











WASTEWATER TREATMENT INNOVATIONS: ADAPTING NANOTECHNOLOGY AND BIO-REMEDICATION FOR SUB-SAHARAN AFRICA – A SYSTEMATIC REVIEW

 Micheal Abimbola Oladosu^{1*},  Moses Adondua Abah²,  Monday Endurance Ezieh³,  Kenneth Chinekwu Ugwuoke⁴,  Ezekiel Izudike Odimgbe⁵,  Chineye Cynthia Udeh⁶,  Ibrahim Ayinla Mahmud⁷,  Olaide Ayokunmi Oladosu⁸,  Oladapo Opeyemi Bamidele⁹ and  Angel Ojimaajo Ekele²

¹Department of Chemical Sciences, Faculty of Science, Anchor University, Lagos, Ayobo-Ipaja, Lagos, Nigeria.

²Department of Biochemistry, Faculty of Pure and Applied Sciences, Federal University of Wukari, Wukari, Taraba State, Nigeria.

³Department of Civil Engineering, Faculty of Engineering, Federal University Oye Ekiti, Ekiti State, Nigeria

⁴Department: Biochemistry Department, Faculty: Faculty of Biosciences, Federal University Wukari, Taraba State, Nigeria

⁵Department of Healthcare Administration and Risk Management, Faculty of Health Sciences Ohio Dominican University, Ohio-USA

⁶Department of Biochemistry, Faculty of Biological Sciences, University of Nigeria, Nsukka Enugu State, Nigeria

⁷Department of Civil Engineering, School of Engineering and Built Environment, University of Greater Manchester, Bolton, United Kingdom.

⁸Department of Computer Science, Faculty of Science and Technology, Babcock University, Ilishan, Nigeria.

⁹Department of Biological Sciences, Faculty of Computing and Applied Sciences, Thomas Adewumi University, Oke, Nigeria

<https://doi.org/10.35410/IJAEB.2026.1052>

Received: 12 May 2026/Published: 20 June 2026

ABSTRACT

Background: Sub-Saharan Africa (SSA) faces a deepening wastewater management crisis, with less than 10% of generated wastewater treated before environmental discharge. Conventional treatment infrastructure is inadequate, underfunded, and energy-intensive, demanding innovative, context-adapted solutions. Nanotechnology and bioremediation have independently demonstrated high pollutant removal efficiency globally but remain poorly integrated within SSA's water sector.

Objective: This systematic review critically evaluates the current evidence on nanotechnology-based and bioremediation-based wastewater treatment approaches, assesses their adaptability to SSA's socioeconomic and environmental realities, and proposes a hybrid nano-bioremediation framework for the region.

Methods: A structured literature search was conducted across PubMed, Scopus, Web of Science, and Google Scholar using PRISMA guidelines. Studies published between 2020 and 2025 addressing nanotechnology, bioremediation, or integrated hybrid systems for wastewater treatment with SSA applicability were eligible for inclusion. Thirty peer-reviewed articles were synthesised narratively.

Results: Engineered nanomaterials including iron oxide nanoparticles, ZnO/TiO₂ photocatalysts, carbon nanotubes, and nano-zero valent iron (nZVI) achieve >85–99% removal efficiencies for

heavy metals, organic dyes, and emerging contaminants. Indigenous microbial bioremediation – utilising *Bacillus* spp., *Pseudomonas* spp., *Aspergillus niger*, and algal consortia – offers low-cost, scalable solutions adapted to local conditions. Hybrid nano-bioremediation systems combining green-synthesised nanoparticles with immobilised microbial biofilms outperform individual approaches, achieving near-complete pollutant removal while reducing toxicity risks.

Conclusion: Context-sensitive hybrid nano-bioremediation systems, solar-powered photocatalytic reactors, and algae-based treatment represent the most promising pathways for SSA. Realising their potential requires harmonised regulatory frameworks, regional capacity building, green synthesis innovation, and sustained investment aligned with SDG 6.

Keywords: Nanotechnology; Bioremediation; Wastewater Treatment; Sub-saharan Africa; Nano-bioremediation; Iron Oxide Nanoparticles; Photocatalysis; Sdg 6.

