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Nanoremediation Research in Nigeria: A Review

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Abstract: *Research on the application of nanotechnology in environmental remediation has been on the increase globally owing to the promising outcomes on the efficient and effective use of nanomaterials in the removal of contaminants from the environment in comparison to their bulkier counterparts and the traditional remediation technologies. This paper aimed to review the status of nanoremediation research in Nigeria. This study also highlighted the various remediation technologies and the applications of nano remediation in soil, water and air remediation. The materials employed in this review were obtained from research papers published in various journals. Results obtained showed that only little research on nanoremediation exist, as most published works in nanotechnology concentrated on biomedical applications. This review acknowledges funding as the major challenge facing nano remediation research in Nigeria. If Nigeria is to keep up with international trends in nano remediation techniques, research funding is urgently needed as it will elevate the nation's technological and socioeconomic standing.*

Key Words: *Nanotechnology, nanoremediation research, Nigeria, remediation technologies*

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1.0 Introduction

Environmental remediation involves the removal of pollutants from the soil, sediment, groundwater, or surface water by the application of physical, chemical, or biological methods depending on the properties of the pollutant, the type of media as well as the condition of the environment (Zabbey *et al*., 2017). Pollutants reduce the quality of the environment thereby causing environmental degradation. When the environment is contaminated, both the biotic and abiotic components are at risk. Environmental pollution has both environmental and health consequences. The environmental consequences include climate change, ozone depletion, acid rain, and eutrophication. The health consequences include an increased rate of morbidity and mortality. For instance, air pollution has been linked to various respiratory and cardiovascular diseases (Manisalidis *et al*., 2020).

Nanotechnology has been considered not just a rising remedy for cleaning the environment but also for fighting pollution by preventing pollutants formation or the reduction of the release of pollutants (Mehnirrata *et al*., 2013;

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Kaur *et al.,* 2017). Unlike traditional methods, nanotechnology uses materials that will not end up as pollutants after the remediation of contaminants. This technology employs materials that are biodegradable in remediation (Eddy and Gag, 2021; Guerra *et al*., 2018).

The use of nanomaterials in the removal of contaminants is referred to as nanoremediation. Nanoremediation can be used in the detection and prevention of pollution and contaminants purification and remediation. In addition, it can be used in developing specific and cost-effective methods for soil, water, groundwater and air remediation (Kaur *et al*., 2017).

The use of nanotechnology in the remediation of various contaminants has been experimented with at the laboratory and field scale with promising outcomes recorded (Kemp *et al.,* 2013; Guerra *et al*. 2018). For instance, iron nanoparticles have been used in the remediation of a good number of contaminated sites (Phenrat *et al*. 2019). Research on the application of nanotechnology in environmental remediation has been on the increase globally owing to the promising outcomes on the use of nanomaterials in the removal of contaminants from the environment in comparison to their bulkier counterparts and the traditional remediation technologies. Currently, there are few researches information on the level of nanoremediation research in Nigeria. Hence, the object of this review is to x-ray the level of research in the field of nanoremediation in Nigeria. In addition, the types of remediation technologies and applications of nanoremediation in soil, water and air remediation are highlighted.

2.0 Environmental remediation technologies

2.1 Physical remediation

Physical methods of remediation are the oldest remediation technologies and can be used in the removal of a wide range of pollutants from the soil. However, contaminants removed by physical methods require further processing and is associated with high cost compared to other methods (Sharma *et al*., 2018). Physical remediation methods include heat treatment, soil washing, soil vapor extraction, soil flushing, etc. (Ingle *et al*., 2014; Sharma *et al*., 2018). Heat treatment involves heating the contaminated soil or sludge at high temperatures to evaporate hydrocarbons and heavy metals, which are later recovered by condensation (Sharma *et al*., 2018). In soil washing, liquids, mainly water, are sometimes combined with solvents, and mechanical processes to scrub soil, resulting in the separation of fine soil (clay and silt) containing hydrocarbon contaminants from coarse soil (sand and gravel). Fine soil particles can be further treated by other methods. Soil vapor extraction is used to evaporate the volatile constituents of the contaminated soil or groundwater, which are then treated.

