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EDITED BY
Shahid Hussain,
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REVIEWED BY
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Agronomy and Veterinary Institute Hassan II, Morocco
Tamer A. Elbana,
National Research Centre (Egypt), Egypt

*CORRESPONDENCE
Bal Ram Singh
balram.singh@nmbu.no

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Soil pollution and agriculture in sub-Saharan Africa: State of the knowledge and remediation technologies

Hamisi J. Tindwa[1] and Bal Ram Singh[2*]

[1]Soil Science Laboratory, Department of soil and Geological Sciences, College of Agriculture, Sokoine University of Agriculture, Morogoro, Tanzania, [2]Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences (NMBU), Aas (Ås), Norway

The sub-Saharan Africa (SSA) region bears the blunt of soil pollution mainly due to-haphazard disposal and gross mismanagement of a wide assortment of pollutants generated from within and outside the region. Pollution of agricultural soils in the region is so intense that out of the 80 countries substantially affected by land degradation (soil pollution, inclusive) in the world, 36 are found in Africa, the SSA, in particular. Pollution of soils has resulted into a significant reduction in their ability to support crop growth and yield apart from jeopardizing safety and security of agricultural produce in SSA. Consequences of pollution of soils on human health in the region are inadequately reported, but they range from non-fatal, life-changing effects like skin damage due to acute, invariably fatal incidences of exposure to milt by chronic effects. We show in this review, that while science and advancement in technology has provided a multitude of alternative techniques to pollution control and remediation of affected soils, such techniques are largely inaccessible to most SSA countries. There is also lack of coordination on development, enforcement and implementation of legal and political instruments to tackle the growing risk of pollution to human health from soil contamination across the SSA region. Couple with this, lack of data on status of soil pollution in most SSA countries affects the countries' capacity to devise and plan policies that can help reduce soil pollution. Countries need to maximize efforts to reverse the status of already polluted pieces of land through strengthening remediation programs, research on how best to gather, maintain and complement soil pollution data and actions that inform decision-making.

KEYWORDS

soil pollution, agriculture, remediation technology, sub Saharan Africa, human health

1 Introduction

Pollution is the world's leading environmental cause of disease and premature death (1). It affects sustainability of the land resources and their ability to support life systems (2, 3). The problem is more serious in most of the SSA, where the major sources of soil pollution are agricultural activities, mining, roadside emissions, auto-mechanic workshops, refuse dumps and e-waste. Studies have shown that oil spills are the biggest problem especially in oil-rich countries such as Nigeria and Angola, where mining, industrial activities and refuse dumps are widespread all over such countries. In recent years, e-waste recycling has become one of the biggest contributor to soil pollution with Pb, Cu and Zn (4). This work reviews the interactions between pollution and agriculture, technological options for its control, the state of the knowledge on its magnitude and remediation technologies across the SSA

2 Soil and sediment pollution in African agriculture: Main sources of pollutants and extent of the problem

The Sub-saharan Africa region is facing a growing challenge on how to maintain a balance between economic development and sustainable environmental protection. This is because over a long time, countries have prioritized short-term benefits from increased production over pollution prevention technologies and initiatives. Pollution of agricultural soils and sediments in the SSA soils can be traced both from anthropogenic and geological origins. Anthropogenic sources range from industrial activities, agricultural production, mining and quarrying to waste disposal and management (5). Consequently, predominant contaminants of soils and sediments in SSA are trace elements, followed by pesticides, hydrocarbons and polychlorinated biphenyls (PCBs). If the current trends are not intercepted, Africa as whole is expected to witness an exponential growth in waste generation in the next 20 to 50 years which may reach a peak in the years beyond 2100 (6).. Main sources of wastes generation in the region are discussed hereunder.

2.1 Industrial production activities

The current quantity of wastes generated in SSA remains proportionally small when compared to that generated by the developed regions of the world, although SSA is forecast to become the global giant in terms of total waste generation if current trends remain uninterrupted (7). In 2016, for example, Africa generated around 174 million tons of wastes and that figure is expected to reach 244 million tons per year as early as 2025 (7, 8). Estimates by the World Bank suggest that waste generation in the SSA will triple by the year 2050 (9). Organic wastes constitute the bulk (57%) of total wastes produced in the SSA with the rest being plastic (13%), metal (4%), paper (9%), glass (4%) and others (13%) (7: 8). A greater part of these wastes is attributable to both population growth and industrialization (8–11). Consequently, contaminants in the form of gaseous emissions, liquid and solid wastes have ended up in land resources including surface and underground waters, the soils, and sediments mainly due to less stringent regulations overseeing management of wastes in SSA countries. Total environmental pollution tends to rise in areas where more polluting industries like petrochemicals or cement manufacturing are increasing their share of production leading, in turn, to tremendous stress on the entire ecosystem and natural system components like water, air, soil, and bio-diversity (12, 13).

