Rare Earth and Platinum Group Elements In Sub-Saharan Africa and Global Health: The Dark Side of the Burgeoning of Technology

Environmental Health Insights
Volume 18: 1–25
© The Author(s) 2024
Article reuse guidelines:
sagepub.com/journals-permissions
DOI: 10.1177/11786302241271553
Sage

Chiara Frazzoli[1], Beatrice Bocca[2], Beatrice Battistini[2], Flavia Ruggieri[2], Joaquim Rovira[3,4], Cecilia Nwadiuto Amadi[5], Samuel James Offor[6] and Orish E Orisakwe[7,8]

[1]Department of Cardiovascular and Endocrine-Metabolic Diseases, and Ageing, Istituto Superiore di Sanità (Italian National Institute of Health), Rome, Italy. [2]Department of Environment and Health, Istituto Superiore di Sanità, Rome, Italy. [3]Laboratory of Toxicology and Environmental Health, School of Medicine, IISPV, Universitat Rovira i Virgili, Reus, Catalonia, Spain. [4]Environmental Engineering Laboratory, Department d'Enginyeria Quimica, Universitat Rovira i Virgili, Tarragona, Catalonia, Spain. [5]Department of Experimental Pharmacology & Toxicology, Faculty of Pharmacy, University of Port-Harcourt, Port-Harcourt, Rivers State, Nigeria. [6]Department of Pharmacology and Toxicology, Faculty of Pharmacy, University of Uyo, Uyo, Akwa Ibom State, Nigeria. [7]African Centre of Excellence for Public Health and Toxicological Research (ACE-PUTOR), University of Port Harcourt, Port Harcourt, Choba, Nigeria. [8]Advanced Research Centre, European University of Lefke, Lefke, Northern Cyprus, Turkey.

ABSTRACT: Despite steady progress in the development and promotion of the circular economy as a model, an overwhelming proportion of technological devices discarded by the Global North still finds its way to the Global South, where technology-related environmental health problems start from the predation of resources and continue all the way to recycling and disposal. We reviewed literature on TCEs in sub-Saharan Africa (SSA), focussing on: the sources and levels of environmental pollution; the extent of human exposure to these substances; their role in the aetiology of human diseases; their effects on the environment. Our review shows that even minor and often neglected technology-critical elements (TCEs), like rare earth elements (REEs) and platinum group elements (PGEs), reveal the environmental damage and detrimental health effects caused by the massive mining of raw materials, exacerbated by improper disposal of e-waste (from dumping to improper recycling and open burning). We draw attention of local research on knowledge gaps such as workable safer methods for TCE recovery from end-of-life products, secondary materials and e-waste, environmental bioremediation and human detoxification. The technical and political shortcomings in the management of TCEs in SSA is all the more alarming against the background of unfavourable determinants of health and a resulting higher susceptibility to diseases, especially among children who work in mines and e-waste recycling sites or who reside in dumping sites.This paper demonstrates, for the first time, that the role of unjust North-South dynamics is evident even in the environmental levels of minor trace elements and that the premise underlying attempts to solve the problem of e-waste dumped in Africa through recycling and disposal technology is in fact misleading. The influx of foreign electrical and electronic equipments should be controlled and limited by clearly defining what is a 'useful' second-hand device and what is e-waste; risks arising from device components or processing by-products should be managed differently, and scientific uncertainty and One Health thinking should be incorporated in risk assessment.

KEYWORDS: Mining, e-waste, dumping, circular economy, One Health, global health

RECEIVED: March 28, 2024. **ACCEPTED:** July 1, 2024.

TYPE: Review

FUNDING: The author(s) received no financial support for the research, authorship, and/or publication of this article.

DECLARATION OF CONFLICTING INTERESTS: The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

CORRESPONDING AUTHORS: Chiara Frazzoli, Department of Cardiovascular and Endocrine-Metabolic Diseases, and Ageing, Istituto Superiore di Sanità (Italian National Institute of Health), Via Giano della Bella 34, Rome 00162, Italy. Email: chiara.frazzoli@iss.it

Orish E Orisakwe, World Bank Africa Centre of Excellence in Public Health and Toxicological Research (PUTOR), University of Port Harcourt, PMB 5323, Port Harcourt, Rivers State, Nigeria. Emails: orishebere@gmail.com; orish.orisakwe@uniport.edu.ng

Introduction

According to the most updated classifications, thirty elements and minerals fall into the definition of TCEs by the European Commission, including the REEs and PGEs.[1] TCEs are used in high-tech products and everyday consumer products, such as cell phones, thin-layer photovoltaics, lithium-ion batteries, fibre-optic cable and synthetic fuels. Many emerging key technological fields – including renewable energy, energy efficiency, electronics and the aerospace industry – use REEs.[2] TCEs are also used in the transportation industry and particularly in electric motors containing Nd and Dy and batteries containing Li. Automation and robotics, which are increasingly used in artificial intelligence, use TCEs like Nd and Dy.[3]

The mining and processing of REEs has in the past resulted in significant environmental impacts in several countries, including Brazil, China, and the United States.[4] Studies have already proved how the anthropogenic input of TCEs has perturbed the natural biogeochemical cycles and how some elements have rapidly accumulated in specific environmental compartments, for example, Gd in rivers, lakes, coastal waters, groundwater, wastewater and tap water.[5] Roadside soils and street dust are receptacles of

TCEs pollutants (eg, Pt, La, Ce, Nd, etc.), and TCEs can be deposited in plants or transferred into storm water runoff, becoming bioaccessible for humans.[6] Remediation of contaminated sites can be expensive; for example, the estimated cost of remediating the Mitsubishi REE processing site in Bukit Merah, Malaysia, was $100 million.[7]

TCEs have been scarcely investigated so far in terrestrial or marine environments. They remain unregulated and out of routine environmental or human safety monitoring plans.[2] This may also depend on the analytical determination of TCEs which is extremely difficult and time-consuming owing to TCEs typical ultratrace concentrations. Only a few studies have explored human exposure to TCEs through food,[8,9] herbal products,[10] soil for geophagic consumption,[11] and food-contact materials, toys, and other consumer plastics.[12] Whilst there are significant knowledge gaps regarding TCE environmental levels, fate, and potential (eco and human) toxicological impact, the current and future expanded extraction and use of TCEs makes their unknown toxicity and potential as inorganic contaminants a substantial concern.[2,13]

Resource sustainability: Circular economy

There is an urgent need to minimize the demand for virgin TCEs through alternative materials, recycling, reuse, and other means. The engagement in: (i) circular economies, for example, safe and regulated extraction and recovery of TCEs from secondary materials and e-waste[14]; (ii) environmental regulations and (iii) metals bioavailability predictive modelling[15] are expected to facilitate the sustainability of TCEs usage.

Considerable efforts are underway to extract REEs from secondary materials (eg, tailings, bauxite residues, coal combustion ash) and e-waste.[16] For example, the recycling of elements from wind turbines and solar panels becomes necessary for the expansion of renewable energy production.[17] To promote circular economy and resource efficiency, the anthropogenic and global fluxes of TCEs have to be globally monitored.[18]

Urban mining is based on the value recovery of secondary raw materials from anthropogenic sources. The use of by-products as secondary resources rather than treating them as waste can keep the circular economy moving. The recovery of TCEs from sources as old tailings or contaminated soils is often challenging from an engineering and economic viewpoint.[19,20] In some cases, materials dissipated into the environment might be recovered as technologies advance – for example, recovery of PGEs such as Pt and Pd from roadside dust,[21] while in other cases recovery might not be possible due to the high energy requirements involved.[22] Several pre-treatment and acidic leaching processes are identified with promise to recover REEs at full scale in e-waste recovery plants and thereby advancing goals for a sustainable circular economy.[23]

Recycling is a way to reduce mining impacts. Elements will have to be sourced from wastes, including e-waste and mine tailings, thus requiring a change in waste management systems.[24] The level of collection and recycling of metals from secondary resources depends on various factors such as market prices for the materials, product compositions, recycling infrastructures in place,[25] and other issues. A significant fraction of societal material inputs (from imports and domestic extraction) are not recycled at the end of product life and will become societal outputs (waste and emissions) in the future. Currently only 1% of REEs are recycled from end-of-life products; the rest is disposed of in landfill.[26] Anticipating such future emissions is important for environmental policy to prevent problems and take timely action.[27]

Green mining

The impact of TCEs mining on biodiversity and forests includes loss of biodiversity through direct land clearance and deforestation, with habitat loss, land degradation, and changes in abiotic and biotic conditions.[28] Indeed, because TCEs are relatively scarce, their extraction often involves the processing of large amounts of material, sometimes causing environmental damage like the emission of greenhouse gases from burning fossil fuels and large chunks of forest and ore processing.[29] In plants, PGEs and REEs might affect germination, root and shoot development and flowering.[30] Green mining, infrastructures and best practices in mining processes may reduce the environmental impacts associated with the extraction and processing of TCEs.[14]

The Global North and the Global South

Governance of resources should shield the public from the adverse impacts of TCEs changing patterns in the environment. The USEPA recommended the application of environmental management strategies to identify sources, pathways, and fate of contaminants from REE-related industries.[4] On a global perspective, Oceania generates the higher per inhabitant, followed by Europe, America, Asia and Africa.[31] Notwithstanding the availability of resources and technologies in e-waste producing countries,[32] the e-waste burden is so high that more often than not the solution is the formal or informal dumping of e-waste to countries like, mainly, Ghana, Nigeria, Egypt, Kenya and South Africa.[33] Despite advances in governance and technological solutions, the overwhelming market of technological devices still finds its solution in unjust dynamics between the Global North and South. While socio-economically developed countries increase their safety standards, the maintenance of high consumption rates (without reducing waste and changing habits) in all sectors means the exportation or dumping of hazardous materials or exploitation of intensive activities in countries where prevention is insufficiently structured to protect public health.[34]

In SSA, the complexity of e-waste management is linked to the insidious nature of the e-waste flow. In fact, the high level

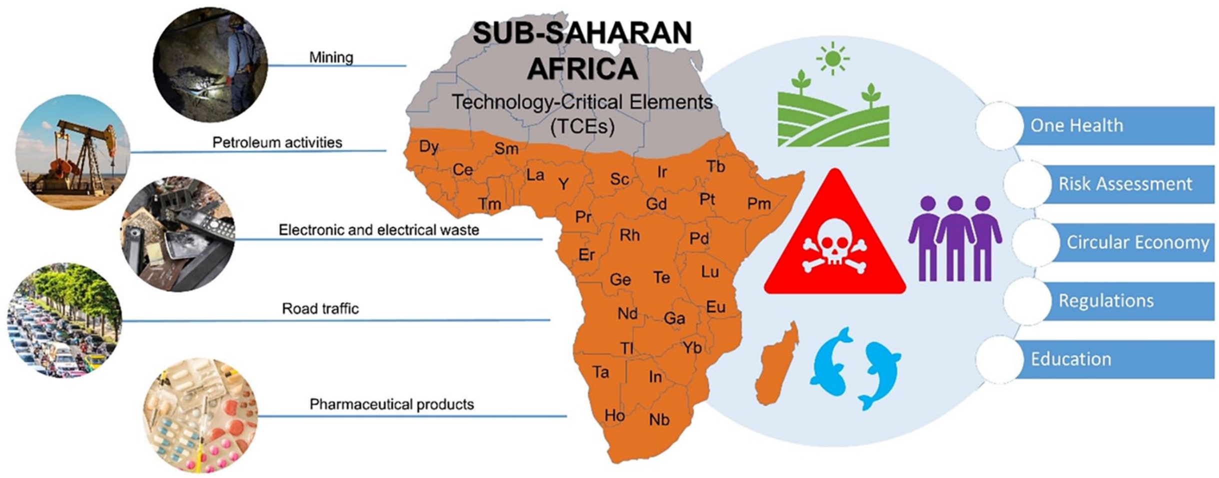

Figure 1. The diverse sources of TCEs environmental pollution in sub-Saharan Africa; the impact of TCE on environmental and human health; possible approaches and solutions to manage the technology-related challenges in SSA.

of trans-boundary movement of electric and electronic devices into SSA is due to the assumed presence of second-hand electronic equipment in the shipment. In the desire of bridging the 'digital divide', more often than not, such bulk of tons of e-waste are dumped from e-waste producing countries in SSA where scavengers and other groups of informal recyclers see e-waste as a source of income and livelihood. In fact, e-waste contains potentially useful and precious fractions that, when not properly managed and separated, are a source of hazardous and persistent toxic cocktails.[35]

This state-of-the-art review collected and discussed data regarding: (i) TCEs pollution from diverse sources (mining, petroleum, e-waste, road traffic, pharmaceutics) in SSA; (ii) TCEs level and impact in environmental compartments, living organisms and food-chain in SSA; (iii) their association with human health effects and diseases; (iv) prevention and remediation strategies (eg, circular economy, environmental bioremediation, education programmes, etc.) that can minimize TCEs exposure; (v) workable approaches and solutions in SSA.

Our goal is to identify workable approaches and solutions for urgent risk management (Figure 1).

Review Methodology

This review was conducted by a Web-based search for journal articles published in English until February 2024. This review provided information about the research findings on exposure and effects to TCEs, PGEs, REEs, metals and metalloids associated to selected activities (mining, petroleum, e-waste, road traffic and pharmaceutics) in SSA lands in particular but also in other Countries. Databases as PubMed/Medline, Scopus, Web of Science and the web were searched following 6 main items:

(1) '**TCEs sources and exposure':** identification of published studies using terms as 'mining', 'oil spills', "open burning", 'dumping', 'e-waste', 'road traffic', 'pharmaceutical products' and 'hospital wastes'.

(2) "**Environmental and food contamination of TCEs:** identification of published studies using terms as 'environment', 'soil', 'sediment', 'water', 'food' and 'feed'.

(3) '**Bioaccumulation of TCEs':** identification of published studies that reported bioaccumulation and uptake in both terrestrial and marine organisms, and studies that explored the phenomena of bioavailability and biomagnification.

(4) '**Human exposure to TCEs':** identification of published studies that investigated research data in human matrices as 'hair', 'blood', 'serum', "urine, 'breast milk', 'liver', 'lungs', etc.,

(5) '**Human health effects of TCEs exposure':** identification of published studies on the association of TCEs with health problems and diseases like congenital anomalies, cancer, respiratory, cardiovascular, hepato-renal, neurodegenerative, infectious diseases.

(6) '**Prevention and control of TCEs exposure':** identification of published studies that deal with prevention and remediation strategies including One Health thinking, animal and human biomonitoring, risk assessment, circular economy, recycling, regulations, education programmes, communication, etc.

TCEs Sources and Fate

Environment

Contamination of the environment by TCEs is one of the most serious problems in the world (Figure 2). In the past decade, several metals and metalloids have been accumulated in SSA landscapes, making the African environment a hotspot of environmental pollution at levels exceeding international limits.[36] Important sources of TCEs coexist and include uncontrolled waste disposal such as open burning of domestic and industrial waste, wood, paper products, plastics, discarded tyres, battery casings, agricultural wastes, etc, but also dumped e-waste.[37,38] The use of wood fuel for cooking, leaded gasoline, illegal crude

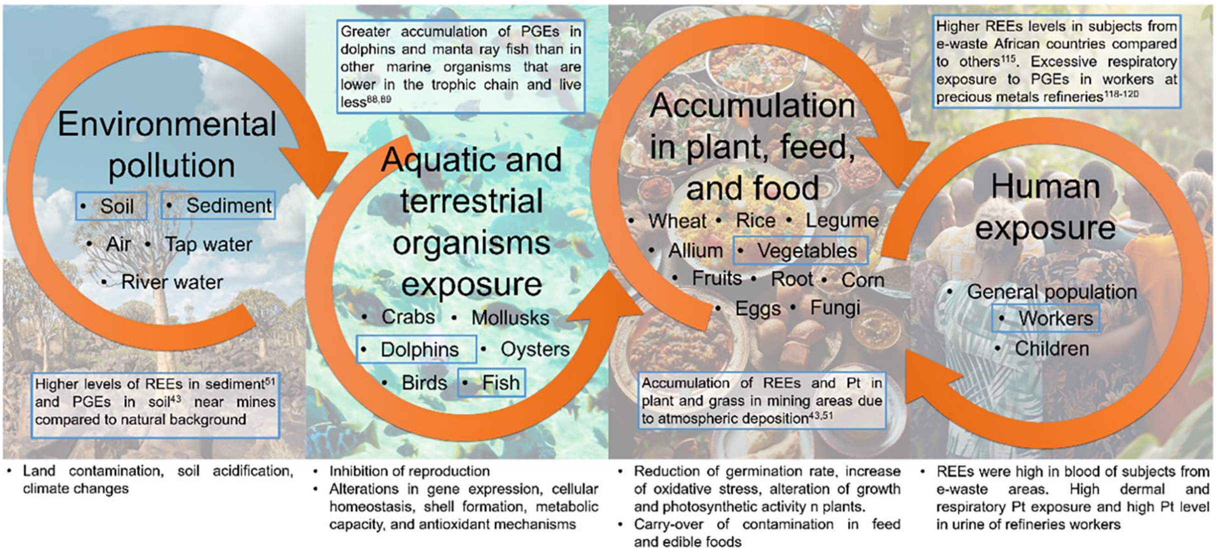

Figure 2. A One Health snapshot of TCEs fate.

oil refining, industrial and artisanal mining activities equipped with limited or absent pollution control increases exposure to pollutants.[36,39] Poor city planning (characterized by the absence of clear demarcation between industrial and residential areas), improper disposal of drugs, lack or absence of environmental legislation and attendant non-implementing policies are recurring features that aggravate the environmental and public health problems in SSA.[36] An overview of research studies on the occurrence and quantification of TCEs in Africa from these pollution sources is reported in Table 1.