2.2 Chemical remediation

Chemical remediation involves the addition of some chemicals to remove the pollutants from contaminated soils, wastewater and sludges. There are various types of chemical treatments for soil remediation. They include chemical leaching, chemical fixation and chemical oxidation, which can be performed on-site (Koul and Taak, 2018). Chemical leaching involves the washing of the contaminated soil with chemical reagents, which can help in leaching heavy metals such as palladium, zinc, mercury, arsenic, etc. from the polluted soil, which are then recovered from the leachate (Ou-Yang *et* al., 2010) Chemical reagents such as nitric acid, sulphuric acid, phosphoric acid, hydrogen peroxide, etc. have been used in chemical leaching. Chemical fixation involves the addition of chemicals or materials such as metallic oxides, clays, or biomaterials to the polluted soil, to stabilize the pollutants, thereby converting them into less toxic forms, hence reducing their bioavailability and ecological risk (Wuana and Okieiman 2011). This method use chemicals such as silica, lime, cement and fly ash to immobilize or stabilize toxic metals and is suitable for lead, arsenic and chromium. Islam *et al.*, (2017) used calcinated cockle shells containing lime for the immobilization of lead, zinc and cadmium in mine tailing soils, with 91, 85 and 85% reductions in the concentration of zinc, lead and cadmium recorded respectively within 28 days of incubation.

Chemical oxidation, on the other hand, is used to degrade a wide variety of contaminants including organic pollutants and heavy metals. Different oxidants such as ozone, hydrogen, persulphate, permanganate and peroxides have been studied for their efficiency to extract contaminants from polluted soil, with activated persulphate and permanganate showing maximum polycyclic aromatic hydrocarbons removal capacity (Zhao *et al*., 2011). One disadvantage of the chemical oxidation technique is that reactants other than the target contaminant can react with the oxidants, thereby affecting their efficiency. In addition, the by-products of chemical oxidation are a potential risk to the environment (Liao *et al*., 2018).

2.3 Bioremediation

Bioremediation involves the use of microorganisms in the removal or neutralization of pollutants through the metabolic process and can be carried out *ex-situ* or *in situ*. The *ex-situ* bioremediation technique involves the removal of contaminated material and transporting it to another site for treatment, while *in situ* bioremediation involves treating the contaminated material on site (Ingle *et al*., 2014). Bioremediation can occur on its own (natural attenuation) or stimulated. Bioremediation techniques include biopile, land farming, bioventing, bioslurping and biosparging (Azubuike *et al*., 2016). Biopile technique includes aeration, irrigation, nutrients, leachate collection and bed systems treatment. Biopile can be used in the treatment of low molecular weight volatile pollutants and can also be used to remediate very cold polluted environments (Gomez and Sartaj 2014). Inland farming, the polluted soil is tilled and excavated and can be treated *ex-situ* or *in situ*. It is the simplest bioremediation technique because it is cheap and requires less equipment for operation (Azubuike *et al*., 2016). Its disadvantages include large operation space, reduction in microbial activity due to unfavourable environmental conditions and reduced efficacy in inorganic pollutant removal (Maila and Colete 2004). Bioventing involves controlled stimulation of airflow by delivering oxygen to the vadose (unsaturated) zone to increase the indigenous microbial activities for bioremediation. This technique is modified by the addition of nutrients and moisture to increase bioremediation to achieve microbial transformation of pollutants to a harmless state. Bioslurping technique combines vacuum-enhanced pumping, soil vapour extraction and bioventing to achieve soil and groundwater remediation by providing oxygen indirectly and the simulation of pollutant biodegradation (Gidarakos and Aivalioti 2007). This technique is used for product recovery such as light non-aqueous phase liquids (LNAPLs) by remediating capillary, unsaturated and saturated zones. It is also used in the remediation of soils contaminated with volatile and semi-volatile organic compounds. This method is cost-effective but it is not suitable to remediate soil with low permeability. Biosparging is similar to bioventing but unlike bioventing, the air is injected into the saturated zone, which helps in the upward movement of volatile organic compounds to the unsaturated zone to stimulate biodegradation. This method is used in the treatment of aquifers contaminated with diesel and kerosene and can also be used in the treatment of groundwater contaminated with benzene, toluene, ethylbenzene and xylene (BTEX) (Azubuike *et al*., 2016). Bioremediation is simple, cheap and does not use toxic chemicals. However, it is restricted to biodegradable compounds and takes a longer time. Also, remediating microorganisms may be rendered inactive in sites with high concentrations of contaminants such as hydrocarbons, volatile organic compounds and heavy metals (Rizwan *et al*., 2014).