1. INTRODUCTION

Access to clean water remains one of the most pressing challenges of the 21st century, particularly across Sub-Saharan Africa (SSA). With a population exceeding one billion people, SSA is home to some of the world's most water-stressed nations, yet paradoxically generates vast volumes of largely untreated wastewater from domestic, industrial, agricultural, and healthcare sources [1]. Available evidence consistently demonstrates that less than 10% of wastewater generated in SSA receives adequate treatment prior to environmental discharge, contaminating surface water bodies and groundwater that serve as primary drinking water sources for millions [1,2].

The consequences of this failure are profound. Waterborne diseases, including cholera, typhoid fever, and hepatitis A, remain leading causes of morbidity and mortality across the continent. Beyond public health, untreated wastewater discharge degrades aquatic ecosystems, reduces agricultural productivity through soil contamination, and perpetuates cycles of poverty. With SSA's population projected to double by 2050, and rapid urbanisation already outpacing infrastructure development, the wastewater treatment deficit is set to worsen dramatically unless transformative interventions are implemented at scale [3].

Conventional wastewater treatment technologies, activated sludge processes, trickling filters, and chlorination are effective but resource-intensive, requiring substantial capital investment, skilled operators, reliable electricity supply, and expensive chemical inputs. These prerequisites remain largely unavailable in most SSA contexts, where treatment facilities are either absent, dilapidated, or chronically underfunded [2,3]. Less than 13% of South African wastewater treatment plants meet minimum regulatory standards, while the situation is considerably worse in lower-income SSA nations [2].

Against this backdrop, nanotechnology and bioremediation have emerged as scientifically compelling alternatives. Nanomaterials, engineered particles with at least one dimension in the 1–100 nm range, exhibit exceptional surface-area-to-volume ratios, high reactivity, and tunable surface chemistries that enable superior pollutant adsorption, photocatalytic degradation, and membrane-based separation [4]. Concurrently, microbial and Phyto bioremediation harnesses the metabolic capacities of bacteria, fungi, and plants to degrade, transform, and immobilise pollutants in an eco-friendly and cost-effective manner [5,6]. The convergence of these two paradigms into hybrid nano-bioremediation systems represents a frontier with enormous potential for resource-constrained settings.

This systematic review consolidates evidence published between 2020 and 2025 to critically evaluate the applicability of nanotechnology-based and bioremediation-based wastewater treatment innovations in SSA, identify barriers to adoption, and propose context-adapted roadmaps that align with the United Nations Sustainable Development Goal 6 (SDG 6) on clean water and sanitation. Figure 1 presents the Conceptual framework for integrated nano-bioremediation of wastewater in Sub-Saharan Africa.