On the other hand, Small-scale industrial operations ranging from dry cleaning, auto-mechanical workshops and lead battery recycling to cottage industries account for a significant share of soil pollution in sub-Saharan Africa (5). Auto-mechanical workshops through provision of a range of services such as engine repair and maintenance, welding and paint spraying, do release a variety of pollutants to the surrounding soils (5). The released pollutants may include paints, paint primers and solvents, old hydraulic liquids, lubricating oil and grease (14). All of these pollutants could be a significant source of polycyclic aromatic hydrocarbons (PAHs), some of which can be cancer-causing agents upon prolonged exposure.

Cottage industries, which refer to a group of home-based small-scale industries, can act as a source of income to many families in Africa. Nonetheless, they are also a serious source of pollutants in sub-Saharan Africa. They are usually completely unregulated and exempt from worker compensation laws and other occupational health and safety regulations (15). During operations, cottage industries use highly toxic heavy metals such as lead, mercury, cadmium and arsenic (15, 16). Table 1 shows metals reported in literature, characteristic of cottage industrial operations that eventually end up polluting the environment, notably soils, and sediments.

2.2 Artisanal and small-scale mining

Gold, tin, cobalt and lead are some of the heavy metals usually mined by Artisanal and small-scale mining activities across the SSA. ASM is known to provide a source of income to approximately 20 to 30 million miners globally (29). Among them, tens of millions of people in SSA rely on ASM for their disposable incomes (13).

TABLE 1 Metals originating from cottage industrial operations that pollute the soils and sediments.

Type of cottage industry/operation	Toxic heavy metals released	Environmental segment polluted	References
Electrical appliance repair	Pb, Cd, Hg, As	Air, land (soil and water bodies)	(15, 17)
Car repair and garage services	Pb	Soils, water, air	(18–20)
Welding	Pb, Cd	Soils, water, air	(15, 21)
Scrap metal recycling	Pb, Zn, Cu, Ni, Cr, Cd, Cr	Soils, waters	(17, 22, 23)
Spray painting	Pb, Cd, Cr	Air, water, soils	(24, 25)
Metal jewelry making	Ag, Cu, Sn, B, Ni, Zn, Pb, Cd	Soils, air, waters	(26)
Hair dressing	Pb, Cu, Co, Ni, Cr, Cd, As	Soils, air	(27, 28)

However, Most of the SSA region's ASM activities are informal, largely unregulated and hence surrounded by episodes of illegality, partly because registration is often a costly and bureaucratic undertaking. Evidence suggests that, for over the last 20 to 25 years, majority of people in SSA, both skilled and non-skilled, have entered into the ASM activities because of hardships in sustaining daily lives (30). As a result, mining through ASM presents a heavy environmental and human cost making it a source of serious environmental pollution. Absence of legislation and government controls in most SSA countries has opened ASM activities to little or no waste management and health protection measures leading to dangerous exposure of the miners as well as destruction of ecosystems.

ASM, for example, produces about 20% of the world's gold every year. However, gold mining through ASM releases large amounts of mercury into the environment. Mercury is applied for separating gold from soil as mercury and gold combine to form a gold-mercury amalgam effectively separating mercury from the soil and sediments, after which gold is then extracted by vaporizing the mercury. The mercury vapor can travel over long distances before precipitating with rain to contaminate soils and water bodies far away from the gold mine.

Similarly, Artisanal tin mining creates two major environmental challenges. Over time, the undertaking creates a large area of wastelands apart from numerous ex-tin mining ponds and tailing dumps. Furthermore, finer tin tailing generate dusty pollution in a dry environment. ASM, which is mainly concentrated in the Democratic Republic of Congo (DRC), Uganda, Burundi, Rwanda and Nigeria, is the dominant form of tin mining in SSA in spite of a few existing industrial mines. Artisanal tin mining can cause a variety of environmental damages, such as mine dumps, accumulation of mine tailings that contain radioactive wastes and general destruction of agricultural land in search for tin-containing cassiterites (31). Mine ponds in tin mining areas have resulted into accidental deaths, while soil erosion has caused serious loss of nutrients and soil organic matter, leading to soil pollution and degradation.

More than half of the world's cobalt, a critical base metal and essential component of lithium-ion batteries for smartphones, laptop computers, electric vehicles, comes from the Katanga Copperbelt in the Democratic Republic of Congo (32). Up to 20% of cobalt from the Katanga copper belt, is extracted by artisanal miners who characterized by thousands of diggers who usually work under extremely precarious and hazardous conditions (33, 34).