2.4 Phytoremediation

Phytoremediation involves the use of plants and various plant-related microbes to partially or completely remove pollutants from different polluted sources. The efficiency of the phytoremediation technique is dependent on various biological processes like the interaction of plants and microbes, plant uptake capacity, translocation, tolerance and plant chelation ability (Sharma *et al*., 2018). Phytoremediation techniques are grouped based on the mode of action of plants in the reduction or removal of toxic contaminants from the soil and include phytoextraction, phytotransformation, phytostimulation, phytostabilization, phytovolatilization and rhizofiltration. One of the main advantages of phytoremediation is that some precious metals can bioaccumulate in some plants and recover after remediation (Azubuike *et al*., 2016). Other advantages of phytoremediation include; being environmentally friendly, inexpensive and can be applied on a large scale, but are limited by factors such as longer remediation period, pollutants concentration, plant toxicity, etc. (Vangronsveld *et al*., 2009; Ali *et al*., 2013). It can be used in the removal of pollutants such as hydrocarbons, heavy metals and volatile organic compounds and works well for low to moderately contaminated sites (Nnaji *et al*., 2019).

3.0 Nanoremediation and its Application

Nanoremediation technologies involve the application of reactive nanomaterials for the degradation and mineralization of pollutants (Guerra *et al*., 2018). Nanoremediation is an innovative method that depends on the use of nanomaterials. It facilitates the effort to fight and resolve the difficult problematic challenges facing the 21st century such as pollution issues, contaminated land management and restoration of environmental balance and also presents innovative solutions for fast and efficient removal of pollutants from contaminated environments (El-Ramady *et al*., 2017; Das *et al*., 2019). Nanoremediation technologies cannot only reduce the overall cost of cleaning up contaminants at a large scale but also reduce the time of clean-up, eradicate the need for treatment and disposal of contaminated materials as well as reduce the concentration of contaminants to near zero (Karn *et al*., 2009; Corsi *et al*., 2018). Also, nanoremediation technologies employ *in situ* treatment methods in remediation, unlike traditional methods. For instance, soil and groundwater remediation using nanomaterials involves treating the soil and groundwater without removal, unlike conventional treatment methods in which the soil and groundwater will be removed and then treated in another location (ex-situ). Ex situ treatment is associated with the high cost and a large amount of environmental disruption, which has been overcome using nanoremediation technologies (Agarwal and Liu 2015).

Nanoremediation technologies are very highly promising tools tackling and preventing the environmental challenges and threats posed by contaminants. Nanomaterials have been applied in the remediation of various organic and inorganic contaminants from the soil, groundwater/surface water and air and are summarized below.

3.1 Soil remediation

The use of nanomaterials in soil remediation has been attractive because of their great reactivity, large surface area, functionalization and modification of physical properties. The intercalation of nanoparticles in the soil helps to achieve extensive cleaning of the contaminated areas and reduces the cost and time of remediation because it is being applied in situ. Nanomaterials employed in soil remediation include nano-zerovalent iron (nZVI), metals, metal oxides and magnetic nanoparticles, carbon nanotubes and polymer-based nanoparticles/nanomaterials (He *et al*., 2010; Naderi and Jalali 2018; Del Prado-Audelo *et al*., 2021).