Mining. Artisanal and industrial mining activity destroys physical habitat and natural ecosystems. The excavation of mineral resources produces metal pollution that negatively impacts the environment in SSA.[40,41] Mining activities have been identified as a significant source of PGEs in the environment.[42] In South Africa the major PGEs mining area is called the BIC; here is more than 70% of the world's known Pt resources.[43] Mining activities are responsible for environmental contamination due to the release of PGEs and associated metals (Cr, Cu and Ni) through airborne particles, wastewater discharge, and surface runoff.[44,45] Almécija et al[44] found levels of PGEs – Pt, Pd, Rh and Ir – up to 44-fold higher than the typical upper continental crust (Pt 0.51 ng/g; Pd 0.52 ng/g; Rh 0.06 ng/g; Ir 0.02 ng/g) in river sediments of the Hex River which drains the mining area of the BIC. In two dams along the Hex River (Rustenburg) the Pt concentrations were found between 0.041 and 0.076 μg/l, indicating the entry of Pt from the mining into the aquatic ecosystems.[46]

In the same South Africa area, mining impacted sites showed higher Pt levels in river sediment and soil compared to non-mining areas (0.79 μg/g vs 0.038 μg/g) and most sampling sites exhibited a high toxicological potential, mainly driven by Cr and Ni.[47] The sediment from the same mining site had threefold higher Pt concentrations (Pt, 0.015-0.608 μg/g) respect to a site located approximately 6 km downstream of the mining area.[45] Comparably, Rauch and Fatoki[43] reported elevated Pt concentrations in the BIC mining area in soil (0.698 μg/g). Whilst, another study in South Africa levels of PGEs were relative low in both river water (Pt < 0.017 μg/l; Pd < 0.011 μg/l; Rh < 0.008 μg/l) and sediment (Pt < 2.3 ng/g; Pd < 1.23 ng/g; Rh < 1.10 ng/g) samples.[48] The Pt mine's inhalable concentration in the range 0.03 to 2.2 mg/m^3, coupled with the limited use of respiratory protective equipment, increased the health risks for Pt mine workers.[49]

The DRC is the leading producing country of Cu and Co in Africa, followed by Zambia, with consequent accumulation of several metals mainly on the surface of soils in the surrounding area.[50] These soils have accumulated trace metals due to a single or combined effect(s) of (i) deposition of atmospheric fallout from ore-smelter, (ii) weathering of soil metal-bearing minerals or (iii) presence of mine deposits. The enrichment factor and geoaccumulation index indicated the important impact of mining activities on the natural background in the DRC Copperbelt area.[51,52] The ΣREE concentration reached values of 2306 and 733 in sediment and soil.[51] In a recent study, Thomas et al[53] showed the impact of mine drainage on soil from Johannesburg (South Africa) on the retention and distribution of REEs. The ΣREE content in soils ranged from 51.7 to 110 μg/g, and soils presented evidence of acidification and high sulphate content.[53] This last study demonstrated that acid mine drainage increases the mobilization of REEs facilitating the transport of REEs out of the topsoil, into deeper soil horizons or into groundwater and surrounding water bodies.[53]

Petroleum activities. The African continent is among the top oil-producing areas in the world.[54] Severe environmental hazards have been attributed to petroleum activities, arising from the discharge of wastes, drilling fluids, atmospheric emissions,

Table 1. Literature data on contamination and bioaccumulation of technology-critical elements (TCEs) in Africa.

ELEMENT	CONCENTRATION LEVELS	SAMPLE	AREA	REFERENCE
ΣREEs, Ce, Dy, Er, Eu, Gd, Ho, La, Lu, Nd, Pr, Sc, Sm, Tb, Tm, Y, Yb	ΣREEs, 51.7-110.4 µg/g; Ce, 19.1-63.4 µg/g; Dy, 0.2-0.3 µg/g; Er, 0.3-0.9 µg/g; Eu, 0.4-0.5 µg/g; Gd, 1.4-2.7 µg/g; Ho, 0.1-0.3 µg/g; La, 7.7-12.0 µg/g; Lu, 0-0.1 µg/g; Nd, 7.4-11.3 µg/g; Pr, 2.0-3.0 µg/g; Sc, 2.8-4.9 µg/g; Sm, 1.5-2.2 µg/g; Tb, 1.4-2.7 µg/g; Tm, 0-0.1 µg/g; Y, 2.1-7.7 µg/g; Yb, 0.3-0.7 µg/g	Soil	Johannesburg, Gauteng, South Africa	Thomas et al[53]
Pt	Pt, 0.014-0.040 µg/l	Water	Hex River, Rustenburg, North West, South Africa	Erasmus et al[94]
	Pt, 0.011-0.015 µg/l	Sediment		
Pt	Pt, 0.005-0.079 µg/g	Soil	Hex River, Rustenburg, North West, South Africa	Díaz-Morales et al[47]
Pt	Pt, 0.025-0.472 µg/l	Water	Hex River, Rustenburg, North West, South Africa	Erasmus et al[45]
	Pt, 0.015-0.608 µg/g	Sediment		
Pt	Pt, 0.03-2.2 mg/m^3	Inhalable dust	Limpopo, South Africa	Sepadi et al[49]
Pt	Pt, 0.0415-0.0762 µg/l	Water	Hex River, Rustenburg, North West, South Africa	Labuschagne et al[46]
ΣREEs, Sc, La, Ce, Pr, Nd Sm, Eu, Gd, Tb, Dy, Ho, Er	ΣREEs, 67.3-2306.5 µg/g; Sc,0.70-10.8 µg/g; La, 11.4-497.8 µg/g; Ce, 27.0-873.3 µg/g; Pr, 3.60-128.4 µg/g; Nd, 12.4-483.8 µg/g; Sm, 12.4-96.1 µg/g; Eu, 0.40-20.0 µg/g; Gd, 2.10-92.7 µg/g; Tb, 0.20-11.9 µg/g; Dy, 1.20-61.4 µg/g; Ho, 0.20-10.6 µg/g; Er, 0.60-30.5 µg/g	Sediment	Kolwezi, Lualaba, DRC	Atibu et al[51]
	ΣREEs, 66.2-732.7 µg/g; Sc, 0.50-10.7 µg/g; La, 9.70-126.6 µg/g; Ce, 29.0-304.3 µg/g; Pr, 3.0-40.4 µg/g; Nd, 12.2-150.9 µg/g; Sm, 2.40-35.1 µg/g; Eu, 0.50-7.40 µg/g; Gd, 1.90-28.9 µg/g; Tb, 0.20-3.80 µg/g; Dy, 1.0-20.8 µg/g; Ho, 0.20-3.50 µg/g; Er, 0.50-10.4 µg/g	Soil		
ΣPGEs, Pt, Pd, Rh and Ir	ΣPGEs, 0.014 µg/g; Pt, 0.004 µg/g; Pd, 0.0073 µg/g; Rh, 0.0014 µg/g; Ir, 0.0005 µg/g	Sediment	Hex River, Rustenburg, North West, South Africa	Almécija et al[44]
ΣREEs, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu	ΣREEs, 53.4-331.2 µg/g; La, 8.8-63.2 µg/g; Ce, 19.5-147.2 µg/g; Pr, 2.3-16.0 µg/g; Nd, 9.4-58.4 µg/g; Sm, 2.5-12.0 µg/g; Eu, 0.5-2.8 µg/g; Gd, 3.0-10.8 µg/g; Tb, 0.5-2.6 µg/g; Dy, 2.7-10.6 µg/g; Ho, 0.6-1.9 µg/g; Er, 1.7-4.4 µg/g; Tm, 0.2-1.9 µg/g; Yb, 1.6-5.6 µg/g; Lu, 0.2-1.7 µg/g	Sediment	Katanga, DRC	Atibu et al[52]
Pt, Pd, Rh	Pt, 0.001-0.017 µg/l; Pd, 0.002-0.011 µg/l; Rh, 0.001-0.008 µg/l	Water	Elands, Leragane and Hex Rivers, North West, South Africa	Somerset et al[48]
	Pt, 0.02-2.3 ng/g; Pd, 0.05-1.23 µg/g; Rh, 0.01-1.10 µg/g	Sediment		
Pt	Pt, 0.698 µg/g	Soil	BIC mining area South Africa	Rauch and Fatoki[43]
Nd, Gd, Dy, Er, Yb, Lu, Sc, Y, La, Ce, Pr, Sm, Eu	Nd, 2687.1 µg/g; Gd, 22.3 µg/g; Dy, 15.9 µg/g; Er, 17051.9 µg/g; Yb, 3.7 µg/g; Lu, 21.7 µg/g; Sc, 24.0 µg/g; Y, 10.1 µg/g; La, Ce, Pr, Sm, Eu, nd	Soil	Matruh Governorate, Egypt	Saleh et al[61]

(Continued)

Table 1. (Continued)

ELEMENT	CONCENTRATION LEVELS	SAMPLE	AREA	REFERENCE
ΣREEs, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu	ΣREEs, 69.5 μg/l; La, 13.9 μg/l; Ce, 12.9 μg/l; Pr, 3.98 μg/l; Nd, 16.1 μg/l; Sm, 3.11 μg/l; Eu, 1.13 μg/l; Gd, 4.06 μg/l; Tb, 0.61 μg/l; Dy, 3.13 μg/l; Ho, 0.58 μg/l; Er, 1.69 μg/l; Tm, 0.24 μg/l; Yb, 1.56 μg/l; Lu, 0.23 μg/l	Water	Lagos, Nigeria	Ayedun et al[68]
ΣREEs, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu	ΣREEs, 282.6 μg/g; La, 114.8 μg/g; Ce, 126.2 μg/g; Pr, 6.57 μg/g; Nd, 22.7 μg/g; Sm, 3.82 μg/g; Eu, 0.48 μg/g; Gd, 3.37 μg/g; Tb, 0.39 μg/g; Dy, 1.91 μg/g; Ho, 0.36 μg/g; Er, 0.89 μg/g; Tm, 0.16 μg/g; Yb, 0.89 μg/g; Lu, 0.14 μg/g	Atmospheric dust	Ibadan, Oyo, Nigeria	Kolawole et al[78]
	ΣREEs, 143.6 μg/g; La, 19.4 μg/g, Ce, 89.9 μg/g; Pr, 4.41 μg/g; Nd, 17.5 μg/g; Sm, 3.00 μg/g; Eu, 0.52 μg/g; Gd, 2.98 μg/g; Tb, 0.37 μg/g; Dy, 2.35 μg/g; Ho, 0.40 μg/g; Er, 1.15 μg/g; Tm, 0.13 μg/g; Yb, 1.12 μg/g; Lu, 0.18 μg/g	Soil		
Pt, Pd, Rh	Pt, nd-0.189 μg/g; Pd, nd-0.537 μg/g; Rh nd-0.055 μg/g	Sediment	Beposo, Bosomdo, Krobo and Shama Beach along the Pra River, Ghana	Essumang et al[77]
	Pt, nd-0.009 μg/l; Pd, nd-0.037 μg/l; Rh, 0.0013-0.0067 μg/	Water		
Pt	Pt, 39 ng/g	Road dust	Accra, Ghana	Kylander et al[76]
	Pt, 15 ng/g	Soil		
ΣREEs, La, Ce, Nd, Sm, Eu, Gd, Dy, Ho, Er, Tm,	ΣREEs, 7-81 μg/l; La, 0.9-12.1 μg/l; Ce, 1.3-31.1 μg/l; Nd, 1.9-18.3 μg/l; Sm, 0.9-5.1 μg/l; Eu, 0.3-1.4 μg/l; Gd, nd-7.3 μg/l; Dy, nd-5.2 μg/l; Ho, 0.01-0.8 μg/l; Er, 1.1-2.8 μg/l; Tm, nd-0.4	Waste water	Cotonou, Benin	Atinkpahoun et al[84]
Pt	Pt, 0.002-0.006 μg/g	Fish	Hex River, Rustenburg, North West, South Africa	Erasmus et al[94]
Pt	-	Macroinvertebrates	Hex River, Rustenburg, North West, South Africa	Erasmus et al[45]
Pt	Pt, 0.001-0.008 μg/g	Fish	Hex River, Rustenburg, North West, South Africa	Erasmus et al[95]
	Pt, 0.010-0.014 μg/g	Parasite taxa		
Pt	Pt, nd	Clams	Hex River, Rustenburg, North West, South Africa	Labuschagne et al[46]
	Pt, 0.002-0.003 μg/l	Artificial mussels		
Pt, Pd	Pt, 0.52 μg/g; Pd, 1.2 μg/g	Bird eggs	Vaal River South Africa	van der Schyff et al[96]
Pt, Pd, Rh	Pt, 0.541-0.1281 μg/g (muscle), 0.114-1.283 μg/g (body flesh), 0.149-0.617 μg/g (hepatopancreas); Pd, 0.407-0.972 μg/g (muscle), 0.576-0.799 μg/g (body flesh), 0.236-2.680 μg/g (hepatopancreas); Rh, 0.200-0.500 μg/g (muscle), 0.300-0.600 μg/g (body flesh), 0.039-0.400 μg/g (hepatopancreas)	Crab	Elands, Leragane and Hex Rivers, North West, South Africa	Somerset et al[48]
Pt, Pd, Rh	Pt, 0.15-0.85 μg/g; Pd, 0.033-0.67 μg/g; Rh, 0.007-0.145 μg/g	Manta	Dixcove, Ahanta West, Ghana	Essumang[89]
Pt, Pd, Rh	Pt, 0.010-0.099 μg/g; Pd, nd-0.131 μg/g; Rh, 0.001-0.006 μg/g	Fish, shrimp, oysters	Beposo, Bosomdo, Krobo and Shama Beach along the Pra River, Ghana	Essumang et al[90]

(Continued)

Table 1. (Continued)

ELEMENT	CONCENTRATION LEVELS	SAMPLE	AREA	REFERENCE
Pt, Pd, Rh	Pt, 0.004-0.083 μg/g; Pd, 0.007-0.172 μg/g; Rh, 0.001-0.057 μg/g	Fish, crab, shrimp, mollusc	Beposo, Bosomdo, Krobo and Shama Beach along the Pra River, Ghana	Essumang et al[91]
Pt, Pd, Rh	Pt, nd-0.345 μg/g (kidney), nd-0.946 μg/g (liver), nd-0.258 μg/g (muscle); Pd, nd-0.1611 μg/g (kidney), nd-0.481 μg/g (liver), nd-0.299 μg/g (muscle); Rh, nd-0.025 μg/g (kidney), nd-0.037 μg/g (liver), nd-0.013 μg/g (muscle)	Dolphin	Dixcove, Ahanta West, Ghana	Essumang[88]
ΣREEs, Sc, La, Ce, Pr, Nd Sm, Eu, Gd, Tb, Dy, Ho, Er	ΣREEs, 1.2-2796.8 μg/g; Sc, 0.00-4.60 μg/g; La, 0.20-672.3 μg/g; Ce, 0.50-902.9 μg/g; Pr, 0.10-182.2 μg/g; Nd, 0.20-680.0 μg/g; Sm, 0.10-119.7 μg/g; Eu, 0.00-99.5 μg/g; Gd, 0.10-99.5 μg/g; Tb, 0.00-12.4 μg/g; Dy, 0.00-59.1 μg/g; Ho, 0.00-28.3 μg/g; Er, 0.00-28.3 μg/g; Tm, 0.00-3.60 μg/g	Plant	Kolwezi, Lualaba, DRC	Atibu et al[51]
Pt	Pt, 0.256 μg/g	Grass	BIC mining area South Africa	Rauch and Fatoki[43]
Pt, Pd, Rh, Ir, Ru, Os	Pt, nd-0.041 μg/cm²; Pd, nd-0.030 μg/cm²; Rh, nd-0.096 μg/cm²; Ir, nd-0.044 μg/cm²; Ru, nd-0.009 μg/cm²; Os, nd	Skin wipe (no. 40)	African precious metal refineries	Linde et al[119]
	Pt, 0.004-28.18 μg/m³; Pd, 0.003-36.77 μg/m³; Rh, 0.003-3.752 μg/m³; Ir, 0.002-1.875 μg/m³; Ru, 0.003-2.238 μg/m³; Os, nd-0.028 μg/m³	Personal air (no. 40)		
Pt	0.002-0.071 μg/cm²	Skin wipe (no. 40)	African precious metal refineries	Linde et al[118]
	0.021-28.18 μg/m³	Personal air (no. 40)		
	nd-0.576 μg/g creatinine	Urine (no. 40)		
Pt	nd-3.0 μg/g creatinine	Urine (no. 40)	African precious metal refineries	Linde et al[120]
Eu, Er, Ga, La, Nb, Pr, Pt, Sm, Sn, Ta, Dy, Gd, Ho, In, Lu, Os, Ru, Tb, Tm, Y, Yb	Eu, 0.0-0.04 μg/l; Er, 0.0-0.02 μg/l; Ga, 0.0-1.88 μg/l; La, 0.0-0.03 μg/; Nb, 0.0-0.02 μg/; Pr, 0.0-0.42 μg/; Pt, 0.0-0.05 μg/; Sm, 0.0-0.42 μg/; Sn, 0.0-50.8 μg/; Ta, 0.0-0.03 μg/; Dy, Gd, Ho, In, Lu, Os, Ru, b, Tm, Y, Yb nd	Blood	Sub-Saharan immigrants in Gran Canaria Spain	Henríquez-Hernández et al[116]

Abbreviations: ΣREEs, total rare earth elements; ΣPGEs, total platinum group elements; BIC, Bushveld Igneous Complex; DRC, Democratic Republic of the Congo; nd, not detected (or <limit of detection).

oily drill, distillation plants, treatment fluids and improper management.[55,56] Oil spills are a source of metals and metalloids contamination of aquatic and terrestrial environments, for example, in Nigeria.[57,58] In Nigeria, 3.1 million barrels of crude oil enriched in metals and metalloids were spilt from 1976 to 2014.[59] The PGEs and REEs were used as catalysts during crude oil refining and then contaminated the environment.[60,61] The soil sampled close to an oil and gas exploration site in Egypt was highly contaminated compared to background concentration, with REEs ranging from 3.71 μg/g of Yb to 17 051 μg/g of Er.[62] Surface and subsurface soil samples at Bodo City in the Niger Delta were contaminated with crude oils and showed a positive correlation between metals (as Cu, Cr, Fe, V) and pollution from oil spillage.[63] In the same area, levels of As, Cd and Pb in underground water exceeded the maximum contaminant levels recommended by the WHO (As 0.01 mg/l, Cd 0.003 mg/l, Pb 0.01 mg/l), suggesting that it was not fit for domestic use.[64] The above results indicate the risk of living near oil spills and crude oil production sites due to exposure to metals that are detrimental to health. The cumulative risk assessment approach was proposed as a viable approach for a comprehensive understanding of the size of this problem in Nigeria.[58]

Electrical and electronic waste (e-waste). Constituents of EEE and e-waste include REEs, PGEs and other precious metals, such as Ag or Au.[65] Previous works confirmed that dismantling and sorting of e-waste, especially in open air, can be a source of uncontrolled emissions of Ge, Te and Tl in dust and fine particles.[66] The journey of EEE minerals often starts in African mines and ends with the dumping of e-waste back in Africa.[14] E-waste is a hot issue with negative health and environmental impacts worldwide, mainly in recipient countries, like SSA, where recycling is not developed.

