Prospects of emerging PAH sources and remediation technologies: Insights from Africa

Kabari Sam[1,2], Amarachi P. Onyena[2*], Nenibarini Zabbey[3,4], Chuks K. Odoh[5], Goodluck N. Nwipie[3], Dumbari K. Nkeeh[6], Leo C. Osuji[7], and David I. Little[8]

[1]School of Environment, Geography and Geoscience, University of Portsmouth, University House, Winston Churchill Ave, Portsmouth PO1 2UP, United Kingdom

[2]Department of Marine Environment and Pollution Control, Faculty of Marine Environmental Management, Nigeria Maritime University, Okerenkoko, Delta State, Nigeria

[3]Department of Fisheries, Faculty of Agriculture, University of Port Harcourt, East-West Road, PMB 5323, Choba, Port Harcourt, Rivers State, Nigeria.

[4]Environment and Conservation Unit, Centre for Environment, Human Rights and Development (CEHRD), D-line, Port Harcourt, Rivers State, Nigeria.

[5]Division of Biotechnology, Dalian Institute of Chemical Physics, CAS, Dalian 116023, China

[6]Department of Environmental Technology and Management, World Bank Africa Centre of Excellence, Centre for Oilfield Chemicals Research, University of Port Harcourt, Choba, P.M.B.5323, Rivers State, Nigeria.

[7]Petroleum Chemistry Research Group, Department of Pure and Industrial Chemistry, University of Port Harcourt, P.M.B 5323, Choba, Port Harcourt, Nigeria.

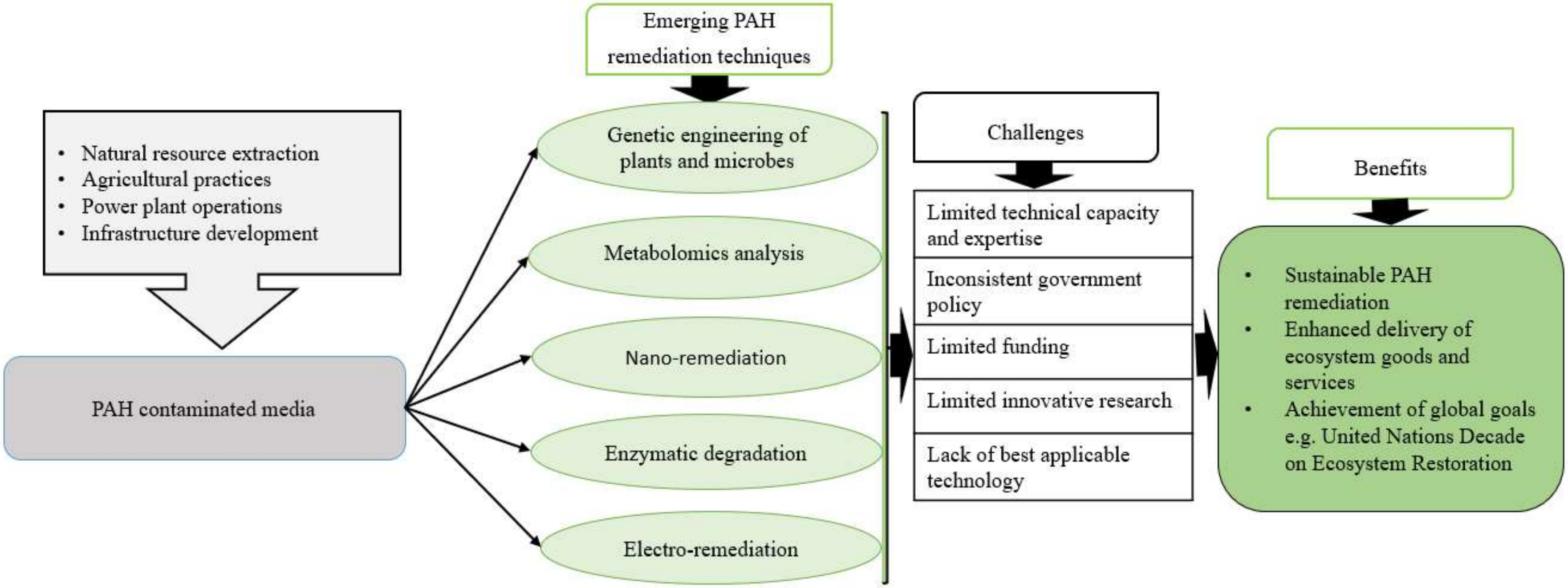
[8]Environmental Consultancy, Swavesey, Cambridgeshire, Cambridge, CB24 4RL, United Kingdom.

Corresponding author: amarachionyena@gmail.com

Highlights

- Continuous PAH contamination threatens the vision of the United Nations Decade on Ecosystem Restoration.
- Adopting emerging green technology for PAH remediation in Africa is crucial.
- Remediation should aim to achieve low greenhouse gas emissions and net environmental benefits.
- Lack of best applicable technology and limited expertise are the key challenges

Graphical Abstract



Abstract

Remediation of polluted environmental media is critical to realization of the goals of the United Nations Decade on Ecosystem Restoration (UNDER) project. Many natural-resource dependent economies in Africa are characterized by numerous contaminated sites resulting from conventional and artisanal natural-resource mining. Alongside these extractive activities, there are refining, processing, and power plant operations, agriculture, urban, and infrastructure developments that contribute to increased discharges of toxins into the environment, particularly polycyclic aromatic hydrocarbons (PAHs), which are carcinogenic in nature. As a result, human and environmental receptors (i.e., air, water, soil, and biota) face increasing risk of exposure to higher concentrations of PAH. Evidence exists of widespread PAH contamination and in some instances where corrective action has been taken, residual contaminant levels exceeding regulatory thresholds remain in the environment due to the use of inappropriate and unsustainable remedial methods. Considering the long-term harmful effects of PAH on human and ecosystem health, land use, and the complexity of Africa's environmental deterioration, it is essential to explore remediation strategies that benefit both the environment and the economy. This review examined the status, opportunities, and challenges related to the application of emerging green technologies to remediate PAH-contaminated sites in five African countries (South Africa, Nigeria, Angola, Egypt and Kenya). This paper concludes that bioremediation presents a sustainable option, considering its low net emissions and environmental footprints, and its low economic cost to Africa's poor communities and overburdened economy. However, an integration of biological and physico-chemical approaches could address various compounds and concentrations of PAH contamination.

Key words: PAH remediation. Nanoremediation. Metabolomics. Environmental footprint. PAH contamination

Introduction

Remediation of polluted environment is critical to the realization of the United Nations Decade on Ecosystem Restoration (UNDER). However, with 33% of global land already degraded, it would require concerted action, first to prevent new contamination and then to adopt green technologies to remediate and restore existing contaminated sites. In combination, these could restore the life-supporting ecosystem services that are delivered by healthy land (Abhilash 2021; Tripathi et al. 2019; Sam et al. 2022). With the increasing population and industrialization of the African continent, various conventional and artisanal natural resource extraction and mining activities continue to exacerbate environmental contamination. An increase in these activities, as well as refining, processing, and power plant operations, agricultural practices, and infrastructural developments, contribute to the discharge of toxins into the environment, particularly polycyclic aromatic hydrocarbons (PAHs; also called polynuclear aromatic hydrocarbons). As a result, human and environmental receptors face increasing risks of exposure to higher concentrations of PAHs and other compounds in different environmental media. Consequently, natural resource-dependent economies suffering from legacy or new site contamination have a responsibility to deploy sustainable remediation technologies that target persistent and carcinogenic contaminants such as PAHs.

PAHs are aromatic hydrocarbons with two or more fused benzene rings, bonded in linear, cluster, or angular structures (Sharma 2014). In terms of composition, PAH mixtures (natural and anthropogenic) range from simple to complex, thus reflecting the thermal history and nature of the precursors from which they are formed. Some rare PAH compounds consist of a single PAH in pure form. Coal tar is estimated to contain some 30,000 PAHs (including S-, O-, and N-analogs and their alkyl homologs). Most PAHs, including acenaphthylene, naphthalene, phenanthrene, acenaphthene, etc., are composites composed of different structural components (Ilechukwu and Osuji 2013; Sharma 2014).