Nano-zerovalent iron (nZVI) has been the most common and widely used nanomaterial for soil remediation. It has been employed in the removal of chlorinated organic solvents, polychlorinated biphenyls (PCBs), organochlorine pesticides, trichloroethene (TCE), dichlorobiphenyls chloroethane (DDT) and heavy metals like chromium (VI), lead, cadmium as well as nitrates with high percentage removal recorded (Guerra *et al*. 2018; Linley and Thomson 2021). The mechanism of action of nZVI is reduction and adsorption (Linely and Thomson 2021). Nano-zerovalent iron (nZVI) is prone to aggregation and filtration thereby reducing the transport distances in the soil to less than 10 cm. To improve its mobility, various polymeric coating materials such as carboxymethyl cellulose (CMC), polyacrylic acid (PAA) and xanthan gum are used (Kumar *et al*., 2017). Naderi and Jalali (2018) studied the use of SiO_2, Al_2O_3 and TiO_2 nanoparticles for the remediation of non-calcareous and calcareous soil contaminated by zinc (Zn), nickel (Ni) and cadmium (Cd). They found that the application of 3 % of SiO_2 resulted in the maximum reduction of Cd by 56.1. %, while 1 % of Al_2O_3 reduced the concentration of Cd by 38.3 % for calcareous and non-calcareous soils respectively. In the case of Zn, the maximum reduction was 57.1 % for TiO_2 (3 %) and 28.8 % for Al_2O_3 in calcareous and non-calcareous soils respectively. Gil-Diaz *et al*. (2022) employed three types of nanoparticles – nZVI, nZVI-Pd and nFe_3O_4 (nano magnetite) in the removal of Cr and PCBs from co-contaminated soil for a period of 15, 45 and 70 days. The three nanoparticles showed significant reduction in Cr concentration (> 98 %) at the three sampling times. In terms of PBCs removal, the nZVI-Pd reduced PCBs concentration in the soil faster than nZVI. The incorporation of Pd with iron helped to achieve PCBs removal at a shorter period of time. nZVI-Pd could be used in the remediation of Cr and PCBs contaminated soil. Carbon nanotubes have been successfully employed in the remediation of heavy metal ions such as Pb^{2+}, Ni^{2+}, Cu^{2+}, Zn^{2+}, Cd^{2+} and Cr^{6+}. Carbon nanotubes are also used in petroleum hydrocarbons, DDT and crude oil remediation The application techniques involve incorporating them into membrane filters, separation columns and dispersion in an aqueous medium (Del Prado-Audelo *et al*., 2021). Cheng *et al*. (2019) assessed the efficiency of modified carbon black nanoparticles for petroleum biodegradation and heavy metal immobilization in contaminated soil remediation by combining plant-microbe remediation. Results of their finding showed that in a petroleum – nickel co-contaminated soil, 65 % petroleum degradation was achieved, while in petroleum – cadmium co-contaminated soil, 50 % petroleum degradation was achieved using the carbon nanotubes. Table 1 shows some other nanoparticles/nanomaterials and their optimum removal efficiency of contaminants.

3.2 Water remediation

Groundwater is an important source of drinking water in various parts of the world. The quality of groundwater is deteriorating and the level of pollution increasing daily due to the growth in industrial, agricultural and urban activities. Besides groundwater, surface water has been highly contaminated. Various harmful chemicals such as organochlorines, organophosphorus, heavy metals and other harmful substances are being discharged into water bodies resulting in a decrease in water quality and availability, hence the need for remediation.

Nanoremediation technologies have proven to be an efficient method for groundwater and wastewater decontamination compared to other remediation technologies (Ganie *et al.*, 2021). Nanotechnology is used in the detection and removal of contaminants in water by the use of nanosensors, nanofilters and nanoparticles (Taran *et al*., 2021).