2.3 Agricultural activities

The main contributor of soils and sediment pollution in agricultural settings are fertilizers, pesticides and organic wastes used in agricultural production. The term 'pesticide' refers to all chemicals, natural or synthetic, applied to kill or control pests either in agricultural fields or in other environments such as storerooms, human houses and gardens (35). Pesticides or any other chemicals and elements become contaminants in the soil when their concentrations are higher than their natural level (36). Pesticides can enter the soil in different ways, the main ones being *via* spray drill during foliage treatment, wash-off from treated foliage or release from granulates and treated seeds in soil (37). Pesticides can also enter the soil through direct application of pesticides and fumigants to control soil born pests and plant (38).

Pesticide contaminated hotspots are scattered all across the SSA region due to injudicious use of pesticides to control pests and damping of obsolete pesticides by burying into the soils. Classical examples include the pesticide contamination in the Gezira scheme of Sudan and copper contamination and accumulation in soils grown to coffee in northern Tanzania (39, 40). Contamination of soils due to burying of DDT, a powerful insecticide that is highly persistent in soils has been documented across the region. For example, persistent organic pollutants (POPs) such as aldrin, DDT, dieldrin, endrin, endosulfan, chordane and heptachlor, previously buried in five different locations in Tanzania, were subsequently reported to have aged but with significantly slow degradation rate (41) hence continuing to present a significant health risk to plant, animals and humans that come in contact with the contaminated soils.

Some chemical and organic fertilizers utilized in agricultural production across the SSA countries, contain toxic by-components such as trace elements inorganic acids and organic pollutants. Primarily, toxic trace elements (e.g. cadmium), are contained in phosphatic fertilizers, originating from phosphate rocks applied for manufacturing P fertilizers. Naturally-occurring phosphate rocks, may contain varying amounts of toxic trace elements depending on their source of origin. Phosphate rocks are the largest single source of raw materials for the production of phosphatic fertilizers in the world (42). When the resultant fertilizers are continuously applied to soils for crop production, the trace elements concentrations build up to toxic levels presenting a potential health risk to plants, animals, and humans (43). Some of the trace elements commonly found in phosphate rock ores and consequently in phosphatic fertilizers include cadmium (Cd), arsenic (As), lead (Pb), uranium (U) and radium (Ra) (42, 44).

Organic fertilizer materials such as sewage sludge and compost can also be good sources of toxic trace elements when continuously applied to farms. Although rich in important plant nutrients such as N and P, sewage sludge is composed of a wide range of organic compounds, macro- and micronutrients, organic micropollutants, harmful microorganisms and non-essential trace metals (44, 45). Without proper methods of containing the trace elements which may include composting and chemical immobilization, sewage sludge use as fertilizers in crop lands carries a high risk of elevating toxic trace elements concentrations in the soils to which it is applied (44).

2.4 Natural processes as sources of pollutants

Most of the common natural processes that may be responsible for pollution of soils include earthquakes, volcanic eruptions, and tsunamis. Rifting and separation of the African and Arabian tectonic plates, presents one of the greatest examples of natural processes that cause pollution of soils and the general ecosystem along the path of the African Rift Valley (ARF). Associated volcanism brings with it toxic ashes and metallic elements such as fluorine, iodine, copper, molybdenum, mercury, cobalt arsenic, boron and lithium, thereby contaminating rootzone soils as well as surface and groundwater bodies (46). Another, well known natural processes of soil contamination involves the formation of perchlorates- a group of compounds containing the perchlorate anion (ClO_4^-) characteristic of some dry, arid ecosystems (47, 48).

3 Bottlenecks negatively impacting the mitigation efforts

3.1 Overview of the effects of soil pollution on national economies

By far, pollution of African soils is caused by introduction of man-made chemicals or other alteration in the natural soil environment. Most of man-made pollution incidences typically arise from application of pesticides, oil and fuel dumping, poor management of landfills leading to leaching of its toxic contents. Other sources of pollution include direct discharge of industrial solid and liquid wastes to the soil and accidental discharge following rupture of underground storage vessels. Out of all these scenarios common chemicals that end up contaminating the soils include petroleum hydrocarbons, solvents, pesticides, and heavy metals. Soil pollution contributes significantly to soil degradation, which decreases crop yields and in turn reduces both food safety and food security. Polluted soils are a major reason for reduced quality and quantity of water supply as well as poor sanitation conditions, which in turn, leads to the proliferation of disease vectors and generates other public health concerns.