Based on physicochemical properties, PAHs are classified into high molecular weight (4-6 aromatic rings) and low molecular weight (2-3 aromatic rings) types (Wang et al. 2015; Rocha and Palma 2018; Crnković et al. 2020). PAHs are hydrophobic in nature due to their extremely low water solubility, which decreases with increasing molecular weight or the number of fused aromatic rings. The high molecular weight PAHs are also less volatile and more lipophilic than lower molecular weight PAHs (Wania and Mackay 1996; Van Jaarsveld et al. 1997). They are also resistant to biological transformation, which makes them more likely to persist in the environment (Wang et al. 2016a; Abdel-Shafy and Mansour 2016).

Thousands of PAH compounds exist in different environmental media. However, the United States Environmental Protection Agency (USEPA) listed 16 PAHs as potentially toxic priority substances. These individual PAHs differ significantly in physical and chemical characteristics (El-Shahawi et al. 2010). PAHs in the environment could have petrogenic, pyrogenic, or biogenic origins. Natural sources of pyrogenic PAH include wildfires and volcanic eruptions; however, anthropogenic pyrogenic sources of PAHs are mainly produced by the partial combustion and pyrolysis of wood, fossil fuels, and discharge of petroleum products (Chimuka et al. 2016; Kaur et al. 2022). The petrogenic sources of PAH are crude oil spills and seepages as well as petroleum products (Ren et al. 2015; Sun et al. 2016; Yogaswara et al. 2020). PAHs may be emitted by industrial facilities such as thermal power plants, iron and steel mills, coke ovens, coal gasification, petroleum refineries, fuel storage tanks, and pipelines (Kumar et al. 2016a). PAHs are also released into the atmosphere due to the combustion of fossil fuels, which are extensively utilized for transportation, home heating, power generation, and domestic sources such as kerosene, wood, and waste combustion. PAHs have also been discovered in automotive exhaust, cigarettes, coal tar, asphalt, and in certain consumer items such as paints, coatings, and pesticides. In addition, PAHs have been identified in polluted soil and groundwater due to human activities, including oil and gas extraction, hazardous waste disposal, and agricultural runoff (Dai et al. 2022). Other biogenic PAH sources arise from the diagenesis of organic compounds in anoxic deposits, which transforms biological material into aromatic hydrocarbons (Wakeham and Canuel 2015).

PAHs are ever-present in agricultural produce, terrestrial soils, aerosols, marine deposits, and marine biota (Pongpiachan 2015; Pongpiachan, et al. 2017a; 2017b). PAH levels in roadside soil are caused by the deposition of traffic-generated organic compounds on road surfaces and are high in carcinogenicity (Kumar and Kothiyal 2011; 2012; Nekhavhambe et al. 2014; Kumar and Kothiyal 2016b). PAH are notoriously difficult to degrade due to the complexities of their chemical composition. Thus, they tend to persist for extended periods. The relatively non-degrading features of PAHs lead to their accumulation in living and non-living entities (Pongpiachan et al. 2018). For example, an increase in PAH levels has been shown to affect agricultural soils and crop yield over a period of time (Tay and Biney 2013; Wu et al. 2016). Wu et al. (2016) also highlighted that changes in the ambient soil pH occasioned by PAH could result in reduced abundance, composition, and activities of soil organisms responsible for soil enrichment and nutrient cycling.

However, some PAHs including anthracene, fluorene, fluoranthene, phenanthrene, benzo(a)pyrene, and naphthalene are beneficial given their commercial use (Franck and Stadelhofer 1987). However, there is growing concern over the prevalence of PAHs in the environment given their carcinogenic and toxic nature, and spread in different environmental media (Kumar and Kothiyal 2011; 2012; USEPA, 2014). PAHs have received significant attention in recent years due to their carcinogenic, mutagenic, and teratogenic properties, which pose a significant risk to human health (Apiratikul et al. 2019; Mallah et al. 2022; Wang et al., 2019; Szataowicz and Hawrylik, 2022). Evidence exists that prolonged human exposure to high concentrations of the 'beneficial' PAHs can lead to various adverse health effects, such as leukemia, DNA mutations, cancer of the bladder, scrotum, lung, brain, and bone, as well as reproductive defects (Nadal et al. 2004; Song et al. 2006).

Studies have shown that chronic and acute exposures to PAH induce antioxidant enzymes and causes cognitive deficits, gene alterations, oxidative damage, and apoptotic cell mortality in various human and animal organs (Nasr et al., 2016; Moyano et al., 2017). The effects of PAHs on human health are dependent upon their transport, fate, duration of exposure, and concentration (Lee et al. 2021). The risk of lung cancer, cardiovascular disease, hypertension, and myocardial infarction is expected to be the most significant health effect of inhalation exposure to PAHs (Kim et al. 2013; Abdel-Shafy and Mansour 2016). Additionally, PAH mixtures irritate and inflame the skin (Abdel-Shafy and Mansour 2016). Chronic exposure to PAHs has been linked to impaired immunological function, kidney and liver damage, respiratory problems, biochemical disruptions, and cellular damage (Moyano et al. 2017; Okpashi et al. 2018). The exposure may also result in an increased rate of birth defects, gene mutations, and cancers (Barhoumi et al. 2016). Other health problems that are related to chronic exposures to PAHs include decreased immunity, eye cataracts, kidney damage, liver damage, breathing problems, asthma and other lung function abnormalities, as well as skin redness and inflammation (Okpashi et al. 2018). Similarly, repeated exposure to PAHs causes different types of cancer in aquatic animals, especially PAH forms that can easily penetrate the affected cell and corrupt the DNA (Okpashi et al. 2018), which in turn can affect humans through the food chain.

Thus, considering the biological and health consequences of PAH, it is essential to assess PAH contaminations in different environmental media and identify appropriate technologies for their removal. Different countries in Africa adopt different approaches and techniques to achieve PAH remediation, namely the use of physical, biological, or chemical methods. This review explores the opportunities for future large-scale application of bioremediation to remediate PAH contaminated media on the African continent. Specifically, it assesses the status and application of PAH bioremediation in selected African countries (Nigeria, Angola, Egypt, South Africa, and Kenya; see Figure 1).