Various nanomaterials have been applied in groundwater, wastewater and water remediation including nZVI, Fe/Al, Ag/Fe, Ni/Fe, TiO_2, ZnO, carbon nanotubes and polymer-based nanomaterials (Patil *et al.*, 2016; Del Prado – Audelo *et al*., 2021). nZVI is used in the removal of chlorinated compounds (trichloroethylene, 1,2-dichloroethane and 2,4-dichlorophenol) organic pollutants and heavy metals (Pd, Cr, Cu, As, Cr, Pb and Zn) from groundwater and wastewater. Shukla *et al.* (2018) synthesized cobalt-impregnated silica (Co/SiO_2) nanoparticles and evaluated its use as an adsorbent in the removal of methylene blue, trinitrotoluene and mercury (II) from contaminated water. Co/SiO_2 nanoparticles showed a maximum adsorption capacity of 240 mg/g for methylene blue, 20.49 mg/g for trinitrotoluene and 40.24 mg/g for Hg (II).

Table 1: Literature on some nanoparticles for the treatment of contaminated soil

Nanoparticles	Contaminants	Optimum removal efficiency	References
Nano-zerovalent iron (nZVI)	Dichloro-diphenyl-trichloroethane (DDT)	2.5 %	Blundell and Owens (2021)
	Chromium(VI), Cr^{6+}	62 %	
ZnO	Cu	70 %	Akhtar *et al*. (2021
	Cr	60 %	
	Pb	85 %	
Carboxymethylcellulose (CMC)-nZVI	Chromium(VI), Cr^{6+}	95 %	Zhang *et al*. (2016)
Nanomagnetite (nFe_2O_3)	Polycyclic aromatic hydrocarbons (PAHs)	85.5 %	Barzegar *et al*. (2017)
TiO_2-Chitosan nanolayer	Cd	88.01 %	Mahmoud *et al*. (2018)
	Cu	70.67 %	
Polyvinyl pyrrolidone (PVP) coated iron oxide	Cd and Pb	100 %	Cao *et al*. (2020)
Carbon nanotubes (CNTs)	Polycyclic aromatic hydrocarbons (PAHs)	66.1 %	Zhang *et al.* (2019)
Modified carbon black nanoparticles	Petroleum/nickel	65 %	Cheng *et al.* (2019)
	Petroleum/cadmium	50 %	

Gu *et al.* (2020) in their study, used zinc oxide (ZnO) nanoparticles in heavy metal remediation from wastewater. They observed that ZnO nanoparticles selectively adsorbed Cr^{3+} from wastewater containing a mixture of Cr^{3+}, Ni^{2+}, Pb^{2+} and Cu^{2+}. Between the pH of 3 – 7, ZnO nanoparticles showed very high affinity towards Cr^{3+} within 20 mins contact time. The maximum adsorption capacity for Cr^{3+} was 88.6 mg/g. Zno nanoparticles could be used to selectively remove Cr^{3+} from wastewater contaminated with different heavy metals. Some authors reported successes on the use of nanoparticles in the purification of contaminated water are presented in Table 2 below. The consideration of the entries to the table indicates that adsorption and photodegradation is one of the commonest methods of applying nanoparticles for the treatment of some environmental contaminants such as heavy metals, dyes and antibiotics.

3.3 Air remediation

Air pollution occurs when there is an alteration in the natural composition of the atmosphere due to the introduction of chemical, physical or biological substances emitted from anthropogenic, geogenic, or biological sources. Among all the environmental hazards, air pollution is the biggest, causing approximately 7 million deaths annually. Exposure to air pollution above the WHO guideline levels results in an increased risk of adverse health consequences mainly lung cancer, and cardiovascular and respiratory diseases (WHO 2022).