Environmental pollution and human health effects due to indiscriminate e-waste recycling activities were reported in several locations in SSA. Open burning figures out as a common practice among the disparate e-waste processing techniques, with even open burning sites, for instance in the e-waste recycling area of Agbogbloshie in Accra (Ghana) and in Alaba international electronic market and Ikeja computer village in Lagos (Nigeria).[67] Lagos state groundwater is enriched with mean ΣREE content of 69.5 µg/l and sources may be from the ocean and leaching from wastes dumpsites.[68]

Regarding metals, soil contamination in Ghana by primitive, unconventional informal e-waste recycling ranged from 70.25 to 0.37 mg/kg (Pb > Cd > Hg > Cu > Zn > Cr > Co > Ba > Ni). The contamination spread to residential, recreational, farming, and commercial areas were also proven.[69,70] Similarly, topsoils from the burn area and dismantling area in the Agbogbloshie e-waste recycling site were strongly contaminated by Pb.[71]

The concentrations of Cu and Pb in soils collected near crude e-waste recycling sites in Ibadan, Nigeria, were many times higher compared with background concentrations, and respect to regulatory limits for soil set by numerous countries.[72] Open-burning soils and rudimentary methods of e-waste processing in Agbogbloshie, Accra, Ghana significantly contributed to high levels of bioaccessible metals, as As, Cd, Cu, Sb and Pb in soil.[73]

Road traffic. The vehicle catalytic converters contained percentages between 0.10 and 0.15% w/w of PGEs (Pd, Pt and Rh) and the emission during automobile operation is the main source of these elements in the urban atmosphere.[74,75] In SSA, the release of PGEs in the environment is due to imports from developed countries of catalytic converter-equipped old cars, as well as to the use of leaded petrol that is known to affect catalyst activity and promote thermal sintering and mechanical abrasion.[76] This possible synergism prompted the high levels of Pb (365 µg/g in dust and 291 µg/g in soil) and Pt (0.039 µg/g in dust and 0.015 µg/g in soil) in Ghana. Several factors, such as high temperatures, chemical stress, ageing of the car, traffic density, driving speed and stop-and-go patterns, resulted in an even greater release of PGE particles from the catalyst.[75] Elevated concentrations of Pt (0.003-0.189 µg/g), Pd (0.049-0.537 µg/g) and Rh (0.0269-0.047 µg/g) in water and sediment samples were found in the Pra estuary in Ghana where it is estimated that more than 2000 cars pass over the bridge under which the river flows to join the sea each day.[77]

Regarding REEs, Kolawole et al[78] showed high mean concentrations of Ho (0.36 µg/g), Lu (0.14 µg/g) and Yb (0.89 µg/g) in the atmospheric dust in a traffic area in Ibadan (Nigeria), identifying the traffic as a source of REEs atmospheric pollution. Indeed, the average total REE values in dust collected from a traffic area (282.57 µg/g) were twofold higher than the normal REE levels in the soil.[78]

Pharmaceutical manufacturing plants wastes. The application of REEs and PGEs as contrast agents in magnetic resonance imagery, nuclear medicine imaging, cancer treatment and dental care is widely reported.[79,80] Wastewater from hospitals can represent another important source of contaminants in the environment in Nigeria.[81] The 70% of Pt-based drugs (*cis*-platin and *carbo*-platin), used to treat malignant neoplasms entered the hospital wastewater.[80] Effluents from pharmaceutical manufacturing plants are an additional contamination source, with unrestricted discharge of Pt-based drugs into the environment.[82]

The REEs were used in different medical applications given their unique properties, such as radiation emission or magnetism. For example, Gd is used as a contrast agent in MRI measurements and its consistent concentration in wastewater treatment plants indicated hospital wastes and contrast agents disposal as sources of Gd in the environment.[83] In Cotonou (Benin), 30 to 620 times more Gd in wastewater samples than in drinking and well water samples were observed. These high Gd values were attributed to the presence of gadopentetic acid or other Gd salts used in medical MRIs.[84] Even the analysis of pharmaceutical samples impurity showed appreciable amounts of REEs: lanthanum (La) ~25 µg/g; cerium (Ce) ~7 µg/g; Gd ~8 µg/g.[85] The use of TCEs in health and medical applications and their release from pharmaceutical products deserves attention, but the implications in African countries have not been addressed so far.

Living organisms

The TCE mining activities, such as cutting, drilling, blasting, transportation, stockpiling and processing, can release dust containing TCEs, with consequent negative effects on wildlife (Figure 2).[37] Mining activities may lead to the formation of acid mine drainage, and this acidification can kill marine and freshwater organisms, disturb aquatic biodiversity and harm ecosystems.[86] Several REEs have been reported in rivers and the sea, indicating that living organisms are already impacted by the geochemical cycle of these elements.[87]

Significant levels of PGEs were reported in liver of dolphins (*Stenella* sp.), a fish popularly consumed in Ghana, ranging from 0.239 to 0.946 µg/g, from 0.040 to 0.481 µg/g, and from 0.011 to 0.037 µg/g for Pt, Pd and Rh.[88] Bioaccumulation of PGEs was also shown in tissues of the Manta ray fish (*Manta birostris*) with levels ranging 0.15 to 0.85, 0.033 to 0.67, and 0.007 to 0.145 µg/g of Pt, Pd and Rh.[89] Dolphins and manta fishes are on the top of the food chain, live relatively long, and may tend to accumulate higher PGE concentrations than other marine organisms. Indeed, lower PGEs concentrations were recorded in oysters, that is, Pd at level of 0.161 μg/g, followed by Pt at 0.113 μg/g and Rh 0.009 μg/g in fish from Pra Estuary in Ghana.[90] In agreement, the concentrations of PGEs were 0.004 to 0.083 μg/g of Pt, 0.007 to 0.172 μg/g of Pd and 0.001 to 0.057 μg/g of Rh, and the highest levels were accumulated by crabs and molluscs, followed by mudfish and prawn.[91] The transplanted clams in dams of the Hex River contained higher As, Cd, Co, Cr and Zn concentrations, whereas Pt data were all below the detection limit of 0.0009 mg/kg.[92] In crab samples (*P. warren*) collected in the Northwest Province of South Africa, the Pb, Cd, Pt, Pd and Rh concentrations indicated that mining activities affected the uptake of metals in the analysed crab samples, whereas the presence of Ni and Cu may be attributed to general anthropogenic contamination, but not to mining.[48] It was found a significant concentration-response relationship between the Pt concentrations in aqueous eluates from sediment and soil samples of the mining area and the reproduction inhibition of *C. elegans*.[47] According to Schertzinger et al,[93] Pd is at around five times more toxic than Pt to *C. elegans* in terms of reproduction.

The bioaccumulation analysis showed mainly Ni and Cu metals in digestive organs and Pb, Cd, Pt, Pd and Rh metal ions in all tissues of crab with different patterns of uptake in the muscle, hepatopancreas and body flesh tissues.[48] Pt mine activities and urban and industrial effluents into the Hex River caused the high As, Cr, Ni and Pt contamination in fish; the ingestion of small quantities of contaminated fish (*Cyprinus carpio, Clarias gariepinus and Oreochromis mossambicus*) may lead to increased human health risks.[94] Erasmus et al[45] found that aquatic macroinvertebrates taxa accumulated the highest Cr and Pt levels at sites directly downstream of Pt mining activities. This study demonstrated the bioavailability and bioaccumulation of metals associated with Pt mining in aquatic macroinvertebrates taxa and their use to monitor environmental contaminations.[45]

In this regard, a study on metals accumulation in fish parasite-host systems from Hex River impacted by Pt mining activities showed that parasite taxa (*Atractolytocestus huronensis*) accumulated significantly higher concentrations of Cr, Ni, Pt and Zn than their fish host (*Cyprinus carpio*), proving to be sensitive indicators of accumulation.[95] In the eggs of aquatic birds breeding in the Vaal River, Van der Schyff et al[96] measured the high level of toxic metals, such as Hg, Pb, Cd, etc., and elements associated with mining, such as Au, Pd and Pt. These birds consume prey such as fish, some of which may be utilized by humans as well as wild bird eggs that are food source for humans.[96] In Chile, the biomagnification of Ta along marine food webs was reported.[97] Briant et al[98] reported a systematic increase in REEs in bivalves located near estuarine environments in France, with different REE patterns in two species of mussels (*Mytilus edulis*, *Mytilus galloprovincialis*). Regarding the bioaccumulation and effects of Gd, most of the literature revealed a concentration of Gd in freshwater species ranging from 0.006 to 0.223 mg/mg. Impacts of Gd in invertebrate aquatic species were identified at different biological levels, including alterations in gene expression, cellular homoeostasis, shell formation, metabolic capacity and antioxidant mechanisms.[99] In Canada, Aharchaou et al[100] investigated the bioavailability and uptake of Gd in green algae (*Chlamydomonas reinhardtii*) and reported the lack of competition from Al and Fe but competitive effects among the lanthanides. Loveridge et al[101] reported that the acute toxicity of another REE, Tm, on an amphipod crustacean (*Hyalella azteca*) appeared not to be modified by the presence of major cations, but it was affected by the formation of organic complexes. The accumulation of La and Yb in the soil negatively impacts the health of earthworms due to the inhibition of acetylcholinesterase, leading to neurotoxicity, reduction in digestive enzymes, increased mortality, and reduced reproduction.[102,103]

Vegetation, food and feeds

TCE levels in soil, air and vegetation around roads and mining communities[104] are all the more important considering that plant, animal feeds, and food producing animals can accumulate them (Figure 2). Airborne pollutants trapped by rainfall can be transferred into plants via their foliage, or absorbed from the soil via the plant roots, with impact on dietary exposure of the general population.[105] Rauch and Fatoki[43] measured elevated Pt concentration (0.256 μg/g) in the grass collected near BIC mining area, in comparison with the background site (0.0002 μg/g). The authors indicated that the atmospheric deposition was the main source of Pt in grass, while a smaller contributor was likely derived to the uptake of bioavailable Pt from soil.[43] In the DRC mining area the level of ΣREEs accumulation in the plant (*Phalaris arundinacea L.*) varied widely from 1.2 to 2796.8 μg/g and the levels of REEs followed the order of Ce > Nd > La > Pr > Sm > Gd > Dy > Er > Eu > Yb > Tb > Ho > Tm.[51] The same samples showed elevated concentration of metals and metalloids, as follow Fe > Co > Cu > Mn >> Zn > Pb > Ni > Cr > U > Cd > As > Th > Sc, but particularly the high concentration of Cu and Co would lead to the plant being considered a hyperaccumulator.[51]

The REEs have already been found in edible plant-based foodstuffs, like fresh edible fungi, vegetables (leafy, fruiting, legume, root, brassica, and bulb), and cereals (corn, rice and wheat flour).[106] Zhuang et al[9] measured the concentration levels of REEs in food samples from a large REEs mining area and they showed a mean value of total REEs of 286 μg/kg, with Ce, La, Nd and Pr as dominant elements. The REEs content of different food categories showed that leafy vegetables, wheat and allium had a higher content of REEs; root vegetables, fruits and eggs had the lowest content.[9] The same results were obtained by

Galhardi et al[10] in crops close to a mining area. They observed that levels of REEs were influenced by their concentration in soil and the bioaccumulation factor was higher for leaves than roots.[10]

Garcia-Vazquez et al[107] measured a high level of metals (As, Hg and Pb) in tuna fish from African coast impacted by e-waste disposal activities. These fishes are consumed not only in African countries but also in European countries such as Spain.[107] These results confirm the importance of local but also Global Health and One Health perspectives when dealing with e-waste, and the urgency of international cooperation and global and local legislation.[34]

The REEs content in rice from a mining area was significantly higher than that in a non-mining area. REEs may enter the human body through the food chain, so food security in the REE mining area deserves more attention.[108] In Nigeria, Orisakwe et al[109] found levels of Cd and Pb higher than the safe standard for food in farm produce and food producing animals around goldmine. Also, the commonly consumed cereals and fruits in Nigeria were contaminated by high levels of Cd, Ni and Pb.[110] In Zambia and especially in the DRC, Muimba-Kankolongo[111] et al measured concentrations of metals and metalloids higher in food crops and water near mining compared to concentrations in sites remote from mining. Preliminary data on TCEs in milk and bread samples analysed in Italy were probative of the significant portion of the total exposure to PGEs, which is due to the diet. The mean values for PGEs were found to be as follows (in μg/g) full-cream milk: Pd, 3.79E + 03; Pt, 8.32E + 05; Rh, 1.68E + 03; skim milk: Pd, 1.24E + 02; Pt, 8.36E + 05; Rh, 1.09E + 03; wholemeal bread: Pd, 3.21E + 03; Pt, 1.71E + 04; Rh, 1.39E + 04; white bread: Pd, 2.74E + 02; Pt, 2.57E + 04; Rh, 2.23E + 03.[8]

When considering carry-over in food and food producing animals, edible insects (in close contact with soil) should not be overlooked in SSA, where considerable scientific data exist on the use of insects as food and livestock feed.[112]

Interestingly, some REEs compounds (eg, La and Ce salts) or their mixtures are deliberately used in agricultural and zootechnical applications, such as fertilizers and feed additives, with the objective of increasing crop productivity and improving livestock yield (eg, egg production or piglet growth, milk production). Both gains in plant growth and livestock yield occur at low concentrations, possibly suggesting hormesis.[113] The controversy between toxicological and ecotoxicological adverse and favourable REE-associated effects has not yet been fully exploited.[114]

Levels in human matrices

In general terms, in SSA the higher level of economic development the higher the blood levels of inorganic pollutants including TCEs.[115] This suggests that in the absence of solid and enforced regulations protecting public health, economic development directly affects the level of hazardous contamination of the population (Figure 2).[115] Nevertheless, measurement of human exposure to TCEs in Africa is limited. Henríquez-Hernández et al observed high levels of Pb (28.95 μg/l vs 23.19 μg/l) and REEs (2.03 μg/l vs 0.39 μg/l) in anaemic SSA immigrants with respect to non-anaemic.[116] Blood of participants from e-waste processing/importing African countries showed significantly higher levels of REEs compared to participants from other African countries (1.21 μg/l vs 0.32 μg/l).[116] The same authors found an association between the use of motor vehicles and e-waste and the level of Ag, Al, As, Be, Cd, Co, Cr, Hg, Ni, Pb, Sb and V contamination in blood of African immigrants.[115]

In SSA the workers respiratory exposure to Pt at precious metals refineries was reported by Linde et al to exceed the OEL of 2 $\mu g/m^3$,[117] for the 22% of respiratory exposure measurements, especially in concentrate handling areas where reached 28.18 $\mu g/m^3$.[118] The highest respiratory exposure was found for Pd (mean, 0.342 $\mu g/m^3$), followed by Pt, Rh, Ru, Ir and Os; while the highest skin exposure was observed for Pt (mean, 0.008 $\mu g/cm^2$), followed by Rh, Ir, Pd, Ru and Os.[119] Various surfaces in production and non-production areas were contaminated with soluble Pt which could be potential sources of skin exposure with a mean of 0.008 $\mu g/cm^2$.[118] Even though workers used PPE – standard polycotton overalls, hard hats, RPE and gloves – the highest skin exposure was found on the palms which indicated that workers occasionally removed their gloves and that the use of gloves did not guarantee protection for skin exposure. The relationship between skin exposure and respiratory routes and urinary Pt levels were found.[118] The Pt concentrations (mean, 0.21 μg/g creatinine; maximum value, 3.0 μg/g creatinine) measured in urine of precious metals refinery workers in SSA[120] were higher than the 90th percentile of urinary Pt excretion value (0.023 μg/g creatinine) in the USA population.[121]

Regarding the other metals and metalloids, there are some studies on the SSA population exposure associated to working and/or polluted environment. For example, the mining area affect the exposure to Hg (used for gold extraction) measurements in breast milk, urine, blood and hair of mother-child pairs showing a significantly higher amount of Hg in the women working or living close to goldmines in Zimbabwe respect to controls.[122] The urine samples of adults and children from the DRC area revealed abnormal high contents of As, Cd, Co, Cu, Mm, Ni, Pb, U and Zn in all subjects, and the levels in urine of children were higher than those of adults.[111] Similarly, Bose-O'Reilly et al[123] showed Pb intoxication in children living close to mining area in Zambia. Over 95% of children showed a Pb blood level $>$10 μg/dl (ca. 50% $\geq$ 45 μg/dl), despite the WHO asserted that 'for an individual with a blood Pb concentration $\geq$5 μg/dl appropriate action should be taken to terminate exposure'.[124] The exposure to Pb in infants living in a Pb-mining area in Zambia was due to both lactation and soil/dust exposure.[125] Overall, these studies confirmed how children are more vulnerable than adults to pollutants.[34]

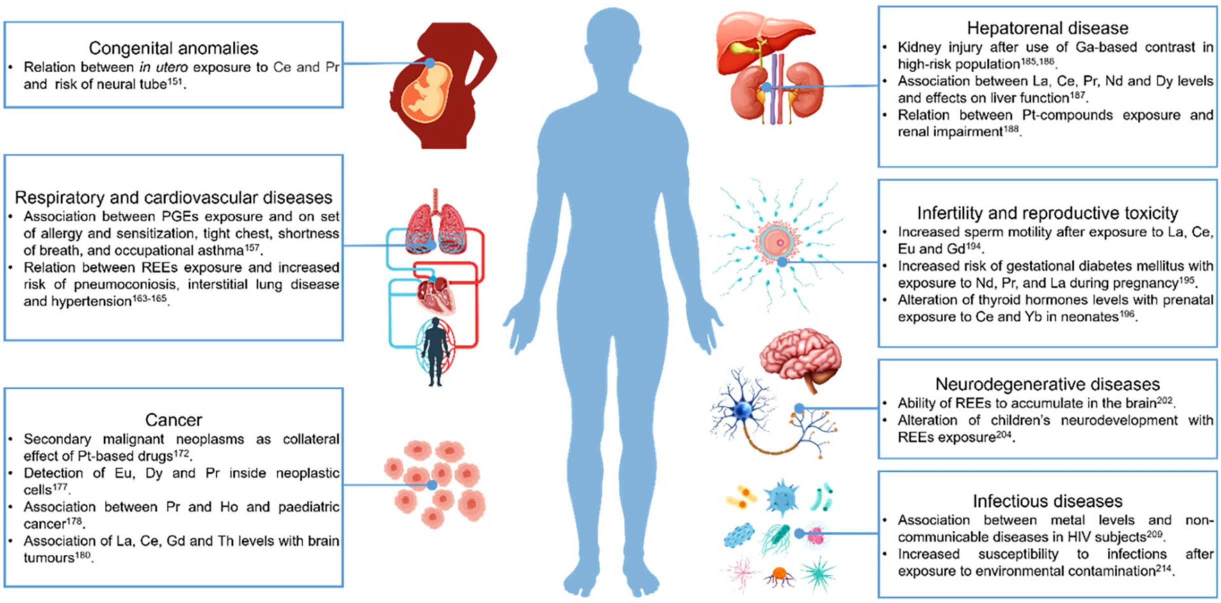

Figure 3. TCEs' impacts on human health: An overview.