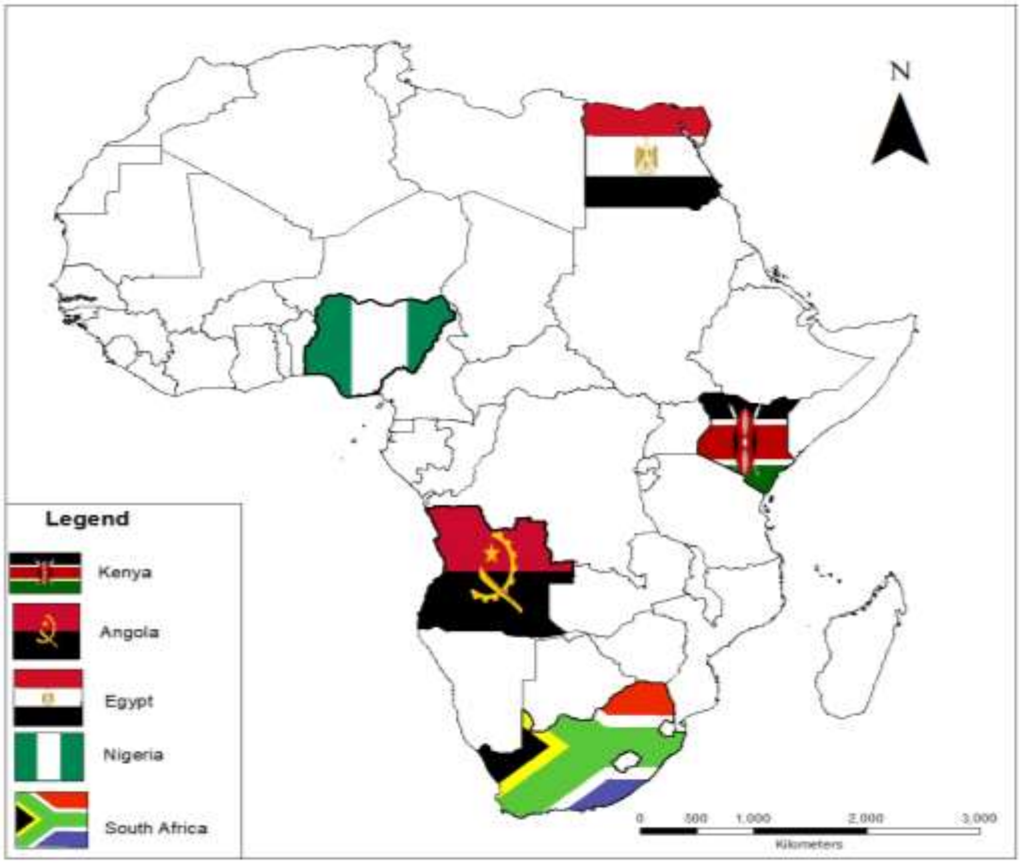


Figure 1: Selected natural resource-dependent economies in Africa explored as case studies

Prospects and challenges of different PAHs remediation technologies

Remediation is the process of restoring the functionality of contaminated air, water, soil, and sediment to their pre-contamination states.

Africa is endowed with various geological natural resources, including gold, crude oil, coal, metal ores, and phosphate ores, which are distributed unequally across the continent (Table 1). As a result, the number of power plant construction projects, artisanal and industrial mining sites, and businesses mining and utilizing the resources is increasing. These ventures contribute various fluxes of PAH to the total environment. In addition to the risk to human health, contaminants have significant ecological consequences, and can create related socioeconomic problems since the populations largely depend on the environment for livelihoods (Sam et al., 2017; Zabbey et al., 2017; Odoh et al., 2019).

Table 1 Natural resource deposits in African countries that have potential for releasing PAH into the environment (modified from Odoh et al. 2019).

Countries	Geological Natural Resources	**References**
Algeria	Gold, zinc, Iron ore, phosphate, and lead	Wafa et al. 2017
Angola	Copper and diamond	Ngole-Jeme and Fantke 2017
Botswana	Coal, diamond, gold, copper, cobalt, nickel, and soda ash	Mogopodi et al. 2008
Burkina Faso	Limestone, zinc, gold, nickel, manganese, bauxite, copper, and marble	Porgo and Gokyay 2017
Egypt	Tantalite, gold, Iron ore, coal, phosphate, and manganese	Mowafa 2013;
Gabon	Manganese, crude oil, cement, diamond, phosphate, and Iron ore	Younes et al. 2016
Ghana	Crude oil, diamond, bauxite, gold, and manganese ore	Bansah and Addo 2016
Guinea	Iron ore, Bauxite, and gold	Bertram et al. 2011
Ivory Coast	Manganese, nickel, Iron ore, gold, diamond, bauxite, copper, and cobalt	Guety et al. 2017
Kenya	Natural soda ash, tantalite, zirconium, cement, gemstones, and gold	Maobe et al. 2012
Liberia	Gold, diamond and Iron ore	Stocklin-Weinberg 2017
Libya	Uranium, crude oil, manganese, gold, phosphate and Iron ore	Elbagermi et al. 2017
Mali	Diamond, chromium, gold, copper, bauxite, and Iron ore	Lawrence et al. 2016
Mauritania	Petroleum, copper, Iron ore, gypsum, copper, and natural gas	Mowafa 2016

Morocco	Manganese, silver, tin, Iron ore, gas, phosphate, barites, gold, coal, and zinc,	Harold 2013
Mozambique	Mineral sand, tantalite, gold, precious stones, and coal	Lehto and Gonçalves 2008
Namibia	Uranium, zinc, diamond, copper, vanadium, cadmium, phosphate, and gold	Kohrs and Kafuka 2014
Nigeria	Iron tantalite, crude oil, tin, zinc, bitumen, lead, natural gas coal, gold, and Iron ore	Merem et al. 2017
Rwanda	Tourmaline gold, wolfram, topaz, sapphires, ambrigonites, and cassiterite	Schütte et al., 2011
Sierra Leone	Lead, gold, Iron ore, copper, rutile, chromium, platinum, bauxite, and diamond	Adam et al. 2017
South Africa	Manganese, platinum, chromium, vanadium, titanium, coal, gold and silver	Arthur and Davies 2014
Tanzania	Uranium, coal, Iron ore, tanzanite, phosphate, diamond, gold, and graphite	UNEP 2012; Mganga et al. 2011
Tunisia	Iron ore, lead, phosphate, and zinc	Mekki and Sayadi 2017
Uganda	Silica sand, copper, gold, nickel, limestone, cobalt, marble, and zinc	Ssenku et al. 2017
Zambia	Lead, zinc, nickel, Iron ore, copper, cobalt, and manganese	Soto-Viruet et al. 2013
Zimbabwe	Palladium, coal, nickel, chromium, Iron ore, and graphite	Ghaderian et al.2007

Remediation is imperative in order to restore ecosystem functionality, which may be narrowly defined as the supply of ecosystem goods and services. This can be accomplished by physical, chemical, or biological means (Zabbey et al. 2017). Given the nature of PAH and its potential health consequences for various habitats, interconnected water bodies, and diverse soil types, it is critical to investigate the method or a combination of appropriate and sustainable technologies for the African region. Table 2 summarizes existing PAH remediation procedures that are used on both small and large scales globally, whereas Table 3 summarizes global state-of-the-art PAH remediation approaches.

Table 2 Different PAH remediation techniques and their strengths and weaknesses

Remediation Approach	**Principle of Operation**	**Class of Remediation**	**Description**	**Successful Application of the approach**	**Strengths**	**Weaknesses**	**Reference**
Chemical oxidation	Several cleanup strategies for oil-contaminated soil were evaluated.	Chemical	Chemical oxidation effectively removes hazardous waste from oil spilled soil.	Chemical approach provides a rapid method for remediating contaminated soil.	Chemical oxidation uses Fenton's reagent, hydrogen peroxide and ferric ion. Hydroxyl ions in the Fenton reaction remove soil pollutants very effectively. It also involves using ozone to remove crude oil from the soil. Since ozone degrades into oxygen, it may help soil microbial communities flourish during bioremediation.	Certain procedures, like incineration, must be used with precaution since they are typically unacceptable in the majority of countries. Also leaching of chemicals could be a threat to lives	Ahmad et al. 2020
Landfarming	*In-situ* treatment of soils using processes that could enhance the population of PAH degraders	Biological application	A classical agricultural practice that involves tilling, bulking, irrigation and fertilizer application	a) In the field, 86 percent of total PAHs were removed, with a reduction in high molecular weight (HMW) PAHs. b) In the United States, a wood-treatment site polluted with about 13,000 mg/kg PAHs was cleaned using	a) Encourage native soil microorganisms to degrade PAHs by supplying water, oxygen, and nutrients, b) It also moistens and homogenizes the soil, facilitating	It is a time-consuming remediation technique as an average of 6 months to 1year is needed for effective results	Kuppusamy et al. 2017 Wang et al. 2016b

