.02 to 81.30 µg/L), 0.45 µg/L (range = 0.100 to 6.00 µg/L) in the medium- / low-exposure village and 0.15 µg/L (range = < limit of detection (LOD) to 29.30 µg/L) in the control site [76]. The median soil arsenic levels in the high-exposure village were 23.91 mg/kg, the median blood arsenic concentration was 1.6 µg/L (range = 0.7 to 4.2 µg/L); 0.90 µg/L (range = < LOD to 2.5 µg/L) in the medium-/low-exposure village and 0.6 µg/L (range = < LOD to 3.3 µg/L) in the control village [76]. Most of the investigated samples of drinking water, soil, and blood samples from the exposed sites were above the internationally recommended guidelines (namely, 10 µg/L, 20 mg/kg, and 1 µg/L, respectively) [76]. In this area majority of participants (86%) relied on borehole water for drinking and there was a significant positive correlation between arsenic in blood and borehole water (p-value = 0.031) [76], this indicate potential for exposure through contaminated water. Children with immature immune systems and pregnant women who experience changes in physiological response that increase their sensitivity to specific adverse reactions are vulnerable populations [266], measures are required to ensure ecological health and safety. Among the well-known case of toxic chemical elements pollution in SSA is lead poisoning crisis in Nigeria [63,267,268]. The case of 2010 involved, death of over 400 children, and thousands were affected due to lead pollution in Zamfara state resulting from gold mining activities, the incident highlighted the devastating impact of toxic chemical elements and the need for proper management to ensure ecological health and safety.

Report of Pb poisoning to crocodiles was recorded by Humphries and Coallegues, with blood Pb values ranging from 86 to 13,100 ng/mL

Table 3
Data on toxic chemical elements pollution of aquatic organisms in selected SSA countries.

Study	Year	Country	Matrix	Results	Implication	References
Investigation of toxic chemical elements in tissues of selected limpet and algae species	**2021**	South Africa	Tissues of selected limpet and algae species	Limpets from Silaka had the highest heavy metal levels, with elevated Hg levels. Cd showed biomagnification (TTF $>$ 1) across all species and sites.	Levels above the maximum limits set by the South African Department of Health.	[243]
Investigation of toxic chemical elements in fish	2020		Fish	Presence of Cd (0.1 mg/kg), and Pb (0.2 mg/kg),	Below the maximum limits for edible fish recommended by FAO and WHO	[244]
Investigation of heavy metals in selected aquatic species	2022		Aquatic species	Heavy metal levels were species-specific Hg, As, Pb were higher in *C. capensis*. The lower shore species *S. longicosta* and *S. cochlear* were notable accumulators of Cd.	Potential for exposure through the food chain	[245]
Levels of toxic metals in fishes investigated.	2020	Togo	Fishes (Oreochromis noliticus and Clarias anguillaris)	Toxic metals in the rivers decreased in the order of Hg $>$ Pb $>$ Cd $>$ As. For the fish samples, values ranged from 0 −0.08, 0.04 −0.42, 0 −0.04, and 0.40-0.60 mg/kg for Cadmium, Lead, Arsenic and Mercury respectively. Toxic metals concentrations in the rivers decreased in the order of Hg $>$ Pb $>$ Cd $>$ As.	Potential exposure through the food chain	[246]
Assessment of heavy metals in three dominant fish species	2021		Dominant fish species	Levels of Hg in fish species from the river exceed recommended limits for human consumption.	The measure must be taken to prevent toxic chemical elements pollution of aquatic ecosystems	[247]
Assessment of toxic chemical elements in fish	2023		Muscles of *Sardinella maderensis*, *Dentex angolensis*, *Sphyraena* and *Penaeus notialis*	Results indicate that *Penaeus notialis* had the highest concentrations of As: 8.46 µg/g, and Cd: 0.03 µg/g except Hg. Mercury was relatively high in D. angolensis 0.14 µg/g	Potential exposure through the food chain	[248]
Assessment of toxic chemical elements in the molluscs	2006	Senegal	African bivalve molluscs, living in the sand*:*	Cadmium levels of 6.82 and 13.77 µg Cd/g than *D. isocardia with* 3.88 µg/g and *P. perna with* 2.37 µg/g	Potential exposure ecosystems	[199]
Assessment of the presence of toxic chemical elements in molluscs	2006		Molluscs collected from the Senegal coast	Cadmium levels of 6.82 and 13.77 µg Cd/g than D. isocardia: 3.88 µg/g and P. perna 2.37 µg/g.		[200]
Investigation of toxic chemical elements in the edible fish	2017		Fish and seafood from the Senegal coast	Cd levels of 0.394 mg kg − 1, and Pb 0.185 mg kg − 1		[198]
Assessment of heavy metal levels in sediments and *Cyprinus carpio* from Maqalika Reservoir	2020	Lesotho	Sediments and *Cyprinus carpio* from Maqalika Reservoir	Mean levels of As and Pb in sediment were 2.34, and 0.29 mg/kg, respectively, while in the gills of *Cyprinus carpio*, were 1.29, and 0.33 mg/kg. Spatially, the levels of As and Pb followed the order: downstream $>$ midstream $>$ upstream in both sediment and fish gills.	Measures should be taken to reduce heavy metal levels in sediment and *Cyprinus carpio* exposure in the general population to minimize adverse effects	[152]
Assessment of toxic metals in selected marine organisms	2024	Gabon	Marine organisms	The *Oyster Crassostrea* gasar was the most contaminated	Measures should be taken for ecological safety	[249]
Oceanic tropical fish species' hematological and gill histopathological parameters evaluated	2007		Tropical marine fish species	High levels of mercury content in seawater 6.4 µg/L, traces of iron (0 µg/L	Threats to aquatic ecosystem	[250]
Evaluation of toxic chemical elements in edible Oysters	2014		Oysters from the coastal zones	Results indicate a low level of Pb	Threats to aquatic ecosystem	[195]
Toxic chemical components investigation in sediment, zooplankton, and epibenthic invertebrates	1993		Sediment, zooplankton, and epibenthic invertebrates	On a dry weight basis, there are relatively high concentrations of harmful chemical elements, ranging from 15 to 90 for Cu, 70 to 580 for Zn, 12 to 55 for Pb, and 4 to 10 for Cd.	Marine ecosystems in various climatological zones have lower quantities of harmful chemical components.	[157]
			Surface sediments, epibenthic invertebrate species	Low levels of Cd were found in the bivalve mollusc *Pitaria tumens*, and in shrimp, ranging from 0.10 to 0.12 g g1.		

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Table 3 (*continued*)

Study	Year	Country	Matrix	Results	Implication	References
Assessment of toxic chemical elements in fish	2020	Kenya	*Fish*	Concentration levels in fish were above MAC levels	Potential exposure through the food chain	[3]
Investigation of heavy metal exposure in aquatics	2020		*Aquatic organisms*	The invertebrates accumulated Cd and Pb.	Potential exposure through the food chain.	[251]
Investigated levels of toxic chemical elements in sediment and tilapia	2016	Zambia	Sediment and tilapia fish from the Kafue River	High metal concentrations were recorded, including Pb (36.2 mg/kg)	Potential exposure through the food chain	[129]
Heavy metal accumulation in fish species were investigated.	2021	Ethiopia	Fish species (*Clarias gariepinus* and *Sarotherodon melanotheron*)	Only the EDI for arsenic in the gills of *C. gariepinus* obtained from the Ogun River exceeded the set limit.		[252]
Assessment of toxic chemical elements in aquatics	2020	Mozambique	Tilapia (*Oreochromis mossambicus* Peters).	Fish were exposed to 3 sub-lethal concentrations of $CdCl_2$: 7.4 μg/L (high), 3.7 μg/L (medium) and 1.85 μg/L (low)	pollution of aquatic ecosystems, and through the food web	[204]
Investigation of toxic chemical elements in fish	2021	Nigeria	Fish	The presence of Cd, and Pb in all fish species	May pose a danger to consumers of food and water	[253]
Investigation of toxic chemical elements in fish	2021		Fish	Heavy metal concentrations in the fish organs are within the permissible limits implying no pollution.	Measures are required to maintain the status of this ecosystem	[254]
Investigation of toxic chemical elements in fish	2022		Fish	fish samples analyzed had Cd and Pb greater than the WHO and Standard Organization of Nigeria (SON) standard permissible limits	Potential for exposure through the food chain	[255]
Investigation of metals and metalloids	2023	Burkina-Faso	Fish	Fish from the pit lakes contained higher amounts of metals and metalloids than fish from the river.		[256]
Investigation of heavy metal in fish	2024	Benin	Fish	*Brycinus macrolepidotus* and *Chrysichthys nigrodigitatus* were the most abundant fish species caught in the Mono River., with cadmium levels below the permissible levels.	Cadmium levels in the fish flesh were below the WHO/FAO standard (0.05 mg·kg − 1), and lead concentrations exceeded the WHO/FAO standard (0.3 mg·kg − 1).	[257]
Investigation of heavy metal in fish	2022	Zambia	Fish	All metals were found to be below the maximum limits (MLs) set by WHO/EU.	Safe for consumption	[258]
Investigation of heavy metal in fish	2019	Democratic Republic of Congo	Fish	The maximum metal concentration of Pb with 4.96 mg kg − 1 wet weight, in muscle tissues	Pb and Hg values in fish samples exceeded FAO AND WHO the permissible levels	[259]

Table 4
Data on toxic chemical elements in industrial products, humans (Hair, urine, and blood), and other animals in selected SSA countries.

Study	Year	Country	Matrix	Results	Implication	References
The presence of toxic chemical elements in human hair was investigated.	2020	Kenya	Human hair	Presence of toxic chemical elements in human hair and consumer products.	Pollution from Migori gold mining contributes to an increased body burden of potentially harmful elements	[3]
The presence of toxic chemical elements in blood was investigated.	2022		Blood	Median blood concentrations were 1.82 µg/dL for Pb, 0.24 µg/L for Cd, and 0.16 µg/L for Hg.	Mercury levels were inversely related to anemia	[269]
Investigation of toxic chemical elements in urine	2021		Urine	Presence of quantifiable levels of As, Cd, and Pb in urine.	Urinary concentrations at a population level inferred excess intake	[270]
Investigation of heavy metal content in personal care products	2016	Nigeria	Personal care products	There were high concentrations of Cd, and Pb in some of the samples	Potential exposure to users	[271]
Investigation of heavy metal in soft drinks	2015		Soft drinks	Presence pf Pb ranging from 0.17 to 3.39 mg/L with a mean of 0.8, Hg ranging from 0.29 to 11.32 mg/L with a mean of 2.08 mg/L while cadmium was present only in one sample (0.149 mg/L).	EPA, WHO, and NIS standards, the levels of the heavy metal were above the tolerated limits for good quality drinking water	[272]
Heavy metals from the consumption of locally manufactured painkiller drugs in Nigeria	2020		Painkiller drugs	Some painkiller drugs had Pb ranging from 1.11 mg/kg to 2.47 mg/kg,	Continuous consumption of these painkiller drugs may expose the subjects to heavy metal toxicity.	[273]
Assessment of heavy metal content in Paint fumes	2022		Paint fumes	Chronic exposure to paint fumes in automobile artisans may impair renal, and liver function, and induce oxidative stress and toxicity.	The use of protective equipment by artisans will reduce occupational hazard	[124]
Assessment of toxic chemical elements in cosmetics	2016		Hair care products, soap	Presence of toxic chemical elements	Potential exposure	[274,275]
Assessment of heavy metal pollution of breast Milk	2023		Milk of lactating mothers	Presence of Pb, Cd and Hg in some breast milk.	Monitoring of levels of toxic elements in expectant mothers is required.	[276]
Investigation of heavy metal exposure in African giant rats	2017		African giant rats	Pb was prevalent in woodland/tall grass savanna agroecological zones.	Potential for environmental exposure	[277]
Levels of toxic chemical elements in urine sample abnormalities were examined.	2019		Urine from patients (tissue samples (kidney, liver, and lung)	The study revealed that urine samples (male and female) contained elevated levels of Cd (0.052–0.093 µg/mL), Pb (0.150–0.376 µg/mL), compared to control samples and WHO-recommended standard levels for human urine.	The high concentrations of heavy metals obtained confirmed the associated health complications noticed in the patients	[278]
Assessment of toxic chemical elements in blood from children	2019		Blood from children	Mean concentrations in blood were Pb was 4.516 mgl − 1; Cd 1.03 mgl − 1. In urine; Pb 1.912 mgl − 1; Cd 0.39 mgl − 1 were generally lower than concentrations in blood.	Maximum metal concentrations in blood were higher than values for the USA Academy of pediatrics.	[279]
Assessment of toxic chemical elements in blood workers	2020		Blood from battery manufacturing factory workers	Elevated levels of As, and Pb were observed in the blood of the factory workers compared with control ($p < 0.05$).	This indicates major source is occupational exposure.	[280]
Assessment of toxic chemical elements in human	2014		Blood and urine	The concentrations of the metals in blood samples were significantly higher in male subjects compared to female subjects.	This indicates exposure to these toxic chemical element measures are required to ensure good health and wellbeing	[281]
Toxic chemical element exposure is investigated, then covered in a review	2017		Blood	Women with a history of miscarriage showed elevated blood levels of heavy metals during pregnancy, which significantly increased miscarriage rates. Lead levels above 25 µg/dL were linked to a 41.61 % increase, cadmium levels of 85.96 µg/dL to an 83.93 % increase, and mercury exposure to a 9.50 % increase in miscarriage incidence.	The need for mitigation strategies for toxic chemical elements is evident, to ensure ecological safety.	[282]
	2017	Egypt	Blood	Similarly, in Egypt a notable increase in miscarriage rates linked to Cd (1.17 %) and Pb (32.33 %) exposure		
Internal exposure to heavy metals in the general population was investigated	2023	DRC	Blood and urine of the adult population living in Kinshasa	Results indicate that in blood, the proposed RIs [P5-P95 (GM)] were 0.089–2.365 µg/L (0.262), 41.41–199.20 µg/L (84.43), and 0.100–1.964 µg/L (0.450) for Cd, Pb, and Hg respectively.	The measure is required to mitigate the effects of toxic chemical element pollution	[283]
						[283]