The problem of soil pollution and degradation is particularly large in SSA (49), because out of the 80 countries substantially affected by land degradation in the world, 36 are found in Africa. Data shows that SSA accounted for 17% of the global 3.623 billion ha that experienced land degradation that occurred between 1982 and 2006. Overall, the eastern, central, and southern African sub-regions of the SSA experienced the most widespread degradation (49). Ironically, most economies of SSA countries have a high dependence on the environment and natural resources. At the same time, environmental pollution and/or degradation is not included in the economic analysis and hence not reflected as a loss to the countries' respective economies. Consequently, the total cost related to soil degradation is ignored, directly undervaluing its contribution to the national economies. Instead, policies are formulated that may end up promoting environmental degradation (50).

Some of the most common constraints to tackling soil pollution in the SSA include lack of requisite infrastructure and inadequate political will. Analytical infrastructure that can help detect type and magnitude of pollution in soil samples is largely missing in the SSA. As a result, advanced pollutant testing is usually done by transporting the samples to facilities outside the region. Consequently, routine soil analysis as a way of monitoring pollution becomes unaffordable in most SSA countries

3.2 Main health effects associated with soil pollution in the region

Within the soil, contaminants or pollutants can exist in all three phases, i.e.- solid, liquid, and/or gaseous phase. From any of these phases, the pollutants/contaminants can find their way and cause harm to human beings either through direct contact of the human skin on the contaminated soil, through inhalation of contaminated soil dust or through consumption/ingestion of contaminated plant products growing on a contaminated soil. Plants grown in polluted soil may accumulate high concentrations of soil pollutants through a process known as bioaccumulation. When these plants are consumed by herbivores and/or omnivorous animals, man inclusive, accumulated pollutants are passed up the food chain. This can result in the loss/extinction of many desirable animal species. Also, these pollutants can eventually make their way to the top of the food chain and manifest as diseases or physical deformations in human beings.

The type and extent of the impacts of soil pollutants on human health are dependent on the type and level of exposure to the soil pollutant. Considerable volume of information is available on the impact of heavy metals contaminating the soil on human health (51–53). For, example, some of the world's worst cases of poisoning due to exposure to soils contaminated by lead were documented in SSA. Such cases occurred in towns built close to lead-mining sites, including towns of Kabwe in Zambia, Zamfara State in Nigeria and Aggeneys in South Africa (54). Elevated blood lead levels of up to 16 µg/dl in children of the town of Aggeneys in South Africa had been associated with having a father who worked in the lead mine. In the Kabwe town of Zambia, where soils lead levels had reached 51188 mg/kg in some areas, contamination in children had reached markedly up to 427.8 µg/dl (55). A separate study in Zamfara state had concluded that up to 400 children who had died of lead poisoning in 2010 had experienced convulsions prior to death (54).

Another common category of soil pollutants in the SSA is a large assortment of agricultural pesticides used in crop production. Studies show that most cases of acute pesticidal poisoning, both occupational and non-occupational, are highly underreported (56). A few of the reported cases with adverse human health effects include cases of asthma in farm-working women in rural South Africa due to exposure to agricultural pesticides such as organophosphates (chlorpyrifos, diazinon, dichlorvos, and malathion) and carbaryl- a carbamate (57). Similarly, a mass poisoning following consumption of lindane-contaminated food by over 300 people was reported in Gombe, Nigeria. Victims of the Gombe mass poisoning incidence exhibited symptoms of transient loss of consciousness, jerking episodes of convulsions and hyper-salivation (58). A recent case report (59) revealed an incident involving four non-fatal and four other fatal cases caused by ethion pesticide poisoning in Botswana. The victims had ingested an ethion-contaminated homemade herbal preparation meant to rid the victims of Sejeso- an imaginary ailment claimed to arise from poisoning by sorcery. These are a few examples of cases of acute pesticide poisoning that are becoming more common in recent times.

4 Pollution assessment and monitoring tools in the SSA region

To be able to assess and contain the dangers of soil pollution, countries need to have requisite expertise and pollution assessment and control/management tools. Although the science and technology for pollution assessment and monitoring is readily accessible (60), the administration of the assessment and monitoring exercises are complicated by the lack of national mechanisms/systems of pollution monitoring and assessment. As a result, requisite human and financial resources are not provided by state machinery. Apart from the externally funded initiatives such as the Stockholm Convention National Implementation Plans (NIPs), only a few national soil pollution-monitoring systems are available, one in Nigeria and the other in South Africa. While both countries have voluntary systems for reporting pollution, their approaches for collection of pollution data are different. Nigeria mainly monitors the extent of the oil spills through the National Oil Spill Detection and Response Agency (NOSDRA) (61). NOSDRA encourages everyone including concerned or affected citizens to use templates provided on its website to report incidents of pollution and provides contact details for emergency notifications (61). On the other hand, the South African voluntary site reporting system is more encompassing as it gives provision for reporting any activity that is causing or has caused soil pollution with contaminants listed in the National Norms and Standards for the Remediation of Contaminated Land and Soil Quality (62). No other well-organized pollution monitoring system in SSA region is known.