				conventional landfarming practices in conjunction with bioaugmentation and bio-stimulation.	PAH biodegradation. b) It is a low-cost treatment option.		Selina and Banfor 2005
Composting/ biopiling	*Ex-situ* treatments	Biological application	Through homogenization of PAHs-contaminated soil, this method employs fresh organic matter to maintain continuous hydration in the soil-compost mix.	a) In a field application, this approach eliminated 50 percent of the HMW PAH in 210 days. b) In Australia, it is used in the rehabilitation of gas work plants. c) It has been used to treat PAHs in a Serbian oil refinery.	Easy to monitor and control	a) Less expensive than in-situ treatment b) Age of PAHs and soil thickness affect pollutant biopile remediation.	Alexander 1995 Guerin 2000
Soil washing	Solvent extraction	Physico-chemical	The extraction of PAHs from solid matrix involves two steps: elution from the solid into the extraction fluid and extraction of PAHs from the extraction fluid.	Demonstrated successfully in the United States and Europe.	Aside from producing hazardous pollutants such as carbon dioxide and other greenhouse gases, it is a quick clean-up and remediation method.	This procedure is costly, and it has the potential to contaminate other environmental media, such as air and water bodies, throughout the remediation process. This approach is age dependent since PAHs are difficult to extract in older or more polluted sediments.	Gan et al. 2009 Cappuyns 2013 Zabbey et al. 2017
Incineration	Destruction and volatilization of	Thermal heat application	High temperatures ranging from 900 to 1200 degrees	Because this method does not need excavation, it is regarded generally safe	The installation of incinerator off-gas control	In Louisiana, a combination of excavation and	Kuppusamy et al. 2016a

	PAHs by conductive heating		Celsius were used to effectively destroy PAHs in the contaminated plume.	and releases less PAH compounds.	systems is frequently expensive and consumes a lot of energy.	burning of polluted silt produced positive results by removing 90 percent of PAHs in 40 months.	Acharya and Ives 1994 Kuppusamy et al. 2016b
Bioremediation	This is a procedure in which microorganisms (bioaugmentation) or their growth conditions (biostimulation) are increased in order to breakdown PAHs.	Biological application	PAHs are biotransformed or biodegraded to an environmentally safe level employing both fungi (*A. niger*, *Phanerochaete chrysosporium*) and bacterial taxa (*Burkholderia* sp., *Pseudomona*s sp., *Achromobacter* sp.).	At 10 ppm PAHs concentration, *Agaricomycetes* sp. can degrade up to 99 percent of PAHs in 15-30 days.	Techniques that are safe, low-cost, and eco-friendly	Variable weather conditions have a significant impact on on-site bioremediation processes.	Hadibarata and Teh 2014 Eze et al. 2018
Phyto-remediation	The use of plant material as a base material for pollutant extraction	Biological application	Pollutant absorption, mineralization, and degradation are enhanced through phytostabilisation, phyto-volatilisation, phytoextraction, phytodegradation, and rhizodegradation.	a) Sunflower was employed for cleanup in Zambia's Kabwe province. b) In China, agricultural areas were cleaned utilizing microorganisms and alfalfa phytoremediation.	This method of cleaning up a polluted area has low maintenance costs, is easy to do on-site, and works best in places where plants usually grow.	a) It is a slow remediation method, so it could only be used for long-term projects. b) Environmental and climatic factors, such as pollutant concentrations, water content, soil chemical characteristics, and plant resistance, all factor into its application.	Odoh et al. 2019 Teng et al. 2011

Photocatalytic degradation	Organic contaminants are destroyed in the presence of light radiation.	Photo-catalyst	Previously used for wastewater treatment. Its use, particularly for PAH-contaminated soil, is gaining popularity.	Under UV light, photocatalytic degradation of benzo(a)pyrene, pyrene, and phenanthrene, and on soil surfaces using titanium dioxide (TiO2).	It is possible for several forms of PAH, particularly in mixed contaminated media	It is reliant on power supply, which may be difficult in an African setting.	Zhang et al. 2008
Chemical oxidation	Soil oxidant injection	Chemical application	Potassium permanganate (KMnO4), ozone, hydrogen peroxide (H2O2), sodium (Na2+), and iron (Fe2+) were among the oxidants that activated persulfate and peroxy-acid.	Industrial, Italy and manufactured gas plant (MGP), US Slurry bioreactor combined with ozone oxidation 0.75-1.5 kg Ozone and Fenton's reagent are the most commonly used chemical oxidants. In slurry reactors treated with Fe^{2+} and 2.5% H_2O_2 solution, 70-95% PAHs mineralization of MGP soils was achieved.	It has a massive environmental impact since the residual risk from the chemical application may have an impact on microbial life.	The main limiting factor is the low availability of PAHs and their partial sequestration in aged soil.	Ferrarese et al. 2008 Derudi et al. 2007

196 **Table 3** Emerging PAH remediation technologies applied globally

Technologies	**Country**	**Description of study**	**Outcome**	**Reference**
Enzymatic degradation of PAH	China	The research investigated the transformation of PAHs by a fungal laccase both in reaction mixtures and in soil	Laccase considerably altered the majority of the PAHs examined (13 out of 15), with the two notable exceptions of naphthalene and chrysene. Anthracene and benzo(a)pyrene, on the other hand, decomposed faster than the other key PAHs evaluated.	Wu et al. 2008
	India	The study used fungal strains that could secrete extracellular enzymes using PAH from polluted soil.	The study discovered that PAHs in soil can be destroyed by fungal consortia lipases (*P. chrysogenum, M. racemosus* and *L. theobromae)*	Balaji et al. 2014
	North Carolina, USA	This study was a continuation of prior research on the use of nonionic surfactants following conventional bioremediation to increase soil PAH desorption and biodegradation.	Nonionic surfactant polyoxyethylene sorbitol hexaoleate proved successful in eliminating significant amounts of the oxy-PAHs and PAHs left over following traditional slurry-stage bioremediation, including over 80% of residual 4-ring PAHs.	Adrion et al. 2016
Biosurfactant enhanced remediation	Pretoria, South Africa	This research examined into the efficacy of employing a biosurfactant (Lipopeptide) to breakdown PAH in soil and how to boost in-situ biosurfactant production.	After 45 days, 86.5 % of PAHs from contaminated soil had been degraded in the presence of biosurfactant, but only 57 % had been degraded in the exclusion of surfactant.	Bezza and Chirwa. 2015
	Australia	The study focused at how a biosurfactant generated from the leaves of the Australian red ash (*Alphitonia excelsa*) could help with bioremediation of a soil severely contaminated with PAHs.	After 12 weeks of application, 78.7 % degradation was obtained in the presence of surfactant, whereas 62.0 % degradation was seen in the absence of surfactant.	Blyth et al. 2015
Photochemical remediation	Indonesia, Southeast Asia	The potential of improving biodegradation of TPHs in crude oil-contaminated soil by combining chemical oxidation utilising TiO2 as a photocatalyst and bioremediation through the landfarming system	The quantity of eliminated TPHs increased when a photocatalyst was added compared to bioremediation alone. Within 12 weeks, the maximum rate of TPHs degradation was seen when 2% TiO2 was added, with up to 67%	Effendi and Aminati (2019)
	Ontario, Canada	To decompose PAH in polluted soil, this study used phytoremediation in combination with other	Multi-process remediation method to remove 16 priority PAHs was twice as effective as land farming, 50% greater than	Huang et al. 2004