Exposure to PGEs from automotive catalysts may lead to accumulation in human samples. For example, in the blood of traffic policemen exposed to polluted dust, levels of Pt > 6.65, Pd > 2.15, and Rh > 4.95 µg/l were found, and the bioaccumulation depended on the age of personnel and exposure duration.[126] In Italy, although differences between urine Pt levels in subjects engaged in traffic police officers and the control group were not observed, levels were higher than those reported for other urban populations.[127]

In humans, Pt from the cis-platin drug administration is retained in the body for years.[128] Authors found plasma Pt levels (64.9 pg/g) in 61 patients 10 to 20 years after *cis*-platin administration significantly higher than levels found in the control group (below or equal to the limit of detection).[129] An increase in Pt blood level has been reported in staff nurses who administered *cis*-platinum (3.8 ± 4.0 ng/ml) in comparison with unexposed subjects (1.2 ± 0.69 ng/ml), suggesting possible exposure while attending treated patients.[130]

Health Hazards of TCEs Exposure

In Africa, the increased mining has raised concern about the impact of TCEs on human, animal and environmental health.[131] There are still gaps in the understanding of the adverse effects of TCEs on human health (Figure 3), particularly with respect to their anthropogenic levels and fate, their biogeochemical or anthropogenic cycling, and their individual and additive toxicological effects. More studies are needed in these and related areas.[132]

The increased health risks of PGEs are mostly due to factors such as their mobilization and solubility in the environment, and transformation into highly toxic substances after uptake by organisms.[6,80] Palladium, Pt and Rh may affect the membrane permeability/integrity, interfere with protein synthesis, inhibit mitochondrial enzyme production, and alter the structure of the lipid bilayer of the mitochondria.[133] The presence of chloride in lung fluids may lead to the formation of halogenated PGE complexes that have a greater potential to induce cellular damage. Palladium has been also implicated in autoimmune diseases such as type 1 diabetes and thyroid diseases in humans.[134] The presence of PGEs in the fine fraction of airborne was associated with increases in morbidity and mortality.[6] Some studies indicate that the chemicals used in TCEs ore processing, extraction and refining processes have resulted in health hazards to workers and local residents.[135] Exposure to REEs has been reported to increase the risk of respiratory and lung-related diseases such as pneumoconiosis.[136]

Besides the occupational settings, studies indicated that chronic low dose environmental exposures to TCEs may result in adverse effects on a chronic, subclinical level.[6] Particularly in children, studies suggest that some of these elements might indirectly negatively affect spatial learning and memory ability. Such effects are triggered by processes like the production of ROS, lipid peroxidation and modulation of antioxidant activities.[106]

Low levels of REEs can cause human health problems by accumulating in bones and brain.[137] Liver, lungs and blood are the primary organs to be affected by REEs.[138] A study conducted near smelting and mining areas of Hezhang (China) showed a positive correlation between REEs in agricultural soils and their levels in human scalp hair and urine.[139] Some TCE minerals contain significant amounts of radioactive elements, such as U and Th, which can contaminate air, water, soil and groundwater.[140] Carvalho et al[141] investigated the risks of human exposure to radiation associated with tantalite mining in Ethiopia and confirmed that there were risks associated with the high concentration of various radionuclides in rock materials, especially in the tantalite concentrate.

Despite the Convention concerning the Prohibition and Immediate Action for the Elimination of the Worst Forms of Child Labour was adopted by the International Labour Organization in 1999, child labour continues to be common in the mining and recycling sectors, where safety and environmental hazards pose significant risks. Table 2 summarizes studies on the impact of TCEs on human health in African contaminated countries.

Congenital anomalies

Congenital anomalies represent diseases whose pathogenesis is related to non-genetic factors among which environmental pollution.[142] Since 1989 congenital cleft deformities have been observed in Nigerian areas of oil wells, gas flares and petroleum refinery.[143] An escalating burden is expected in oil production areas of Nigeria[144] where a retrospective study highlights effects on the central nervous and skeletal systems. A couple of studies performed in the crude oil exploring areas of Nigeria reported congenital birth defects among newborns in Delta State.[145,146] Parental occupational mining exposure in the DRC area was associated with birth defects.[147,148] Elevated levels of Mn (48.6 μg/l vs 33.5 μg/l) and Zn (4692 μg/l vs 3288 μg/l) in cord blood samples and Mn (0.2 mg/kg vs 0.1 mg/kg) foetal side of the placenta were found in cases controls-study and paternal mining jobs were linked with congenital malformations.[147] Kayembe-Kitenge et al[148] reported 3 neonates, whose father had a mining-related job, with clinically diagnosed holoprosencephaly associated with a high level of urinary U, blood Mn and core blood Mn. In DRC and Lagos (Nigeria), high levels of exposure to environmental pollution during pregnancy, such as heavy metals from mining activities, polluted fish consumption, etc., were identified as novel risk factors for cleft lip and/or cleft palate in newborns.[149,150]

A possible relationship between levels of REEs in pregnant women and risk of neural tube defects was observed.[151] The hair concentrations of Ce (9.14 ng/g) and Pr (1.06 ng/g) in the case group were higher than those in the control group (6.73 and 0.782 ng/g), whereas there were no significant differences for La and Nd.

Respiratory and cardiovascular diseases

Living in exposed communities, age, smoking habits, a history of occupational exposure to dust/chemical fumes, and use of gas for cooking/heating at home were found to be significant risk factors for comorbidity of respiratory and CVDs among the elderly residing close to mine dumps in SSA.[152] Previous results showed high proportions of overweight, pre-diabetic and pre-hypertensive individuals, all are major risk factors for CVDs in the workforce of Tenke Fungurume Mining, in southern DRC.[153] Significantly high prevalence of respiratory diseases and CVDs, and eye, nose, and throat irritations were reported in residents living in Zimbabwe exposed to PGEs smelting facilities[154] and in another South African city (Rustenburg region).[155] Persistently high SO_2 emissions from PGEs smelting constitute a major health hazard to communities located around smelters.[156]

Human exposure to PGEs has been linked to allergy and sensitization, tight chest, shortness of breath, and occupational asthma.[157] Water soluble Pt compounds have been identified as respiratory sensitizers in South Africa with OEL of 2 $\mu g/m^3$.[158] These compounds have been implicated in several adverse skin reactions such as dermatitis, eczema and urticaria as well as respiratory symptoms like asthma, rhinitis and shortness of breath.[159] Some of PGEs-salts are among the most potent sensitizers and allergens encountered in the workplace, and respiratory sensitization to PGEs-salts is a significant health problem for the workers in the PGEs industry.[160] Pulmonary silicosis has been reported at autopsy in SSA miners employed in the Pt mines.[161] Removing workers from places of exposure to soluble Pt after developing respiratory symptoms does not always prevent the manifestation of chronic asthma later in life. It is recommended that workers should be removed from exposure immediately after positive skin prick tests irrespective of the symptoms.[162]

The inhalation of REEs, especially in the case of long-term occupational inhalation exposure, may be linked with adverse health effects targeting the respiratory system such as pneumoconiosis and interstitial lung disease in humans.[163,164] The association of REEs in the hair and hypertension risk was observed in housewives living near REEs mining areas.[165] Except for Eu, concentrations of the REEs in hair were higher in cases than controls (Ce > La > Nd > Y > Pr > Gd > Sm > Dy > Eu > Er > Yb > Tb > Ho > Lu > Tm).

Cancer

In 2020 4.2% of the world total new cancer cases and 5.2% of the world total cancer deaths were registered in SSA.[166] Despite rising incidence and mortality rates in Africa, cancer has been given low priority in the research field and healthcare services so far. The number of studies establishing a close association between exposure to metal pollution and cancer in SSA is increasing.[167] The carcinogenic health risks due to As, Cr, Cd, Co and Pb in children and adults living in the vicinity of gold mining environs in Nigeria were estimated at 5.77E–06 and 7.07E–06, implying that 6 out of 1 million children and 7 out of 1 million adults may develop excess cancer in their lifetime as a result of exposure to heavy metals in the studied area.[168] Both the burn area and the dismantling area in the Agbogbloshie e-waste recycling site were strongly contaminated by Pb (5080 and 2380 mg/kg), and the non-carcinogenic risk for children were 7.4 to 7.6 higher than for adults.[71] Breast cancer risk evaluated in a Nigerian population was associated with the levels of Pb in blood (6.1 μg/dl in cases vs 5.0 μg/dl in controls).[169] Hnizdo and Sluis-Cremer[170] reported the relationship between lung cancer and gold mining dust exposure in miners in South

Table 2. Adverse effects of technology-critical elements (TCEs) on human health in Africa.

STUDY DESIGN (SAMPLE SIZE)	HEALTH EFFECTS (INCIDENCE/PREVALENCE%)	AREA	REFERENCES
Congenital anomalies			
Case-control (no. 246)	Total congenitally malformed (0.1%): multiple defects (41.7%), neural tube defects (19.4%) and orofacial defects (19.4%)	Lubumbashi, Katanga, DRC	Van Brusselen et al[147]
Case report (no. 3)	Holoprosencephaly (1.2%)	Lubumbashi, Katanga, DRC	Kayembe-Kitenge et al[148]
Case-control (no. 374)	Thrombocytopaenia (9.4%) with higher prevalence in Warrai (13.2%) than Asaba (5.4%)	Central Hospital, Warri, and Federal Meical Center, Asaba, Niger Delta, Nigeria	Adjekuko et al[146]
Case-control (no. 172)	Cleft lip and/or cleft palate (0.08%)	Lubumbashi, Katanga, DRC	Mbuyi-Musanzayi et al[149]
Cross-sectional (no. 7670)	Total congenitally malformed (2.1%): anomalies of the central nervous system (27.0%), gastrointestinal system (11.9%), cardiovascular system (10.7%), anterior abdominal wall (8.2%), skeletal system (6.3%), and chromosomes (5.7%).	Port Harcourt, River State, Nigeria	Abbey et al[145]
Case-control (no. 225)	Cleft lip and palate (45%), clef lip (27%), rare orofacial cleft deformities (8.9%)	Lagos, Nigeria	Fadeyibi et al[150]
Case-control (no. 19,572)	Total congenitally malformed (0.4%): anomalies of the central nervous system (46.2%), skeletal system (43.6%), urogenital system (5.1%), respiratory system (2.6%) and gastrointestinal tract (2.6%)	University of Port Harcourt Teaching Hospital, Port Harcourt, River State, Nigeria	Ekanem et al[144]
	Total congenitally malformed (0.2%): anomalies of the central nervous system (34.0%), skeletal system (48.9%), oral and special senses (2.1%), urogenital system (6.4%) and gastrointestinal tract (4.3%)	Braithwaite Memorial Hospital, Port Harcourt, River State, Nigeria	
Respiratory and cardiovascular diseases			
Retrospective (no. 40)	Coughing, nasal congestion, shortness of breath, sneezing and changes in heart rate (86.7%)	Selous Metallurgical Complex in Zimbabwe	Gwimbi[154]
Cross-sectional (no. 2749)	Hypertension (18.2%), pre-hypertension (47.8%)	Tenke Fungurume Mining, Lualaba, DRC	Mawaw et al[153]
Cross-sectional (no. 2397)	Asthma + emphysema (1.7%), asthma + hypertension (12.6%), asthma + pneumonia (5.0%), emphysema + myocardial infarction (0.8%), emphysema + pneumonia (2.5%), Hypertension + myocardial infarction (6.5%), hypertension + pneumonia (11.9%) and pneumonia + arrhythmia (1.9%)	Mine dumps in Gauteng and Northwest Provinces	Nkosi et al[152]
Retrospective (no. 12,241)	Silicosis (2.2%), fibrotic nodules (12.7%)	Platinum-Mining Industry in South Africa	Nelson[161]
Cancer			
Retrospective (no. 19.3 million world cancer case)	New cancer case (4.2%): cancer of the breast (27.3%) and cervix (23.3%) in female, prostate (23.6%), liver (7.6%) and colorectal (7.2%) in male	Sub-Saharan Africa	Bray et al[166]
Case-control (no. 12)	Breast cancer	Obafemi Awolowo University Teaching Hospital Complex, Ile-Ife, Osun State, Nigeria	Alatise and Schrauzer[169]

(Continued)

Table 2. (Continued)

STUDY DESIGN (SAMPLE SIZE)	HEALTH EFFECTS (INCIDENCE/PREVALENCE%)	AREA	REFERENCES
Retrospective (no. 2,561,720)	Respiratory system (13.8%), hepatocellular carcinoma (12.8%), oesophagus (11.3%), buccal cavity (5.4%), non-Hodgkin's lymphoma (4.0%), larynx (8.8%), colorectal (3.3%), leukaemia (3.3%), Hodgkin's lymphoma (3.1%), myeloma (3.0%), other (<3.0%)	15 territories in South Africa	McGlashan et al[171]
Hepatorenal diseases			
Case-control (no. 120 contaminated area vs 120 control area)	Renal function indices (urea, sodium, bicarbonate, chloride, KIM-1) and liver function indices (GGT, ALP, ALT, AST, total and conjugated bilirubin) higher in contaminate area compared to control ($P < .05$); total protein and albumin lower in contaminate area compared to control ($P < .05$)	Agbidiama and Odi, Ekeremor, Bayelsa, Nigeria	Thomas et al[184]
Infertility and reproductive toxicity			
Cross-sectional (no. 75)	Azospermics (20%), oligospermics (29%) and normospermics (48%)	Abakaliki, ebonyi, nigeria	Famurewa and Ugwuja[192]
Neurodegenerative diseases			
Retrospective (no. 187)	Parkinson's disease (25.7%) measured by UPDRS3 test for motor signs (bradykinesia, rigidity, tremor, postural instability, and gait impairment) with threshold greater than or equal to 15	Hotazel, Northern Cape	Dlamini et al[201]
Prospective (no. 1753)	Dementia (6.8%): Alzheimer's disease (7.5%), vascular dementia (9.2%), dementia with depression (4.2%), Parkinson's dementia (1.7%), and other dementia (2.5%)	Idikan Ward, Ibadan, Nigeria	Ogunniyi et al[199]
Infectious diseases			
Review (no. of globally case)	Malaria (94%), HIV (68%), tuberculosis (25%)	Africa	Niohuru[208]
Review	COVID-19 (65.1%)	Africa	Lewis et al[218]

Abbreviations: ALP, alkaline phosphatase; ALT, alanine aminotransferase; AST, aspartate amino-transferase; DRC, Democratic Republic of the Congo; GGT, gamma glutamyl transferase; KIM-1, kidney injury molecule-1; UPDRS3, Unified Parkinson Disease Rating Scale motor subsection 3.

Africa. Similarly, McGlashan et al[171] reported the correlation between lung, liver, oesophageal and lymphatic system cancer with exposure to mining dust in SSA.

No mutagenicity/genotoxicity effect was evaluated for PGEs exposure, but the wide use of platinum-based anticancer drugs (*cis*-platin, *carbo*-platin, etc.) as cytostatic agents in the treatment of cancer raised concerns about their side effects. Secondary effects of Pt therapy may include secondary malignant neoplasms.[172] Indeed, mutagenicity/genotoxicity effects of Pt-based drugs were shown both in laboratory animals and humans.[173-175] The frequency of detection was significantly different for Pd between brain tumour tissues and normal brain tissues suggesting a possible important role in tumour activities.[176]

The study of the impact of REEs on human carcinogenesis is a new area of research. Roncati et al[177] detected REEs uptake in the neoplastic cells belonging to a single woman who worked in the ceramic industry. More in detail, Eu, Dy and Pr were detected inside the neoplastic cells. Another study suggested that the REEs could contribute to the pathogenesis of paediatric cancer given that Pr (0.033 µg/g vs 0.001 µg/g) and Ho (0.003 µg/g vs 0.002 µg/g) were found significantly higher in sick children compared to healthy control.[178]

The eivronmental pollution of REEs around the mining areas and leukaemia seemed to be related.[179] The association of REEs concentration and brain tumours was observed by Zhuang et al[180] who reported higher levels in brain tumour tissue versus normal brain tissue of La (43 ng/g vs 13 ng/g), Ce (89 ng/g vs 20.5 ng/g), Gd (5.67 ng/g vs 1.8 ng/g) and Th (5.84 ng/g vs 1.32 ng/g). Gaman et al[176] measured significantly higher level of Gd in blood of brain tumour patients with respect to healthy controls (0.899 ng/ml vs 0.003 ng/ml), probably due to the use of Gd as a contrast agent in MRI.

Hepatorenal diseases

The functional roles of the kidney (filtration, reabsorption and concentration of divalent ions) and the liver (metabolism) predispose them as target organs in metal and metalloid toxicity and have been implicated in diverse hepatorenal pathologies.[36,181] The prevalence of chronic kidney disease in Nigeria has been reported to range from 2.5% to 26%.[182]

Exposure to Cr(VI), Pb, and to a lesser extent inorganic As were associated with nephrotoxicity.[183]

Effects of metals on liver and renal functions were observed in the residents of an oil contaminated area in Nigeria, with blood levels of Pb, Cd, As and Hg significantly higher compared to those from a non-contaminated area.[184] The levels of some renal function biomarkers and liver function biomarkers were significantly higher in residents of the oil contaminated area when compared to residents of the control area.

Gadolinium-based contrast media are reported to induce acute kidney injury in a high-risk population group at the usual dose for magnetic resonance imaging and magnetic resonance angiography examinations.[185,186] Also other REEs, as La, Ce, Pr, Nd and Dy, were associated to effects on liver function,[187] and incidence of renal impairment were linked to the administration of Pt-compounds.[188]

Infertility and reproductive toxicity

Metal exposure was implicated in decreasing sperm count in the African population from 1965 to 2015.[189,190] Significant relationships between Cd and Pb exposures and semen quality have been reported in both industrialized and semi-industrialized cities in Nigeria.[191,192] An increased incidence of miscarriages and stillbirths was observed in Nigerian women exposed during pregnancy to Cd (83.93%), Pb (41.61%), Hg (9.50%), As (5.88%) and Cr (1.60%).[193]

Marzec-Wróblewska et al[194] observed that REEs in human sperm showed no harmful effect on the sperm quality. Indeed, levels of La (19.5 µg/kg), Ce (41.9 µg/kg), Eu (0.68 µg/kg) and Gd (3.19 µg/kg) were estimated to increase sperm motility and enhance the percentage of normal spermatozoa.[194] The exposure to REEs (mainly Nd, Pr and La) during pregnancy exposed the mothers to an increased risk of gestational diabetes mellitus.[195] In a cohort study on neonates, the alteration of thyroid hormones levels was observed due to Ce and Yb prenatal exposure.[196]

Neurodegenerative diseases

Despite the scarcity of epidemiological data on NDDs in SSA, Lekoubou et al[197] reported that the population-based prevalence of Dementia, Parkinson's disease, amyotrophic lateral sclerosis, and Huntington's disease range from 56 to 2494 per 100 000, 10 to 235 per 100 000, 5 to 15 per 100 000 and 3.5 per 100 000. Alzheimer disease was the most common form of neurodegenerative disease, representing 57.4% to 89.4% of all cases,[197] with an incidence per year of 9.5-11.5 per 1000 only in Nigeria.[198,199] Likelihood environmental and contaminants exposure, such as metals, are risk factors implicated in the development of NDDs.[200] The cumulative exposure to Mn ($5.4\,mg/m^3$/years) was associated with Parkinson's disease signs in a cohort of employed Mn mine workers from SSA.[201]

Potential concerns about the neurotoxicity of continuous/chronic exposure to low levels of REEs are due to the ability of these elements to accumulate in the brain.[202] Gadolinium deposits were confirmed in brain tissue, but no data are available so far to show adverse clinical effects due to Ga deposition in the brain.[203] The impact of REE exposure on children's neurodevelopment was found to be related to differences in intelligence.[204]

Infectious diseases

Human exposure to potentially toxic metals has been associated with alterations in the immune system with implications for infectious diseases like increased susceptibility to infections, prolonged recovery periods, and reduced responses to vaccinations.[205,206] Several evidence suggest that infectious diseases may result from the interplays among the characteristics of the infectious agent, the population and environmental pollution.[207] Infectious diseases such as HIV, malaria and tuberculosis have been recognized as major concerns in Africa, but preventive care services allowed for the reduction of death rate.[208]

The causal association between metals and non-communicable diseases in HIV subjects is largely unknown. Lead, Cd and Hg blood levels are higher in HIV-seropositive than HIV-seronegative subjects, whereas Zn serum level is lower in HIV-seropositive than HIV-seronegative subjects in Nigeria.[209] In Nigeria, significantly higher mean levels of Pb, Cd, Ni, Hg were measured in HIV-1 infected subjects compared with controls. Blood toxic metals levels appeared to be higher in pharmacological treated subjects than in not-treated subjects.[210] According to some epidemiological studies, a strong association between inorganic As exposures has been established with viral infections, highlighting As potential to increase infection susceptibility.[211-213]

