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

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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

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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

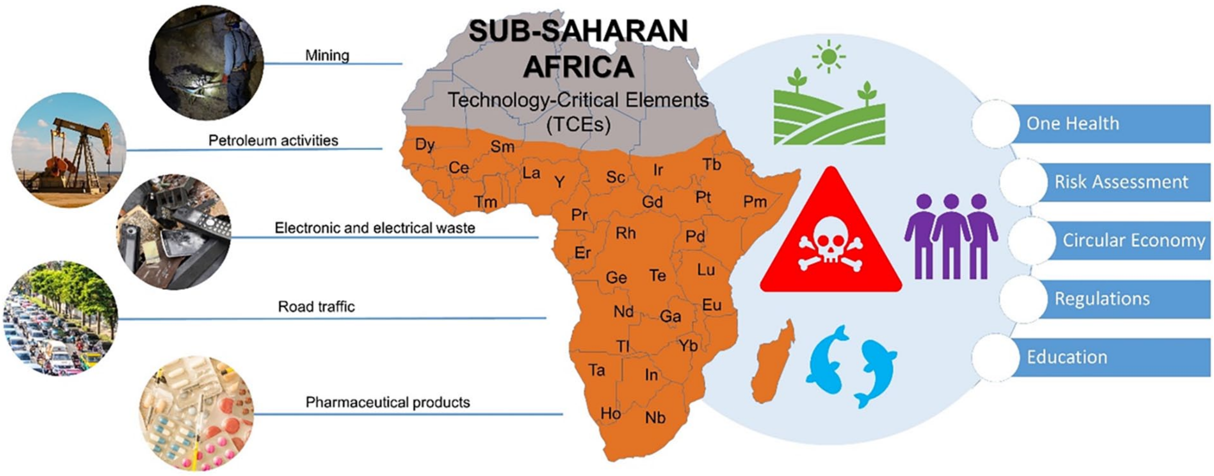

Figure 1. The diverse sources of TCEs environmental pollution in sub-Saharan Africa; the impact of TCE on environmental and human health; possible approaches and solutions to manage the technology-related challenges in SSA.

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, hepatorenal, 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

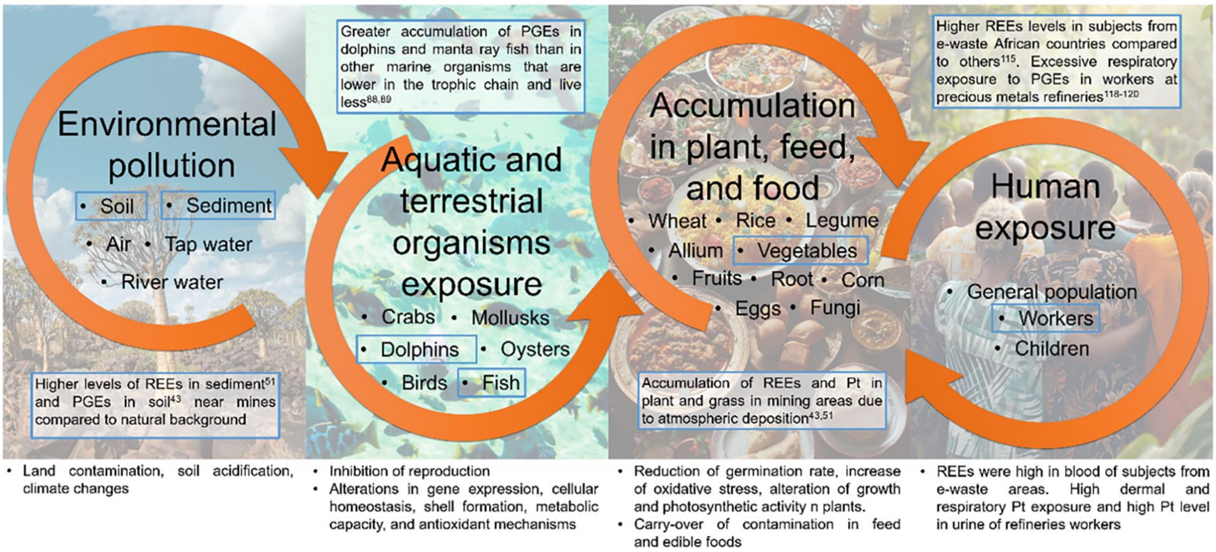

Figure 2. A One Health snapshot of TCEs fate.