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Table 4 (*continued*)

Study	Year	Country	Matrix	Results	Implication	References
				Urinary levels [(P5-P95 (GM)] were 0.142–1.430 µg/L (0.458) for Cd, 1.910–17.840 µg/L (5.424) for Pb, and 0.349–2.295 µg/L (0.816) for Hg		
Assessment of toxic chemical elements in children	2018	Uganda	Blood	High blood levels were elevated for Cd (17 %), Pb (97 %). Cd levels were higher among children who attended school ($p < 0.01$	This indicates exposure to these toxic chemical element measures are required to ensure good health and wellbeing	[284]
Assessment of toxic chemical elements in children	2023		Bood	Toxic chemical element exposure to children	Exposure to toxic chemical elements measures are required to ensure good health and wellbeing	[285]
Assessment of toxic chemical elements in children	2018	Tanzania	Urine	Heavy metal concentrations in urine samples varied, ranging from non-detectable (ND) to 1.92 mg/L for Pb.	The pollution levels were generally high in samples from both areas indicating exposure from various sources	[286]
Assessment of toxic chemical elements in human	2024		Blood	In both people living with HIV (PLWH) and HIV-uninfected adults, blood levels of total Cd (T-Cd), total Pb (T-Pb), and total Hg(T-Hg) were often above the reference values of 5, 50, and 20 µg/L, respectively.	Contributing factors to these elevated levels include water sources, obesity, alcohol use, exposure to indoor smoke, and HIV infection.	[287]
Assessment of toxic chemical elements in cow milk	2023	Tanzania	Cow milk	The results revealed that cow's milk is contaminated with toxic metals, particularly Pb which exceeded the WHO maximum permissible level of 0.02 mg/L.	Potential for exposure through the food chain	[288]
Assessment of toxic chemical elements among pregnant women	2019		Blood and urine	Among pregnant women from ASGM areas, 25 % had urinary T-As and 75 % had blood T-Hg above the established human biomonitoring reference values of 15 and 0.80 µg/L.	Arsenic and mercury concentrations among women in non-ASGM areas suggest exposure sources beyond ASGM activities	[289]
Assessment of toxic chemical elements in human	2024		Blood	Geophagy was prevalent in 36.2 % of the population (95 % CI: 33.6, 39.4 %), and 6.3 % worked in mining as their primary occupation. Practicing geophagy was associated with a 22 % increase in blood Pb levels (BLLs) ($\beta = 1.22$, 95 % CI: 1.116, 1.309, $p < 0.0001$). Living in a gold mining area raised BLLs by 33.4 % ($\beta = 1.334$, 95 % CI: 1.2, 1.483, $p < 0.0001$).	This indicates exposure, therefore developing a comprehensive inventory capturing sources of community-level lead exposure is essential	[290]
Assessment of heavy metal exposure to human	2020	Zambia	Hair, nail	The levels of potentially harmful elements varied across age groups. Pb, and Cd, exceeded normal reference ranges	Potential exposure through the food chain	[291]
Blood and urine of pregnant women practicing geophagia was investigated	2016	South Africa	Blood and urine of pregnant women	The study revealed that soil eaters had lower hemoglobin levels (10.7 g/dL) compared to non-consumers. Their blood contained Pb (2.90 µg/L) . Urine analysis showed elevated levels of Pb (8.88 µg/g creatinine), As (17.66 µg/g creatinine), and Hg (2.40 µg/g creatinine).	These trace metal levels exceeded the recommended limits by the WHO	[292]
Toxic chemical elements in blood from petrol station forecourt attendants	2024		Blood	The highest Pb concentration (60.2 µg/L) was observed in a forecourt attendant who had worked 11–20 years, and the average Pb concentration in this group (24.5 µg/L) was significantly ($p < 0.05$) higher than in forecourt attendants who had worked 2–5 years (10.4 µg/L).	Potential for toxic effects and harm	[293]
Assessment of toxic chemical elements in the blood of workers	2020		Blood of occupationally exposed casual mine workers	The mean blood levels for occupationally exposed mine workers ranged between 0.5 and 6.49 µg/dL for Pb, As 0.33 – 2.19 µg/L, and Cd 0.05 – 1.87 g/L.	The levels in some participants exceeded the permissible limits set by WHO in human blood.	[294]
Kidney injury molecule 1 (KIM − 1), and toxic chemical elements were evaluated in residents'	2023	Ethiopia	Urine and nail	Most analyzed elements, excluding Pb, As, and Cd, were present in all nail samples,	Hence, the observed KIM − 1 might be related to exposure to toxic substances or factors other than those included in this study.	[295]
Heavy metals in nails were investigated	2022		Nails	The mean concentrations (µg/g) of the elements were 0.09 and 0.63 for Pb; and 0.16 and 0.25 for As, in nail samples from Akaki-Kality and Gullele, respectively.	Hence, the observed 8-OHdG might have been caused by environmental exposure to toxic substances	[296]

(*continued on next page*)

Table 4 (*continued*)

Study	Year	Country	Matrix	Results	Implication	References
Heavy metals in hair were investigated	2020		Human hair	The highest average levels of Pb (3.1 mg kg − 1)	Exposure to these toxic elements	[297]
Heavy metals in nails were investigated	2020		Nails	The mean nail levels of As and Pb were 0.74, and 1.23 μg/g respectively.	This study stresses the need for increased investigation of adverse health impacts of metal exposure in tannery industries.	[298]
Toxic chemical elements investigated in urine and nails	2024		urine, nails	Arsenic levels in urine ranged from < 0.01 to 126.13 μg/L, with a mean of 16.02 μg/L and a median of 13.5 μg/L. In nails, levels ranged from < 0.01 to 2.54 μg/g, with a mean of 1.01 μg/g and a median of 1.0 μg/g.	Groundwater sources and cigarette smoking were significantly linked to acute arsenic exposure	[299]

[300], with female crocodiles Pb values of 266 ng/mL, and male crocodiles had a greater prevalence of Pb poisoning [300]. The amounts of Pb in blood and tail fat tissue ranged from undetectable to 4175 ng/g wet weight, though most of the crocodiles sampled appeared to be in good physical condition [300], significantly higher blood Pb concentrations (> 6000 ng/mL) were linked to significantly reduced packed cell volumes (4.6–10.8%) and severe degradation in tooth condition. These results suggest that anemia and teeth loss may be clinical signs of long-term environmental exposure to Pb [300]. Crocodile Pb toxicity has not been documented, but these symptoms are similar to Pb poisoning seen in birds and mammals indicating that crocodiles may be more vulnerable to the long-term toxic effects of Pb [300]. According to Moruf et al. [301], *T. Fuscatus var*. radula had higher levels of Hg, Pb, and Cd than water, despite sediments acting as a significant storehouse for these trace elements. The capacity of metal concentrated in the water to affect this snail was greater than that of sediment, further, it was established that there is a favorable association between tissue and sediment contents of Pb and Cd, indicating potential exposure to aquatic organisms. Therefore, there is a need to mitigate the impacts of toxic chemical elements for ecological health and safety.

2.1. Combatting toxic chemical element pollution

Some techniques employed for soil remediation include leaching [197,198], solidification, biodegradation, vitrification, isolation, encapsulation, and removal in addition to phytoremediation [302,303]. However, plant uptake (phytoremediation) of e.g., Pb and Cd, are affected by soil properties, plant species, cultivars, fertilizers, agronomic management and properties of the source metals. Therefore, these factors need to be considered while choosing the remediation techniques, for resource-limited settings like Africa similarly, studies are needed. These plants, known as hyperaccumulators, can uptake and accumulate toxic chemical elements, thereby reducing their levels in the soil. Furthermore, implementing wastewater treatment systems in industries helps toxic chemical elements from effluents before their discharge, preventing water pollution and protecting aquatic ecosystems. The provision of education and awareness programs are crucial components of remediation strategies [304–306]. This includes educating individuals about proper waste disposal methods, the dangers of illegal mining activities, and the importance of adopting sustainable production processes that reduce toxic chemical elements usage. Equally important, international collaboration and support are instrumental [307,308], in addressing toxic chemical elements pollution. Collaboration allows for the sharing of knowledge, expertise, and resources, enabling the region to develop and implement effective regulatory frameworks and remediation strategies [309,310]. Potential strategies for combatting toxic chemical pollution are presented in Fig. 3.

Funding, and technology transfer from international partners can support capacity building, promote sustainable practices, and aid in the implementation and monitoring of remediation projects.

2.2. Regulatory framework

In Sub-Saharan Africa, the regulatory framework and remediation strategies for addressing toxic chemical elements pollution are of paramount importance [12,193–195], to safeguard the environment and protect ecosystem health. Governments and regulatory authorities have a crucial role in formulating and implementing robust laws, regulations, and standards to control [196], the release of toxic chemical elements into the environment. Similarly, the need to ban direct release and or set emission limits for industries, establishing mining regulations, and implementing proper waste management practices. Most countries established organizations to oversee the regulations to ensure environmental safety, these organizations include National

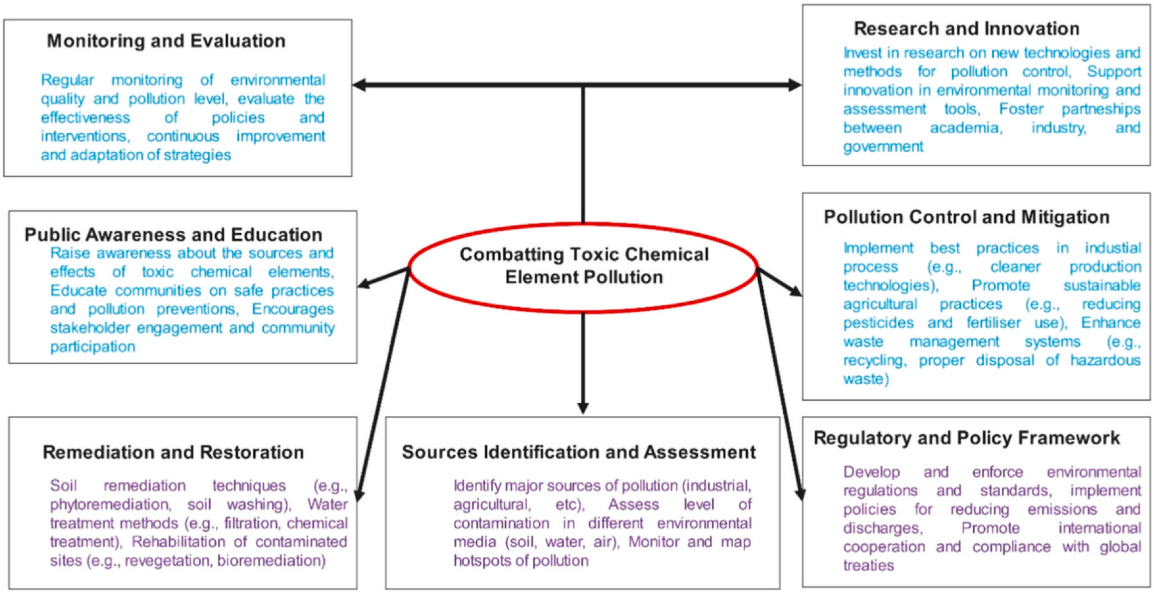

Fig. 3. Brief description of potential strategies for combatting toxic chemical element pollution.

Environment Management Council (NEMC) for Tanzania, National Environment Management Authority (NEMA) for Kenya, and National Environment Management Policy (NEMP) for Uganda.