5 Remediation efforts: Available technology and future prospects

Remediation of soil pollution in the countries of the SSA region is still only rudimental. Inborn national mitigation systems are either non-existent or poorly documented. Where such efforts or some activities related to remediation of soil pollution exist, they are likely a result of external architecture or at least donor funded. Such interventions usually collapse when the external funding ends. Exceptions are Nigeria and South Africa where pollution monitoring and assessment systems are both inborn and operational. Countries in region, however, have subscribed to both regional and multinational legal frameworks for soil pollution mitigation and remediation as detailed below.

5.1 Multinational and regional legal frameworks on mitigation of soil pollution in SSA region

The sub-Saharan Africa region has participated in either ratification, accession or acceptance of at least four international frameworks/conventions addressing soil pollution mitigation in the region. These include the Basel convention, the Rotterdam convention, the Minamata convention and the Stockholm convention. The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes is a multinational agreement aimed at protecting human health and the environment against the adverse effects resulting from the generation, transboundary movements and management of hazardous and other wastes. The Basel convention has international coverage with over 175 parties globally and it been ratified, accepted or entered into force in 47 of 48 countries in the SSA region (63). The convention regulates toxic, poisonous, explosive, corrosive, flammable, ecotoxic and infectious wastes by giving parties an obligation to (a) minimize the quantities that are transported, (b) treat and dispose of wastes as close as possible to their place of generation and (c) prevent or minimize the generation of wastes at source. The Rotterdam convention, on the other hand, aims to protect the environment from hazards that would result from unregulated and irresponsible trade and use of hazardous chemicals (64). It requires that the receiving country provides its informed consent prior to consignment of any of the chemicals listed in the convention. Since its inception in 1998 in Roterdarm, the Netherlands, at least 43 countries in the SSA region have brought the Convention into force.

Countries of the SSA have also signed, ratified and started implementing both the Minamata convention on mercury (65) and the Stockholm convention on Persistent Organic Pollutants (POPs) (66). While the Minamata convention requires action by countries to curtail anthropogenic emissions and releases of mercury and mercury compounds (67), the Stockholm convention requires action by participating countries to protect human health from toxic chemicals collectively referred to as POPs. A summary of countries that have signed and made the conventions into force in the SSA region is presented in the Table 2.

Overall, there is progress on strengthening the legal and regulatory frameworks for environmental pollution in the world and in the SSA region in particular. However, governance of the environmental issues is still very poor in most of the SSA such that

TABLE 2 Summary of countries in the SSA region where regional and international conventions related to soil pollution have either not been ratified or not entered into force by 2020.

A (International conventions)					
Country	Basel Convention	Rotterdam Convention	Minamata Convention	Stockholm Convention	Reference(s)
South Sudan	x	x	x	x	(68)
DR Congo			x		
Commoros		x			
C. A Republic			x		
Seychelles					

(Continued)

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TABLE 2 Continued

A (International conventions)					
Country	Basel Convention	Rotterdam Convention	Minamata Convention	Stockholm Convention	Reference(s)
Somalia					
B (Regional Conventions)					
Country	**Bamako Convention**	**Libreville Declaration**	**Maputo (Revised African) Convention on conservation of nature and natural resources**		
Botswana	x		X		(69–72)
C. A Republic	x		X		
Cape Verde	x	x	X		
Djibouti	x	x	X		
Equatorial Guinea	x		X		
Eritrea	x	x	X		
Eswatini	x		X		
Gabon			X		
Ghana	x				
Guinea	x		X		
Guinea Bissau	x		X		
Kenya	x		X		
Lesotho	x				
Madagascar	x		X		
Malawi	x		X		
Mauritania	x		X		
Mauritius			X		
Namibia	x		X		
Nigeria	x		X		
Seychelles	x		X		
Sierra Leone	x		X		
Somalia	x	x	X		
South Africa	x				
South Sudan	x	x	X		
Zambia	x				

monitoring, and enforcement of environmental regulations remains very challenging.

5.2 Most promising remediation technologies suitable for sub-Saharan Africa

Remediation of polluted soils must start with a careful evaluation of applicable technologies in order to, among many other things, establish the feasibility level of the most promising of the available alternatives. Technologies for remediation of polluted and/or contaminated soils' would largely depend on the predominating pollutant-heavy metals, persistent organic pollutants (POPs) or organic wastes. Accordingly, remediation technologies for polluted soils range from expensive, resource-intensive technologies to gentler cost-effective technologies. The resource-intensive technologies are usually unaffordable for most countries of the SSA region, and the high costs often prevent remediation of polluted soils from being carried out in those countries (73). Nonetheless, technologies suitable for remediation of polluted soils in the SSA are presented below.