		approaches (volatilization, photooxidation, and microbiological remediation).	bioremediation alone, and 45% higher than phytoremediation alone.	
Microbial biodegradation	Nigeria	The study focused on the use of two Candida strains (MN1 and MC1), isolated from isolated after a repeated batch enrichment technique for biodegradation of Nigerian crude oil, Escravos light	MN1 strain degraded aliphatic fractions by 97.6% and the aromatics by 74.61%, the corresponding MC1 values 97.2% and 67.29% during it 14-day cultivation.	Ilori et al. 2011
Biodegradation	Nigeria	The study used microorganisms to breakdown PAH in soil	*Pleurotus Sajor-Cajor* upon incubation for 6 weeks, offers a significant reduction in PAHs concentrations	Ipeaiyeda et al. 2015
Phytoremediation (multi-process approach)	China	The study examined into how to improve the efficacy of PAH phytoremediation. The impacts of introducing arbuscular mycorrhizal fungi, aromatic hydrocarbon degrading bacteria (ARDB), and rhamnolipids into a phytoremediation model were studied together.	The results showed a 60.5% increase in average PAHs elimination effectiveness, which was 251.8% higher than phytoremediation alone (17.2%). The results also demonstrated a high ability to degrade large molecular weight PAHs from soil, which may be difficult to achieve when a single approach is used.	Zhang et al. 2010
	UK	A planar electrode configuration method was used to investigate electro-remediation of multi-polluted soil.	When 973.2g dry weight soil was used, there was a 94% reduction in concentration in the soil closest to the anode after 23 days. However, when 46.7kg dry weight soil was employed, PAHs compounds were pushed towards the cathode, with soil PAH concentrations decreasing by 99% after 22 days, from 720mgkg-1 to 4.7mgkg-1.	Maini et al. 2000
Electro-remediation	Finland	The combined use of in-situ electrokinetics and chemical oxidation to remediate PAH-contaminated soil was studied.	Electrokinetically improved oxidation with sodium persulphate eliminated more PAHs (35%) than either electrokinetics (24%) or persulphate oxidation (12%) alone.	Isosaari et al. 2007
Nano-remediation	USA	Nano-sulfonated graphene (SGE) was utilized as a washing agent to assess its ability to remove PAHs from a coking plant soil.	The results demonstrated that SGE has a high adsorption capacity for PAHs due to the participation of H-π, π-π, and anion-π interactions. Over 80% of the PAH was eliminated when contaminated soils were washed with an SGE concentration of 2000 mg l^{-1}, a liquid/soil (L/S) ratio of 10:1, and 4 cycles of sequential washing.	Gan et al. 2017

Vermi-remediation	USA	The study evaluated the ability of earthworm (*Eisenia fetida*) to remove benzo(a)pyrene, anthracene, and phenanthrene from soil.	Average removal of anthracene by native microorganisms was 23%, 77% for phenanthrene, and 13% for benzo(a)pyrene. However, earthworms were able to remove 51% of anthracene, 47% of benzo(a)pyrene, and 100% of phenanthrene from the soil.	Contreras-Ramos et al. 2006
	Netherlands	The study evaluated the use of earthworms in decomposing PAH in contaminated soil.	The findings revealed that earthworm colonisation and activity influenced the degradation of PAH in sediment.	Eijsackers et al. 2001
Bioremediation (incl., bioventing, biosparging, soil vapour extraction, phytoremediation)	Malaysia	Review and case studies of biodegradation, at demonstration-scale	In-situ remediation approaches such as soil vapour extraction, bioremediation, biosparging, phytoremediation, and biovenenting are all cost effective,	Uche and Dadrasnia, 2017
Physiological and molecular tools to study microbial adaptation	Saudi Arabia	Molecular methods for identifying strains capable of PAH biodegradation in extreme conditions.	PAH biodegradation under high acidity, alkalinity, salt, heat, cold, and pressure. Biodegradation pathways in response to environmental stresses, as well as unique PAH biodegradation pathways.	Arulazhagan et al. 2017
Bioremediation of volatile pollutant hydrocarbons	Spain	Two-Phase Partitioning Bioreactors (TPPB) in laboratory tests on air pollutants (VHs)	VH bioremediation using TPPB was evaluated, design concepts were examined, and non-aqueous phase additives were outlined. Aromatics in TPPB can be harmful to microorganisms. Some VHs with low aqueous solubility are difficult to remove. It is unclear what, if any, restorative action TPPB may have on HMW compounds (e.g. PAH).	Quijano et al. 2017
Bioremediation of crude-oil contaminated wastewater from petrochemical plant	Malaysia	Twelve (12) bacteria were isolated for their ability to digest n-alkanes, with two (2) Acinetobacter species and one (1) *Proteus* species showing potential.	*Acinetobacter* preferred non-agitated environments, but Proteus liked agitated ecosystems. More research on indigenous microbial strains is required to advance bioremediation of hydrocarbon-contaminated areas in underdeveloped countries.	Heng et al. 2017

Microbial upgrading of heavy crude oils	Portugal	Microorganisms (bacterial strains and consortia, fungi and yeast) and enzymes have the potential to bioconvert problematic crude oils.	Enhanced characteristics of problematic unconventional heavy crude oils, such as resins and asphaltenes (and whether latter consist of single PAH or many cross-linked PAHs). Possibility of improving OSR by enhancing the physicochemical qualities of oil before transport and in the event of unintentional discharges	Gudiñ*a* and Teixeira 2017

Status of PAH Contamination in Different African Countries

This section reviews PAH contamination in five African nations (Figure 1) whose economies are dominated by natural resource mining and exploitation process including processing, transport, infrastructure and urbanization. The aim of this section is not to present a detailed approach to PAH remediation in African countries, but to demonstrate the presence of PAH in selected industrialized economies in Africa, and the actions being taken to reduce PAH levels to regulatory thresholds. Principally, the prevalence of PAH is occasioned by the dependence of African countries on natural resource mining as a vital source of revenue. Five countries were selected from the different regions of Africa including Southern, West, East, North, and Central Africa. They were selected based on their economic viability, significant mineral deposits and mining activities that could potentially result in increasing levels of PAH contamination in the environment.

PAH Contamination in South Africa

South Arica is the most developed country in Africa, although environmental PAH levels have so far been poorly monitored (Nieuwoudt et al. 2011). Nekhavhambe et al. (2014) determined specific PAH values in Limpopo Province. The PAH level was largely attributed to the accumulation of traffic-generated organic chemicals on road surfaces. The recorded PAH concentrations were highest in sediment (61,754 µg/kg), while the lowest PAH concentrations were found in water (38.2 µg/kg).

PAH has also been detected in the water and sediments of the Buffalo River Estuary. Adeniji et al. (2019) reported the presence of PAH originating from pyrolytic sources. Individual PAH concentrations in the estuary's water and sediment samples varied from not detected (ND) to 24.91 µg/L and ND to 7792 µg/kg, respectively. The total PAH values in water and sediment samples were between 14.91 and 206 µg/L and 1107 and 22,310 µg/kg, respectively. The combustion of biomass has been found to be a significant source of PAHs in the Vhembe District (Edokpayi et al. 2016). They detected PAH concentrations in water ranging from 13.174 to 26.382 mg/L and in sediment samples ranging from 27.10 to 55.93 mg/kg. Bello-Akinosho et al. (2016) reported that soil contaminated with PAH from spent engine oil was remediated in South Africa using PAH-degrading bacterial isolates, resulting in increased soil fertility.

PAH Contamination in Nigeria

Petroleum exploration and production (E&P) is the primary source of PAH in Nigeria's Niger Delta, where PAHs have been detected in sediments and soils across various oil E&P sites. Sojinu et al. (2009) reported that the quantities of 28 target PAHs in sediment and soil samples from oil E&P sites varied from 65-331 ng/g and from 24 – 120 ng/g, respectively. Igbiri et al. (2017) reported that USEPA-16 PAHs (PAH_{16}) concentrations in edible mushrooms from the Niger Delta ranged from 0.02 mg/kg to 3.37 mg/kg. The Warri River, Ubeji, has been reported to contain high amounts of PAH derived from an oil refinery (Asagbra et al. 2014). The river's sediment, fish, and water contained mean PAH_{16} concentrations of 4587.7 ng/g, 1098.5 ng/g, and 34 ng/ml, respectively.