Sub-Saharan Africa faces significant gaps in regulatory frameworks for managing toxic chemical element pollution, impeding effective mitigation [311–315]. Many countries lack comprehensive, targeted legislation for toxic chemical elements, and enforcement of existing laws is weak due to limited institutional capacity and funding [316–318]. The monitoring systems are underdeveloped, resulting in insufficient data to guide policy and identify toxic chemical element pollution hotspots. The delays in updating standards often fail to address SSA unique challenges like limited funding to purchase state of art equipment for analysis of trace levels or full speciation of toxic chemical element, while weak cross-sectoral coordination may reduce accountability and results in regulatory incompetence. Public awareness about the risks of toxic chemical element remains low, and communities are rarely involved in policymaking or monitoring, further weakening governance. Legacy pollution from past industrial and mining activities remains unaddressed in many areas [319–321], posing ongoing health risks. The regulatory frameworks rarely incentivize the adoption of green technologies like bioremediation, other ecofriendly technologies, and limited regional cooperation weakens responses to transboundary pollution. These gaps require stronger legislation, better monitoring, community engagement, and regional collaboration, this will protect public health and nurture sustainable development.

2.3. *Future research directions*

Toxic chemical element pollution is a complex issue which requires deeply interconnected solutions across science, technology, policy, and socio-economic factors. Future research needs to prioritize interdisciplinary solutions emphasizing new paradigm creation, integration, and shifts. Emerging areas may include the development of bioengineered plants and or microorganisms with controlled metal-accumulating or degrading. A study by Yao et al. (2022) [322], reported that mutation of the AtCUP1 gene in *Arabidopsis thaliana* reduced cadmium (Cd) accumulation in roots and shoots, with CRISPR/Cas9-mediated disruption of the gene achieving significant alterations [322]. Similarly, editing the orthologous BnCUP1 gene in *Brassica napus* (canola) through CRISPR/Cas9, decreased Cd accumulation in hydroponic assays. Field experiments showed a reduction in in Cd accumulation of 52% in roots and 77% in shoots of BnCUP1-edited lines compared to wild-type [322]. The edited lines exhibited a 42% increase in biomass and a 47% increase in yield without noticeable impacts on agronomic traits [322], indicating polluted soils can be used for crop production and maintain productivity while ensuring public safety. This was reported by other scholars [323–326], needs research considering our local environments.

Similarly, designing and use of eco-friendly, recyclable nanoparticles for targeted metal removal, holds promise for reducing environmental footprints resulting from toxic chemical elements. Studies indicate the use of nanoparticles for targeted remediation of lead [327–329], which may be used for the remediation of contaminated water and wastewater effluents ensuring the availability of clean, safe, and affordable water for all, with environmental safety.

The use of circular economy models, including efficient recovery and recycling of toxic chemical elements from industrial [330–332], agricultural, and electronic wastes, can create sustainable resource circles while mitigating toxic chemical element pollution. Integrating real-time monitoring systems [332–334], such as IoT-enabled sensors and drones equipped with spectroscopic technology [335–337], can provide high-resolution data on toxic chemical element hotspots, enabling proactive management. Additionally, research on low-cost, readily available Indigenous materials for remediation, like jamun seed for biochar preparation [338,339], and other biowaste from agricultural residues, will offer scalable solutions for resource-constrained settings like Africa. Equally important research should focus on ecotoxicological impacts of mixed toxic chemical pollutants and their interactions with emerging contaminants, such as microplastics and antibiotics, this will deepen understanding of synergistic effects on ecosystems and health. Finally, focusing on policy-oriented research that evaluates the socio-economic impacts of toxic chemical elements pollution and develops evidence-based regulatory frameworks will bridge the gap between science and implementation, nurturing international collaboration and sustainable development.

3. Conclusions

Results indicate presence of quantifiable levels of toxic chemical elements in water, soils, aquatic organisms, vegetables, other crops, and wastewater effluents, and even in humans, which may be through environmental, occupational exposure, or and through the food chain. In some countries, levels are higher than the limit set by regulatory authorities including WHO. These results indicate the potential for exposure to humans and other organisms through the food chain. As effluents are used as a source of water for irrigation, may lead to the pollution of soils, waters, and crops, potentially harming the entire ecology. The widespread pollution with high levels of toxic chemical elements may lead to reduced biodiversity and a non-resilient environment.

Mitigating toxic chemical element pollution in Africa needs to take in green and sustainable technologies custom-made to local conditions. Phytoremediation and bioremediation leverage plants and microorganisms like *Brassica juncea* and *Pseudomonas putida* to extract or degrade toxic chemical element, while green adsorbents such as Jamun seed biochar and other agricultural waste may effectively trap toxic chemical elements. The use of constructed wetlands and solar-powered remediation, including solar distillation and photocatalytic degradation, offer eco-friendly water treatment options. Similarly, advanced technologies like membrane filtration, including reverse osmosis, and green nanotechnology using nano-adsorbents may provide precise and efficient solutions ensuring ecological safety. Electrokinetic remediation and soil stabilization with geopolymers made using aluminosilicates with an alkaline solution, help manage contaminated soils. Further, recycling and circular economy practices, such as urban mining and metal recovery from industrial waste, may reduce environmental burdens while creating economic value for improved livelihood. The inclusion of policy tools like Geographic Information Systems (GIS) and IoT-based sensors may enhance monitoring and regulation of toxic chemical element pollution. The utilization of these approaches, with international collaboration and community engagement, will foster sustainable development and environmental restoration.

Declaration of Competing Interest

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

References

[1] Y. Cui, et al., Assessment of heavy metal contamination levels and health risks in environmental media in the northeast region, Sustain. Cities Soc. (2022) 103796.
[2] A.I. Chowdhury, M.R. Alam, Health effects of heavy metals in meat and poultry consumption in Noakhali, Bangladesh, Toxicol. Rep. (2024).
[3] V. Ngure, G. Kinuthia, Health risk implications of lead, cadmium, zinc, and nickel for consumers of food items in Migori Gold mines, Kenya, J. Geochem. Explor. 209 (2020) 106430.
[4] L.J. Gorenflo, et al., Co-occurrence of linguistic and biological diversity in biodiversity hotspots and high biodiversity wilderness areas, Proc. Natl. Acad. Sci. 109 (21) (2012) 8032–8037.
[5] D. Sono, Y. Wei, Y. Jin, Assessing the climate resilience of Sub-Saharan Africa (SSA): a metric-based approach, Land 10 (11) (2021) 1205.
[6] N. Nunes, et al., Review of sewage sludge as a soil amendment in relation to current international guidelines: a heavy metal perspective, Sustainability 13 (4) (2021) 2317.
[7] R. Dhanker, et al., Influence of urban sewage sludge amendment on agricultural soil parameters, Environ. Technol. Innov. 23 (2021) 101642.
[8] K. Wajid, et al., Effect of organic manure and mineral fertilizers on bioaccumulation and translocation of trace metals in maize, Bull. Environ. Contam. Toxicol. 104 (2020) 649–657.
[9] L. Hlisnikovský, et al., The effect of farmyard manure and mineral fertilizers on sugar beet beetroot and top yield and soil chemical parameters, Agronomy 11 (1) (2021) 133.
[10] N. Joseph, et al., Investigation of relationships between the geospatial distribution of cancer incidence and estimated pesticide use in the US West, GeoHealth 6 (5) (2022) p. e2021GH000544.
[11] A. Castellano-Hinojosa, N.S. Boyd, S.L. Strauss, Impact of fumigants on non-target soil microorganisms: a review, J. Hazard. Mater. 427 (2022) 128149.
[12] D.E. Penman, et al., Silicate weathering as a feedback and forcing in Earth's climate and carbon cycle, Earth-Sci. Rev. 209 (2020) 103298.
[13] D.A. Sokolov, V.A. Androkhanov, E.V. Abakumov, Soil Form. Technog. Landsc.: Trends Results Represent. Curr. Classif. (2021).
[14] M. Zhou, et al., Impact of water–rock interaction on the pore structures of red-bed soft rock, Sci. Rep. 11 (1) (2021) 7398.
[15] J. Lu, et al., Topography-dependent formation and transformation of lithogenic and pedogenic iron oxides on a volcano under a tropical monsoon climate, Catena 217 (2022) 106521.
[16] Y. Li, et al., Advanced oxidation processes for water purification using percarbonate: Insights into oxidation mechanisms, challenges, and enhancing strategies, J. Hazard. Mater. 442 (2023) 130014.
[17] Z. Xu, et al., A critical review on chemical analysis of heavy metal complexes in water/wastewater and the mechanism of treatment methods, Chem. Eng. J. 429 (2022) 131688.
[18] UN, Sanitation and Wastewater Atlas of Africa. UN - Environmental Programme.
[19] B.S. Johnson Grayson Mshana, Assessment of heavy metal pollution in octopus cyanea in the coastal waters of Tanzania. J. Health Pollut. 4 (6) (2014) 10–17.
[20] M. Pohanka, Copper and copper nanoparticles toxicity and their impact on basic functions in the body, Bratisl. Lek. Listy 120 (6) (2019) 397–409.
[21] A. Sarker, et al., Heavy metals contamination and associated health risks in food webs—a review focuses on food safety and environmental sustainability in Bangladesh, Environ. Sci. Pollut. Res. 29 (3) (2022) 3230–3245.
[22] P.K. Rai, C. Sonne, K.-H. Kim, Heavy metals and arsenic stress in food crops: elucidating antioxidative defense mechanisms in hyperaccumulators for food security, agricultural sustainability, and human health, Sci. Total Environ. 874 (2023) 162327.
[23] M.S. Nkinda, et al., Heavy metals risk assessment of water and sediments collected from selected river tributaries of the Mara River in Tanzania, Discov. Water 1 (1) (2021) 3.
[24] K.O. Ouma, A. Shane, S. Syampungani, Aquatic ecological risk of heavy-metal pollution associated with degraded mining landscapes of the Southern Africa River Basins: a review, Minerals 12 (2) (2022) 225.
[25] H.D. Nguyen, M.-S. Kim, Effects of heavy metals on cardiovascular diseases in pre and post-menopausal women: from big data to molecular mechanism involved, Environ. Sci. Pollut. Res. 29 (51) (2022) 77635–77655.
[26] X. Tian, et al., Mixed heavy metals exposure affects the renal function mediated by 8-OHG: a cross-sectional study in rural residents of China, Environ. Pollut. 317 (2023) 120727.
[27] M.J. Mohammadi, et al., Ecological risk assessment of heavy metals in urban dust in Iran: a systematic review and meta-analysis, Toxicol. Rep. (2023).
[28] O. Oladeji, et al., Assessment of heavy metals and their human health risks in selected spices from South Africa, Toxicol. Rep. 11 (2023) 216–220.
[29] M. Mandal, et al., Breathing fresh air in the city: implementing avenue trees as a sustainable solution to reduce particulate pollution in urban agglomerations, Plants 12 (7) (2023) 1545.
[30] F.U. Umeoguaju, et al., Heavy metals contamination of seafood from the crude oil-impacted Niger Delta Region of Nigeria: a systematic review and meta-analysis, Toxicol. Rep. (2023).
[31] Z. Haidar, et al., Disease-associated metabolic pathways affected by heavy metals and metalloid, Toxicol. Rep. (2023).
[32] I.A. Idowu, et al., An analyses of the status of landfill classification systems in developing countries: Sub Saharan Africa landfill experiences, Waste Manag. 87 (2019) 761–771.
[33] S. Spiegel, et al., Implic. Minamata Conv. Mercury Informal Gold. Min. Sub-Sahar. Afr.: Glob. Policy Debates Grassroots Implement. ? Environ., Dev. Sustain. 17 (2015) 765–785.
[34] S.J. Spiegel, Socioeconomic dimensions of mercury pollution abatement: engaging artisanal mining communities in Sub-Saharan Africa, Ecol. Econ. 68 (12) (2009) 3072–3083.
[35] C.N. Boocock, Environmental impacts of foreign direct investment in the mining sector in Sub-Saharan Africa, Foreign Direct Invest. Environ. (2002) 19.
[36] C. Bartrem, et al., Unknown risk: co-exposure to lead and other heavy metals among children living in small-scale mining communities in Zamfara State, Nigeria, Int. J. Environ. Health Res. 24 (4) (2014) 304–319.
[37] K. Sardar, et al., Heavy metals contamination and what are the impacts on living organisms, Greener J. Environ. Manag. Public Saf. 2 (4) (2013) 172–179.
[38] H. Ali, E. Khan, I. Ilahi, Environmental chemistry and ecotoxicology of hazardous heavy metals: environmental persistence, toxicity, and bioaccumulation, J. Chem. 2019 (2019).
[39] J. Mantey, et al., Mercury contamination of soil and water media from different illegal artisanal small-scale gold mining operations (galamsey), Heliyon 6 (6) (2020) e04312.
[40] E. Moto, et al., Ecological consequences of microplastic pollution in sub-Saharan Africa aquatic ecosystems: an implication to environmental health, HydroResearch 7 (2024) (2023) 39–54.
[41] H. Miraji, et al., Biotransformation of 1, 4-Dioxane by the Use of Bacteria in the Soil, Land Remediation and Management: Bioengineering Strategies, Springer,, 2023, pp. 79–102.
[42] R. Moodley, N.T. Mahlangeni, P. Reddy, Determination of heavy metals in selected fish species and seawater from the South Durban Industrial Basin, KwaZulu-Natal, South Africa, Environ. Monit. Assess. 193 (2021) 1–11.
[43] C.N. Amadi, C. Frazzoli, O.E. Orisakwe, Sentinel species for biomonitoring and biosurveillance of environmental heavy metals in Nigeria, J. Environ. Sci. Health, Part C. 38 (1) (2022) 21–60.
[44] D.S. Petrov, et al., Assessment of heavy metal accumulation potential of aquatic plants for bioindication and bioremediation of aquatic environment, Environ. Monit. Assess. 195 (1) (2023) 122.
[45] M. Tarish, et al., Plant tissues as biomonitoring tools for environmental contaminants, Int. J. Plant Biol. 15 (2) (2024) 375–396.
[46] E. Sababa, A.Z. Ekoa Bessa, Heavy metals signature in stream sediments at Eséka Gold District, Central Africa: a pre-mining environmental assessment, Chem. Afr. 5 (2) (2022) 413–430.