5.2.1 Technologies that are based on the principle of containment

where the pollutant is either sealed in a protective barrier or modified to limit its release to other unpolluted segments of the environment. Most common technologies of this category are (i). Solidification and stabilization – which uses technology that involves physical or chemical mixing of the contaminated material (soil or waste) with binding materials to produce a stabilized mass (i.e. solidification) or that makes the contaminant less-bioavailable and less mobile (stabilization). Most common binding materials used in this technology are fly-ash, cement, lime kiln dusts, thermoplastics and pozzolanas. Solidification can be done *in situ* or *ex situ* but when done *in situ*, the process can hinder future uses of the site (74). *In-situ* chemical stabilization technology has been widely accepted because of its efficiency, low cost and technology (75, 76). A few studies have been demonstrated both at a laboratory and field scale, inside and outside the SSA region. A study in Egypt, for example, showed that treating heavy metal-contaminated soils with amendments such as biochar, humic substances or iron oxide significantly enhances immobilization of heavy metals leading to their reduced accumulation in cultivated plants (77).

On the other hand, **Pollutant/waste containment** is a practice where the contaminated medium (soil, sediments, and waters) is encapsulated within an engineered waste site to limit release of the contents (POPs, or heavy metals or other hazardous materials) into the environment. This limits exposure of the pollutant directly or indirectly to the public and other site users (74). Although this technology uses a low permeability physical containment barrier separating the contaminant/pollutant from the uncontaminated natural ground, it is relatively expensive and thus not a common alternative in low-income countries such as those in the SSA.

5.2.2 Technologies designed to destroy the hazardous pollutant such as POPs or municipal solid wastes to less toxic products

This can be achieved either through non-combustion means like the chemical process of dehalogenation changing the basic chemistry of the organic molecule of the wastes (especially for POPs and other organic wastes) or through combustion (e.g. incineration, thermal desorption) eventually breaking down the toxic pollutant to simple inorganic compounds such as CO_2, methane (CH_4) and water (H_2O). When the pollutant includes hazardous heavy metals, combustion technologies will not destroy them but most metals with an exception of mercury and other volatile metals will be retained in the ash in which case application of stabilization technologies discussed above become necessary (78, 79).

5.2.3 Technologies that involve extraction of the contaminant from the matrix through either (i) concentration or (ii) liberation/stripping of the contaminant:

Examples of such technologies include *ex situ* soil washing, *ex situ* solvent extraction, *in situ* soil flushing, soil vapor extraction, *ex situ* bioremediation and *in situ* bioremediation. Soil washing is a volume-reduction technology that maximizes the recovery of the re-usable fraction of the soil -most likely by technologies under category A or B above- prior to their safe disposal (80, 81). *In situ* approach, on the other hand, uses a vacuum system of extraction wells creating a concentration gradient leading to enhanced removal of volatile gases from the contaminated matrix such as the soil (80, 81). In this category, technologies that are less costly and may be feasible in most SSA economies include bioremediation and phytoremediation (80) as detailed hereunder:

Bioremediation: This technology relies on the use of high performing microorganisms, enzymes or amendments that would enhance microorganism-mediated degradation or transformation of the pollutants in a contaminated media. Through the process, toxic pollutants are degraded and transformed into less toxic, innocuous products like CO_2 and H_2O. Bioremediation can either use native-indigenous microorganisms to degrade or transform the toxins (POPs or heavy metals) in a contaminated site or involve deployment of a non-native strain proven to perform better than indigenous counterparts in biodegrading a known type of pollutant. In each of these alternatives, the process can be enhanced by supplying to the designated site additional nutrients and sometimes oxygen to stimulate a speedy biodegradation/biotransformation process. This practice of adding nutrients and oxygen with the intention of increasing bioremediation of POPs is referred to as biostimulation or bioaugumentation. Bioremediation can be aerobic or anaerobic done *in* or *ex situ*. Choice of bioremediation technique to deploy depends on several factors which may include nature of pollutant, concentration of pollutant, type of environment, cost of remediation technique, depth of contaminant, and environmental policies (82). Ex situ methods of bioremediation involve the removal of the polluted medium, the soil in this case from site of pollution to another site for treatment. The treatment options may include treatment of the contaminated soil with solids containing bioremediators either in biopiles, windrows, land farming, composting (83, 84). With *in situ* bioremediation, polluted soil is treated right at the site of pollution and is, therefore, more cost-effective than the ex-situ bioremediation techniques (80, 82, 84). Techniques commonly used in the *in situ* bioremediation include bioventing, bioslurping, biosparging and bioaugumentation (82).