Contamination from dumpsites in the Ikpa River Basin in the Eastern Niger Delta was 926.6 µg/l PAH_{16} in water samples and 1099.7 µg/kg PAH_{16} in sediment samples. Higher PAH concentrations of 3025.8 µg/kg, 3645.7 µg/kg, and 2457.2 µg/l were also documented in nearby municipal dumpsite soil, hospital dumpsite soil, and landfill leachates, respectively (Inam et al. 2016). Also, in Rivers State, eastern Niger Delta, following two significant operational oil spills of Bonny Light crude oil into Bodo Creek in 2008 and 2009, the deleterious effects of oil spills on mangroves and other biota have been explored in unpublished and published studies (UNEP 2011; Pegg and Zabbey 2013; Zabbey and Uyi 2014; Bonte et al. 2019; Onyena and Sam 2020). Little et al. (2018) examined total PAH_{16} levels in surface and subsurface sediments from Bodo Creek. However, the PAH_{10} data in Bodo sediments did not exceed the Nigerian regulatory objective of 40 mg/kg, 27% of the PAH_{16} data exceeded the International Sediment Quality Guidelines (Environment Canada’s 7.07 mg/kg Probable Effects Level; PEL). Concentrations exceeding the PEL were detected in surface and subsurface sediments at concentrations ranging from 8.98 to 24.2 mg/kg and 7.7 to 22.8 mg/kg, respectively. These PAH levels were considerably greater than expected, and the PAH isomer distribution differed from that of a fresh crude oil E&P spill. The comparatively high molecular weight (HMW) indicated both contamination from other PAH sources and the current weathering of the crude oil.

Using double ratio cross-plots, Little et al. (2018) attributed the PAH to petroleum-derived sources in about half of the sediment samples taken. The fingerprints of the remaining Bodo samples were dominated by pyrogenic PAHs, which were interpreted as reflecting non-point sources from urban, vehicular, or industrial emissions, but also including gas flaring and illegal activities at nearby artisanal refinery sites (Little et al. 2018). In the same area, Gundlach (2018) mapped the steady increase in the number and adverse effects of the illegal refineries over the decade following the two main E&P operational spills.

However, UNEP (2011) expressed reservations regarding its implementation in Ogoniland, remediation using enhanced natural attenuation (RENA) is necessary due to the non-biodegradable residues from incomplete mineralization. Remediation by increased natural attenuation (RENA) is an in-situ bioremediation approach that enhances nutrient, aeration, and moisture content in land farming. Various organic and inorganic substrates are utilized as biostimulants during RENA to speed up bioremediation. However, RENA is ineffective in legacy sites where soil contamination is beyond 5 m depth (Sam et al., 2022), its use has been successful in removing pollutants from the environment. For instance, in Bayelsa State, it was stated that a PAH decrease of 85 percent of crude oil-impacted soil was obtained (Chikere et al., 2017).

PAH Contamination in Egypt

A study of PAHs and petroleum markers in the atmospheric environment of Alexandria, Egypt indicated that diesel vehicles were more important PAH sources than gasoline vehicles (Barakat 2002). Investigation of diagnostic PAH in Assiut, Egypt, revealed that vehicular combustion and traffic exhaust emissions are the major sources of PAHs, with a higher contribution from gasoline than diesel vehicles (Abdallah and Atia 2014).

In another study that assessed PAH concentrations in Lake Manzala, Egypt (El-Kady et al. 2018), PAH levels in sediment and fish were below the level of environmental concern. Fluoranthene, pyrene and benzo(a)pyrene have been identified as the dominant PAHs in the waters off the coast of Alexandria, Egypt (El-Nemr and Abd-Allah 2003). Water samples from the Nile were reported to have PAH from the combustion of fuel, wood, and grasses at concentrations ranging between 235.9 ng/L and 10,368 ng/L (Haiba 2019). Rawash et al. (2018), documented PAH concentrations between 1.3 μg/g and 8.2 μg/g in Egyptian milk and dairy-based products. PAH concentrations of 13.5 ng/g and 22,600 ng/g have been documented in the Mediterranean coastal environment of Egypt (Barakat et al. 2011). PAH from pyrolytic sources at levels within the range of 6.6 - 1770 ng/g sediment have been reported in the Gulf of Suez, Egypt (Ahmed et al. 2017).

After undergoing remediation using microbial degradation methods, soil polluted by PAH from crude oil in Egypt, had naphthalene, phenanthrene, pyrene, and anthracene PAHs removed by over 90% (Hesham et al. 2014).

PAH Contamination in Kenya

Sediment and water samples from Lake Victoria, Kenya, were found to contain PAH from car washing in the range of 0.04 to 31.95 μg/g dry weight and 3.32 to 55.8 μg/L, respectively (Kwach and Lalah 2009). The water, soils, and sediment of Kakamega County, Kenya, were reported to have PAH levels of 0.092±0.03 ng/L, 9.74±1.97 ng/g and 8.94±3.33 ng/g, respectively (Basweti et al. 2018). Fuel burning and road traffic emissions in Nairobi, Kenya produced a median total PAH concentration in the air of 201 ng/m^3 (Muendo et al. 2007). In Kenyan households, PAH from the combustion of organic fuels such as charcoal and biomass has been reported to cause average gaseous concentrations per household of 0.81-6.09 μg/m^3 and 0-2.59 μg/m^3 for rural and urban homes, respectively (Munyeza et al. 2020). PAHs have been reported in beef (17.88 μg/kg) and goat meat (4.77 μg/g) from Kisumu City, Kenya (Onyango et al. 2012).

Soil contaminated by a model mixture of PAHs (phenanthrene, pyrene, and fluoranthene) in a Kenyan laboratory was remediated using biodegradation, leading to PAH reductions to 78%, 62%, and 36% of phenanthrene, pyrene, and fluoranthene, respectively (Rehmann et al. 2008).

PAH Contamination in Angola

Angola, like other oil producing African countries, has been impacted by crude oil spills, which is a major source of PAH in the country. According to Franca et al. (2014), PAH of 70.1±5.0 mg/kg (phenanthrene) and 102.7±10.5mg/kg (anthracene), were found in sediment in Angola. The sediment polluted by PAH from crude oil was remediated using bioremediation methods. The remediated sediment was reported to indicate the complete removal of the 16 PAHs treated (Franca et al. 2014).

Prospects of emerging PAH contaminated sites remediation in Africa

Reviewed literature indicated emerging contaminated land management technologies have been successfully applied in Europe, the UK and America. African economies dependent on natural resources will benefit significantly from the adoption of these technologies (Figure 2). Microorganisms in soil possess the capability to degrade PAH and reduce the higher concentrations that could potentially pose unacceptable risks to human and environmental health (Ebuehi et al. 2005; Laraia 2013). Bioremediation has been extensively explored at various scales, mostly small, but a few successful large-scale applications have been reported. However, the case studies analyzed indicate that bioremediation is approaching commercialization (Røberg et al. 2007), given its extensive application, limited environmental impacts, and popularity in the remediation of contaminated environmental media (Yang et al. 2009; Guimarães et al. 2010).

Several contaminated land remediation technologies exist (Zabbey et al. 2017); however, microbes offer many benefits, such as cost-effectiveness, reusability, and minimal or no harmful by-products. Microbes are abundant, rapidly reproducing, highly diverse, and capable of utilizing a wide variety of toxic materials as nutrients (Das and Dash, 2014).