[47] M.-D. Nguyen, et al., Assessment of potentially toxic and rare earth elements in surface soils of Dong Nai, Vietnam, Environ. Geochem. Health 47 (2) (2025) 1–21.
[48] P.J. Jannetto, C.T. Cowl, Elementary overview of heavy metals, Clin. Chem. 69 (4) (2023) 336–349.
[49] W. Reineke, M. Schlömann, Heavy metals and other toxic inorganic ions, in Environmental Microbiology, Springer,, 2023, pp. 331–348.
[50] M. Schwartz, J. Kgomanyane, Modelling natural attenuation of heavy-metal groundwater contamination in the Selebi-Phikwe mining area, Botswana, Environ. Geol. 54 (2008) 819–830.
[51] K. Gajaje, et al., Rhizosphere properties and heavy metal accumulation of plants growing in the fly ash dumpsite, Morupule power plant, Botswana, Environ. Sci. Pollut. Res. 28 (2021) 20637–20649.
[52] L. Ferreira-Baptista, E. De Miguel, Geochemistry and risk assessment of street dust in Luanda, Angola: a tropical urban environment, Atmos. Environ. 39 (25) (2005) 4501–4512.
[53] M.M.V.G. Silva, et al., Spatial and seasonal variations of surface and groundwater quality in a fast-growing city: Lubango, Angola, Environ. Earth Sci. 76 (2017) 1–17.
[54] B. Shakhane, Accumulation of selected nutrients and heavy metals in the Khubelu river catchment, Mokhotlong, Lesotho, Cape Peninsula University of Technology,, 2019.
[55] S. Syurin, D. Vinnikov, Occupational multimorbidity in the nickel industry workers, Int. J. Circumpolar Health 82 (1) (2023) 2231618.
[56] M.B.M. Ahmed, et al., Potential health risk assessment for heavy metals in Tilapia fish of different spatiotemporal monitoring patterns in Kafr El-Shaikh and El-Faiyum Governorates of Egypt, Toxicol. Rep. 10 (2023) 487–497.
[57] J. Nriagu, School of Public Health, University of Michigan, Zinc Toxic. Hum. (2007) 1–7.
[58] D.S. Ávila, et al., Manganese neurotoxicity, in Handbook of neurotoxicity, Springer,, 2023, pp. 2305–2329.
[59] C. Hopenhayn, Arsenic in drinking water: impact on human health, Elements 2 (2) (2006) 103–107.
[60] M. Gorguner, M. Akgun, Acute inhalation injury, Eurasia J. Med. 42 (1) (2010) 28.
[61] P.B. Tchounwou, et al., Heavy metal toxicity and the environment, Mol., Clin. Environ. Toxicol.: Vol. 3: Environ. Toxicol. (2012) 133–164.
[62] S.M. Yahaya, F. Abubakar, N. Abdu, Ecological risk assessment of heavy metal-contaminated soils of selected villages in Zamfara State, Nigeria, SN Appl. Sci. 3 (2) (2021) 168.
[63] S.A. Anka, Lead Poisoning in Zamfara State Nigeria: Effects on Environmental Health, in Poisoning-Prevention, Diagnosis, Treatment and Poison Repurposing, IntechOpen,, 2024.
[64] O.O. Oladipo, et al., Lead toxicoses in free-range chickens in artisanal gold-mining communities, Zamfara, Nigeria, J. Health Pollut. 10 (26) (2020) 200606.
[65] F.A. Harun, et al., Bioremediation of lead contaminated environment by Bacillus cereus strain BUK_BCH_BTE2: isolation and characterization of the bacterium, Case Stud. Chem. Environ. Eng. 8 (2023) 100540.
[66] R. Baieta, et al., Smelter-derived soil contamination in Luanshya, Zambia, Sci. Total Environ. 867 (2023) 161405.
[67] A. Muimba-Kankolongo, et al., Contamination of water and food crops by trace elements in the African Copperbelt: a collaborative cross-border study in Zambia and the Democratic Republic of Congo, Environ. Adv. 6 (2021) 100103.
[68] B. Kříbek, et al., Impact of mining and ore processing on soil, drainage and vegetation in the Zambian copperbelt mining districts: a review, Minerals 13 (3) (2023) 384.
[69] D. Phiri, et al., An assessment of forest loss and its drivers in protected areas on the Copperbelt province of Zambia: 1972–2016, Geomat., Nat. Hazards Risk 13 (1) (2022) 148–166.
[70] O. Isinkaralar, K. Isinkaralar, T.N.T. Nguyen, Spatial distribution, pollution level and human health risk assessment of heavy metals in urban street dust at neighbourhood scale, Int. J. Biometeorol. (2024) 1–13.
[71] C.N. Brunnschweiler, D. Karapetyan, P. Lujala, Opportunities and risks of small-scale and artisanal gold mining for local communities: Survey evidence from Ghana, Extr. Ind. Soc. 17 (2024) 101403.
[72] M.E. Mimba, et al., Environmental impact of artisanal and small-scale gold mining in East Cameroon, Sub-Saharan Africa: an overview, Ore Energy Resour. Geol. (2023) 100031.
[73] M.J. Rwiza, et al., Artisanal and small-scale mining in Tanzania and health implications: a policy perspective, Heliyon 9 (4) (2023).
[74] M.C. Laker, Environmental impacts of gold mining—with special reference to South Africa, Mining 3 (2) (2023) 205–220.
[75] P. Mukube, et al., Geochemistry of terrestrial plants in the central African Copperbelt: implications for sediment hosted copper-cobalt exploration, Minerals 14 (3) (2024) 294.
[76] T. Kapwata, et al., Relations between personal exposure to elevated concentrations of arsenic in water and soil and blood arsenic levels amongst people living in rural areas in Limpopo, South Africa, Environ. Sci. Pollut. Res. 30 (24) (2023) 65204–65216.
[77] N.T. Mandizha, J. Kugara, E.T. Mombeshora, M.F. Zaranyika, Elemental composition and speciation trends in Upper Mazowe River, a typical sub-tropical river ecosystem impacted by gold mining and agriculture in Zimbabwe, Environ. Adv. 14 (2023) 100443.
[78] A.M. Balasha, I. Peša, “They polluted our cropfields and our rivers, they killed us”: Farmers’ complaints about mining pollution in the Katangese Copperbelt, Heliyon 9 (4) (2023).
[79] B.O. Anyanwu, et al., Heavy metal mixture exposure and effects in developing nations: an update, Toxics 6 (4) (2018) 65.
[80] A.F. Bon, et al., Groundwater flow patterns, hydrogeochemistry and metals background levels of shallow hard rock aquifer in a humid tropical urban area in sub-Saharan Africa-A case study from Olézoa watershed (Yaoundé-Cameroon), J. Hydrol.: Reg. Stud. 37 (2021) 100904.
[81] A.S. Mohammed, A. Kapri, R. Goel, Heavy metal pollution: source, impact, and remedies, Biomanagement Met. -Contam. Soils (2011) 1–28.
[82] U. Okereafor, et al., Toxic metal implications on agricultural soils, plants, animals, aquatic life and human health, Int. J. Environ. Res. Public Health 17 (7) (2020) 2204.
[83] E.O. Igwe, et al., Assessment of potentially toxic metals from mine tailings and waste rocks around mining areas of Oshiri-Ishiagu Region, Southeastern Nigeria, Earth Syst. Environ. 6 (2) (2022) 597–615.
[84] A. Osmanlioglu, Uranium mining techniques and waste management, Eur. J. Sustain. Dev. Res. 6 (4) (2022).
[85] L. Ricolfi, et al., Potential toxic elements in groundwater and their health risk assessment in drinking water of Limpopo National Park, Gaza Province, Southern Mozambique, Environ. Geochem. Health 42 (9) (2020) 2733–2745.
[86] R.O. Oruko, et al., Investigating the chromium status, heavy metal contamination, and ecological risk assessment via tannery waste disposal in sub-Saharan Africa (Kenya and South Africa), Environ. Sci. Pollut. Res. 28 (2021) 42135–42149.
[87] J. Wen, et al., Migration characteristics of heavy metals in the weathering process of exposed argillaceous sandstone in a mercury-thallium mining area, Ecotoxicol. Environ. Saf. 208 (2021) 111751.
[88] V.B. Singh, et al., Weathering and erosion processes in the natural environment, John Wiley & Sons,, 2023.
[89] A.K. Tiwari, et al., Bioadsorbent and adsorbent-based heavy metal removal technologies from wastewater: new insight, Biomass-.-. Convers. Biorefinery (2022) 1–22.
[90] R.N. Khalef, A.I. Hassan, H.M. Saleh, Heavy Metal’s Environ. Impact (2022).
[91] P. Bakshe, R. Jugade, Phytostabilization and rhizofiltration of toxic heavy metals by heavy metal accumulator plants for sustainable management of contaminated industrial sites: a comprehensive review, J. Hazard. Mater. Adv. (2023) 100293.
[92] P. Barua, S. Eslamian, Exploitation of agro-chemicals and its effect on health of farmers and environment on south-easter n coast of Bangladesh, Front. Agric. Food Technol. 11 (2) (2022) 001–009.
[93] P. Cullen, J. Whittington, G. Fraser, Likely ecological outcomes of the COAG water reforms, La Trobe,, 2023.
[94] A. Ripanda, et al., Evaluation of potentiality of traditional hygienic practices for the mitigation of the 2019–2020 Corona Pandemic, Public Health Nurs. 39 (4) (2022) 867–875.
[95] S.A.H. Vuai, et al., A comparative in-vitro study on antimicrobial efficacy of on-market alcohol-based hand washing sanitizers towards combating microbes and its application in combating Covid-19 global outbreak, Heliyon 8 (11) (2022).
[96] X. Li, et al., Accumulation and source apportionment of heavy metal (loid) s in agricultural soils based on GIS, SOM and PMF: a case study in superposition areas of geochemical anomalies and zinc smelting, Southwest China, Process Saf. Environ. Prot. 159 (2022) 964–977.
[97] R. MAHAJAN, Curr. World Environ. (2023).
[98] S. Naik, J.S. Eswari, Electrical waste management: Recent advances challenges and future outlook, Total Environ. Res. Themes (2022) 100002.
[99] Ezeh, E. Chukwu, Small scale mining and heavy metals pollution of agricultural soils: the case of Ishiagu Mining District, South Eastern Nigeria. J. Geol. Min. Res. 3 (4) (2011) 87–104.
[100] A. Nsabimana, V. Habimana, G. Svetlana, Heavy metal concentrations in water samples from Lake Kivu, Rwanda, Rwanda J. Eng., Sci., Technol. Environ. 3 (2) (2020).
[101] A. Okem, et al., Heavy metal contamination in South African medicinal plants: a cause for concern, South Afr. J. Bot. 93 (2014) 125–130.
[102] H.M. Tauqeer, V. Turan, M. Iqbal, Production of safer vegetables from heavy metals contaminated soils: the current situation, concerns associated with human health and novel management strategies, Advances in bioremediation and phytoremediation for sustainable soil management: principles, monitoring and remediation, Springer,, 2022, pp. 301–312.
[103] E. Anang, et al., Mercury and lead pollution in rivers in Ghana: geo-accumulation index, contamination factor, and water quality index, Water Pract. Technol. (2023).
[104] C. Yao, et al., Water quality degradation in urban rivers of Dar es Salaam, Tanzania: changes, status, and causes, Water, Air, Soil Pollut. 234 (4) (2023) 1–19.
[105] G. Chanzi, Heavy metal pollution assessment along Msimbazi River, Tanzania, J. Sci. Res. Rep. 17 (5) (2018) 1–8.
[106] W. Mwegoha, C. Kihampa, Heavy metal contamination in agricultural soils and water in Dar es Salaam city, Tanzania, Afr. J. Environ. Sci. Technol. 4 (11) (2010) 763–769.
[107] M.A. Kishe, and J.F. Machiwa, Distribution of heavy metals in sediments of Mwanza Gulf of Lake Victoria, Tanzania. Environ. Int. 28 (7) (2003) 619–625.
[108] T.M. Mungai, J. Wang, Heavy metal pollution in suburban topsoil of Nyeri, Kapsabet, Voi, Ngong and Juja towns, in Kenya, SN Appl. Sci. 1 (9) (2019) 960.
[109] C. Nyambura, et al., Cancer and non-cancer health risks from carcinogenic heavy metal exposures in underground water from Kilimambogo, Kenya, Groundw. Sustain. Dev. 10 (2020) 100315.
[110] G.K. Kinuthia, et al., Levels of heavy metals in wastewater and soil samples from open drainage channels in Nairobi, Kenya: community health implication, Sci. Rep. 10 (1) (2020) 8434.
[111] P. Prabu, Impact of heavy metal contamination of Akaki River of Ethiopia on soil and metal toxicity on cultivated vegetable crops, Electron. J. Environ., Agric. Food Chem. 8 (9) (2009).