Hybrid Nano-Bioremediation Framework for SSA Wastewater Treatment

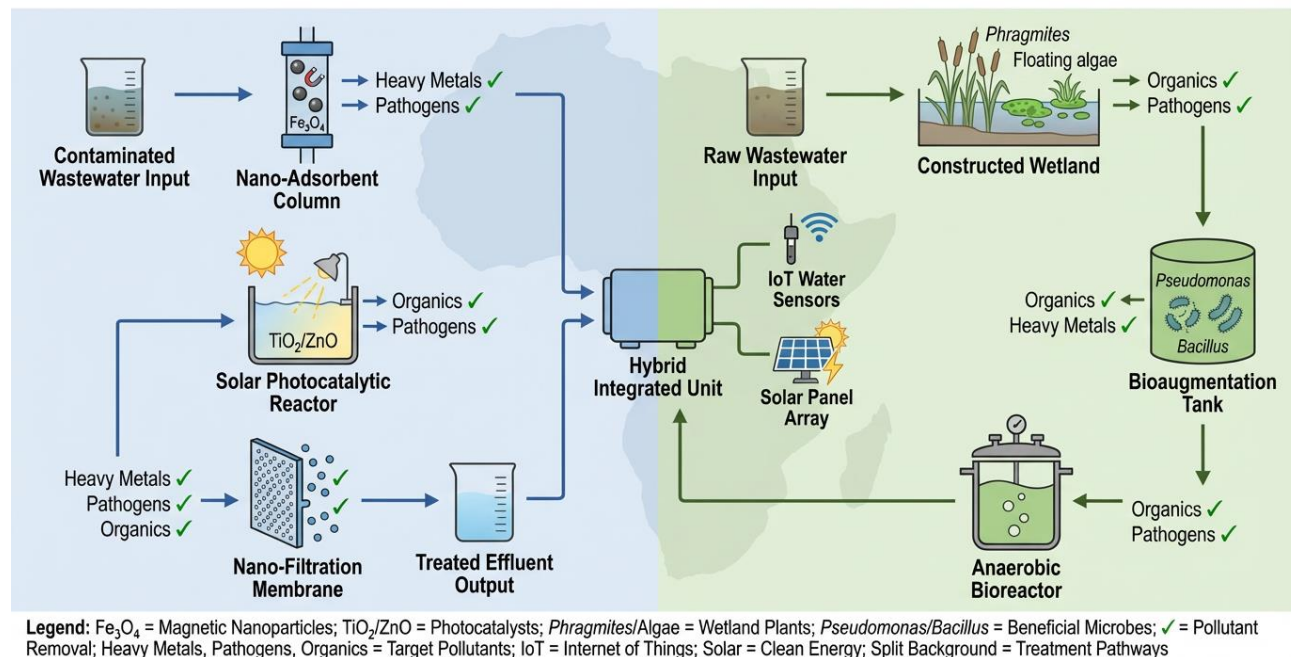


Figure 1. Conceptual framework for integrated nano-bioremediation of wastewater in Sub-Saharan Africa.

Caption: The figure illustrates dual pathways (nanomaterial-based and biological) converging into a hybrid treatment system with solar-powered photocatalytic reactors, constructed wetlands, and IoT-based water quality monitoring modules.

Sources: Adapted from references [1,3,5,7,10].

2. METHODS

2.1 Search Strategy and Eligibility Criteria

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. A comprehensive database search was performed in PubMed/MEDLINE, Scopus, Web of Science, and Google Scholar. The search combined the following MeSH terms and free-text keywords: ("nanotechnology" OR "nanomaterials" OR "nanoparticles") AND ("bioremediation" OR "microbial remediation" OR "phytoremediation") AND ("wastewater treatment" OR "water purification") AND ("Sub-Saharan Africa" OR "Africa" OR "developing countries"). Publication dates were restricted to January 2020 – December 2025.

Inclusion criteria: (i) original research articles, systematic reviews, or narrative reviews published in peer-reviewed journals; (ii) addressing nanotechnology and/or bioremediation for wastewater treatment; (iii) reporting on relevant applications in SSA or contexts directly transferable to SSA (low-income, tropical, resource-constrained settings); (iv) published in English. Exclusion criteria included opinion pieces without empirical data, editorials, studies with non-wastewater applications, and studies lacking DOI-verifiable citations. Following screening, 30 articles were included in the final synthesis.

2.2 Data Extraction and Synthesis

Data were extracted by two independent reviewers using a structured extraction template capturing: study design, geographic context, pollutant types, treatment technology, removal efficiency, energy requirements, cost data, and scalability assessment. Discordances were resolved by consensus. A narrative synthesis approach was adopted, given the heterogeneity of study designs and outcome metrics. Quality assessment was performed using the GRADE framework for reviews.