Table 2: Literature on some nanoparticles for the treatment of contaminated water

Nanoparticles	Contaminants and applied technology	Optimum removal efficiency	References
nano-zero-valent iron and nano-copper	Lefloxacin by adsorption	95%	Hamad *et al*. (2023)
CaO nanoparticles	Bromocresol green dye by adsorption	90%	Ogoko *et al*. (2023)
Nickel-ferrite nanoparticles	Cr, Pb and Cd ions	79-89%	Khoso *et al*. (2021)
Mesoporous nanoparticles from orange peel	Trypan blue by adsorption	>94%	Eddy *et al*. (2022a)
Nanoalumina	Congo red by adsorption	89%	Odiongenyi and Afangide (2019)
CaO nanoparticles	Methylene blue by adsorption	96%	Eddy *et al*., (2022b)
Graphen oxide nanoparticles	Ethyl violet by adsorption	90%	Odiongenyi (2021)
Biosynthesized silica-based zinc oxide	Ni, Cu and Cd ions	Cu^{2+} (32.53 mg/g), Ni^{2+} (32.10 mg/g), and Cd^{2+} (30.98 mg/g)	Garg *et al*.(2022)
ZnO nanoparticles	Cr^{6+} by adsorption	88.6 mg/g	Gu *et al*. (2020)
Ni/TiO_2 nanoparticles	Methyl orange by photocatalysis	95.89 %	Pirsaheb *et al.* (2020)
SiO_2 nanoparticles	Methyl orange by photocatalysis	95 %	Alhadrami *et al.* (2022)
Co/SiO_2 nanoparticles	Methylene blue Trinitrotoluene Hg (II) by adsorption	240 mg/g 20.49 mg/g 40.24 mg/g	Shukla *et al.* (2018)

Nanotechnology is an advanced treatment technology to control and remediate air pollution in different ways by taking advantage of the nanomaterial-specific properties and applying them as nano adsorbents, nanocatalysts, nanosensors and nano filters/membranes (Saleem *et al*., 2022). A few examples of nanomaterials employed in the detection, monitoring and remediation of air contaminants are highlighted. Qiang *et al.* (2018) evaluated the nitrous oxide (NO_2) gas sensing performance of functionalized porous silica/WO_3 nanorods with palladium (Pd) nanoparticles (PS/WO_3-Pd). The PS/WO_3 exhibited the highest sensor response of 5.2 to 2 ppm NO_2. PS/WO_3-Pd sensors detected NO_2 at a very low concentration of 0.25 ppm at room temperature. The response of the sensors was also found to increase with an increase in the concentration of NO_2. The NO_2 gas sensing of the nanocomposites followed adsorption – reaction mechanism.

The gas-sensing properties of ZnO nanorods and a bunch of nanowires were studied by Navale *et al*. (2017). The zinc oxide nanorod exhibited a high sensor response of 622 % upon exposure to 100 ppm of NO_2, with a response time of 35 secs at 200°C while ZnO bunch of nanowires sensor showed a maximum response of 101 % upon exposure to 100 ppm of NO_2 at 200°C. At 1 ppm concentration of NO_2 and 200°C, sensor responses for ZnO nanorods and ZnO nanowires were 41 % and 7.5 % respectively. Azam *et al.* (2017) used Si–doped single-walled carbon nanotubes in the adsorption CO_2 and methanol gas molecules. Titanium dioxide reduced – graphene oxide has been employed as a nanofillers for gaseous methanol while Ag/ZnO nanoparticles showed an assuring result as nanofillers in the elimination of airborne microorganisms (Pokhum *et al*. 2018). Rabiee and Mahanpoor (2019) showed that manganese-supported copper slag nanoparticles under UV irradiation removed 99 % of SO_2. Yu and coworkers used titanium oxide-reduced graphene oxide (TiO_2-rGO) to degrade formaldehyde under visible light irradiation. TiO_2-rGO removal efficiency of 60 % towards formaldehyde after 100 mins of irradiation compared to titanium oxide and reduced graphene oxide with removal efficiencies of 10 % and 20 % respectively (Yu *et al*., 2018). Carbon nanotubes, and metallic and metal oxide nanomaterials could be successfully employed in the detection and removal of toxic contaminants from the air. Other literature on the use of nanoparticles for the detection and purification of contaminated air are presented in Table 3.