[112] M. Swaibuh Lwanga, et al., Heavy metals in Lake George, Uganda, with relation to metal concentrations in tissues of common fish species, Hydrobiologia 499 (1) (2003) 83–93.

[113] A. Muwanga, E. Barifaijo, Impact of industrial activities on heavy metal loading and their physico-chemical effects on wetlands of lake Victoria basin (Uganda), Afr. J. Sci. Technol. 7 (1) (2006) 51–63.

[114] A. Tagumira, S. Biira, E.B. Amabayo, Concentrations and human health risk assessment of selected heavy metals in soils and food crops around Osukuru phosphate mine, Tororo District, Uganda, Toxicol. Rep. 9 (2022) 2042–2049.

[115] D. Getachew, D. Habtamu, Heavy metal pollution of soil around solid waste dumping sites and its impact on adjacent community: the case of Shashemane open landfill, Ethiopia, J. Environ. Earth Sci. 5 (15) (2015) 169–178.

[116] G.D. Gebre, H.D. Debelie, Heavy metal pollution of soil around solid waste dumping sites and its impact on adjacent community: the case of Shashemane open landfill, Ethiopia, J. Environ. Earth Sci. 5 (15) (2015) 169–178.

[117] A.A. Adeyemi, Z.O. Ojekunle, Concentrations and health risk assessment of industrial heavy metals pollution in groundwater in Ogun state, Nigeria, Sci. Afr. 11 (2021) e00666.

[118] B.U. Ukah, et al., Extent of heavy metals pollution and health risk assessment of groundwater in a densely populated industrial area, Lagos, Nigeria, Int. J. Energy Water Resour. 3 (4) (2019) 291–303.

[119] E.A. Ajeh, F.J. Modi, I.P. Omoregie, Health risk estimations and geospatial mapping of trace metals in soil samples around automobile mechanic workshops in Benin city, Nigeria, Toxicol. Rep. 9 (2022) 575–587.

[120] F.E. Olubunmi, O.E. Olorunsola, Evaluation of the status of heavy metal pollution of sediment of Agbabu bitumen deposit area, Nigeria, Eur. J. Sci. Res. 41 (3) (2010) 373–382.

[121] U.C. Emmanuel, et al., Human health risk assessment of heavy metals in drinking water sources in three senatorial districts of Anambra State, Nigeria, Toxicol. Rep. 9 (2022) 869–875.

[122] J.K. Nduka, H.I. Kelle, J.O. Amuka, Health risk assessment of cadmium, chromium and nickel from car paint dust from used automobiles at auto-panel workshops in Nigeria, Toxicol. Rep. 6 (2019) 449–456.

[123] A. Sani, I. Abdullahi, S. Ibrahim, Histopathological changes associated with exposure to metal welding fumes in some organs of Rattus norvegicus in Kano, Nigeria, Toxicol. Rep. 8 (2021) 422–428.

[124] I.C. James, et al., Effects of chronic exposure to paint fumes among artisans in Lagos State, Nigeria, Toxicol. Rep. 9 (2022) 663–669.

[125] J.O. Okonkwo, M. Mothiba, Physico-chemical characteristics and pollution levels of heavy metals in the rivers in Thohoyandou, South Africa, J. Hydrol. 308 (1) (2005) 122–127.

[126] E. Atangana, P.J. Oberholster, Using heavy metal pollution indices to assess water quality of surface and groundwater on catchment levels in South Africa, J. Afr. Earth Sci. 182 (2021) 104254.

[127] M. Oliva, et al., Oxidative stress biomarkers in Senegal sole, Solea senegalensis, to assess the impact of heavy metal pollution in a Huelva estuary (SW Spain): seasonal and spatial variation, Ecotoxicol. Environ. Saf. 75 (2012) 151–162.

[128] M.N. Chileshe, et al., Physico-chemical characteristics and heavy metal concentrations of copper mine wastes in Zambia: implications for pollution risk and restoration, J. For. Res. 31 (4) (2020) 1283–1293.

[129] G. Mbewe, et al., Assessment of heavy-metal pollution in sediments and tilapia fish species in Kafue River of Zambia, Arch. Environ. Contam. Toxicol. 71 (3) (2016) 383–393.

[130] B. Chilikwazi, J.M. Onyari, J.M. Wanjohi, Determination of heavy metals concentrations in coal and coal gangue obtained from a mine, in Zambia, Int. J. Environ. Sci. Technol. 20 (2) (2023) 2053–2062.

[131] K. Gnandi, H. Tobschall, Heavy metals distribution of soils around mining sites of cadmium-rich marine sedimentary phosphorites of Kpogamé and Hahotoé (southern Togo), Environ. Geol. 41 (5) (2002) 593–600.

[132] K.F. Kondo, et al., Heavy metal contamination levels in clams (Galatea Paradoxa, Born 1778) and surface sediments from Mono River Estuary, Togo, and its health implications, J. Biol., Agric. Healthc. 11 (2021) 81–94.

[133] M.A. Nkansah, et al., Heavy metal content and potential health risk of geophagic white clay from the Kumasi Metropolis in Ghana, Toxicol. Rep. 3 (2016) 644–651.

[134] K. Kodom, K. Preko, D. Boamah, X-ray fluorescence (XRF) analysis of soil heavy metal pollution from an industrial area in Kumasi, Ghana, Soil Sediment Contam.: Int. J. 21 (8) (2012) 1006–1021.

[135] J.D. Kpan, B.K. Opoku, A. Gloria, Heavy metal pollution in soil and water in some selected towns in Dunkwa-on-Offin District in the Central Region of Ghana as a result of small scale gold mining, J. Agric. Chem. Environ. 3 (02) (2014) 40.

[136] I. Nhapi, et al., Distribution of heavy metals in Lake Muhazi, Rwanda, Open Environ. Eng. J. 5 (1) (2012).

[137] J. Abah, P. Mashebe, S. Onjefu, Preliminary assessment of some heavy metals pollution status of Lisikili River Water In Zambezi Region, Namibia, Int. J. Environ. Pollut. Res. 4 (2) (2016) 13–30.

[138] J. Abah, E.K. Simasiku, S.A. Onjefu, Assessment of heavy metals pollution status of surface soil dusts at the Katima Mulilo urban motor park, Namibia, Geomat., Nat. Hazards Risk 14 (1) (2023) 2204181.

[139] S.A. Onjefu, N. Kgabi, S. Taole, Heavy metal seasonal distribution in shore sediment samples along the coastline of Erongo Region, western Namibia, Eur. J. Sci. Res. 139 (1) (2016) 49–63.

[140] C.A. Marove, et al., Assessment of soil, sediment and water contaminations around open-pit coal mines in Moatize, Tete province, Mozambique, Environ. Adv. 8 (2022) 100215.

[141] V. Lumami Kapepula, et al., Evaluation of commercial reverse osmosis and nanofiltration membranes for the removal of heavy metals from surface water in the democratic republic of congo, Clean. Technol. 4 (4) (2022) 1300–1316.

[142] F. Mununga Katebe, et al., Assessment of heavy metal pollution of agricultural soil, irrigation water, and vegetables in and nearby the cupriferous city of Lubumbashi, (Democratic Republic of the Congo), Agronomy 13 (2) (2023) 357.

[143] J.L.C. Ladu, X. Lu, M.K. Loboka, Experimental study on water pollution tendencies around Lobuliet, Khor bou and Luri streams in Juba, South Sudan, Int J. Dev. Sustain 1 (2012) 381–390.

[144] C. Mussa, et al., Occurrence and ecological risk assessment of heavy metals in agricultural soils of Lake Chilwa catchment in Malawi, Southern Africa, SN Appl. Sci. 2 (2020) 1–8.

[145] Kumwenda, S., et al., Determination of biological, physical and chemical pollutants in Mudi River, Blantyre, Malawi. 2012.

[146] A.T. Mlangeni, et al., Evaluation of Metal (loids) concentrations in soils of selected rice paddy fields in Malawi, Agronomy 12 (10) (2022) 2349.

[147] C. Mussa, et al., Levels and spatial distribution of heavy metals in Lake Chilwa Catchment, Southern Malawi, ChemSearch J. 10 (2) (2019) 66–73.

[148] Y. Fodoué, et al., Heavy metal contamination and ecological risk assessment in soils of the pawara gold mining area, eastern cameroon, Earth 3 (3) (2022) 907–924.

[149] C. Defo, et al., Assessment of heavy metals in soils and groundwater in an urban watershed of Yaoundé (Cameroon-West Africa), Environ. Monit. Assess. 187 (2015) 1–17.

[150] A.F. Lum, et al., Phytoremediation potential of weeds in heavy metal contaminated soils of the Bassa Industrial Zone of Douala, Cameroon, Int. J. Phytoremediat. 16 (3) (2014) 302–319.

[151] K. Gajaje, et al., Pollution index of soils along and against the wind direction within a 40 km distance of Morupule Fly Ash Dumpsite, Botswana, Environ. Qual. Manag. (2023).

[152] P. Gwimbi, M.J. Selimo, Heavy metal concentrations in sediments and Cyprinus carpio from Maqalika Reservoir–Maseru, Lesotho: an analysis of potential health risks to Fish consumers, Toxicol. Rep. 7 (2020) 475–479.

[153] J.A. Ondo, et al., Translocation of metals in two leafy vegetables grown in urban gardens of Ntoum, Gabon, Afr. J. Agric. Res 7 (42) (2012) 5621–5627.

[154] D. Daby, Coastal pollution and potential biomonitors of metals in Mauritius, Water air Soil Pollut. 174 (2006) 63–91.

[155] M. Yehdhih, et al., Assessment of heavy metals pollution in the marine sediments of the lévrier bay (Nouadhibou, Mauritania), Ecol. Eng. Environ. Technol. 23 (5) (2022) 84–90.

[156] M.B. Ammar, et al., Assessment of heavy metals content in sewage discharges from health structure in mauritania, J. Pharm. Pharmacol. 10 (2022) 190–194.

[157] J. Everaarts, R. Heesters, C. Fischer, Heavy metals (Cu, Zn, Pb, Cd) in sediment, zooplankton and epibenthic invertebrates from the area of the continental slope of the Banc d'Arguin (Mauritania), Hydrobiologia 258 (1993) 41–58.

[158] M.K. Somda, et al., Assessment of heavy metals and microbial pollution of lettuce (Lactuca sativa) cultivated in two sites (Paspanga and Tanghin) of Ouagadougou, Burkina Faso, J. Environ. Prot. 10 (3) (2019) 454–471.

[159] Y.Z. Sawadogo, et al., Evaluation of heavy metal pollution and physico-chemical parameters in agricultural soils of bouly, burkina-faso, J. Mater. 11 (2) (2023) 38–47.

[160] L.I. Ezemonye, et al., Potential health risk consequences of heavy metal concentrations in surface water, shrimp (Macrobrachium macrobrachion) and fish (Brycinus longipinnis) from Benin River, Nigeria, Toxicol. Rep. 6 (2019) 1–9.

[161] A. Punia, R. Bharti, Impact of decades long mining on weathering, Arab. J. Geosci. 16 (5) (2023) 1–13.

[162] A. Dhiman, et al., Heavy metal distribution in various environmental matrices and their risk assessment in Ganga River Basin, India, Hum. Ecol. Risk Assess.: Int. J. 29 (2) (2023) 621–650.