The association between human exposure to metals and metalloids and the severity of viral diseases, including influenza and respiratory syncytial virus, has been demonstrated.[214] The COVID-19 pandemic has amplified the debates on the plausibility of the impact of toxic exposures, especially metals and metalloids, on the occurrence and/or severity of infectious diseases.[215,216] One overlooked scenario is the body burden of toxic environmental pollutants in viral diseased populations, which is also associated with such diverse factors as diet, health status, education, socio-economic status etc. Questions are linked to environmental pollution, like the severe impact of contaminated water and agricultural soil, and polluted foods on susceptibility to viral diseases like HIV, COVID-19, co-infections and their prevention. Some evidence suggests the plausibility of this association.[217] The COVID-19 seroprevalence in Africa rose from 3.0% in 2020% to 65.1% in 2021.[218]

Approaches to Risk Analysis in SSA

One Health: An approach of system thinking

One Health is an integrated, unifying approach that aims to sustainably balance and optimize the health of people, animals and ecosystems (Figure 4). According to One Health, if the sources of pollution are not secured, they are not punctual but

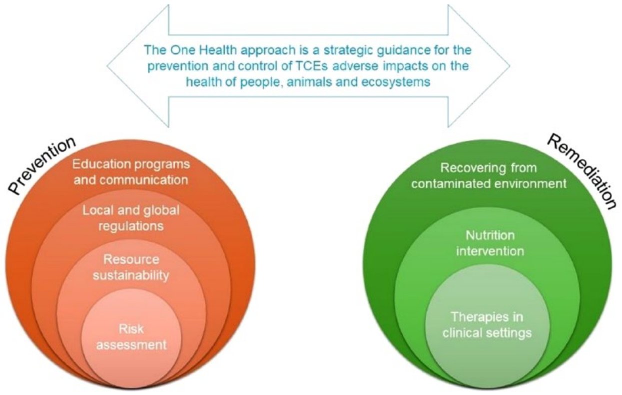

Figure 4. One Health approach is the strategic guidance for prevention and control of TCEs adverse impacts to protect the health of people, animals and ecosystems.

toxic contamination expands with soil, food chains and atmospheric phenomena. Even among humans, toxic contamination may be transmitted vertically (mother-child)[219-221] and horizontally, for example, by blood donation.[222] Noteworthy, the modern concept of zoonosis considers exposure to toxic substances through foods of animal origin.[220] Foods of animal origin represent an increasingly important share in the diet of SSA populations.[223,224] The review of toxicants in most consumed foods of animal origin in Cameroon suggests an important contamination by toxic metals.[225] For instance, due to land scarcity in urban areas in SSA, potentially contaminated land in the vicinity of industrial dumps (eg, tailings dams or tailing dam effluent) is used for the cultivation of food crops.[226] Crops are only one of the examples in the web of relations between the environment and consumers, with implications for the local consumers but also the global market.[227] As a key element of the 'farm-to-fork' approach, feedstuffs can be a major vehicle for pollutants, and potential risks include fish farming and ruminants grazing in polluted areas.[228]

The One Health strategies are still rudimentary in many national health systems, but effective tools for the identification and characterization of sentinel animals are increasingly available, for both farm animals[229] and wildlife.[230,231] Among farm animals, sheep could be of special interest due to the higher intake of soil during grazing in the Peak District contaminated mining area of Derbyshire in UK.[232] Biomonitoring campaigns and the search for reliable biomarkers of exposure should be applied for the surveillance of sentinel animals,[229] with benefits for both food safety and food security. Apart carry-over and subsequent exposure of consumers and food producing animals higher in the trophic chain,[233] the toxicity of pollutants on food-producing organisms (eg, fish) can affect animal health and productivity, and also human food security.

Up to date, no country has imposed limit values for TCEs in the environment. Besides limited knowledge of REE toxicology and bioavailability,[234] contaminant limit values in soils lack a consistent (European) guideline. Most countries in SSA have no guideline values for TCEs in soils for various land uses. Where such guidelines exist, they are based on total soil concentrations whereas risk depends on their bioavailability.[235] Defining bioavailable levels of metals becomes very important in the risk assessment process, and geochemical speciation modelling has proved to be a valuable tool in the risk assessment of metal-contaminated soils.[226]

The lack of toxicovigilance in Africa has not helped this situation. Toxicovigilance – that is, the process of identifying specific circumstances or agents giving rise to poisoning, or certain populations suffering a higher incidence of poisoning – implies the registration of cases of poisoning or the analysis of enquiries made to poison control centres. Once an issue has been identified, appropriate authorities can take the necessary preventive and regulatory measures. Less than 9 out of 54 African countries have a legally recognized toxicovigilance system; of these systems, the majority were established only recently and are facing many challenges at regional and country levels.[236]

In the web of relations within ecosystems, a lot lies in planning, and in the careful observation of the environment (flora and fauna) before the planning itself. This approach is particularly crucial to provide a science (and risk analysis)-guided design of living environment where systems thinking will draw, for instance, the best options on the place where dispose and incinerate waste. Indeed, if the impact of toxic human exposure can become manifest in the long run, the monitoring of animals, for example, give faster hints that can find response in local and international scientific knowledge on environmental and human effects.[229,230]

The role of knowledge gaps and uncertainty in risk management

Increasing research funds, infrastructures, analytical data and risk assessment is a necessity that must be faced in SSA. Based on the increasing awareness of SSA, concepts of knowledge gaps and uncertainties should be taken into account and distinguished in a stepwise approach to avoid falling into unmanageable complexity. On one hand, uncertainty analysis is the process of identifying limitations in knowledge and evaluating their implications for scientific conclusions. On the other hand, knowledge gaps should be identified and, afterwards, their possible impact on risk assessment should be evaluated, defining whether or not they are uncertainties.[237] Whereas it is difficult to quantify the impact of each specific uncertainty on the outcome, it should be possible to quantify the combined effect of identified uncertainties. A stepwise approach is envisaged, focussing on those issues where a detailed appraisal of uncertainties is needed. Uncertainties are, for example, gaps of knowledge and/or data sets that can exert an unwanted influence on the outcome of a risk assessment. Uncertainties should be described and weighted transparently.[237] As stated by Taruscio and Mantovani,[238] uncertainty analysis should be a stable component of risk assessment and should be used in decision-making. It would also be appropriate to identify in which direction the uncertainties act on risk assessment, that is, if they make it more or less precautionary (conservative).[237] Indeed, based on the scientific literature, low-resource countries may achieve more with less.

When conducting risk assessment in data-poor scenarios and when dealing with uncertainty analysis, approaches such as expert knowledge elicitation may be considered. For instance, risk analysis can be fed based on field anthropological research to highlight previously unrecognized/overlooked real-life risk scenarios.[239] Knowledge return initiatives feed awareness raising, informed choice and empowerment of communities. Feeding stakeholder involvement, data sharing and open science have the power to highlight previously unrecognized/overlooked real-life risk scenarios. Uncertainties can be reduced. Models can be built using available data to predict ecotoxicity, bioaccumulation, carry-over, and also to derive health-based guidance values for ecosystems, farm animals and humans. For instance, if data on the impact of TCEs exposure on the health and productivity of food producing animals are limited (or absent), this is an uncertainty of considerable importance for a One Health-based risk assessment.

Science-society dialogue in preventive medicine. It is timely to address the hitherto neglected rising public health crisis of pollution associated diseases in SSA through comprehensive awareness creation among physicians and diverse health workers. This can be obtained by continuous education programmes that highlight the critical role played by environmental pollutants in pathology. Toxicology and nutrition should be introduced as disciplines in undergraduate medical curricula based on the recent concepts of (i) environmental origin of diseases and (ii) One Health.

Increasing exposure to such new health risk factors in SSA needs top-down choices for diseases prevention, but also public awareness and empowerment on how to avoid behavioural exposure, following the 'from public protest to scientific discourse' approach.[240] For instance, the majority of the people who are exposed to SO_2 emissions in economically developing countries live near PGEs smelting facilities and have limited information about their rights to defend themselves or influence policy decisions.[241]

Awareness-empowerment vortexes should be also developed on everyday habits (eg, jewellery, piercing, tattooing) and on bad practices (eg, open burning of garbage, use of wood fuel for cooking). The literature reported cases of contact allergic granuloma due to Pd present in jewellery (eg, earrings)[242] or cases of pseudolymphoma due to metals composition in permanent tattoos.[243] Another habit of concern is geophagy, that is, pica characterized by craving and eating soil,[11] especially among African pregnant women with a prevalence between 15% and 84% in Sudan and Uganda, reaching 50% in Nigeria-that is one of the most populated countries in Africa.[244] This practice is associated with a higher intake of toxic metals, especially but not limited to Cd and Pb[245] with possible negative associations between maternal geophagy during pregnancy and child poor motor function.[246-248] Lastly, good practices to minimize exposure during cooking should inform choice and empower people.[249]

Determinants of health: The environmental impact on malnutrition

Plausibility of additive/synergistic effects of TCEs in the environment is even more worrying in SSA where human (and animal) susceptibility is amplified by unmet determinants of health, including the deprivation and lack of enforced primordial and primary prevention strategies and malnutrition.[34,223] Indeed, e-waste has been dumped in sub-Saharan Africa for long time and people who work with e-waste are mostly uneducated and vulnerable to toxic substances.

The abysmal ignorance or negligence in both diagnoses and management of diseases in SSA includes physicians' unawareness of the role played by the widespread worrisome body burden of metals, including TCEs. Further to all the mentioned diseases, it is ignored, for instance, how they impact on development and learning ability of children[250] directly or indirectly engaged in mining and e-waste recycling, or the risk in age-related eye diseases.[251] Ingested metals might disturb the function of the gut barrier and cause toxicity to organs or tissues in other sites of the body. This will continue to constitute a pitfall in patient management until enough awareness is created and embraced.[252]

Since nutrition intervention can reduce the amount and toxicity of metals and metalloids in the human body, the interdisciplinarity between nutrition, toxicology, and human health is needed for effective primary and secondary prevention and treatment of diseases.[249] A deeper understanding and integration of nutrition with contemporary therapies in clinical settings should be encouraged, as deficiencies of certain nutrients make therapy, for example, art or psychiatric difficult even with appropriate medication.[222] Increasing literature demonstrates the benefits of bioactive dietary nutrients in foods, from folic acid to lower blood arsenic levels, due to the increase of dimethylarsenic formation, flavonols (antioxidant and anti-inflammatory agents in fruits and vegetables) to lower cardiovascular and cancer risks, and polyunsaturated fatty acids (eg, omega-3 in fish) to prevent or decrease toxicant-induced inflammation.[253] From the anthropological perspective, it is worth mentioning how the physiological significance of geophagy made it important in the evolution of human dietary behaviour.[11] Indeed, some African clays release Ca, Cu, Fe, Mg, Mn or Zn in amounts of nutritional significance.[254]

Risk Management in SSA

Regulation and monitoring of the entry of foreign e-waste in SSA

Globally, large quantities of e-waste still go undocumented, thus feeding the informal disposal and recycling in open-dumpsites and landfills in SSA. Local governments should enforce specific measures to avoid the acceptance of undesired end-of-life products and e-waste, like:

- E-waste flow formalization, quantification and characterization.
- Enforced specific legislative and policy regulations.
- Enforced confirmation of the functionality of second-hand devices at reception, with technical training at customs to discriminate and reject e-waste items.
- Enforced costal (including rivers) monitoring to support the regulation of the formal entry of foreign e-waste.

While governments accept second-hands devices in their desire to bridge the digital divide, they should accurately define the characteristics of what they call an acceptable 'second-hand' device. This definition will set the acceptable compromise and threshold between what is 'worthwhile' (functioning, with a reasonable lifetime) second-hand device and what is e-waste and, therefore, unacceptable.

Management of locally generated e-waste in SSA

Poor waste management – ranging from open burning, crude recycling, to mechanical shredding – causes air pollution, water and soil contamination. Open and unsanitary dumps and landfills are a hot issue in public health worldwide, and in particular in SSA. According to Akan et al[255] only 9% to 12% of the total generated wastes are recycled and incinerated in Nigeria; the remaining is discarded into waste dumps (and a few available landfills) or natural environments. While a landfill is a government-regulated place where waste is treated, monitored and properly layered, a dump is most often an illegal and unregulated site that poses risks to the environment. Local governments should enforce specific measures to manage end-of-life products and e-waste, like:

- Specific national policies and stringent policy instruments to enforce proper collection and recycling systems.
- An inventory of end-of-life electronic products, through the regulatory regime for recycling.
- Establishment of formal facilities and infrastructures for safe mining and recycling, from collection, dismantle, separation to recovery and treatment of hazardous and complex fractions.[14]
- Planned landfill design based on system thinking and One health.
- Mandated network registry, and monitoring facilities at landfill.
- Economic and financial investments to set up resourced environmental government agencies for effective systematic monitoring and auditing at the regional levels, and formal take-back system.
- Provision of incentive and other fiscal policies/subsidies.
- Stimulation of community awareness and engagement (e-waste disposal methods and behaviour). To date, the general public might see e-waste only as an aesthetic problem.
- Integration of the formal and informal sectors. Informal e-waste actors dominate the e-waste chain from collection to material extraction and refurbish through rudimentary methods and tools that are highly toxic. A major limitation to the integration of informal e-waste collectors and scavengers within the government waste management system is the social acceptance of e-waste management as a viable source of income, and of citizens as environmental agents.
- Partnerships between local governments, international organizations, and private sector (e.g. start-ups in emerging recycling operations).
- Access to technologies and training, with cyclical and One Health vision, from mining to recycling and disposal. Safer plans should be embodied for TCE recovery from end-of-life products, secondary materials and e-waste. For instance, the distinction between chemical present as device's component and chemical derived as by-products of recycling and open burning has significant implication for both risk assessment and risk management.[35]
- Research on cost-efficient treatment system that simultaneously liberates and refines target fractions without polluting the environment. Openness to futuristic and eco-friendly approaches such as chelation, inducing ionic liquids, integrated processes or hybrid technologies, micro factories, photo catalysis, and green adsorption will substantially harness the current barriers of the e-waste management[256] and pyrolysis technologies.[257]

Scientific research for environmental monitoring and remediation, and human detoxification

The most important approach in combating the environmental and public health issues arising from toxic pollution is to eliminate pollution sources and re-establish a clean environment. Remediation strategies are needed to concomitantly clean up and remediate the environment and recover TCEs that contribute to the process circular economy. Techniques such as phytoremediation and electrokinetic treatment showed promising REE extraction. Phytoremediation extracts and transfers REE to the plants to tolerate acidic conditions and contaminant levels. This technique is already being used at large scale in the proximity of mining areas in China, with high removal yields (up to 96% of REE).[258] While the electro-remediation, that is, application of an electric field to artificially contaminated soil or waste, provided lower removal yields (max 42%).[258] Another study reported that microbial communities are able to tolerate and adapt to metals contamination. According to the authors, beneficial microbial activities can be used for remediating many metals associated with mine wastes and reducing the environmental impact of mine wastes.[259] Interestingly, some species of mushrooms are capable of accumulating REEs and PGEs from the environment.[260] Earthworms can also bioremediate soils exposed to La and Yb, with potential for rehabilitating contaminated agricultural soil.[102]

In recent years, 'bionanomining' emerged as a scientific-technological development associated with the application of micro- and macro-organisms to generate valuable nanotechnological products starting from mining and industrial wastes and wastewaters.[261] While the demand for nanoparticles is increasing based on their high surface area and characteristics to improve thermal, electrical and optical properties of materials (metallic ones have themselves antimicrobial activity), the eco-friendly microbial biosynthesis of metal nanoparticles from hazardous waste recovery can be an interesting emerging reality in mining countries.[261,262]

With regards to human detoxification treatment, according to Jomova and Valko,[263] an ideal metal chelator should possess a dual function comprising not only chelation for the treatment of acquired body burden but also antioxidant properties. While classical chelators are scarce and expensive, natural antidotes are affordable and locally available in SSA.[67] Natural antidotes do not only satisfy these dual functions but are also devoid of the many untoward side effects of the classical synthetic chelators.[264] Natural antidotes – which are mainly medicinal plants – deserve due attention in clinical settings.[265] Since they may contain worrisome levels of metals, good practices should be employed in the cultivation and harvesting of these plants.[266-268] Also, some Nigerian probiotics (fermented foods protecting good gut bacteria) are being studied for use in chronic metal exposure.[269] Probiotics, including some lactic acid bacteria, can be used to detoxify due to their safety and effectiveness.

Conclusions

Even minor trace elements like REEs and PGEs demonstrate how the anthropogenic input of TCEs perturbs the natural biogeochemical cycles. Our results on minor and neglected TCEs emphasize how the worrisome technology growth rate in the Global North is a hot issue in global health, especially in the Global South. For the first time, this paper focuses its scientific arguments on the review of literature data on mixtures of PGEs and REEs. Results emphasize how both extensive mining, e-waste dumping, and improper recycling and disposal directly impact the health of people in the Global South and the environment.

While improvements in analytical methods and detection limits will allow characterizing bioaccessibility and biomagnification, internal dose, toxic profiles, and environmental threshold levels of minor TCEs and their mixtures, both scientific uncertainty in risk assessment and One Health thinking can drive risk management. Analytical thinking is necessary at critical control points for political management, since e-waste dumping is insidious in nature: (a) it is received due to the presence of usable second-hand electronic devices among the scrap; (b) it attracts illegal activities due to the valuable resources mixed with hazardous materials. Governments are urged to evaluate their trade-off between the desire to bridge the digital divide and the long-lasting environmental burden, and set up their own risk management plan for safe disposal and recycling. Foreign e-waste must be blocked at borders, after the definition of what is 'worthwhile' second-hand device and what is e-waste. For sure, inertia and inability (eg, due to expensive chemical analysis) in the absence of environmental and food regulations are leveraged by foreign unethical business exploitation of SSA lands and dangerous dumping activities. Local scientific and technological research should engage in solutions to handle, recycle and dispose internally produced e-waste, remediate the polluted environment, and detoxify exposed bodies.

International human rights mechanisms, advocacy with government and private sector, and media attention are crucial to stop harmful environmental exposures, and prohibit child labour in mining and e-waste recycling. Consumers should become aware of environmental and human health impacts associated with end-of-life electronics and economic growth at all costs.