Table 3: Literature on some nanoparticles for the detection and treatment of contaminated air

Nanoparticles	Contaminants	Optimum detection /removal efficiency	References
Graphene-tin oxide nanocomposite	NO_2	72.6 % (heating) and 46.5 % (without heating) (detection/removal)	Kim *et al.* (2017)
Zinc oxide nanorod Zinc oxide nanowire	NO_2	622 % 101 % (detection)	Navale *et al.* (2017)
Tin oxide-reduced graphene oxide (SnO_2-rGO) nanocomposite	H_2S	34.31 % (detection)	Chu *et al.* (2018)
Reduced graphene oxide/hexagonal tungsten oxide (rGO/hWO_3) nanocomposite	H_2S	168.58 % (detection)	Shi *et al.* (2016)
Copper slag nanoparticles	SO_2	99 % (removal)	Rabiee and Mahanpoor (2019)
Titanium oxide-reduced graphene oxide (TiO_2-rGO)	Formaldehyde (HCHO)	60 % (removal)	Yu *et al.* (2018)

4.0 Status of nanoremediation research in Nigeria

Nanotechnology has been identified as an emerging field of science and technology of the twenty-first century and is the art of creating, studying and applying materials at the nanoscale (Elegbede and Lateef 2020). The national initiative of nanotechnology began in 2006, followed by the launching of Science, Technology and Innovation (ST&I) in 2012 by the Federal Ministry of Science and Technology. Also, the National Centre for Nanotechnology and Advanced Materials was formed by the National Agency for Science and Engineering Infrastructure (NASENI), in collaboration with US – Africa Materials Institute, European Union, the Federal Institute of Industrial Research (FIRRO) and the African Institute of Technology. NASENI identified nanotechnology as one of the technologies of the future for Nigeria and was charged with the responsibility for the take-off of nanotechnology and advanced materials in the areas of nanomedicine, nanoelectronics, nanostructured and nanoporous materials (NASENI 2019). Notwithstanding, the progress of nanotechnology has been slow in Nigeria (Elegbede and Lateef 2019). Nigeria is yet to engage meaningfully in nanotechnology research, especially in the areas of need. Most of the published works in nanotechnology in Nigeria is majorly on nanoparticles synthesis and their biomedical applications, with only a few reported on energy/electronics, catalytic and environmental applications (Balogun *et al*., 2020; Eli *et al*., 2020), compared to South Africa and Egypt that have reported the applications of nanotechnology in diverse areas. Muhammad (2020) carried out a comparative study of research and development (R & D) related to nanotechnology in Egypt, Nigeria and South Africa using Malaysia as a control. Results showed that South Africa has the highest ranking (66 %), followed by Egypt (59 %) and Nigeria (38 %), compared to Malaysia (86 %). Lateef *et al*,. (2021), in their survey of nanotechnology research in Nigeria between 2010 – 2020 pointed out that only four institutions were at the forefront of nanotechnology research in Nigeria, contributing a total of 43.88 %, with the University of Nigeria, Nsuka (UNN) topping the chart, followed by Covenant University (CONUNIV), Ladoke Akintola University of Technology (LAUTECH), University of Ilorin (UNILORIN) and University of Lagos (UNILAG). In the area of funding, only 380 out of 799 published works on nanotechnology in Nigeria obtained from Scopus received funding, with only 52 (6.51 %) funded locally. About 419 (representing 52.44 %) research papers had no funding information.