[163] S. Ling, et al., Geochemical Assessment of Heavy Metal Contamination in Coastal Sediment Cores from Usukan Beach, Kota Belud, Sabah, Malaysia, Journal of Physics: Conference Series, IOP Publishing,, 2022.

[164] K. Isinkaralar, Atmospheric deposition of Pb and Cd in the Cedrus atlantica for environmental biomonitoring, Landsc. Ecol. Eng. 18 (3) (2022) 341–350.

[165] M. Vithanage, et al., Deposition of trace metals associated with atmospheric particulate matter: environmental fate and health risk assessment, Chemosphere 303 (2022) 135051.

[166] H. M, A.S. Ripanda, Rational integration of principal component analysis in soliciting spatial 'Landmark-Contaminants' of Tanzania Groundwater, Int. J. Curr. Res. 11 (1) (2019) 110–116.

[167] H. Miraji, A. Ripanda, E. Moto, A review on the occurrences of persistent organic pollutants in corals, sediments, fish and waters of the Western Indian Ocean, Egypt. J. Aquat. Res. 47 (4) (2021) 373–379.

[168] A.S. Ripanda, et al., Contribution of illicit drug use to pharmaceutical load in the environment: a focus on Sub-Saharan Africa, J. Environ. Public Health 2022 (2022).

[169] A.S. Ripanda, et al., A review on contaminants of emerging concern in the environment: a focus on active chemicals in Sub-Saharan Africa, Appl. Sci. 12 (1) (2021) 56.

[170] M. Hossein, et al., Monitoring of Contaminants in Aquatic Ecosystems Using Big Data, Artificial Intelligence and Modeling for Water Sustainability, CRC Press,, 2023, pp. 129–157.

[171] A.S. Ripanda, et al., Antibiotic-resistant microbial populations in urban receiving waters and wastewaters from Tanzania, Environ. Chem. Ecotoxicol. 5 (2023) 1–8.

[172] H. Miraji, et al., Exploring eco-friendly approaches for mitigating pharmaceutical and personal care products in aquatic ecosystems: a sustainability assessment, Chemosphere (2023) 137715.

[173] A. Makaye, A. Ripanda, H. Miraji, Transport behavior and risk evaluation of pharmaceutical contaminants from Swaswa Wastewater Stabilization Ponds, J. Biodivers. Environ. Sci. 20 (2) (2022) 30–41.

[174] S. Makokola, A. Ripanda, H. Miraji, Quantitative investigation of potential contaminants of emerging concern in dodoma city: a focus at swaswa wastewater stabilization ponds, Egypt. J. Chem. 62 (2019) 427–436 (Special Issue (Part 2) Innovation in Chemistry).

[175] M. Hossein, Toxicological aspects of emerging contaminants, Emerg. Eco-Friendly Approaches Waste Manag. (2019) 33–58.

[176] M. Hossein, et al., Spatial occurrence and fate assessment of potential emerging contaminants in the flowing surface waters, Chem. Sci. Int. J. 24 (2018) 1–11.

[177] H. Miraji, et al., Analytical perspectives on emerging organic contaminants in the aquatic ecosystem, Effects of Emerging Chemical Contaminants on Water Resources and Environmental Health, IGI Global,, 2020, pp. 68–80.

[178] H. Miraji, et al., Research trends in emerging contaminants on the aquatic environments of Tanzania, Scientifica 2016 (2016).

[179] H. Miraji, Brination of coastal aquifers: prospective impacts and future fit-for-use remedial strategies in Tanzania, World Wide J. Multidiscipl. Ina. Res. Dev. 4 (2018) 202–206.

[180] A. Ripanda, et al., Data from the batch adsorption of ciprofloxacin and lamivudine from synthetic solution using jamun seed (Syzygium cumini) biochar: response surface methodology (RSM) optimization, Data Brief. 47 (2023) 108975.

[181] M.J.R. Asha Ripanda, Elias Charles Nyanza, Ramadhani Bakari, Hossein Miraji, Karoli N. Njau, Said Ali Hamad Vuai, Revocatus L. Machunda, Removal of lamivudine from synthetic solution using jamun seed (Syzygium cumini) biochar adsorbent, Emerg. Contam. (2023).

[182] H. Miraji, et al., Naturally occurring emerging contaminants: where to hide? HydroResearch 6 (2023) 203–215.

[183] H. Miraji, C. Mgina, F. Ngassap, A Physico-Chemical and Bacteriological Investigation of Groundwater Quality for Domestic Supply, A Case Study of Temeke Municipal, University of Dar es Salaam: Dar es Salaam,, 2014.

[184] D.V. Mtenga, A.S. Ripanda, A review on the potential of underutilized Blackjack (Biden Pilosa) naturally occurring in sub-Saharan Africa, Heliyon (2022) e09586.

[185] M.O. Fashola, V.M. Ngole-Jeme, O.O. Babalola, Heavy metal pollution from gold mines: environmental effects and bacterial strategies for resistance, Int. J. Environ. Res. Public Health 13 (11) (2016) 1047.

[186] M.A. Acheampong, R.J. Meulepas, P.N. Lens, Removal of heavy metals and cyanide from gold mine wastewater, J. Chem. Technol. Biotechnol. 85 (5) (2010) 590–613.

[187] L.J. Esdaile, J.M. Chalker, The mercury problem in artisanal and small-scale gold mining, Chem. Eur. J. 24 (27) (2018) 6905–6916.

[188] E.T. Tech, Determination of some heavy metals in wastewater and sediment of artisanal gold local mining site of Abare Area in Nigeria, J. Environ. Treat. Tech. 1 (3) (2013) 174–182.

[189] S. Boudjabi, H. Chenchouni, Comparative effectiveness of exogenous organic amendments on soil fertility, growth, photosynthesis and heavy metal accumulation in cereal crops, Heliyon 9 (4) (2023).

[190] S.K. Chakraborty, P. Sanyal, R. Ray, Pollution, Environmental Perturbation and Consequent Loss of Wetlands, Wetlands Ecology: Eco-biological uniqueness of a Ramsar site (East Kolkata Wetlands, India), Springer,, 2023, pp. 521–582.

[191] S. Roy, et al., A global perspective of the current state of heavy metal contamination in road dust, Environ. Sci. Pollut. Res. 29 (22) (2022) 33230–33251.

[192] P.S. Hooda, Trace elements in soils 618 Wiley Online Library,, 2010.

[193] O.R. Kam, et al., Assessing the source of thallium contamination in ground and surface waters in the locality of Yamtenga (Burkina-Faso): Correlation with some heavy metal ions, Int. Res. J. Pure Appl. Chem. 19 (4) (2019) 1–14.

[194] F.A. Adekola, O.A.A. Eletta, A study of heavy metal pollution of Asa River, Ilorin. nigeria; trace metal monitoring and geochemistry, Environ. Monit. Assess. 125 (1) (2007) 157–163.

[195] P. Bissessur, et al., Heavy Metal Quantification in Edible Oysters from the Coast of Mauritius, University of Mauritius Research Week,, 2014, pp. 15–19.

[196] J.A. Ondo, et al., Accumulation of soil-borne aluminium, iron, manganese and zinc in plants cultivated in the region of Moanda (Gabon) and nutritional characteristics of the edible parts harvested, J. Sci. Food Agric. 93 (10) (2013) 2549–2555.

[197] J.A. ONDO, et al., Characteristics of a manganese-rich soil and metal accumulation in edible parts of plants in the region of Moanda, Gabon, Afr. J. Agric. Res. 9 (25) (2014) 1952–1960.

[198] M. Diop, et al., Concentrations and Potential Human Health Risks of Trace Metals (Cd, Pb, Hg) and Selected Organic Pollutants (PAHs, PCBs) in Fish and Seafood from the Senegalese Coast, Int. J. Environ. Res. 11 (3) (2017) 349–358.

[199] Z. Sidoumou, et al., Heavy metal concentrations in molluscs from the Senegal coast, Environ. Int. 32 (3) (2006) 384–387.

[200] Z. Sidoumou, et al., Heavy metal concentrations in molluscs from the Senegal coast, Environ. Int. 32 (3) (2006) 384–387.

[201] E.K. Atibu, et al., Concentration of metals in surface water and sediment of Luilu and Musonoie Rivers, Kolwezi-Katanga, Democratic Republic of Congo, Appl. Geochem. 39 (2013) 26–32.

[202] J. Bentum, et al., Assessment of heavy metals pollution of sediments from Fosu lagoon in Ghana, Bull. Chem. Soc. Ethiop. 25 (2) (2011).

[203] J. Abah, P. Mashebe, S. Onjefu, Survey of the levels of some heavy metals in roadside dusts along Katima Mulilo Urban road construction, Namibia, Am. J. Environ. Prot. 3 (1) (2014) 19–27.

[204] A.P. Naik, S.K. Shyama, A.H. D'Costa, Evaluation of genotoxicity, enzymatic alterations and cadmium accumulation in Mozambique tilapia Oreochromis mossambicus exposed to sub lethal concentrations of cadmium chloride. Environ. Chem. Ecotoxicol. 2 (2020) 126–131.

[205] B. Genthe, et al., The reach of human health risks associated with metals/metalloids in water and vegetables along a contaminated river catchment: South Africa and Mozambique, Chemosphere 199 (2018) 1–9.

[206] K. Taslima, et al., Impacts of heavy metals on early development, growth and reproduction of fish–a review, Toxicol. Rep. 9 (2022) 858–868.

[207] J. Briffa, E. Sinagra, R. Blundell, Heavy metal pollution in the environment and their toxicological effects on humans, Heliyon 6 (9) (2020) e04691.

[208] D. Thippesh, K. Velayudhannair, D. Sayantan, Ecological risk assessment and seasonal variation of heavy metals in water, sediment and biota collected from shambhavi estuary, mulki, Karnataka, J. Surv. Fish. Sci. 10 (4S) (2023) 2329–2344.

[209] C.P.A. de Oliveira, et al., Does environmental pollution affect male reproductive system in naturally exposed vertebrates? A systematic review, Theriogenology (2023).

[210] D. Goyal, et al., Effect of Heavy Metals on Plant Growth: An Overview, in: M. Naeem, A.A. Ansari, S.S. Gill (Eds.), Contaminants in Agriculture: Sources, Impacts and Management, Springer International Publishing, Cham, 2020, pp. 79–101.

[211] G.N. Lion, J.O. Olowoyo, Population health risk due to dietary intake of toxic heavy metals from Spinacia oleracea harvested from soils collected in and around Tshwane, South Africa, South African Journal of Botany 88 (2013), pp. 178–182.

[212] B. Moyo, V. Matodzi, M.A. Legodi, V.E. Pakade, N.T. Tavengwa, Determination of Cd, Mn and Ni accumulated in fruits, vegetables and soil in the Thohoyandou town area, Water SA 46 (2) (2020) 285–290.

[213] R. Mongi, L. Chove, Heavy metal contamination in cocoyam crops and soils in countries around the lake victoria basin (Tanzania, Uganda and Kenya), Tanzan. J. Agric. Sci. 19 (2) (2020) 148–160.

[214] T.E. Bahemuka, E.B. Mubofu, Heavy metals in edible green vegetables grown along the sites of the Sinza and Msimbazi rivers in Dar es Salaam, Tanzania, Food Chem. 66 (1) (1999) 63–66.

[215] M. Marco Mng'ong'o, K. L, P.A. Ndakidemi, W. Blake, S. Comber, T.H. Hutchinson, Accumulation and bioconcentration of heavy metals in two phases from agricultural soil to plants in Usangu agroecosystem-Tanzania, Heliyon 7 (7) (2021).

[216] T.R. Sanga, K.K. Maseka, M. Ponraj, C. Tungaraza, E.B. Mwakalapa, Accumulation and distribution of mercury in agricultural soils, food crops and associated health risks: a case study of Shenda gold mine-Geita Tanzania, Environ. Chall. 11 (2023) 100697.

[217] R.M. Tomno, et al., Heavy metal contamination of water, soil and vegetables in urban streams in Machakos municipality, Kenya, Sci. Afr. 9 (2020) e00539.

[218] N. John Ng'ang'a, M.J. Bosco, M.P. Wasike, K.A. Wanjiru, Heavy metal occurrence within urban agriculture practices in eastern zones of Nairobi city, *J. Agric.* Sci. Technol. 22 (3) (2023) 146–158.

[219] Y. Gelaye, S. Musie, Impacts of heavy metal pollution on ethiopian agriculture: a review on the safety and quality of vegetable crops, Adv. Agric. 2023 (2023).

[220] G. Habte, et al., Heavy metal contamination and health risk assessment of horticultural crops in two sub-cities of Addis Ababa, Ethiopia, Toxicol. Rep. 11 (2023) 420–432.

[221] M. Mbodji, et al., Speciation of metals by sequential extractions of agricultural soils located near a dumpsite for prediction of element availability to vegetables, Talanta 244 (2022) 123411.