A few studies have demonstrated use of bioremediation techniques to reclaim contaminated soils of the SSA region. For example, one study demonstrated a successful natural attenuation of Fe, Cu and Co - a phenomenon that relies on iron-oxidizing microorganisms in aerobic conditions or sulfate reducing bacteria (SRB) in anaerobic condition - in a Zambian copperbelt (85, 86),. A review (87) summarized the successful use of microorganisms in bioremediation of contaminated soils from gold, coal and other acid rock drainage in six different studies all in South Africa. Overall, although very promising results were obtained, most of these studies were performed at a laboratory scale as opposed to field conditions.

Entomoremediation:- the technique of using insects to reclaim soils contaminated by toxic wastes such as heavy metals has also been demonstrated in SSA soils. In one *ex situ* study (88), researchers demonstrated that activities of African mound termites, *Macrotemes bellicosus*, significantly reduced levels of the chemical loads of the dumpsite soils containing Fe(III), Mn(III), Zn, Cu(II), Cr(III), Cd, Pb and Ni.

Phytoremediation: This is a technology that uses specific plants enzymes from vegetation to accelerate the rate of isolation, destruction, transportation, and removal of organic pollutants including POPs and heavy metals from contaminated soils and water. Phytoremediation can be achieved by either the sub process of *phytoaccumulation*, also known as *phytoextraction*:- where contaminants are taken up by plant roots and translocated into shoots and leaves. It can also be achieved through *phytodegradation* and/or *phytotransformation*-which refers to metabolism of the contaminant within the plant tissues that may lead to transformation of the original contaminant into less-toxic byproducts within the plant. There can also be *phytostabilization*- a process by which the plant produces phytochemicals which help to immobilize the pollutant at the interface between plant roots and the soil. Furthermore, decontamination techniques also include the use of hyperaccumulator or high-biomass crops that accumulate high trace element levels in shoots and thus can remove the toxic metals from contaminated soils (89). Studies on successful application of phytoremediation techniques on contaminated soils of the SSA region do exist. Phytoremediation of gold tailings- contaminated soils in South Africa using Vetiver grass (*Chrysopogon zizanioides*) has also been reported (90). Others include use of water hyacinth for bioremediation of water and sediments in the Hartbeespoort Dam, South Africa (91) and *Cyperus textilis* for phytoremediation of soils contaminated with glyphosate-based herbicide pollutants along the Breede River of the Western Cape Province of South Africa (92).

Details of a selected number of pollution remediation studies implemented on SSA soils and or laboratories are summarized in Table 3 below. The feasibility of each technology discussed in this review can be evaluated based on technical, economic or operational feasibility. Technical feasibility must take into account as to whether the required remediation technology is available or not and whether the required resources (e.g. manpower, and infrastructural needs) are available, while the economic feasibility looks at how much money and other resources would be required to bring the technology to operational stage as they compare to returns out of the investment. Economic feasibility helps to judge whether the expected benefits of employing the technology equals or exceeds the costs of the investment. Operational feasibility, on the other hand, answers the question if the remediation technology will be accepted and used or not once established. In certain instances, a technology may be put in place after a relatively huge investment only to be rejected by the community and, therefore, left non-operational.

6 Addressing the knowledge and Infrastructural gaps

6.1 State of policy frameworks on soil pollution in the SSA

The policy infrastructure related to control, management and remediation of soil pollution is weak in SSA. A few multinational commitments do exist, that have been put forward to encourage development of policy, laws and strategies that protect the environment and ultimately human health against the adverse effects of toxic chemicals and products containing toxic chemicals. In the East African Community, for example, the protocol on Environment and Natural Resources on Management of Chemicals commits partner states to develop and harmonize policies, laws and strategies to protect human health and environment in articles 28 and 29 of the protocol. In Tanzania, the overarching policies are the National Environmental Policy (NEP) of 1997 and the Environmental Management Act (EMA) of 2004. Both are general frameworks on the environment, having no specific or direct insistence to protection of the soils from pollution

TABLE 3 Examples of remediation techniques tried/applied in various parts of the SSA.