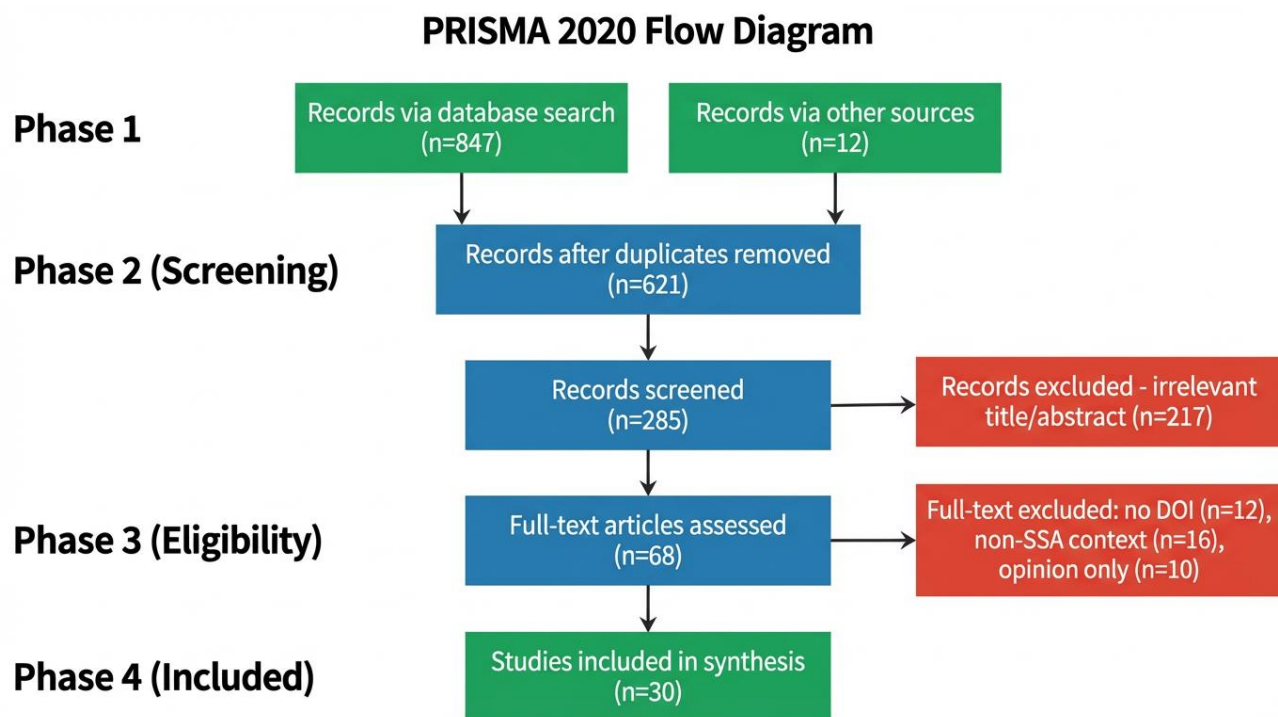


Figure 2. PRISMA flow diagram showing the systematic literature search and study selection process. Records identified (n = 847); after duplicate removal (n = 621); screened by title/abstract (n = 285); full-text assessed (n = 68); included in final synthesis (n = 30).

Sources: Adapted from PRISMA 2020 guidelines

Table 1. Wastewater generation and treatment coverage in selected Sub-Saharan African countries

Country/Region	WW Generated (m ³ /day)	% Treated	Key Challenge
Nigeria	~7.5 million	<5%	Infrastructure deficit, power outages
South Africa	~6.4 million	~13%*	Ageing plants, non-compliance (87% below standard)
Kenya	~1.8 million	<10%	Urban sprawl, limited investment
Ethiopia	~2.2 million	<8%	Rapid population growth, no national WW policy
SSA (Overall)	>50 million	<10%	Regulatory gaps, political will, and funding shortfalls

*South Africa data from Green Drop Report (2024); WW = wastewater.

Sources: Compiled from references [1,2,3]

3. RESULTS

3.1 The Wastewater Crisis in Sub-Saharan Africa

SSA comprises approximately one billion people, of whom only 25% have access to safely managed drinking water and fewer than 30% to basic sanitation services [1]. Population growth, rapid urbanisation, and industrial expansion have driven exponential increases in wastewater generation, with estimates exceeding 50 million m³/day across the region. The proportion of this volume receiving any form of treatment remains below 10%, starkly below the global average and the SDG 6 target of halving the proportion of untreated wastewater by 2030 [1,2]. Table 1 summarises current wastewater statistics across selected SSA countries.

The principal barriers to effective treatment include crumbling and absent infrastructure, chronic electricity deficits, shortage of qualified operators, weak regulatory enforcement, corruption in plant management, and political reluctance to fund the sector [2,3]. Climate change exacerbates the situation by increasing drought frequency and flooding events that overwhelm existing treatment systems. The net result is a cycle of environmental degradation and public health burden from waterborne diseases that disproportionately affect women, children, and low-income urban dwellers.

3.2 Nanotechnology-Based Wastewater Treatment: Mechanisms and Evidence

Nanotechnology-based wastewater treatment exploits the extraordinary physicochemical properties of nanoscale materials, including high surface area-to-volume ratios, quantum confinement effects, and functionalisable surface chemistries, to achieve superior pollutant

removal efficiencies compared to conventional adsorbents and disinfectants [4,7]. Several classes of nanomaterials have demonstrated particular promise.

Iron oxide nanoparticles (IONPs), especially magnetite (Fe₃O₄), represent among the most studied nano-adsorbents. Functionalized Fe₃O₄ nanoparticles achieve near-complete (>95–100%) removal of divalent heavy metal ions (Cd²⁺, Ni²⁺, Pb²⁺, Cr⁶⁺) from synthetic and real wastewater through adsorption mechanisms following Langmuir isotherm kinetics [8,9]. Their superparamagnetic properties enable simple magnetic separation and regeneration, offering reusability advantages critical for resource-constrained settings. Recent innovations in green synthesis of IONPs from plant or fungal extracts further reduce production costs and environmental footprint [9].

