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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.

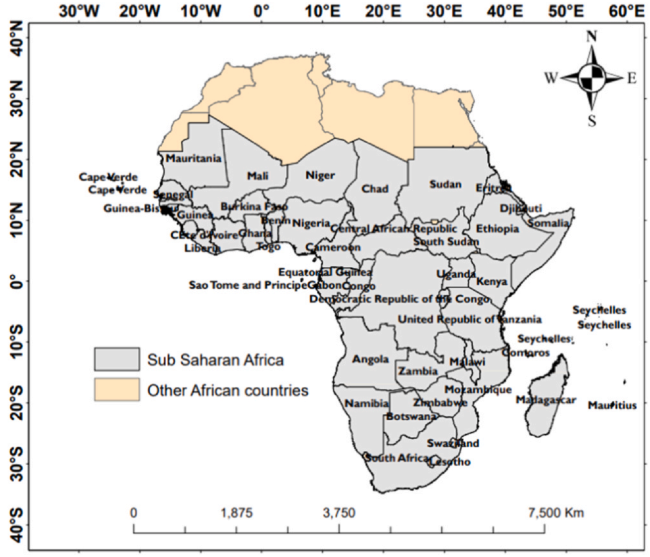

Fig. 1. Presents a map of Sub-Saharan Africa, Base map data
Source: OCHA, https://data.humdata.org/dataset/cod-ab-tza. Map created by authors.

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

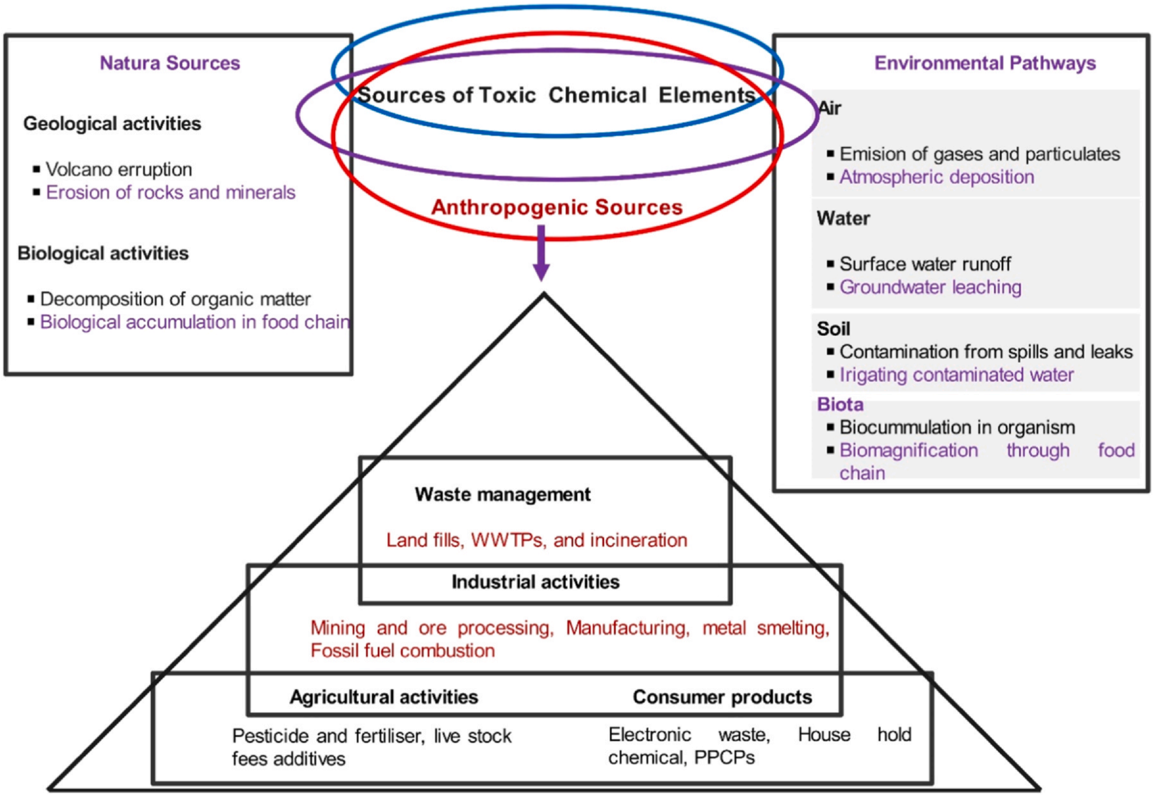

Fig. 2. Brief description of sources of toxic chemical pollution.

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

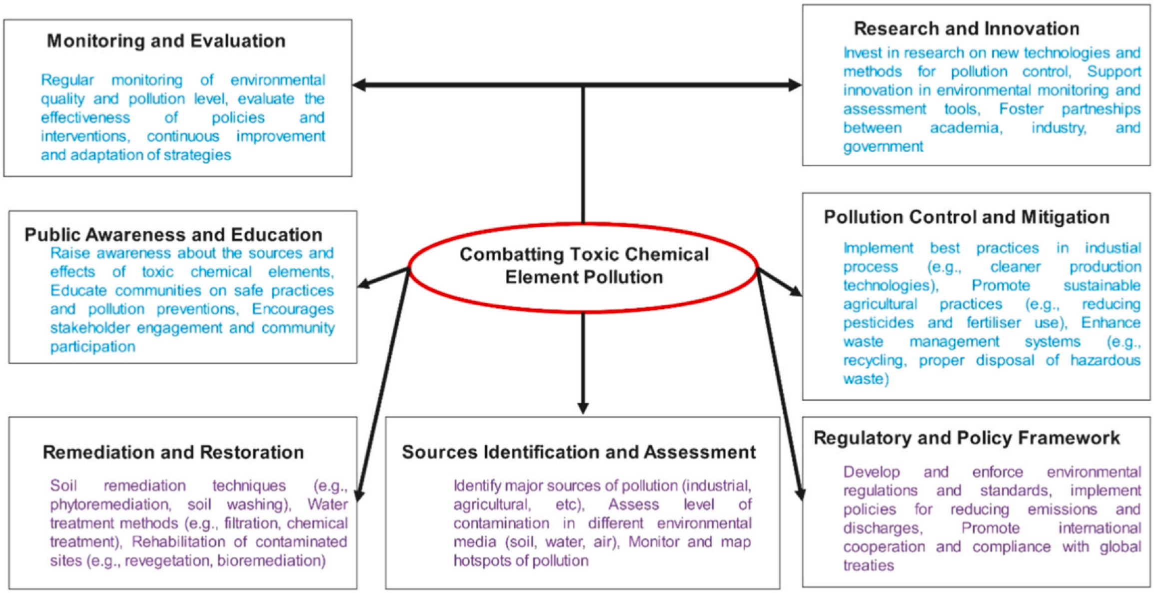

Fig. 3. Brief description of potential strategies for combatting toxic chemical element pollution.

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.

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