[222] R. Adjei-Mensah, et al., Effect of home processing methods on the levels of heavy metal contaminants in four food crops grown in and around two mining towns in Ghana, Toxicol. Rep. 8 (2021) 1830–1838.

[223] A.T. Mlangeni, et al., Health risk assessment of toxic metal (loids)(As, Cd, Pb, Cr, and Co) via consumption of medicinal herbs marketed in Malawi, Toxicol. Rep. 11 (2023) 145–152.

[224] T. Bakary, et al., Evaluation of heavy metals and pesticides contents in market-gardening products sold in some principal markets of Ouagadougou (Burkina Faso), J. Microbiol., Biotechnol. Food Sci. 8 (4) (2019) 1026–1034.

[225] T. Manyiwa, et al., Spatial variability of heavy metals in soils and vegetation and associated risk to grazing animals in the abandoned gold mine in Francistown, Botswana, Environ. Pollut. Bioavailab. 35 (1) (2023) 2254493.

[226] K.I. Kasozi, E.O. Otim, H.I. Ninsiima, G. Zirintunda, A. Tamale, J. Ekou, … O. Otim, An analysis of heavy metals contamination and estimating the daily intakes of vegetables from Uganda, Toxicol. Res. Appl. 5 (2021) p. 2397847320985255.

[227] A. Tagumira, S. Biira, E.B. Amabayo, Concentrations and human health risk assessment of selected heavy metals in soils and food crops around Osukuru phosphate mineTororo District, Uganda, Toxicol. Rep. 9 (2022) 2042–2049.

[228] R. Yadav, et al., Heavy metal toxicity in earthworms and its environmental implications: a review, Environ. Adv. (2023) 100374.

[229] M. Rwiza, N. Mohammed, F. Banzi, The influence of gold mining on radioactivity of mining sites soil in Tanzania, MEWES, NMAIST,, 2022, p. 2022.

[230] J. Bosse Jønsson, E. Charles, P. Kalvig, Toxic mercury versus appropriate technology: artisanal gold miners' retort aversion, Resour. Policy 38 (1) (2013) 60–67.

[231] E. Charles, et al., A cross-sectional survey on knowledge and perceptions of health risks associated with arsenic and mercury contamination from artisanal gold mining in Tanzania, BMC Public Health 13 (1) (2013) 74.

[232] E.C. Nyanza, et al., Spatial distribution of mercury and arsenic levels in water, soil and cassava plants in a community with long history of gold mining in Tanzania, Bull. Environ. Contam. Toxicol. 93 (6) (2014) 716–721.

[233] E.C. Nyanza, et al., Maternal exposure to arsenic and mercury and associated risk of adverse birth outcomes in small-scale gold mining communities in Northern Tanzania, Environ. Int. 137 (2020) 105450.

[234] M.J. Rwiza, K.W. Kim, Sd Kim, Geochemical distribution of trace elements in groundwater from the north mara large-scale gold mining area of Tanzania, Groundw. Monit. Remediat. 36 (2) (2016) 83–93.

[235] A.A.J. Ghanim, et al., The influence of compost amendments on bioaccumulation of potentially toxic elements by pea plant cultivated in mine degraded soils, Arab. J. Geosci. 16 (1) (2023) 46.

[236] I. Kaur, et al., Role of metallic pollutants in neurodegeneration: effects of aluminum, lead, mercury, and arsenic in mediating brain impairment events and autism spectrum disorder, Environ. Sci. Pollut. Res. 28 (2021) 8989–9001.

[237] E.C. Nyanza, et al., Effects of prenatal exposure and co-exposure to metallic or metalloid elements on early infant neurodevelopmental outcomes in areas with small-scale gold mining activities in Northern Tanzania, Environ. Int. 149 (2021) 106104.

[238] M. Balali-Mood, et al., Toxic mechanisms of five heavy metals: mercury, lead, chromium, cadmium, and arsenic, Front. Pharmacol. 12 (2021) 643972.

[239] M. Cabral, et al., Renal impairment assessment on adults living nearby a landfill: early kidney dysfunction biomarkers linked to the environmental exposure to heavy metals, Toxicol. Rep. 8 (2021) 386–394.

[240] C.S.M. Ruano, et al., The impact of oxidative stress of environmental origin on the onset of placental diseases, Antioxidants 11 (1) (2022) 106.

[241] A.-M. Yang, et al., Environmental heavy metals and cardiovascular diseases: status and future direction, Chronic Dis. Transl. Med. 6 (04) (2020) 251–259.

[242] Ç. Sevim, E. Doğan, S. Comakli, Cardiovascular disease and toxic metals, Curr. Opin. Toxicol. 19 (2020) 88–92.

[243] N. Mbandzi, M.D.V. Nakin, G.M. Saibu, A.O. Oyedeji, Heavy metal profiles in limpets and algae on the Eastern Cape coast of South Africa, Afr. J. Mar. Sci. 43 (3) (2021) **293–308**.

[244] L.L.J. Kamzati, C.C. Kaonga, H.W.T. Mapoma, F.G. Thulu, S.M. Abdel-Dayem, A.J. Anifowose, H. Sakugawa, Heavy metals in water, sediment, fish and associated risks from an endorheic lake located in Southern Africa, Int. J. Environ. Sci. Technol. 17 (2020) 253–266.

[245] N. Mbandzi, M.D.V. Nakin, A.O. Oyedeji, Temporal and spatial variation of heavy metal concentration in four limpet species along the southeast coast of South Africa, Environ. Pollut. 302 (2022) 119056p. 302.

[246] N.K. Kortei, et al., Health risk assessment and levels of toxic metals in fishes (Oreochromis noliticus and Clarias anguillaris) from Ankobrah and Pra basins: impact of illegal mining activities on food safety, Toxicol. Rep. 7 (2020) 360–369.

[247] E. Effah, et al., Human health risk assessment from heavy metals in three dominant fish species of the Ankobra river, Ghana, Toxicol. Rep. 8 (2021) 1081–1086.

[248] E. Nyarko, et al., Potential human health risks associated with ingestion of heavy metals through fish consumption in the Gulf of Guinea, Toxicol. Rep. 10 (2023) 117–123.

[249] F. Sardenne, et al., Persistent organic pollutants and trace metals in selected marine organisms from the Akanda National Park, Gabon (Central Africa), Mar. Pollut. Bull. 199 (2024) 116009.

[250] K. Elahee, S. Bhagwant, Hematological and gill histopathological parameters of three tropical fish species from a polluted lagoon on the west coast of Mauritius, Ecotoxicol. Environ. Saf. 68 (3) (2007) 361–371.

[251] J.O. Outa, C.O. Kowenje, A. Avenant-Oldewage, F. Jirsa, Trace elements in crustaceans, mollusks and fish in the kenyan part of Lake Victoria: bioaccumulation, bioindication and health risk analysis, Arch. Environ. Contam. Toxicol. 78 (2020) 589–603.

[252] I.P. Adegbola, B.A. Aborisade, A. Adetutu, Health risk assessment and heavy metal accumulation in fish species (Clarias gariepinus and Sarotherodon melanotheron) from industrially polluted Ogun and Eleyele Rivers, Nigeria, Toxicol. Rep. 8 (2021) 1445–1460.

[253] A.M. Mustapha, A.Y. Ugya, Z. Mustapha, Assessment of heavy metal levels in fish tissues, water and sediment from Epe lagoon, Lagos, Nigeria, Sci. World J. 16 (4) (2021) 464–469.

[254] J.O. Olayinka-Olagunju, A.A. Dosumu, A.M. Olatunji-Ojo, Bioaccumulation of heavy metals in pelagic and benthic fishes of Ogbese River, Ondo State, South-Western Nigeria, Water, Air, Soil Pollut. 232 (2) (2021) 44.

[255] A. Sani, K.M. Idris, B.A. Abdullahi, A.I. Darma, Bioaccumulation and health risks of some heavy metals in Oreochromis niloticus, sediment and water of Challawa river, Kano, Northwestern Nigeria, Environ. Adv. 7 (2022) 100172.

[256] Y.Z. Sawadogo, T.L. Bambara, M. Derra, I. Zongo, K. Kaboré, F. Zougmoré, Evaluation of Heavy Metal Pollution and Physico-Chemical Parameters in Agricultural Soils of Bouly. Burkina-Faso, J. Mater. 11 (2) (2023) 38–47.

[257] I.S. Baglo, D. Lederoun, O. Neya, P.A. Lalèyè, Physicochemical Quality of the Water and Heavy Metal Contamination of the Sediment, Water, and Flesh of Some Fish in the Lower Reaches of the Mono River (Benin, West Africa), J. Fish. Environ. 48 (1) (2024) 1–17.

[258] C.K. Simukoko, E.B. Mwakalapa, P. Bwalya, K. Muzandu, V. Berg, S. Mutoloki, … J.L. Lyche, Assessment of heavy metals in wild and farmed tilapia (Oreochromis niloticus) on Lake Kariba, Zambia: implications for human and fish health, Food Addit. Contam.: Part A 39 (1) (2022) 74–91.

[259] H.K. Mata, P. Sivalingam, J. Konde, J.P. Otamonga, B. Niane, C.K. Mulaji, J.W. Poté, Concentration of toxic metals and potential risk assessment in edible fishes from Congo River in urbanized area of Kinshasa, DR Congo, *Hum. Ecol. Risk Assess.* Int. J. 26 (6) (2020) 1676–1692.

[260] B. Shezi, et al., Heavy metal contamination of soil in preschool facilities around industrial operations, Kuils River, Cape Town (South Africa), Int. J. Environ. Res. Public Health 19 (7) (2022) 4380.

[261] G. Baguma, et al., Heavy metal contamination of sediments from an exoreic African great lakes' shores (Port Bell, Lake Victoria), Uganda, Pollutants 2 (4) (2022) 407–421.

[262] L.S. Azevedo, et al., Mercury biomagnification in an ichthyic food chain of an amazon floodplain lake (Puruzinho Lake): Influence of seasonality and food chain modeling, Ecotoxicol. Environ. Saf. 207 (2021) 111249.

[263] M.B. Etsuyankpa, et al., Levels of selected heavy metals in blood and urine of workers of Alkali Kongo Plaza GSM Market within Lafia Metropolis, Nasarawa State, Nigeria, Environ. Chall. 9 (2022) 100649.

[264] A. Ali, et al., Evaluation of heavy metal concentration in body fluid of the inhabitants living along aba river, abia state, Nigeria, J. Nat. Sci. Eng. Technol. 21 (1) (2022) 50–66.

[265] I.L. Abdullahi, A. Sani, B. Aminu Jibril, Occupational exposure to metals among blacksmiths in Kano Metropolis, Nigeria, (مجله مدیریت و مهندسی بهداشت محیط) 7 (2) (2020) 135–141.

[266] K. Zheng, et al., Epidemiological evidence for the effect of environmental heavy metal exposure on the immune system in children, Sci. Total Environ. 868 (2023) 161691.

[267] Thurston, M.L., M. von Braun Mentor, and I. von Lindern Mentor, Spatial Analysis of Soil Lead Exposures from Lead Poisoning Tragedy in Artisanal and Small-Scale Gold Mining Villages of Zamfara, Nigeria. 2020.

[268] M.J. Brown, A.D. Woolf, Zamfara gold mining lead poisoning disaster—Nigeria, Africa, 2010, History of Modern Clinical Toxicology, Elsevier,, 2022, pp. 97–107.

[269] J. Ashley-Martin, et al., Heavy metal blood concentrations in association with sociocultural characteristics, anthropometry and anemia among Kenyan adolescents, Int. J. Environ. Health Res. 32 (9) (2022) 1935–1949.

[270] M.J. Watts, et al., Human urinary biomonitoring in Western Kenya for micronutrients and potentially harmful elements, Int. J. Hyg. Environ. Health 238 (2021) 113854.

[271] S.S. Omenka, A.A. Adeyi, Heavy metal content of selected personal care products (PCPs) available in Ibadan, Nigeria and their toxic effects, Toxicol. Rep. 3 (2016) 628–635.

[272] E.A. Godwill, et al., Determination of some soft drink constituents and contamination by some heavy metals in Nigeria, Toxicol. Rep. 2 (2015) 384–390.

[273] J.K. Nduka, H.I. Kelle, E.C. Ogoko, Hazards and risk assessment of heavy metals from consumption of locally manufactured painkiller drugs in Nigeria, Toxicol. Rep. 7 (2020) 1066–1074.

[274] C.M. Iwegbue, et al., Evaluation of human exposure to metals from some commonly used hair care products in Nigeria, Toxicol. Rep. 3 (2016) 796–803.

[275] C.M. Iwegbue, et al., Evaluation of human exposure to metals from some commonly used bathing soaps and shower gels in Nigeria, Regul. Toxicol. Pharmacol. 83 (2017) 38–45.