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 µg/m^3,[117] for the 22% of respiratory exposure measurements, especially in concentrate handling areas where reached 28.18 µg/m^3.[118] The highest respiratory exposure was found for Pd (mean, 0.342 µg/m^3), followed by Pt, Rh, Ru, Ir and Os; while the highest skin exposure was observed for Pt (mean, 0.008 µg/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 µg/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% $\geqslant$ 45 µg/dl), despite the WHO asserted that 'for an individual with a blood Pb concentration $\geqslant$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]

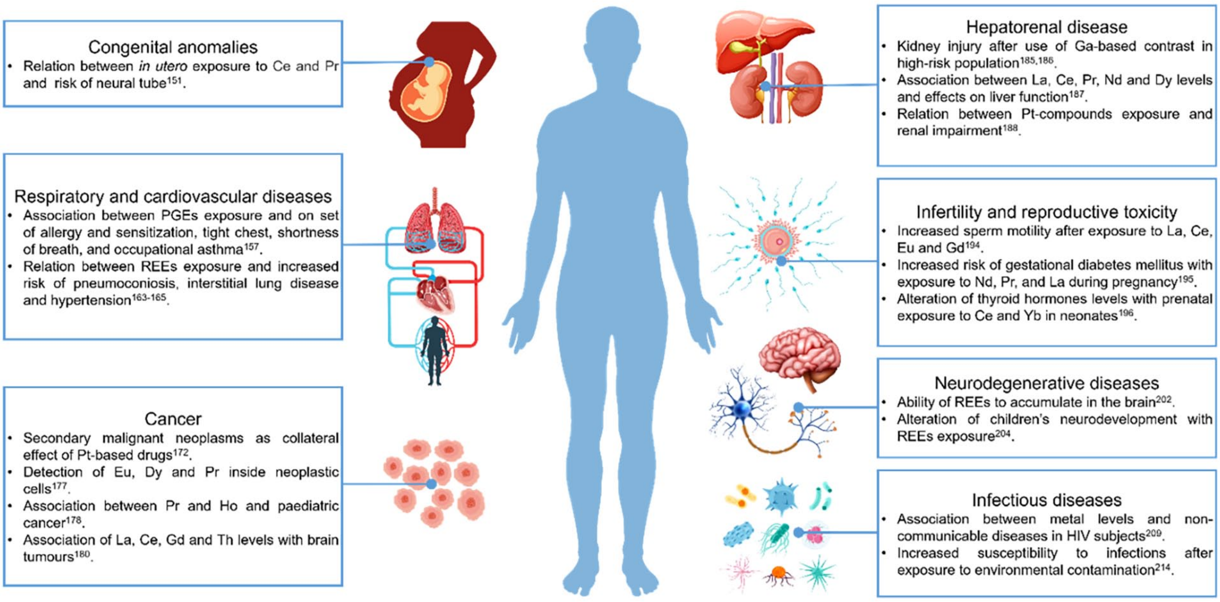

Figure 3. TCEs' impacts on human health: An overview.

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 evironmental 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

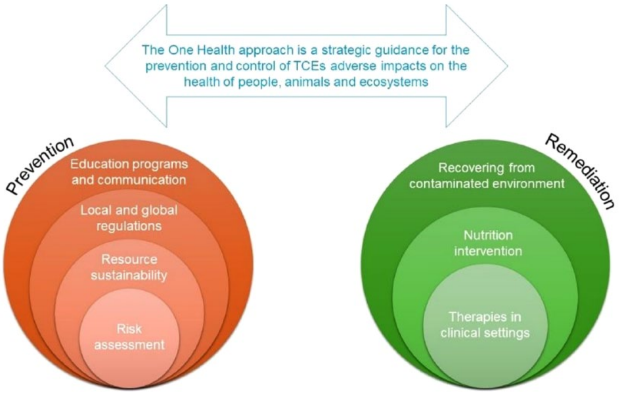

Figure 4. One Health approach is the strategic guidance for prevention and control of TCEs adverse impacts to protect the health of people, animals and ecosystems.

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).

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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.

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