S/N	Remediation Technology/ Approach	Place of study (implementation)	Type of pollutant targeted	Remediation agent used	Reference(s)
1	Bioremediation				
	(natural attenuation)	Copperbelt, Zambia	Cu, Fe, Co	Unidentified microorganisms	(86, 87)
	Ex situ Bioremediation system involving biostimulation of indigenous bacterial communities	Witwatersrand Basin, South Africa	U(VI)	*Desulfovibrio* sp., *Geobacter* sp.	(93)
	Laboratory scale bioremediation of heavy metals and hydrocarbons contaminated soils	Obohia, Abia State, Nigeria	Cr, Pb, Zn, Cu, Zn, Cd	*Candida bombicola*	(94)
2	Phytoremediation/phytostabilization				
	Grass species assisted phytoremediation	Copper mining hill, DRC	Cu	*Grass species* *Andropogon schirensis*; *Eragrostis racemose*; Loudetia simplex)	(95)
	Tree species-assisted phytostabilization	Various tailings dam soils of Zambia	Cu and other heavy metals	*Acacia polycantha*, *Toona ciliate*, *Acacia sieberana*, Bauhnia thoniangii, Peltothorum Africanum	(96)
	Phytoremediation using hyperaccumulator plants	Golden Pride and Geita Gold mines in Western and North western Tanzania	Pb, Cr, Cd, Cu, Mn, Ni, As	Five plant species of *Sporobolus pyramidalis, Melinis repens, Lantana camara*, *Leucaena leucocephala* and *Blepharis Maderaspatensis*	(97)

TDetails of approach, pollutant types targeted and remediation agents deployed.

Elsewhere, in Zambia for example, policy and legislative measures are crafted in very general terms and, in some instances, bereft of specificity on soil governance making it inadequate to properly guard legal framework on soil governance in the country (98). In Nigeria, the basis for environmental policy is contained in the 1999 Constitution of the Federal Republic empowering the state to protect and improve the environment and safeguard the water, air and land, forest, and wildlife. However, soil governance in the country is dominated by inequalities and conflicts over natural resources without specific policy on curtailing soil pollution (99).

Only two countries of the region, Burundi and Namibia, have specific legal instruments for the prevention and management of soil pollution. In Burundi, soil pollution is addressed in the "Decree on Soil Conservation and Use of 1958" and in Namibia by the Soil Conservation Act of 2001 (100). In countries of the rest of the region, other legislation that can address sources of soil pollution such as waste, agrochemicals and mining are also considered relevant in the prevention and addressing of soil pollution. However, three countries namely, Eritrea, Somalia and South Sudan have no legal instruments or regulations at all that aim to combat soil pollution (100). In most countries, the deficiencies in soil pollution control and remediation can be traced back into their respective national constitutional documents. The national constitutions do not entail explicit or substantive provisions on sustainable soil management although some have set out ambitious provisions on natural resources, environmental protection and, partly, even on benefit-sharing (100). Generally, therefore, the shortfalls in the mother law documents give room to tendency of countries assigning low priority in financing of projects aimed at combating soil pollution in most of the low -income countries of the SSA region (101).

Generally, land and soil protection policies differ from country to another ranging from barely existent to well defined frameworks. Overall, land policy frameworks to tackle risk to human health from soil contamination across the SSA region are either scattered or incomplete. Although the 'polluter pays' principle would be the best policy stand, it is not widely applied, leaving soil pollution largely uncontrolled. National policies addressing socioeconomic development have often times overlooked land degradation and soil pollution side effects.

6.2 Inconsistence in scientific records and data

Production and use of hazardous chemicals has declined over the last 10 to 15 years. There exists, however, widespread inconsistencies in scientific record on soil pollution data across the region. As a result, the SSA countries face two main challenges – (i) lack of data on the status and extent of environmental (soil inclusive) pollution and (ii) inadequate capacity to put policy into actual implementation. The lack of data affects the countries' capacity to devise and plan policies that can help reduce soil pollution. A few studies, however, have shed light on the extent of pollution problem including apportioning contributing sources of various pollutants reaching the soils. Sub Saharan Africa endemically lacks data and information on the fate of contaminants once in the soils and their related toxicological effects (102, 103).

7 Conclusions, recommendations and research perspective

In conclusion, the soil pollution problem is growing in sub Saharan Africa and national and reginal administrations have to take firm actions to combat the risks associated with it. Solving the soil pollution problem requires a multi-faceted approach in that, on one hand, authorities will need to seek for immediate actions that help to curtail the soil polluting activities and behaviors by instituting actions and penalties aimed at countering soil pollution. This may include either instituting-where they are non-existent or strengthening regulatory systems-rules, laws and associated incentives and/or penalties that govern handling, disposal and penalties around mismanagement of potentially soil polluting substances and practices. On the other hand, efforts are needed to reverse the status of already polluted pieces of land through strengthening remediation programs, including considerations for cheaper alternatives such as bioremediation. Research on how best to gather, maintain and complement soil solution data and actions will need to be prioritized so that any decisions on how to handle soil pollution are well informed by scientific evidence.

Author contributions

BS conceived the initial idea, reviewed the literature and proofread the final manuscript. HT, reviewed the literature, designed the synopsis, wrote the first draft and proofread the final manuscript. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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