[276] O. Olujimi, et al., Levels of toxic and trace metals in the breast milk of lactating mothers in Abeokuta, Ogun State, Nigeria, Toxicol. Rep. 11 (2023) 168–173.

[277] I.L. Usende, B.O. Emikpe, J.O. Olopade, Heavy metal pollutants in selected organs of African giant rats from three agro-ecological zones of Nigeria: evidence for their role as an environmental specimen bank, Environ. Sci. Pollut. Res. 24 (2017) 22570–22578.

[278] A. Ogunfowokan, et al., Determination of heavy metals in urine of patients and tissue of corpses by atomic absorption spectroscopy, Chem. Afr. 2 (2019) 699–712.

[279] A.V. Wirnkor, et al., Biomonitoring of heavy metals in blood and urine of African children from owerrimetropolis, eastern Nigeria, J. Chem. Health Risks 9 (1) (2019) 11–26.

[280] A.N. Okpogba, et al., Evaluation of some heavy metal levels in blood of lead acid battery manufacturing factory workers in Nnewi, Nigeria, Indian J. Pharm. Pharm. 7 (2) (2020) 82–94.

[281] J. Akan, et al., Determination of heavy metals in blood, urine and water samples by inductively coupled plasma atomic emission spectrophotometer and fluoride using ion-selective electrode, J. Anal. Bioanal. Tech. 5 (9) (2014) 1–7.

[282] C.N. Amadi, Z.N. Igweze, O.E. Orisakwe, Heavy metals in miscarriages and stillbirths in developing nations, Middle East Fertil. Soc. J. 22 (2) (2017) 91–100.

[283] Y. Tuakashikila, et al., Cadmium, Manganese, Mercury and Lead in the general adult population of Kinshasa, DR Congo, Sci. Afr. (2023) e02027.

[284] S.E. Cusick, et al., Assessment of blood levels of heavy metals including lead and manganese in healthy children living in the Katanga settlement of Kampala, Uganda, BMC Public Health 18 (2018) 1–8.

[285] S. Park, et al., Blood levels of environmental heavy metals are associated with poorer iron status in ugandan children: a cross-sectional study, J. Nutr. 153 (10) (2023) 3023–3031.

[286] J.A. Mahugija, Z.S. Kasenya, K.F. Kilulya, Levels of heavy metals in urine samples of school children from selected industrial and non-industrial areas in Dar es Salaam, Tanzania, Afr. Health Sci. 18 (4) (2018) 1226–1235.

[287] E.C. Nyanza, et al., Exposure to toxic chemical elements among people living with HIV/AIDS in Northern Tanzania, Environ. Res. (2024) 119645.

[288] H.R. Ali, et al., Levels of lead (Pb), cadmium (Cd) and cobalt (Co) in cow milk from selected areas of Zanzibar Island, Tanzania, Am. J. Anal. Chem. 14 (7) (2023) 287–304.

[289] E.C. Nyanza, et al., Maternal exposure to arsenic and mercury in small-scale gold mining areas of Northern Tanzania, Environ. Res. 173 (2019) 432–442.

[290] D.S. Thomas, M. Asori, E.C. Nyanza, The role of geophagy and artisanal gold mining as risk factors for elevated blood lead levels in pregnant women in northwestern Tanzania, PLOS Glob. Public Health 4 (2) (2024) e0002958.

[291] L. Nakaona, et al., Using human hair and nails as biomarkers to assess exposure of potentially harmful elements to populations living near mine waste dumps, Environ. Geochem. Health 42 (2020) 1197–1209.

[292] L. Macheka, et al., Trace metals in blood and urine of pregnant women practicing geophagia at Dr. George Mukhari Academic Hospital, Pretoria, South Africa, Med. Technol. SA 30 (1) (2016) 45–48.

[293] J. Olowoyo, et al., Blood lead concentrations in exposed forecourt attendants and taxi drivers in parts of South Africa, J. Trace Elem. Med. Biol. 81 (2024) 127348.

[294] J.O. Olowoyo, et al., Toxic trace metals in blood of occupationally exposed casual mine workers living in shacks around mining area in Brits, South Africa, Trace Elem. Electrolytes 37 (1) (2020) 1.

[295] B.K. Dessie, et al., Absence of significant association of trace elements in nails with urinary KIM-1 biomarker among residents of Addis Ababa in Upper Awash Basin, Ethiopia: a cross-sectional study, BioMetals 35 (6) (2022) 1341–1358.

[296] B.K. Dessie, et al., Urinary 8-OHdG level is not affected by geography and trace elements in nail of residents of Addis Ababa: it is shaped by interactions between different social factors, Toxicol. Rep. 9 (2022) 1777–1787.

[297] M.L. Astolfi, et al., Element levels and predictors of exposure in the hair of Ethiopian children, Int. J. Environ. Res. Public Health 17 (22) (2020) 8652.

[298] B.K. Dessie, et al., Evaluation of toxic elements in nails of tannery workers in Addis Ababa, Ethiopia, Microchem. J. 159 (2020) 105589.

[299] S. Demissie, et al., Assessing acute and chronic risks of human exposure to arsenic: a cross-sectional study in ethiopia employing body biomarkers, Environ. Health Insights 18 (2024) p. 11786302241257365.

[300] M. Humphries, et al., High lead exposure and clinical signs of toxicosis in wild Nile crocodiles (Crocodylus niloticus) from a World Heritage site: Lake St Lucia estuarine system, South Africa, Chemosphere 303 (2022) 134977.

[301] R.O. Moruf, A.F. Durojaiye, G.F. Okunade, Metal contamination and health risks in west african mud creeper (Tympanotonos fuscatus var r adula) from Abule-Agele Creek, Nigeria, Bull. Environ. Contam. Toxicol. 108 (2) (2022) 351–358.

[302] M. Chakrabartty, G.M. Harun-Or-Rashid, Feasibility study of the soil remediation technologies in the natural environment, Am. J. Civ. Eng. 9 (2021) 91–98.

[303] S. Hassan, et al., Revitalizing contaminated lands: a state-of-the-art review on the remediation of mine-tailings using phytoremediation and genomic approaches, Chemosphere (2024) 141889.

[304] A. Saravanan, et al., Removal of toxic heavy metals using genetically engineered microbes: Molecular tools, risk assessment and management strategies, Chemosphere (2022) 134341.

[305] A.K. Awasthi, et al., Assessing strategic management of E-waste in developing countries, Sustainability 15 (9) (2023) 7263.

[306] K.J. Bansah, Artisanal and small-scale mining formalization in Ghana: the government's approach and its implications for cleaner and safer production, J. Clean. Prod. 399 (2023) 136648.

[307] H.J. Oladipo, et al., Global environmental health impacts of rare earth metals: insights for research and policy making in Africa, Challenges 14 (2) (2023) 20.

[308] Ssanyu, G.A., et al., Community perception of heavy metal pollution and related risks in Lake Victoria Wetlands, Uganda. 2023.

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

[310] Z. Khanam, F.M. Sultana, F. Mushtaq, Environmental pollution control measures and strategies: an overview of recent developments, Geospatial Anal. Environ. Pollut. Model.: Anal., Control Manag. (2023) 385–414.

[311] O. Ogbeide, B. Henry, Addressing heavy metal pollution in Nigeria: evaluating policies, assessing impacts, and enhancing remediation strategies, J. Appl. Sci. Environ. Manag. 28 (4) (2024) 1007–1051.

[312] S. Ngwenya, et al., Community perceptions on health risks associated with toxic chemical pollutants in Kwekwe City, Zimbabwe: a qualitative study, Environ. Health Insights 18 (2024) p. 11786302241260487.

[313] E.N.B. Kohio, et al., Review of pollution trends and impacts in artisanal and small-scale gold mining in Sub-Saharan Africa: advancing towards sustainable practices through equitable redistribution of gold spin-offs, J. Clean. Prod. (2024) 143754.

[314] Y. Gelaye, Public health and economic burden of heavy metals in Ethiopia, Heliyon 10 (19) (2024).

[315] M.A. Ondayo, et al., Artisanal gold mining in africa—environmental pollution and human health implications, Expo. Health 16 (4) (2024) 1067–1095.

[316] B.N. Mvile, O.K. Bishoge, Mining and sustainable development goals in Africa, Resour. Policy 90 (2024) 104710.

[317] L.O. Uche, O. Azoro-Amadi, Aligning Nigeria's international obligations: a comprehensive analysis of environmental protection within the industrial law and policy framework, South Afr. Yearb. Int. Law 49 (1) (2024) 1–34.

[318] G.A. Odha, Environmental Policy Implementation Effects on Prevention and Control of River Water Pollution in Kenya: A Case of Ngong River, Nairobi City County, Kenyatta University,, 2024.

[319] Y.U. Sikuzani, et al., Lubumbashi (DR Congo): navigating the socio-ecological complexities of a vital mining hub, Cities 154 (2024) 105341.

[320] O. Analytica, Southern Africa court ruling limits mining liabilities, Emerald Expert Brief. (oxan-db) (2024).

[321] A.K. Donkor, H. Ghoveisi, J.-C.J. Bonzongo, Use of metallic mercury in artisanal gold mining by amalgamation: a review of temporal and spatial trends and environmental pollution, Minerals 14 (6) (2024) 555.

[322] J. Yao, et al., Editing of a novel cd uptake-related gene CUP1 contributes to reducing cd accumulations in Arabidopsis thaliana and Brassica napus, Cells 11 (23) (2022) 3888.

[323] N. Jiang, et al., Expression of OsHARBI1-1 enhances the tolerance of Arabidopsis thaliana to cadmium, BMC Plant Biol. 23 (1) (2023) 556.

[324] M. Pacenza, et al., In Arabidopsis thaliana Cd differentially impacts on hormone genetic pathways in the methylation defective ddc mutant compared to wild type, Sci. Rep. 11 (1) (2021) 10965.

[325] M. De Benedictis, et al., Cadmium treatment induces endoplasmic reticulum stress and unfolded protein response in Arabidopsis thaliana, Plant Physiol. Biochem. 196 (2023) 281–290.

[326] L. Zhou, et al., Overexpression of ApHIPP26 from the Hyperaccumulator Arabis paniculata confers enhanced cadmium tolerance and accumulation to Arabidopsis thaliana, Int. J. Mol. Sci. 24 (20) (2023) 15052.

[327] W. Yang, et al., Magnetically separable and recyclable Fe3O4@ PDA covalent grafted by l-cysteine core-shell nanoparticles toward efficient removal of Pb2, Vacuum 189 (2021) 110229.

[328] X. Zhou, et al., Functionalized lignin-based magnetic adsorbents with tunable structure for the efficient and selective removal of Pb (II) from aqueous solution, Chem. Eng. J. 420 (2021) 130409.

[329] M. Bhaumik, A. Maity, H.G. Brink, Zero valent nickel nanoparticles decorated polyaniline nanotubes for the efficient removal of Pb (II) from aqueous solution: synthesis, characterization and mechanism investigation, Chem. Eng. J. 417 (2021) 127910.

[330] M. Barakat, New trends in removing heavy metals from industrial wastewater, Arab. J. Chem. 4 (4) (2011) 361–377.

[331] M.O. Erdiaw-Kwasie, M. Abunyewah, C. Baah, A systematic review of the factors–Barriers, drivers, and technologies–Affecting e-waste urban mining: on the circular economy future of developing countries, J. Clean. Prod. (2024) 140645.

[332] M. Fatkullin, et al., Nanomaterials/polymer-integrated flexible sensors: a full-laser-processing approach for real-time analyte monitoring, IEEE Sens. J. (2024).

[333] S.S. Nadumane, R. Biswas, N. Mazumder, Integrated microfluidic platforms for heavy metal sensing: a comprehensive review, Anal. Methods (2024).

[334] M.N. Ramadan, et al., Real-time IoT-powered AI system for monitoring and forecasting of air pollution in industrial environment, Ecotoxicol. Environ. Saf. 283 (2024) 116856.

[335] C. Mahobiya, et al., Navigating the future: unmanned aerial systems in IoT paradigms, Unmanned Aircr. Syst. (2024) 355–385.

[336] S.M. Popescu, et al., Artificial intelligence and IoT driven technologies for environmental pollution monitoring and management, Front. Environ. Sci. 12 (2024) 1336088.

[337] K. Sharma, S.K. Shivandu, Integrating artificial intelligence and Internet of Things (IoT) for enhanced crop monitoring and management in precision agriculture, Sens. Int. (2024) 100292.

[338] A. Ripanda, et al., Removal of lamivudine from synthetic solution using jamun seed (Syzygium cumini) biochar adsorbent, Emerg. Contam. 9 (3) (2023) 100232.

[339] A. Ripanda, et al., Optimizing ciprofloxacin removal from water using jamun seed (Syzygium cumini) biochar: a sustainable approach for ecological protection, HydroResearch 7 (2024) 164–180.