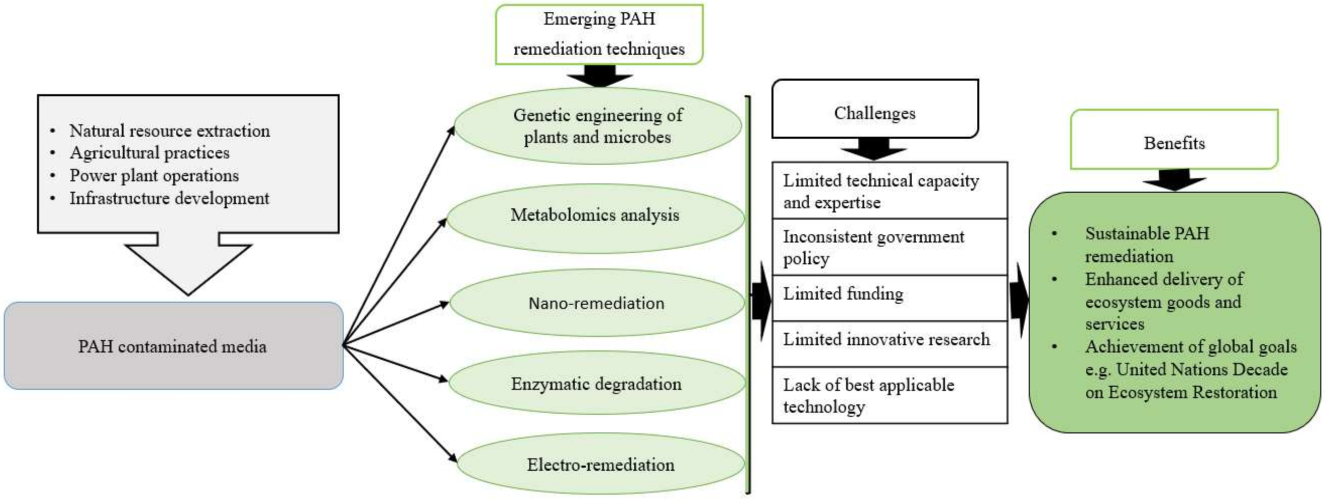


Fig. 2 Conceptual model of PAH emerging remediation techniques, potential green remediation techniques and challenges that need to be addressed to engender benefits

Given the effectiveness, low environmental footprint, and suitability of bioremediation for the clean-up of different contaminants in soil and other environmental media, this approach will benefit African countries, especially where the remediated media could be used for livelihood ventures (e.g., agriculture, in the near future). However, prior to application, there is a need to ensure contamination is within the topsoil and that groundwater has not been contaminated in areas to be treated. In the following section, we explore opportunities for ingenuity towards remediating PAH-polluted media in Africa.

PAH remediation by GMOs in contained environment

High levels of PAH buildup in the environmental media pose a tendency for bioaccumulation in cells. Researchers have recently focused on biological remediation using plants and microbes (Ibanez et al. 2015a). Plants can absorb, accumulate, and metabolise a wide range of toxins, including PAH, and enhance the proliferation and efficiency of microbial pollution degraders (Mackova et al. 2006). While plants are naturally capable of absorbing and storing inorganic and organic contaminants (remediation) in environmental media, genetically modified species have been improved to carefully remediate polluted sites (Macek et al. 2008; Novakova et al. 2010).

When a new trait that does not occur naturally is introduced to a plant, it can mitigate anthropogenic stressors or pollutants and also improve shelf life and yield. Obtaining a transgenic plant with improved phytoremediation capacity depends on a number of factors including: 1) the availability of gene sequences and enzymes involved in removing the pollutant; 2) the presence of a reproducible and highly efficient gene transfer technique; 3) the choice of explants that can easily regenerate; 4) the presence of a reliable regeneration method for the plant species into which the novel gene is to be introduced; and 5) the availability of an effective screening and selection method for the recovery of transformants (Ibañez et al., 2015b).

Genes involved in degradation pathways of pollutant transport and sequestration can be isolated from bacteria, fungi, animals, or plants and introduced into candidate plants. Transformation with genes from other organisms, transformation with genes from other plant species, and overexpression of genes from the same plant species, can all be used to remove contaminants from ecosystems (Ibañez et al. 2015b). However, biosafety concerns for the technique are unresolved. Also, while this provides a nature-based solution to PAH-contaminated site remediation, it might require changes to existing regulations and policies in some countries to allow for genetic modification of plants and microbes.

Metabolomics analysis

Advanced molecular approaches, including genomic, proteomic, and metabolomic methods, are effective tools for understanding the process of PAH-biotransformation in an environmental medium (Sakshi and Haritash 2020). Bacteria *Kocuria flava* and *Rhodococcus pyridinivorans* isolated from an oil-contaminated soil were identified to metabolize pyrene efficiently. The isolated strains produced catabolic enzymes such as Catechol 2,3-dioxygenase (C23O), dehydrogenase, and peroxidase, facilitating the assimilation of pyrene and intermediates during the degradation (Sakshi et al. 2021). Metabolomics has also been widely employed in ecotoxicology to characterize organisms' interactions with their environment (Viant 2008, Samuelsson and Larsson 2008). Hines et al. (2007) proved the utility of metabolomics in monitoring the environment through the use of macroinvertebrates (e.g., *Mytilus galloprovincialis*). The work demonstrates that direct field sampling is superior to laboratory stabilisation for environmental metabolomics because it reduces metabolic variability and enables monitoring of stress-induced phenotypic alterations that would be concealed by laboratory stabilisation. While enabling regulations are being developed, it has been reported that the use of Cytochrome P450 monooxygenases in the breakdown of PAH is promising (Gaur et al. 2018). However, biosafety assessment and effective control of the specified techniques and their widespread application in Africa are in their infancy. There are concerns about the environmental impact and safety of using metabolomics and cytochrome P450 for PAH cleanup in the African environment (Min et al. 2017; Schwitzguébel 2017).

Green nanoremediation

Nanoremediation is a promising strategy for controlling pollution and waste management (El-Ramady et al. 2017). Recent literature has shown nanoremediation to be a major subject of research and development with great potential for decontamination of sites and protecting the environment from pollution (Kuppusamy et al. 2015). The small size (1-100 nm size) and novel surface coatings of the nanoparticles enable them to be more widely distributed in comparison to larger-sized particles, and this unique property makes them best suited for in-situ applications (Tratnyek and Johnson 2006). Because it enables remediation in deeper soils and sediments, nanoremediation is well suited for use with other approaches such as bioremediation and can thus serve as an expanding tool for decontamination (Huang et al. 2016). Nanoremediation can be incorporated with some established PAH bioremediation methods to improve the remedial efficiency and attain speedy PAH degradation under field conditions. Following this, the development and use of nanofertilizers (biostimulation and bioaugmentation), nanominerals (biostimulation), or green synthesized nanooxidizers (PAH oxidation) could be explored to properly exploit the enormous potential significance of nanoremediation in PAH decontamination (Kuppusamy et al. 2017).

Green nanoremediation applications have recently been performed which involve the presence of nanoparticles/nanomaterials with plants in a process described as phyto-nanoremediation (Shalaby et al. 2016; Martínez-Fernández et al. 2017). It could incorporate the use of microbes, known as microbial nanoremediation (Patil et al. 2016; Davis et al. 2017) or animals, as in zoo-nanoremediation (Belal and El-Ramady 2016). Phytoremediation of PAH contaminated environments can be achieved using nanoparticles. To achieve this, nanoparticles such as nano-Au, Ag, CuO, ZnO and C60 can be absorbed and translocated by plants either as nano- or in their ionic form (Mustafa and Komatsu 2016; Singh and Lee 2016; Khan et al. 2016; Patil et al. 2016; Martínez-Fernández et al. 2017).

PAH and other harmful compounds in African environmental media are primarily the results of persistent human activity. They have global implications for environmental quality, greenhouse gas emissions and human health (El-Ramady et al. 2017). Bioremediation has the capacity to remediate PAH contamination in African ecosystems sustainably, especially due to its minimal environmental impacts. However, pilot testing of green nanotechnology is critical to ensuring that the approach is capable of successfully detecting and converting contaminant PAHs.

Challenges of PAHs Management in Africa

Inconsistent government policy

A fundamental challenge to the clean-up of PAH contaminated sites in African settings is the availability of appropriate legislation for effective and efficient remediation (Odoh et al. 2019; Sam, 2022)). Policy framework and implementation, for example, are largely tenure-based in Nigeria (Zabbey et al. 2017). The implication is that a policy or commitment made by an administration might be neglected by succeeding administrations. Meanwhile, restoration of degraded ecosystems in most cases takes decades of sustained scientific and financial commitment. Thus, we recommend that the African power blocs (e.g., African Union) enact the requisite legislation that will ensure the clean-up, remediation, and restoration of highly contaminated sites across the continent.