Abbreviations

Technology-Critical Elements (TCEs), Rare Earth Elements (REEs), Platinum Group Elements (PGEs), Neodymium (Nd), Dysprosium (Dy), Gadolinium (Gd), Lanthanum (La), Cerium (Ce), Yttrium (Y), Erbium (Er), Holmium (Ho), Lutetium (Lu), Ytterbium (Yb), Thulium (Tm), Praseodymium (Pr), Scandium (Sc), Samarium (Sm), Europium (Eu), Terbium (Tb), Promethium (Pm), Platinum (Pt), Palladium (Pd), Rhodium (Rh), Iridium (Ir), Ruthenium (Ru), Osmium (Os), Chromium (Cr), Copper (Cu), Nickel (Ni) Cobalt (Co), Arsenic (As), Cadmium (Cd), Lead (Pb), Iron (Fe), Vanadium (V), Antimony (Sb), Mercury (Hg), Zinc (Zn), Barium (Ba), Germanium (Ge), Tellurium (Te), thallium (Tl), Silver (Ag), Gold (Au), Aluminium (Al), Tantalum (Ta), Manganese (Mm), Uranium (U), Beryllium (Be), Thorium (Th), Sub-Saharan Africa (SSA), Bushveld Igneous Complex (BIC), Democratic Republic of the Congo (DRC), World Health Organization (WHO), U.S. Environmental Protection Agency (USEPA), Electrical and Electronic Equipment (EEE), Occupational Exposure Limit (OEL), Respiratory Protective Equipment (RPE), Personal Protective Equipment (PPE), Neurodegenerative Diseases (NDDs), Cardiovascular Diseases (CVDs), Reactive Oxygen Species (ROS).

Acknowledgements

The work has been developed in the frame of activities of WG3 'Human exposure and toxicology' of the COST Action TD1407 (www.costnotice.net) and of the non-profit organization *Spring to life!* (www.springtolife.ngo). Mrs. Matilde Bocci is thanked for her support in the literature search.

Author Contributions

Authors contributed equally.

Ethics Approval and Consent to Participate

Not applicable.

Consent for Publication

Not applicable.

Data Availability

All data used for this current study are included in the article.

REFERENCES

1. EC (European Commission). Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions. critical raw materials resilience: charting a path towards greater security and sustainability. COM/2020/474 final. Published online 2020.
2. Cobelo-García A, Filella M, Croot P, et al. COST action TD1407: network on technology-critical elements (NOTICE)–from environmental processes to human health threats. *Environ Sci Pollut Res*. 2015;22:15188-15194.
3. Ali S, Katima J. Technology critical elements and the GEF, a stap advisory document. Scientific and technical advisory panel to the global environment facility. 2020.
4. USEPA. (U.S. Environmental Protection Agency). Rare earth elements: a review of production, processing, recycling, and associated environmental issues. USEPA/600/R-12/572. Published online 2012.
5. Zabrecky JM, Liu XM, Wu Q, Cao C. Evidence of anthropogenic gadolinium in triangle area waters, North Carolina, USA. *Water*. 2021;13:1895.
6. Wiseman CLS, Zereini F. Airborne particulate matter, platinum group elements and human health: a review of recent evidence. *Sci Total Environ*. 2009;407:2493-2500.
7. Kuan S, Ghorbani Y, Saw B. A review of rare earths processing in Malaysia. In: *Universiti Malaysia Terengganu International Annual Symposium on Sustainability Science and Management (UMTAS2016)*. Published online 2016.
8. Frazzoli C, Cammarone R, Caroli S. Uptake of platinum-group elements with the diet: a preliminary investigation. *Pure Appl Chem*. 2006;78:69-78.
9. Zhuang M, Xie H, Jiang Y, et al. Probabilistic assessment of dietary rare earth elements intake among people living near a rare earth ore. *Sci Total Environ*. 2023;856:159141.
10. Galhardi JA, Leles BP, de Mello JWV, Wilkinson KJ. Bioavailability of trace metals and rare earth elements (REE) from the tropical soils of a coal mining area. *Sci Total Environ*. 2020;717:134484.
11. Frazzoli C, Pouokam GB, Mantovani A, Orisakwe OE. Health risks from lost awareness of cultural behaviours rooted in traditional medicine: an insight in geophagy and mineral intake. *Sci Total Environ*. 2016;566-567:1465-1471.
12. Turner A, Scott JW, Green LA. Rare earth elements in plastics. *Sci Total Environ*. 2021;774:145405.
13. Yin X, Martineau C, Demers I, Basiliko N, Fenton NJ. The potential environmental risks associated with the development of rare earth element production in Canada. *Environ Rev*. 2021;29:354-377.
14. Frazzoli C, Ruggieri F, Battistini B, et al. E-waste threatens health: the scientific solution adopts the one health strategy. *Environ Res*. 2022;212:113227.
15. Ambaye TG, Vaccari M, Castro FD, Prasad S, Rtimi S. Emerging technologies for the recovery of rare earth elements (REEs) from the end-of-life electronic wastes: a review on progress, challenges, and perspectives. *Environ Sci Pollut Res*. 2020;27:36052-36074.
16. Dang DH, Thompson KA, Ma L, et al. Toward the circular economy of rare earth elements: A review of abundance, extraction, applications, and environmental impacts. *Arch Environ Contam Toxicol*. 2021;81:521-530.
17. Rhodes CJ. Endangered elements, critical raw materials and conflict minerals. *Sci Prog*. 2019;102:304-350.
18. Nuss P, Blengini GA. Towards better monitoring of technology critical elements in Europe: coupling of natural and anthropogenic cycles. *Sci Total Environ*. 2018;613-614:569-578.
19. Mudd GM, Jowitt SM, Werner TT. The world's by-product and critical metal resources part I: uncertainties, current reporting practices, implications and grounds for optimism. *Ore Geol Rev*. 2017;86:924-938.
20. Mudd GM, Jowitt SM, Werner TT. The world's lead-zinc mineral resources: scarcity, data, issues and opportunities. *Ore Geol Rev*. 2017;80:1160-1190.
21. Hunt AJ, Farmer TJ, Clark JH. Elemental sustainability and the importance of scarce element recovery. In: Hunt A, ed. *Element Recovery and Sustainability*. The Royal Society of Chemistry; 2013:1-28.
22. Capilla AV, Delgado AV. *Thanatia: The Destiny of the Earth's Mineral Resources: A Thermodynamic Cradle-to-Cradle Assessment*. World Scientific; 2014.
23. Yuksekdag A, Kose-Mutlu B, Zeytuncu-Gokoglu B, et al. Process optimization for acidic leaching of rare earth elements (REE) from waste electrical and electronic equipment (WEEE). *Environ Sci Pollut Res*. 2022;29:7772-7781.
24. Hunt AJ, Matharu AS, King AH, Clark JH. The importance of elemental sustainability and critical element recovery. *Green Chem*. 2015;17:1949-1950.
25. Reck BK, Graedel TE. Challenges in metal recycling. *Science*. 2012;337:690-695.
26. Jowitt SM, Werner TT, Weng Z, Mudd GM. Recycling of the rare earth elements. *Curr Opin Green Sustain Chem*. 2018;13:1-7.
27. van der Voet E, Kleijn R, Huele R, Ishikawa M, Verkuijlen E. Predicting future emissions based on characteristics of stocks. *Ecol Econ*. 2002;41:223-234.
28. Sonter LJ, Ali SH, Watson JEM. Mining and biodiversity: key issues and research needs in conservation science. *Proc R Soc B*. 2018;285:20181926.
29. Norgate T, Haque N. Energy and greenhouse gas impacts of mining and mineral processing operations. *J Clean Prod*. 2010;18:266-274.
30. Adeel M, Lee JY, Zain M, et al. Cryptic footprints of rare earth elements on natural resources and living organisms. *Environ Int*. 2019;127:785-800.
31. Gollakota ARK, Gautam S, Shu CM. Inconsistencies of e-waste management in developing nations - facts and plausible solutions. *J Environ Manag*. 2020;261:110234.
32. Liu K, Tan Q, Yu J, Wang M. A global perspective on e-waste recycling. *Circ Econ*. 2023;2:100028.
33. Waste Atlas Report. The world's 50 biggest dumpsites. Published online 2020. Accessed June 6, 2024. http://www.atlas.d-waste.com/
34. Frazzoli C. The vulnerable and the susceptible: the weight of *evidenza* to stop exploiting activities generating toxic exposures in unprotected and deprived countries. *J Glob Health*. 2021;11:03046.
35. Frazzoli C, Orisakwe OE, Dragone R, Mantovani A. Diagnostic health risk assessment of electronic waste on the general population in developing countries' scenarios. *Environ Impact Assess Rev*. 2010;30:388-399.
36. Anyanwu BO, Ezejiofor AN, Igweze ZN, Orisakwe OE. Heavy metal mixture exposure and effects in developing nations: an update. *Toxics*. 2018;6:65.
37. Balaram V. Rare earth elements: a review of applications, occurrence, exploration, analysis, recycling, and environmental impact. *Geosci Front*. 2019;10:1285-1303.
38. Gangwar C, Choudhari R, Chauhan A, et al. Assessment of air pollution caused by illegal e-waste burning to evaluate the human health risk. *Environ Int*. 2019;125:191-199.
39. Bede-Ojimadu O, Orisakwe OE. Exposure to wood smoke and associated health effects in Sub-Saharan Africa: a systematic review. *Ann Global Health*. 2020;86:32.
40. Ebenebe P, Shale K, Sedibe M, Achilonu M, Tikilili P. South African mine effluents: heavy metal pollution and impact on the ecosystem. *Int J Chem Sci*. 2017;15:1-12.
41. Abiya SE. Assessment of heavy metal pollution in a gold mining site in Southwestern Nigeria. *Biomed J Sci Tech Res*. 2019;12:9353-9357.
42. Mudd GM, Jowitt SM, Werner TT. Global platinum group element resources, reserves and mining - a critical assessment. *Sci Total Environ*. 2018;622-623:614-625.
43. Rauch S, Fatoki OS. Anthropogenic platinum enrichment in the vicinity of mines in the Bushveld igneous complex, South Africa. *Water Air Soil Pollut*. 2013;224:1395.
44. Almécija C, Cobelo-García A, Wepener V, Prego R. Platinum group elements in stream sediments of mining zones: the Hex River (Bushveld Igneous Complex, South Africa). *J Afr Earth Sci*. 2017;129:934-943.
45. Erasmus JH, Malherbe W, Zimmermann S, et al. Metal accumulation in riverine macroinvertebrates from a platinum mining region. *Sci Total Environ*. 2020;703:134738.
46. Labuschagne M, Wepener V, Nachev M, et al. The application of artificial mussels in conjunction with transplanted bivalves to assess elemental exposure in a platinum mining area. *Water*. 2019;12:32.
47. Díaz-Morales DM, Erasmus JH, Bosch S, et al. Metal contamination and toxicity of soils and river sediments from the world's largest platinum mining area. *Environ Pollut*. 2021;286:117284.

48. Somerset V, Van der Horst C, Silwana B, Walters C, Iwuoha E. Biomonitoring and evaluation of metal concentrations in sediment and crab samples from the north-West Province of South Africa. *Water Air Soil Pollut*. 2015;226:43.
49. Sepadi MM, Chadyiwa M, Nkosi V. Platinum mine workers' exposure to dust particles emitted at mine waste rock crusher plants in Limpopo, South Africa. *Int J Environ Res Public Health*. 2020;17:655.
50. Narendrula R, Nkongolo KK, Beckett P. Comparative soil metal analyses in Sudbury (Ontario, Canada) and Lubumbashi (Katanga, DR-Congo). *Bull Environ Contam Toxicol*. 2012;88:187-192.
51. Atibu EK, Lacroix P, Sivalingam P, et al. High contamination in the areas surrounding abandoned mines and mining activities: an impact assessment of the dilala, Luilu and Mpingiri Rivers, Democratic Republic of the Congo. *Chemosphere*. 2018;191:1008-1020.
52. Atibu EK, Devarajan N, Laffite A, et al. Assessment of trace metal and rare earth elements contamination in rivers around abandoned and active mine areas. The case of Lubumbashi River and Tshamilemba Canal, Katanga, Democratic Republic of the Congo. *Geochem*. 2016;76:353-362.
53. Thomas G, Sheridan C, Holm PE. Arsenic contamination and rare earth element composition of acid mine drainage impacted soils from South Africa. *Miner Eng*. 2023;203:108288.
54. Anyanwu J, Abderrahim K, Feid A. Crude oil and natural gas production in Africa and the global market situation. *Commodities Brief*. 2010;1:1-17.
55. Beyer J, Goksøyr A, Hjermann DØ, Klungsøyr J. Environmental effects of offshore produced water discharges: A review focused on the Norwegian continental shelf. *Mar Environ Res*. 2020;162:105155.
56. Coronel Vargas G, Au WW, Izzotti A. Public health issues from crude-oil production in the Ecuadorian Amazon territories. *Sci Total Environ*. 2020;719:134647.
57. Egbe R, Thompson D. Environmental challenges of oil spillage for families in oil producing communities of the Niger Delta Region. *Journal of Home Economics Research*. 2010; 13: 24-34. https://api.semanticscholar.org/CorpusID:55006643
58. Orisakwe OE. Crude oil and public health issues in Niger delta, Nigeria: much ado about the inevitable. *Environ Res*. 2021;194:110725.
59. Chinedu E, Chukwuemeka CK. Oil spillage and heavy metals toxicity risk in the Niger delta, Nigeria. *J Health Pollut*. 2018;8:180905.
60. Glaister BJ, Mudd GM. The environmental costs of platinum–PGM mining and sustainability: is the glass half-full or half-empty? *Miner Eng*. 2010;23:438-450.
61. Saleh EM, Hamdy GM, Hassan RE. Neuroprotective effect of sodium alginate against chromium-induced brain damage in rats. *PLoS One*. 2022;17:e0266898.
62. Saleh HM, Eskander SB, Mahmoud HH, Abdelaal SA. Study on rare earth elements, heavy metals and organic contents in the soil of oil exploration site at Matruh Governorate, Egypt. *Results Geophys Sci*. 2022;9:100039.
63. Onojake MC, Frank O. Assessment of heavy metals in a soil contaminated by oil spill: a case study in Nigeria. *Chem Ecol*. 2013;29:246-254.
64. Ejike CE, Eferibe CO, Okonkwo FO. Concentrations of some heavy metals in underground water samples from a Nigerian crude oil producing community. *Environ Sci Pollut Res*. 2017;24:8436-8442.
65. Buechler DT, Zyaykina NN, Spencer CA, et al. Comprehensive elemental analysis of consumer electronic devices: rare earth, precious, and critical elements. *Waste Manag*. 2020;103:67-75.
66. Willner J, Fornalczyk A, Jablonska-Czapla M, Grygoyc K, Rachwal M. Studies on the content of selected technology critical elements (germanium, tellurium and thallium) in electronic waste. *Materials*. 2021;14:3722.
67. Orisakwe OE, Frazzoli C, Ilo CE, Oritsemuelebi B. Public health burden of e-waste in Africa. *J Health Pollut*. 2019;9:190610.
68. Ayedun H, Arowolo TA, Gbadebo AM, Idowu OA. Evaluation of rare earth elements in groundwater of Lagos and Ogun States, Southwest Nigeria. *Environ Geochem Health*. 2017;39:649-664.
69. Kyere VN, Greve K, Atiemo SM, Ephraim J. Spatial assessment of potential ecological risk of heavy metals in soils from informal e-waste recycling in Ghana. *Environ Health Toxicol*. 2017;32:e2017018.
70. Kyere VN, Greve K, Atiemo SM. Spatial assessment of soil contamination by heavy metals from informal electronic waste recycling in Agbogbloshie, Ghana. *Environ Health Toxicol*. 2016;31:e2016006.
71. Ackah M. Soil elemental concentrations, geoaccumulation index, non-carcinogenic and carcinogenic risks in functional areas of an informal e-waste recycling area in Accra, Ghana. *Chemosphere*. 2019;235:908-917.
72. Adesokan MD, Adie GU, Osibanjo O. Soil pollution by toxic metals near e-waste recycling operations in Ibadan, Nigeria. *J Health Pollut*. 2016;6:26-33.
73. Cao P, Fujimori T, Juhasz A, Takaoka M, Oshita K. Bioaccessibility and human health risk assessment of metal(loid)s in soil from an e-waste open burning site in Agbogbloshie, Accra, Ghana. *Chemosphere*. 2020;240:124909.
74. Bocca B, Petrucci F, Alimonti A, Caroli S. Traffic-related platinum and rhodium concentrations in the atmosphere of Rome. *J Environ Monit*. 2003;5:563.
75. Omrani M, Goriaux M, Liu Y, et al. Platinum group elements study in automobile catalysts and exhaust gas samples. *Environ Pollut*. 2020;257:113477.
76. Kylander ME, Rauch S, Morrison GM, Andam K. Impact of automobile emissions on the levels of platinum and lead in Accra, Ghana. *J Environ Monit*. 2003;5:91-95.
77. Essumang DK, Dodoo DK, Adokoh CK. The impact of vehicular fallout on the Pra estuary of Ghana (a case study of the impact of platinum group metals (PGMs) on the marine ecosystem). *Environ Monit Assess*. 2008;145:283-294.
78. Kolawole TO, Olatunji OS, Ajibade OM, Oyelami CA. Sources and level of rare earth element contamination of atmospheric dust in Nigeria. *J Health Pollut*. 2021;11(30):210611.
79. Ascenzi P, Bettinelli M, Boffi A, et al. Rare earth elements (REE) in biology and medicine. *Rend Fis Acc Lincei*. 2020;31:821-833.
80. Sobrova P, Zehnalek J, Adam V, Beklova M, Kizek R. The effects on soil/water/plant/animal systems by platinum group elements. *Open Chem*. 2012;10:1369-1382.
81. Zakari-Jiya A, Frazzoli C, Obasi CN, et al. Pharmaceutical and personal care products as emerging environmental contaminants in Nigeria: a systematic review. *Environ Toxicol Pharmacol*. 2022;94:103914.
82. Roque-Diaz Y, Sanadar M, Han D, et al. The dark side of platinum based cytostatic drugs: from detection to removal. *Processes*. 2021;9:1873.
83. Kesava Raju CS, Cossmer A, Scharf H, Panne U, Lück D. Speciation of gadolinium based MRI contrast agents in environmental water samples using hydrophilic interaction chromatography hyphenated with inductively coupled plasma mass spectrometry. *J Anal At Spectrom*. 2010;25:55-61.
84. Atinkpahoun CNH, Pons MN, Louis P, Leclerc JP, Soclo HH. Rare earth elements (REE) in the urban wastewater of Cotonou (Benin, West Africa). *Chemosphere*. 2020;251:126398.
85. Balaram V. Recent advances in the determination of elemental impurities in pharmaceuticals – status, challenges and moving frontiers. *Trends Analyt Chem*. 2016;80:83-95.
86. Ochieng G, Seanego E, Nkwonta O. Impacts of mining on water resources in South Africa: a review. *Sci Res Essays*. 2010;5:3351-3357.
87. Celis JE, Espejo W, González-Acuña D. Chemical elements of emerging technologies are being increasingly demanded worldwide: a possible menace for wildlife conservation? *Anim Conserv*. 2020;23:3-6.
88. Essumang D. Bioaccumulation of platinum group metals in dolphins, *Stenella* sp., caught off Ghana. *Afr J Aquat Sci*. 2008;33:255-259.
89. Essumang DK. First determination of the levels of platinum group metals in manta birostris (Manta Ray) caught along the Ghanaian coastline. *Bull Environ Contam Toxicol*. 2010;84:720-725.
90. Essumang DK, Adokoh CK, Boamponsem L. Levels of platinum group metals in selected species (*Sarotherodon melanotheron,Chonophorus lateristriga, Macrobrachium vollenhovenii* and *crassostrea tulipa*) in some estuaries and lagoons along the coast of Ghana. *Sci World J*. 2010;10:1971-1987.
91. Essumang DK, Dodoo DK, Adokoh CK, Sam A, Doe NG. Bioaccumulation of platinum group metals on some fish species (*oreochromis niloticus, Penaeus laspisulcates, Scylla serrate, Galaxias brevipinnis* and *Mollusc)* in the Pra estuary of Ghana. *Toxicol Environ Chem*. 2008;90:625-638.
92. Labuschagne M, Zimmermann S, Smit NJ, et al. Laboratory and field studies on the use of artificial mussels as a monitoring tool of platinum exposure in the freshwater environment. *Environ Sci Eur*. 2021;33:16.
93. Schertzinger G, Zimmermann S, Grabner D, Sures B. Assessment of sublethal endpoints after chronic exposure of the nematode Caenorhabditis elegans to palladium, platinum and rhodium. *Environ Pollut*. 2017;230:31-39.
94. Erasmus JH, Zimmermann S, Smit NJ, et al. Human health risks associated with consumption of fish contaminated with trace elements from intensive mining activities in a peri-urban region. *Sci Total Environ*. 2022;825:154011.
95. Erasmus JH, Wepener V, Nachev M, et al. The role of fish helminth parasites in monitoring metal pollution in aquatic ecosystems: a case study in the world's most productive platinum mining region. *Parasitol Res*. 2020;119:2783-2798.
96. van der Schyff V, Pieters R, Bouwman H. The heron that laid the golden egg: metals and metalloids in ibis, darter, cormorant, heron, and egret eggs from the Vaal River catchment, South Africa. *Environ Monit Assess*. 2016;188:372.
97. Espejo W, Kitamura D, Kidd KA, et al. Biomagnification of tantalum through diverse aquatic food webs. *Environ Sci Technol Lett*. 2018;5:196-201.
98. Briant N, Le Monier P, Bruzac S, et al. Rare Earth element in bivalves' soft tissues of French metropolitan coasts: spatial and temporal distribution. *Arch Environ Contam Toxicol*. 2021;81:600-611.
99. Trapasso G, Chiesa S, Freitas R, Pereira E. What do we know about the ecotoxicological implications of the rare earth element gadolinium in aquatic ecosystems? *Sci Total Environ*. 2021;781:146273.
100. Aharchaou I, Bahloul F, Fortin C. Competition among trivalent elements (Al, Eu, Fe, Gd, Nd, Tm, and Y) for uptake in algae and applicability of the biotic ligand model. *Arch Environ Contam Toxicol*. 2021;81:612-620.
101. Loveridge A, Smith D, McGeer J. The acute toxicity of Thulium to Hyalella Azteca and the influence of toxicity modifying factors. *Arch Environ Contam Toxicol*. Published online August 10, 2021. doi:10.21203/rs.3.rs-779765/v1