In the area of nanoremediation, there are few types of research, some of which are highlighted. The application of nanotechnology in the detection and removal of organic and inorganic contaminants from the environment has been evaluated by researchers in Nigeria, though there is limited research in this area. Some nanomaterials have been synthesized and used as nanosensors, nano nanocatalysts and nano adsorbents in the detection and removal of inorganic and organic pollutants from the soil and water. Ojo *et al* (2016) employed AuNPs and Ag-AuNPs synthesized from *B. safensis* as a nanocatalyst in the degradation of malachite green. At concentrations of 20 – 100 µg/ml, AuNPs and Ag-AuNPs achieved 89.2 – 92.7 % and 86.1 – 92.6 % decolorization of malachite green dye respectively, after 4 hours. Gbajabiamila *et al* (2020) studied the use of a multi-walled carbon nanotube in the removal of Pb^{2+} from oil-polluted water. The MWCNTs showed the highest percentage adsorption of 99.5 % for Pb^{2+} at 60 mins. Kareem *et al*. (2020) reviewed the photocatalytic activity of silver nanoparticles and their composites and established that silver nanoparticles could be used in the degradation or removal of organic pollutants such as dyes and may find use in the environment and textile industry for dye remediation. Yahaya and Shams (2022) evaluated the sensing performance of poly imidazole multi-walled carbon nanotubes (PIm/MWCNTs) towards volatile organic compounds. Results revealed that PIm/MWCNTs gas sensor had the highest selectivity for ethanol and methanol (0.81 %), while its selectivity towards p-xylene, toluene, dichloromethane and diethyl ether was low (between 0.03 to 0.07 %). Amaku *et al*. (2021) prepared MWCNTs/quartzite nanocomposites modified with the extract of *Dacryodes edulis* leaves. The modified nanocomposite showed optimum Cr(VI) removal of 45.87 mg/g, compared to the unmodified MWCNTs/quartzite (27.50 mg/g), at pH 2.0, 50 mg adsorbent dose, 100 mg/dm^3 initial concentration and 180 minutes contact time.

The research output in nano_remediation in Nigeria is low with only a few institutions engaged in it. Also, in the area of the application of nanoremediation in Nigeria by both public and private organizations, little or no information exists. In terms of funding, only Tertiary Education Trust Fund (TETFund) is the major funding agency for tertiary education and research in Nigeria and is yet to prioritize nano remediation/nanotechnology research. In contrast to South Africa, Egypt and some other African countries, whose governments have committed millions of dollars in nanotechnology (nanoremediation inclusive), Nigeria's budget for nanotechnology/nano_remediation is non-existent. If Nigeria is to keep up with international trends, funding for research on nanoremediation techniques is urgently needed (Nnaji *et al.* 2019). The Federal and State governments, universities, and public and private organizations should invest in nanoremediation research, which will undoubtedly elevate the nation's technological and socioeconomic standing.

5.0 Conclusion

This study reviewed the various remediation technologies and the status of nanoremediation research in Nigeria. The remediation technologies include physical remediation, chemical remediation, bioremediation, phytoremediation and nanoremediation. Compared to other remediation methods which are either associated with high cost and/or long treatment duration, nanoremediation reduce the overall cost of cleaning contaminants at a large scale, time of clean-up and the concentration of contaminants to near zero, being applied in situ. Thus, nanoremediation is a very high promising tool in the removal of contaminants from the environment as various nanomaterials have been successfully employed in the remediation of contaminants at the laboratory, batch and field scale. However, some nanomaterials are prone to aggregation and filtration, which can be overcomed through the incorporation of polymers.

In the area of nanoremediation research in Nigeria, only a little research exist as most published works are concentrated in the biomedical application of nanotechnology. This study identified funding as the major factor hindering nanoremediation research in Nigeria. Therefore, the public and private sector should invest in nanoremediation research if Nigeria is to keep up with international trends

7.0 References

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Declarations

Ethical Approval and Consent to Participate

All authors approve of the ethics and consent to participate in this research.

Consent to Publish

All authors have consented to publish this paper.

Availability of data and materials

The datasets used or analyzed during the current study are available from the corresponding author upon reasonable request.

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Author's Contribution

J.C. Nnaji conceptualized the study while all the authors were involved in the literature search, compilation and writing of the paper