Incoherent environmental management policies result in weak enforcement and compliance. Also, multiple regulatory agencies with overlapping regulatory remits provide multiple interpretations of existing regulations, which confuses environmental management stakeholders. Most laws on environmental management are piecemeal, and often poorly implemented. The defaulters usually either do not face the prescribed and deserved sanctions, or pay derisory fines (Offiong et al. 2018). However, there are still too few environmental statutes that contain regulatory restrictions designed to protect vulnerable ecosystems from PAH pollution (Alegbeleye et al. 2017). In Nigeria, for example, different government agencies have the mandate of environmental management. The Department of Petroleum Resources (DPR) and the National Oil Spill Detection and Response Agency (NOSDRA) have overlapping roles to regulate hydrocarbon pollution (UNEP 2011). There is yet another layer of confusion, the recently created Hydrocarbon Pollution Remediation Project (HYPREP) has exacerbated the overlapping regulatory roles. Thus, licensing procedures and environmental assessments become complex due to overlapping responsibilities. (Sam et al., 2017; Sam et al., 2022). It is extremely important to standardize and commercialize methods for risk assessment and monitoring of contaminated environments, and incorporate these tests into legislation (Maletić et al., 2019).

Lack of best applicable technology

In most parts of the African continent, improved technologies for qualitative and quantitative analysis of PAHs in environmental samples are in their infancy. This is especially true carcinogenic PAHs with 4 and 5 rings (Alegbeleye et al. 2017). The contribution of PAHs compounds to cancer risk in environmental samples may not be quantifiable due to a lack of toxicity equivalency factors for HMW fractions (Bandowe and Nkansah 2016). Additionally, each PAH compound's ecological and human health consequences and their mixtures have not been extensively researched and understood (Alegbeleye et al. 2017). The application of modern, contemporary molecular methods to the microbiomes of PAH-contaminated areas reveals an increased number of microorganisms with untapped biodegradation potential. Comprehensive knowledge of the variety of terrestrial and aquatic ecosystems in Africa is scarce, implying a significant knowledge gap that could jeopardize the potential selection of indigenous species for PAH bioremediation.

Additionally, recent advances in innovative biological remedial techniques are predicted to result in the 'age of green biotechnology' in the near future (Kuppusamy et al. 2016a; 2016b). Examples include nanoremediation, transgenic methods, metabolomics analysis, omics technologies, and visual imaging, as well as photo-hetero- microbial systems. However, their large-scale remediation capacities, are still being explored and could be the focus area for future research to develop a rapid, reliable, low cost, and risk-based PAH remediation strategy (Kuppusamy et al. 2017).

Limited innovative research

Environmental samples are frequently known to have high contaminant concentrations and toxicity, however, there is still a significant underestimation of the incremental lifetime cancer risk from PAH exposure in the environment (Bandowe and Nkansah 2016). Regional monitoring and research on the cumulative health effects of concurrent chronic and acute exposures in economically important species is lacking (Pulster et al. 2019). With the increasing human population, industrialization, and corresponding increasing levels of PAHs in the environment, there is an urgent need for more studies to decipher the distribution and remediation of PAHs in Africa (Chimuka et al. 2016). There is insufficient data from field studies, so there is a need for researchers to move from laboratory to field investigations (Maletić et al. 2019).

In line with international best practice, the precautionary principle should be applied in those areas suffering from critical knowledge gaps if new developments are being considered. In such areas that have legacy PAH contamination, it should be mandatory to consider these in baseline surveys and to oblige developers to remediate prior to permit approval. There is also a need for long-term monitoring data to evaluate the insidious effects of chronic PAH contamination on biota and the recovery potential and processes. *In-situ* techniques can be considered sustainable from an economic perspective, while *ex-situ* techniques should be further investigated to assess the potential persistence of PAH in the environment (Maletić et al. 2019).

Limited expertise and technical know-how

Most works in the literature on Africa rarely look at all the 16 PAHs listed by the USEPA as priority pollutants, which makes it complex to evaluate and draw conclusions with other studies elsewhere. This implies that, while expertise capable of carrying out such studies is present, there is limited access to appropriate analytical instrumentation (Chimuka et al. 2016). This is compounded by lack of a comprehensive review of the status of PAH analyses and composition in environmental samples in Africa. In addition, a lack of air monitoring resources and infrastructure in Africa contributes to the scarcity of data on PAHs accumulated in the atmosphere (Forbes and Rohwer 2008).

Limited funding

Despite efforts to advance research funding, only 30% of African countries have reported detailed analytical procedures for PAHs monitoring and risk assessment in environmental samples. Forbes et al. (2008) attributed the paucity to hindrances such as socio-political priorities and a lack of resources, which result in the unavailability of funding, suitable equipment, and skilled human capital. There is also a lack of advanced technologies for remediation of affected ecosystems in Africa. In an effort to surmount some of these problems, most African environmental studies are carried out in collaboration with partners in developed countries, whereby samples taken in Africa are analyzed in well-equipped laboratories (i.e., in terms of instrumentation and the ingenuity of the analysts) outside the continent (Muendo et al. 2006; Nassar et al. 2011; Taylor and Nakai 2012).

This is an aspect that Africa is increasingly well placed to attain within Sustainable Development Goal 17 (Partnership for Development).

Future perspectives for PAH remediation in African countries

There is a high possibility of PAH contamination in every country dependent on natural resource mining on the African continent. In many of these countries, PAH contamination assessment and the regulatory frameworks for addressing contamination are in their infancy. Evidence from the reviewed case studies indicates that bioremediation is a viable option because it benefits the environment and introduces minimal environmental footprints and net emissions (Dell'Anno et al., 2020). However, the adoption of integrated approaches to PAH remediation could be more sustainable. For example, combining biological and physico-chemical remediation strategies could potentially address different types and concentrations of PAH (Kuppusamy et al., 2017).

Evidence from literature analyzed in this study indicates the success of insitu PAH remediation in African countries including Nigeria, Kenya and South Africa. These successes could be replicated in other African countries or regions with PAH contamination. PAH contaminated sites with high probability of microbial activity, as observed in most of the analyzed case studies, are more amenable using bioremediation. Although bioremediation is recommended as a minimal, because it is cost-effective and introduces minimal environmental footprints, an integration of physical and chemical approaches could be effective depending the site and remediation objectives. Successful PAH remediation requires a customized approach involving site specific investigation of soil types, temporal and spatial distribution of contaminants, potential receptors, current and future land use. Following the extensive presence of PAH contamination on the African continent, further research needs exist to customized approached to PAH detection and remediation (e.g., to develop simpler and non-technical hand-held devices to detect PAH contamination in different environmental media). In the nearest future, as research evolves, attention would shift from insitu PAH remediation to large scale remediation approaches that meets net zero requirements.

Conclusion

Considering dependence on natural resource mining, PAH contamination is commonplace in some African countries as indicated in Nigeria, Kenya, Angola, South Africa and Egypt. With new industrial developments, and the use of new materials, PAH contamination is on the increase. Physical and chemical remediation approaches have been adopted over the years to address PAH contamination in Africa, very modest remedial results have been achieved. In this article, we suggest that bioremediation presents a sustainable option as a minimum, considering its low net emissions and environmental footprints, as well as its low economic cost to Africa's poor communities and overburdened economy. PAH contaminated sites with high microbial community and activity, as observed in most of the analyzed case studies, are more amenable using bioremediation. However, an integration of biological and physico-chemical approaches could address various types and concentrations of PAH contamination. It is however recommended that each site requires a site specific or contextual investigation which might include soil types, level of site characterization, current and future land use should be considered, as these might affect the success of the remediation process. Further research is required to develop customized approaches to PAH detection and remediation, and assessment of large-scale application of emerging technologies in the African environment.

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