102. Adeel M, Shakoor N, Hussain T, et al. Bio-interaction of nano and bulk lanthanum and ytterbium oxides in soil system: biochemical, genetic, and histopathological effects on Eisenia fetida. *J Hazard Mater*. 2021;415:125574.
103. Adeel M, Shakoor N, Ahmad MA, et al. Bioavailability and toxicity of nanoscale/bulk rare earth oxides in soil: physiological and ultrastructural alterations in *Eisenia fetida*. *Environ Sci Nano*. 2021;8:1654-1666.
104. Mikołajczak P, Borowiak K, Niedzielski P. Phytoextraction of rare earth elements in herbaceous plant species growing close to roads. *Environ Sci Pollut Res*. 2017;24:14091-14103.
105. Amadi CN, Bocca B, Ruggieri F, et al. Human dietary exposure to metals in the Niger delta region, Nigeria: Health risk assessment. *Environ Res*. 2022; 207:112234.
106. Doulgeridou A, Amlund H, Sloth J, Hansen M. Review of potentially toxic rare earth elements, thallium and tellurium in plant-based foods. *EFSA J*. 2020;18:e181101.
107. Garcia-Vazquez E, Geslin V, Turrero P, et al. Oceanic karma? Eco-ethical gaps in African EEE metal cycle may hit back through seafood contamination. *Sci Total Environ*. 2021;762:143098.
108. Zhang X, Hu Z, Pan H, et al. Effects of rare earth elements on bacteria in rhizosphere, root, phyllosphere and leaf of soil-rice ecosystem. *Sci Rep*. 2022;12:2089.
109. Orisakwe OE, Oladipo OO, Ajaezi GC, Udowelle NA. Horizontal and vertical distribution of heavy metals in farm produce and livestock around lead-contaminated goldmine in dareta and Abare, Zamfara State, Northern Nigeria. *J Environ Public Health*. 2017;2017:1-12.
110. Orisakwe OE, Nduka JK, Amadi CN, Dike DO, Bede O. Heavy metals health risk assessment for population via consumption of food crops and fruits in Owerri, South Eastern, Nigeria. *Chem Cent J*. 2012;6:77.
111. Muimba-Kankolongo A, Banza Lubaba Nkulu C, Mwitwa J, Kampemba FM, Mulele Nabuyanda M. Impacts of trace metals pollution of water, food crops, and ambient air on Population Health in Zambia and the DR Congo. *J Environ Public Health*. 2022;2022:1-14.
112. Musundire R, Ngonyama D, Chemura A, et al. Stewardship of wild and farmed edible insects as food and feed in Sub-Saharan Africa: a perspective. *Front Vet Sci*. 2021;8:601386.
113. Tommasi F, Thomas PJ, Pagano G, et al. Review of rare earth elements as fertilizers and feed additives: a knowledge gap analysis. *Arch Environ Contam Toxicol*. 2021;81:531-540.
114. Abdelnour SA, Abd El-Hack ME, Khafaga AF, et al. Impacts of rare earth elements on animal health and production: highlights of cerium and lanthanum. *Sci Total Environ*. 2019;672:1021-1032.
115. Henríquez-Hernández LA, Luzardo OP, Boada LD, et al. Study of the influencing factors of the blood levels of toxic elements in Africans from 16 countries. *Environ Pollut*. 2017;230:817-828.
116. Henríquez-Hernández LA, Boada LD, Carranza C, et al. Blood levels of toxic metals and rare earth elements commonly found in e-waste may exert subtle effects on hemoglobin concentration in sub-Saharan immigrants. *Environ Int*. 2017;109:20-28.
117. OSHA (Occupational Safety and Health Administration. Platinum (as Pt), soluble salts occupational safety and health administration, Washington, DC. Published online 2017.
118. Linde SJL, Franken A, du Plessis JL. Urinary excretion of platinum (Pt) following skin and respiratory exposure to soluble Pt at South African precious metals refineries. *Int J Hyg Environ Health*. 2018;221:868-875.
119. Linde SJL, Franken A, du Plessis JL. Skin and respiratory exposure to platinum group metals at two South African precious metals refineries. *Int Arch Occup Environ Health*. 2021;94:1073-1083.
120. Linde SJL, Franken A, du Plessis JL. Urinary excretion of platinum from South African precious metals refinery workers. *Occup Environ Med*. 2018;75:436-442.
121. CDC (Centers for Disease Control and Prevention). *Fourth National Report on Human Exposure to Environmental Chemicals, Updated Tables*. Department of Health and Human Services, Centers for Disease Control and Prevention; 2017.
122. Bose-O'Reilly S, Lettmeier B, Shoko D, et al. Infants and mothers levels of mercury in breast milk, urine and hair, data from an artisanal and small-scale gold mining area in Kadoma/Zimbabwe. *Environ Res*. 2020;184:109266.
123. Bose-O'Reilly S, Yabe J, Makumba J, et al. Lead intoxicated children in Kabwe, Zambia. *Environ Res*. 2018;165:420-424.
124. WHO (World Health Organization). Guideline for clinical management of exposure to lead. Published online 2021.
125. Toyomaki H, Yabe J, Nakayama SMM, et al. Lead concentrations and isotope ratios in blood, breastmilk and feces: contribution of both lactation and soil/dust exposure to infants in a lead mining area, Kabwe, Zambia. *Environ Pollut*. 2021;286:117456.
126. Kamala CT, Balaram V, Satyanarayanan M, Kiran Kumar A, Subramanyam KS. Biomonitoring of airborne platinum group elements in urban traffic police officers. *Arch Environ Contam Toxicol*. 2015;68:421-431.
127. Iavicoli I, Bocca B, Petrucci F, et al. Biomonitoring of traffic police officers exposed to airborne platinum. *Occup Environ Med*. 2004;61:636-639.
128. Rentschler G, Rodushkin I, Cerna M, et al. Platinum, palladium, rhodium, molybdenum and strontium in blood of urban women in nine countries. *Int J Hyg Environ Health*. 2018;221:223-230.
129. Gietema J, Meinardi M, Messerschmidt J, et al. Circulating plasma platinum more than 10 years after cisplatin treatment for testicular cancer. *Lancet*. 2000;355:1075-1076.
130. Nygren O, Lundgren C. Determination of platinum in workroom air and in blood and urine from nursing staff attending patients receiving cisplatin chemotherapy. *Int Arch Occup Environ Health*. 1997;70:209-214.
131. Oladipo HJ, Tajudeen YA, Taiwo EO, et al. Global environmental health impacts of rare earth metals: Insights for research and policy making in Africa. *Challenges*. 2023;14:20.
132. Gwenzi W, Mangori L, Danha C, et al. Sources, behaviour, and environmental and human health risks of high-technology rare earth elements as emerging contaminants. *Sci Total Environ*. 2018;636:299-313.
133. Frazzoli C, Dragone R, Mantovani A, Massimi C, Campanella L. Functional toxicity and tolerance patterns of bioavailable Pd(II), Pt(II), and Rh(III) on suspended Saccharomyces cerevisiae cells assayed in tandem by a respirometric biosensor. *Anal Bioanal Chem*. 2007;389:2185-2194.
134. Helm D. Association between palladium urinary concentrations and diseases of the thyroid and the immune system. *Sci Total Environ*. 2002;299:247-249.
135. Rim KT, Koo KH, Park JS. Toxicological evaluations of rare earths and their health impacts to workers: a literature review. *Saf Health Work*. 2013;4:12-26.
136. Rim KT. Effects of rare earth elements on the environment and human health: a literature review. *Toxicol Environ Health Sci*. 2016;8:189-200.
137. Li X, Chen Z, Chen Z, Zhang Y. A human health risk assessment of rare earth elements in soil and vegetables from a mining area in Fujian Province, Southeast China. *Chemosphere*. 2013;93:1240-1246.
138. Pagano G, Guida M, Tommasi F, Oral R. Health effects and toxicity mechanisms of rare earth elements-Knowledge gaps and research prospects. *Ecotoxicol Environ Saf*. 2015;115:40-48.
139. Meryem B, Ji H, Gao Y, Ding H, Li C. Distribution of rare earth elements in agricultural soil and human body (scalp hair and urine) near smelting and mining areas of Hezhang, China. *J Rare Earths*. 2016;34:1156-1167.
140. IAEA (International Atomic Energy Agency). Radiation Protection and NORM Residue Management in the Production of Rare Earths from Thorium Containing Minerals, Safety Report Series 68; 2011.
141. Carvalho FP, Tufa MB, Oliveira JM, Malta M. Radionuclides and radiation exposure in tantalite mining, Ethiopia. *Arch Environ Contam Toxicol*. 2021; 81:648-659.
142. Taruscio D, Baldi F, Carbone P, et al. Primary prevention of Congenital Anomalies: Special Focus on environmental chemicals and other toxicants, maternal health and Health Services and Infectious Diseases. In: Posada De La Paz M, Taruscio D, Groft SC, eds. *Rare Diseases Epidemiology: Update and Overview*. Vol. 1031. Advances in Experimental Medicine and Biology. Springer International Publishing; 2017:301-322.
143. Datubo-Brown DD, Kejeh BM. Congenital cleft deformities in Rivers state of Nigeria: is there any association with environmental pollution? *J R Coll Surg Edinb*. 1989;34:328-331.
144. Ekanem TB, Bassey IE, Mesembe OE, Eluwa MA, Ekong MB. Incidence of congenital malformation in 2 major hospitals in Rivers state of Nigeria from 1990 to 2003. *East Mediterr Health J*. 2011;17:701-705.
145. Abbey M, Oloyede O, Bassey G, et al. Prevalence and pattern of birth defects in a tertiary health facility in the Niger delta area of Nigeria. *Int J Womens Health*. 2017;9:115-121.
146. Adjekuko C, Emokpae M, Osadolor H, Jeremiah Z. Prevalence of thrombocytopenia among apparently healthy newborns in delta State, Nigeria. *New -l J -med Lab Sci*. 2018;72:54.
147. Van Brusselen D, Kayembe-Kitenge T, Mbuyi-Musanzayi S, et al. Metal mining and birth defects: a case-control study in Lubumbashi, Democratic Republic of the Congo. *Lancet Planet Heal*. 2020;4:e158-e167.
148. Kayembe-Kitenge T, Kasole Lubala T, Musa Obadia P, et al. Holoprosencephaly: a case series from an area with high mining-related pollution. *Birth Defects Res*. 2019;111:1561-1563.
149. Mbuyi-Musanzayi S, Kayembe TJ, Kashal MK, et al. Non-syndromic cleft lip and/or cleft palate: Epidemiology and risk factors in Lubumbashi (DR Congo), a case-control study. *J Craniomaxillofac Surg*. 2018;46:1051-1058.
150. Fadeyibi IO, Adeniyi AA, Jewo PI, et al. Current pattern of cleft lip and palate deformities in Lagos, Nigeria. *Cleft Palate Craniofac J*. 2012;49:730-735.
151. Huo W, Zhu Y, Li Z, et al. A pilot study on the association between rare earth elements in maternal hair and the risk of neural tube defects in north China. *Environ Pollut*. 2017;226:89-93.
152. Nkosi V, Wichmann J, Voyi K. Comorbidity of respiratory and cardiovascular diseases among the elderly residing close to mine dumps in South Africa: a cross-sectional study. *S Afr Med J*. 2016;106:290.
153. Mawaw PM, Yav T, Mukuku O, et al. Prevalence of obesity, diabetes mellitus, hypertension and associated risk factors in a mining workforce, Democratic Republic of Congo. *Pan Afr Med J*. 2017;28:282.

154. Gwimbi P. Monitoring SO2emission trends and residents' perceived health risks from PGM smelting at selous metallurgical complex in Zimbabwe. *Int J Equity Health*. 2017;16:200.
155. Steyn S. The management of aerial particulate pollution : the case of Platinum Industry Smelters in the Rustenburg region of North West Province, South Africa. 2005. https://api.semanticscholar.org/CorpusID:130691969
156. Khokhar M, Platt U, Wagner T. Temporal trends of anthropogenic SO_2 emitted by non-ferrous metal smelters in Peru and Russia estimated from Satellite observations. Published online September 18, 2008.
157. Kielhorn J, Melber C, Keller D, Mangelsdorf I. Palladium – a review of exposure and effects to human health. *Int J Hyg Environ Health*. 2002;205:417-432.
158. DOL (Department of Labour). Hazardous chemical substances regulations, 1995. *Occupational Health and Safety Act and Regulations (Act 85 of 1993)*. 18th ed. Juta and Company (Pty) Ltd; 2017:346-428.
159. Cristaudo A, Sera F, Severino V, et al. Occupational hypersensitivity to metal salts, including platinum, in the secondary industry. *Allergy*. 2005;60: 159-164.
160. Iavicoli I, Fontana L, Bergamaschi A. Palladium: Exposure, uses, and human health effects. *Encyclopedia of Environmental Health*. In: Encyclopedia of Environmental Health (Eds: Nriagu JO). 1st edition.Elsevier; 2011:307-314.
161. Nelson G. Occupational respiratory diseases in the South African mining industry. *Glob Health Action*. 2013;6:19520.
162. Merget R, Pham N, Schmidtke M, et al. Medical surveillance and long-term prognosis of occupational allergy due to platinum salts. *Int Arch Occup Environ Health*. 2017;90:73-81.
163. Yoon HK, Moon HS, Park SH, et al. Dendriform pulmonary ossification in patient with rare earth pneumoconiosis. *Thorax*. 2005;60:701-703.
164. Böhlandt A, Schierl R, Diemer J, et al. High concentrations of cadmium, cerium and lanthanum in indoor air due to environmental tobacco smoke. *Sci Total Environ*. 2012;414:738-741.
165. Wang B, Yan L, Huo W, et al. Rare earth elements and hypertension risk among housewives: a pilot study in Shanxi Province, China. *Environ Pollut*. 2017;220:837-842.
166. Bray F, Parkin DM, Gnangnon F. Cancer in sub-Saharan Africa in 2020: a review of current estimates of the national burden, data gaps, and future needs. *Lancet Oncol*. 2022;23:719-728.
167. Fasinu P, Orisakwe OE. Heavy metal pollution in Sub-Saharan Africa and possible implications in cancer epidemiology. *Asian Pac J Cancer Prev*. 2013;14:3393-3402.
168. Bello S, Nasiru R, Garba NN, Adeyemo DJ. Carcinogenic and non-carcinogenic health risk assessment of heavy metals exposure from Shanono and Bagwai artisanal gold mines, kano state, Nigeria. *Sci Afr*. 2019;6:e00197.
169. Alatise OI, Schrauzer GN. Lead exposure: a contributing cause of the current breast cancer epidemic in Nigerian women. *Biol Trace Elem Res*. 2010;136: 127-139.
170. Hnizdo E, Sluis-Cremer GK. Silica exposure, silicosis, and lung cancer: a mortality study of South African gold miners. *Occup Environ Med*. 1991;48:53-60.
171. McGlashan ND, Harington JS, Chelkowska E. Changes in the geographical and temporal patterns of cancer incidence among black gold miners working in South Africa, 1964-1996. *Br J Cancer*. 2003;88:1361-1369.
172. Liang F, Zhang S, Xue H, Chen Q. Risk of second primary cancers in cancer patients treated with cisplatin: a systematic review and meta-analysis of randomized studies. *BMC Cancer*. 2017;17:871.
173. Dertinger SD, Avlasevich SL, Torous DK, et al. Persistence of cisplatin-induced mutagenicity in hematopoietic stem cells: implications for secondary cancer risk following chemotherapy. *Toxicol Sci*. 2014;140:307-314.
174. Brozovic G, Orsolic N, Knezevic F, et al. The in vivo genotoxicity of cisplatin, isoflurane and halothane evaluated by alkaline comet assay in Swiss albino mice. *J Appl Genet*. 2011;52:355-361.
175. Gandaglia G, Karakiewicz PI, Trinh QD, Sun M. Cisplatin-based chemotherapy and the risk of solid tumors in patients with testicular nonseminoma: still a matter of debate. *J Clin Oncol*. 2014;32:1167-1167.
176. Gaman L, Radoi MP, Delia CE, et al. Concentration of heavy metals and rare earth elements in patients with brain tumours: analysis in tumour tissue, non-tumour tissue, and blood. *Int J Environ Health Res*. 2021;31:741-754.
177. Roncati L, Gatti AM, Barbolini G, et al. In vivo uptake of rare earth metals by triple-negative breast cancer cells. *Pathol Oncol Res*. 2018;24:161-165.
178. Sadeg N, Brousse F, Malonga G, Belhadj-Tahar H. 152P children's exposure to rare earth elements and cancer. *Ann Oncol*. 2020;31:S299-S300.
179. Wu L, Zhou YP, Zhong HJ. [A case-control study on the risk factors of leukemia in mining areas of rare-earth in South Jiangxi]. *Zhonghua Liu Xing Bing Xue Za Zhi*. 2003;24:879-882.
180. Zhuang G, Zhou Y, Lu H, et al. Concentration of rare earth elements, As, and Th in human brain and brain tumors, determined by neutron activation analysis. *Biol Trace Elem Res*. 1996;53:45-49.
181. Lentini P, Zanoli L, Granata A, et al. Kidney and heavy metals - the role of environmental exposure (review). *Mol Med Rep*. 2017;15:3413-3419.
182. Chukwuonye II, Ogah O, Anyabolu E, et al. Prevalence of chronic kidney disease in Nigeria: systematic review of population-based studies. *Int J Nephrol Renovasc Dis*. 2018;11:165-172.
183. Edwards JR, Prozialeck WC. Renal toxicology/nephrotoxicity of metals and nanometallic particles: arsenic, bismuth, cadmium, chromium, indium, lead, platinum, uranium, and metallic mixtures. In: Charlene A. McQueen, ed. *Comprehensive Toxicology*. Vol. 14, 3rd edition. Elsevier; 2018:487-506.
184. Thomas CC, Nsonwu-Anyanwu AC, Usoro CAO, Agoro ES, Idenyi AN. Hepato-renal toxicities associated with heavy metal contamination of water sources among residents of an oil contaminated area in Nigeria. *Ecotoxicol Environ Saf*. 2021;212:111988.
185. Chien CC, Wang HY, Wang JJ, et al. Risk of acute kidney injury after exposure to gadolinium-based contrast in patients with renal impairment. *Ren Fail*. 2011;33:758-764.
186. Bernstein EJ, Schmidt-Lauber C, Kay J. Nephrogenic systemic fibrosis: a systemic fibrosing disease resulting from gadolinium exposure. *Best Pract Res Clin Rheumatol*. 2012;26:489-503.
187. Luo X, Wei L, Liu S, et al. Correlation between urinary rare earth elements and liver function in a Zhuang population aged 35–74 years in Nanning. *J Trace Elem Med Biol*. 2024;84:127426. doi:10.1016/j.jtemb.2024.127426
188. Naganuma M, Motooka Y, Sasaoka S, et al. Analysis of adverse events of renal impairment related to platinum-based compounds using the Japanese adverse drug event report database. *Sage Open Med*. 2018;6:2050312118772475.
189. Sengupta P, Nwagha U, Dutta S, Krajewska-Kulak E, Izuka E. Evidence for decreasing sperm count in African population from 1965 to 2015. *Afr H Sci*. 2017;17:418.
190. Anyanwu BO, Orisakwe OE. Current mechanistic perspectives on male reproductive toxicity induced by heavy metals. *J Environ Sci Health C*. 2020;38:204-244.
191. Orisakwe OE. Environmental pollution and blood lead levels in Nigeria: who is unexposed? *Int J Occup Environ Health*. 2009;15:315-317.
192. Famurewa AC, Ugwuja EI. Association of Blood and seminal plasma cadmium and lead levels with semen quality in Non-Occupationally exposed infertile men in Abakaliki, South East Nigeria. *J Fam Reprod Heal*. 2017;11:97-103.
193. Amadi CN, Igweze ZN, Orisakwe OE. Heavy metals in miscarriages and stillbirths in developing nations. *Middle East Fertil Soc J*. 2017;22:91-100.
194. Marzec-Wróblewska U, Kamiński P, Łakota P, et al. Determination of rare earth elements in human sperm and association with Semen Quality. *Arch Environ Contam Toxicol*. 2015;69:191-201.
195. Xu X, Wang Y, Han N, et al. Early pregnancy exposure to rare earth elements and risk of gestational diabetes mellitus: w nested case-control study. *Front Endocrinol*. 2021;12:774142.
196. Liu Y, Wu M, Zhang L, et al. Prenatal exposure of rare earth elements cerium and ytterbium and neonatal thyroid stimulating hormone levels: findings from a birth cohort study. *Environ Int*. 2019;133(Pt B):105222.
197. Lekoubou A, Echouffo-Tcheugui JB, Kengne AP. Epidemiology of neurodegenerative diseases in sub-Saharan Africa: a systematic review. *BMC Public Health*. 2014;14:653.
198. Hendrie HC, Ogunniyi A, Hall KS, et al. Incidence of dementia and Alzheimer disease in 2 communities: Yoruba residing in Ibadan, Nigeria, and African Americans residing in Indianapolis, Indiana. *JAMA*. 2001;285: 739-747.
199. Ogunniyi A, Lane KA, Baiyewu O, et al. Hypertension and incident dementia in community-dwelling elderly Yoruba Nigerians: hypertension and dementia in elderly Yoruba. *Acta Neurol Scand*. 2011;124:396-402.
200. Oluwole OG, Kuivaniemi H, Carr JA, et al. Parkinson's disease in Nigeria: a review of published studies and recommendations for future research. *Parkinsonism Relat Disord*. 2019;62:36-43.
201. Dlamini WW, Nelson G, Nielsen SS, Racette BA. Manganese exposure, parkinsonian signs, and quality of life in South African mine workers. *Am J Ind Med*. 2019;63:36-43.
202. Guo BJ, Yang ZL, Zhang LJ. Gadolinium deposition in brain: current scientific evidence and future perspectives. *Front Mol Neurosci*. 2018;11:335.
203. Gulani V, Calamante F, Shellock FG, Kanal E, Reeder SB. Gadolinium deposition in the brain: summary of evidence and recommendations. *Lancet Neurol*. 2017;16:564-570.
204. Wang Y, Wang D, Huang Yi N, Sheng P, Yang B. Relationship between rare earth elements, lead and intelligence of children aged 6 to 16 years: a Bayesian structural equation modelling method. *Int Arch Nurs Heal Care*. 2019;5:123. doi:10.23937/2469-5823/1510123
205. Bornstein SR, Voit-Bak K, Schmidt D, et al. Is there a role for environmental and metabolic factors predisposing to severe COVID-19? *Horm Metab Res*. 2020;52:540-546.
206. Bulka CM, Bommarito PA, Aiello AE, Fry RC. Cytomegalovirus seroprevalence, recurrence, and antibody levels: associations with cadmium and lead exposures in the general United States population. *Environ Epidemiol*. 2020; 4:e100.

207. Ackland ML, Bornhorst J, Dedoussis GV, et al. Metals in the environment as risk factors for Infectious Diseases: gaps and opportunities. In: Nriagu JO, Skaar EP, eds. *Trace Metals and Infectious Diseases*. Chapter 17. Cambridge (MA): MIT Press; 2015.
208. Niohuru I. (ed.). Disease Burden and mortality. *Healthcare and Disease Burden in Africa*. SpringerBriefs in Economics. Springer International Publishing; 2023:35-85.
209. Folorunso OM, Frazzoli C, Chijioke-Nwauche I, Bocca B, Orisakwe OE. Toxic metals and non-communicable diseases in HIV population: a systematic review. *Medicina*. 2021;57:492.
210. Emokpae MA, Mbonu I. Blood levels of some toxic metals in human immunodeficiency virus (HIV) type 1- infection. *Ann Heal Res*. 2018;4:75-81.
211. Cardenas A, Smit E, Houseman EA, et al. Arsenic exposure and prevalence of the varicella zoster virus in the United States: NHANES (2003-2004 and 2009-2010). *Environ Health Perspect*. 2015;123:590-596.
212. Cardenas A, Smit E, Bethel JW, Houseman EA, Kile ML. Arsenic exposure and the seroprevalence of total hepatitis A antibodies in the US population: NHANES, 2003-2012. *Epidemiol Infect*. 2016;144:1641-1651.
213. Cardenas A, Smit E, Welch BM, Bethel J, Kile ML. Cross sectional association of arsenic and seroprevalence of hepatitis B infection in the United States (NHANES 2003-2014). *Environ Res*. 2018;166:570-576.
214. Skalny AV, Lima TRR, Ke T, et al. Toxic metal exposure as a possible risk factor for COVID-19 and other respiratory infectious diseases. *Food Chem Toxicol*. 2020;146:111809.
215. Dragone R, Licciardi G, Grasso G, Del Gaudio C, Chanussot J. Analysis of the chemical and physical environmental aspects that promoted the spread of SARS-CoV-2 in the Lombard area. *Int J Environ Res Public Health*. 2021; 18:1226.
216. Domingo JL, Marquès M. The effects of some essential and toxic metals/metalloids in COVID-19: a review. *Food Chem Toxicol*. 2021;152:112161.
217. Metryka E, Chibowska K, Gutowska I, et al. Lead (Pb) exposure enhances expression of factors associated with inflammation. *Int J Mol Sci*. 2018;19: 1813.
218. Lewis HC, Ware H, Whelan M, et al. SARS-CoV-2 infection in Africa: a systematic review and meta-analysis of standardised seroprevalence studies, from January 2020 to December 2021. *BMJ Glob Health*. 2022;7(8):e008793.
219. Oritsemuelebi B, Frazzoli C, Eze EC, et al. Levels of toxic and essential metals in maternal cord blood and anthropometry at birth: a pilot study. *J Glob Heal Rep*. 2021;5:e2021104. doi:10.29392/001c.29888
220. Frazzoli C, Mantovani A. Toxicants exposures as novel zoonoses: reflections on sustainable development, food safety and veterinary public health. *Zoonoses Public Health*. 2010;57:e136-e142.
221. Bocca B, Ruggieri F, Pino A, et al. Human biomonitoring to evaluate exposure to toxic and essential trace elements during pregnancy. Part A. Concentrations in maternal blood, urine and cord blood. *Environ Res*. 2019;177:108599.
222. Offor SJ, Orish CN, Chidi Eze E, Frazzoli C, Orisakwe OE. Blood donation and heavy metal poisoning in developing nations: any link? *Transfus Apher Sci*. 2021;60:103067.
223. Frazzoli C, Mantovani A. Toxicological risk factors in the burden of malnutrition: the case of nutrition (and risk) transition in sub-Saharan Africa. *Food Chem Toxicol*. 2020;146:111789.
224. Frazzoli C, Mantovani A, Mantovani A. One Health/One Prevention/One Resilience and zoonoses applied to the Mediterranean: features analyses for successful intervention based on toxicological risk assessment. 2016:75-86.
225. Pouokam GB, Foudjo BUS, Samuel C, et al. Contaminants in foods of animal origin in Cameroon: a One Health Vision for risk management "from farm to Fork.*Front Public Health*. 2017;5:197.
226. Kaninga BK, Chishala BH, Maseka KK, et al. Review: mine tailings in an African tropical environment—mechanisms for the bioavailability of heavy metals in soils. *Environ Geochem Health*. 2020;42:1069-1094.
227. Pouokam GB, Ajaezi GC, Mantovani A, Orisakwe OE, Frazzoli C. Use of bisphenol A-containing baby bottles in Cameroon and Nigeria and possible risk management and mitigation measures: community as milestone for prevention. *Sci Total Environ*. 2014;481:296-302.
228. Mantovani A, Frazzoli C, La Rocca C. Risk assessment of endocrine-active compounds in feeds. *Vet J*. 2009;182:392-401.
229. Frazzoli C, Bocca B, Mantovani A. The One Health perspective in trace elements biomonitoring. *J Toxicol Environ Health B*. 2015;18:344-370.
230. Amadi CN, Frazzoli C, Orisakwe OE. Sentinel species for biomonitoring and biosurveillance of environmental heavy metals in Nigeria. *J Environ Sci Health C*. 2020;38:21-60.
231. Abdou M, Dutruch L, Schäfer J, et al. Tracing platinum accumulation kinetics in oyster Crassostrea gigas, a sentinel species in coastal marine environments. *Sci Total Environ*. 2018;615:652-663.
232. Abrahams PW, Blackwell NL. The importance of ingested soils in supplying fluorine and lead to sheep grazing contaminated pastures in the Peak District mining area of Derbyshire, UK. *Environ Sci Pollut Res*. 2013;20: 8729-8738.
233. Mantovani A. Sustainability, security and safety in the feed-to-fish chain: focus on toxic contamination. *Int J Nutr Food Sci*. 2015;4:6.
234. Ramos SJ, Dinali GS, Oliveira C, et al. Rare earth elements in the soil environment. *Curr Pollut Rep*. 2016;2:28-50.
235. Xu W, Shafi M, Penttinen P, et al. Bioavailability of heavy metals in contaminated soil as affected by different mass ratios of biochars. *Environ Technol*. 2020;41:3329-3337.
236. Pouokam B, Ahmed H, Ngwafor R, Frazzoli C. Toxicovigilance systems and practices in Africa. *Toxics*. 2016;4:13.
237. Mantovani A. Characterization and management of uncertainties in toxicological risk assessment: examples from the opinions of the European food safety authority. In: Nicolotti O, ed. *Computational Toxicology*. Vol. 1800. Methods in Molecular Biology. Springer; 2018:219-229.
238. Taruscio D, Mantovani A. Multifactorial rare diseases: can uncertainty analysis bring added value to the search for risk factors and etiopathogenesis? *Medicina*. 2021;57:119.
239. Frazzoli C. Field anthropological research for context-effective risk analysis science in traditional cultures: the case of Senegal. *J Glob Heal Rep*. 2020;4:e2020043. doi:10.29392/001c.12922
240. Orisakwe OE, Frazzoli C. *Water Supply in Niger Delta of Nigeria: From Public Protests to Scientific Discourse*. NOVA, Nova Science Publishers, Inc; 2011.
241. Omanga E, Ulmer L, Berhane Z, Gatari M. Industrial air pollution in rural Kenya: community awareness, risk perception and associations between risk variables. *BMC Public Health*. 2014;14:377.
242. Goossens A, De Swerdt A, De Coninck K, et al. Allergic contact granuloma due to palladium following ear piercing. *Contact Dermatitis*. 2006;55:338-341.
243. Cristaudo A, Forte G, Bocca B, et al. Permanent tattoos: evidence of pseudolymphoma in three patients and metal composition of the dyes. *Eur J Dermatol*. 2012;22:776-780.
244. Njiru H, Elchalal U, Paltiel O. Geophagy during pregnancy in Africa: a literature review. *Obstet Gynecol Surv*. 2011;66:452-459.
245. Orisakwe OE, Udowelle NA, Azuonwu O, et al. Cadmium and lead in geophagic clay consumed in southern Nigeria: health risk from such traditional nutraceutical. *Environ Geochem Health*. 2020;42:3865-3875.
246. Gundacker C, Kutalek R, Glaunach R, et al. Geophagy during pregnancy: is there a health risk for infants? *Environ Res*. 2017;156:145-147.
247. Mireku MO, Davidson LL, Zoumenou R, et al. Consequences of prenatal geophagy for maternal prenatal health, risk of childhood geophagy and child psychomotor development. *Trop Med Int Health*. 2018;23:841-849.
248. Msoffe CU, Nyanza EC, Thomas DSK, Jahanpour O, Dewey D. The sources and chemical content of edible soil sticks sold in markets in Tanzania: a cross-sectional analytical study. *Environ Geochem Health*. 2019;41:893-906.
249. Frazzoli C, Mazzanti F, Achu MB, Pouokam GB, Fokou E. Elements of kitchen toxicology to exploit the value of traditional (African) recipes: the case of egusi Okra meal in the diet of HIV+/AIDS subjects. *Toxicol Rep*. 2017; 4:474-483.
250. Hsueh YM, Lee CY, Chien SN, et al. Association of blood heavy metals with developmental delays and health status in children. *Sci Rep*. 2017;7:43608.
251. Bede-Ojimadu O, Orish CN, Bocca B, et al. Trace elements exposure and risk in age-related eye diseases: a systematic review of epidemiological evidence. *J Environ Sci Health C*. 2021;39(3);293–339.
252. Orisakwe O. Lead and cadmium in public health in Nigeria: physicians neglect and pitfall in patient management. *North Am J Med Sci*. 2014;6:61.
253. Hennig B, Petriello MC, Gamble MV, et al. The role of nutrition in influencing mechanisms involved in environmentally mediated diseases. *Rev Environ Health*. 2018;33:87-97.
254. Johns T, Duquette M. Detoxification and mineral supplementation as functions of geophagy. *Am J Clin Nutr*. 1991;53:448-456.
255. Akan OD, Udofia GE, Okeke ES, et al. Plastic waste: status, degradation and microbial management options for Africa. *J Environ Manag*. 2021;292:112758.
256. Rautela R, Arya S, Vishwakarma S, et al. E-waste management and its effects on the environment and human health. *Sci Total Environ*. 2021;773:145623.
257. Joo J, Kwon EE, Lee J. Achievements in pyrolysis process in e-waste management sector. *Environ Pollut*. 2021;287:117621.
258. Lima AT, Ottosen L. Recovering rare earth elements from contaminated soils: critical overview of current remediation technologies. *Chemosphere*. 2021;265: 129163.
259. Newsome L, Falagán C. The microbiology of metal mine waste: bioremediation applications and implications for planetary health. *GeoHealth*. 2021; 5:e2020GH000380.
260. Mleczek M, Niedzielski P, Kalač P, et al. Levels of platinum group elements and rare-earth elements in wild mushroom species growing in Poland. *Food Addit Contam Part A*. 2016;33(1):86-94.
261. Wong-Pinto LS, Menzies A, Ordóñez JI. Bionanomining: biotechnological synthesis of metal nanoparticles from mining waste-opportunity for sustainable management of mining environmental liabilities. *Appl Microbiol Biotechnol*. 2020;104:1859-1869.

262. Grasso G, Zane D, Dragone R. Precision microbial nanobiosynthesis: knowledge, issues, and potentiality for the in vivo tuning of microbial nanomaterials. In: Lateef A, Gueguim-Kana EB, Dasgupta N, Ranjan S, eds. *Microbial Nanobiotechnology*. Materials Horizons: From Nature to Nanomaterials. Springer; 2021:75-112.
263. Jomova K, Valko M. Advances in metal-induced oxidative stress and human disease. *Toxicology*. 2011;283:65-87.
264. Amadi CN, Offor SJ, Frazzoli C, Orisakwe OE. Natural antidotes and management of metal toxicity. *Environ Sci Pollut Res*. 2019;26:18032-18052.
265. Frazzoli C, Grasso G, Husaini DC, et al. Immune system and epidemics: the role of African indigenous bioactive substances. *Nutrients*. 2023;15:273.
266. Obi E, Akunyili DN, Ekpo B, Orisakwe OE. Heavy metal hazards of Nigerian herbal remedies. *Sci Total Environ*. 2006;369:35-41.
267. Street RA. Heavy metals in medicinal plant products — an African perspective. *S Afr J Bot*. 2012;82:67-74.
268. Ndhlala AR, Ncube B, Okem A, Mulaudzi RB, Van Staden J. Toxicology of some important medicinal plants in southern Africa. *Food Chem Toxicol*. 2013;62:609-621.
269. Orisakwe OE, Amadi CN, Frazzoli C, Dokubo A. Nigerian foods of probiotics relevance and chronic metal exposure: a systematic review. *Environ Sci Pollut Res*. 2020;27:19285-19297.