Photocatalytic nanomaterials, principally TiO₂ and ZnO nanoparticles, degrade organic pollutants, pharmaceutical residues, and pathogenic microorganisms via reactive oxygen species (ROS) generation under ultraviolet or visible light irradiation [7,10]. In SSA, where solar irradiance is among the highest globally, solar-driven nano-photocatalytic reactors represent a particularly energy-appropriate innovation, requiring no grid electricity while achieving 85–99% degradation of emerging organic contaminants [10]. Carbon-based nanomaterials, including multi-walled carbon nanotubes (MWCNTs) and graphene oxide (GO), exhibit exceptional adsorption capacities for both inorganic (Cr⁶⁺, fluoride) and organic pollutants through surface electrostatic interactions and pi-pi stacking mechanisms [10,11]. Table 2 summarises key nanomaterials, their target pollutants, and reported removal efficiencies.

Table 2. Summary of engineered nanomaterials for wastewater pollutant removal: mechanisms and efficiencies. Adapted from references [5,6,13–18]

Nanomaterial	Target Pollutant	Removal Efficiency	Mechanism	Reference
Fe ₃ O ₄ (Magnetite) NPs	Cd ²⁺ , Ni ²⁺ , Pb ²⁺ , Cr ⁶⁺	>95% (100 mg/L)	Adsorption, magnetic separation	[7,8,9]
ZnO Nanoparticles	Organic dyes, pharmaceuticals	88–97%	Photocatalytic oxidation	[10]
TiO ₂ Nanoparticles	Emerging contaminants, pathogens	85–99%	Photocatalysis (UV/Vis)	[10]
Carbon Nanotubes (MWCNTs)	Cr ⁶⁺ , fluoride, organics	>90%	Adsorption, electrostatic attraction	[10,11]
Zero-Valent Iron (nZVI)	Chlorinated solvents, heavy metals	~86% (field)	Reductive dechlorination	[11]

Chitosan Nanocomposites	Mercury, heavy metals	80–95%	Chelation, ion exchange	[12]
Graphene Oxide (GO)	Heavy metals, antibiotics	>94%	Electrostatic, ion exchange	[10,11]

Sources: Adapted from [7–12]

3.3 Bioremediation Strategies: Microbial, Fungal, Algal, and Phytological Approaches

Bioremediation leverages the metabolic diversity of microorganisms and plants to transform, immobilise, or mineralise wastewater contaminants through enzymatic reactions, biosorption, bioaccumulation, and phytoextraction [5,6,13]. Unlike nanomaterials, bioremediation agents are inherently available in SSA environments, culturally familiar, and operable without specialised infrastructure.

Bacterial bioaugmentation using *Pseudomonas* spp. and *Bacillus* spp.- Organisms indigenous to African soils and effluents have demonstrated robust heavy metal removal from abattoir effluents and industrial wastewater, with iron, copper, and zinc concentrations reduced below FEPA/WHO permissible limits within 72 hours [5,14]. Biostimulation, which involves nutrient addition to activate native microbial consortia, is particularly suited to petroleum-contaminated industrial effluents common in the Niger Delta and Albertine Rift regions of SSA [15].

Mycoremediation using *Aspergillus niger* and white-rot fungi offers additional versatility, with demonstrated capacity for dye decolourisation, organochlorine degradation, and mercury chelation [16,17]. Constructed wetlands exploiting indigenous macrophytes such as *Phragmites australis* represent low-energy, socially acceptable systems for secondary and tertiary treatment of municipal wastewater, with successful deployments reported in Senegal and South Africa [3,18]. Algal bioremediation, using *Chlorella vulgaris* and *Spirulina platensis*, integrates nutrient recovery with heavy metal removal and generates biomass for bioenergy production – a circular economy approach aligned with SSA's agricultural and energy development needs [5]. Table 3 presents the comparative landscape of bioremediation strategies for SSA application.

Table 3. Comparative analysis of bioremediation strategies and their applicability in Sub-Saharan Africa

Strategy	Microbial Agent	Pollutant Removed	SSA Applicability	Limitation
Bioaugmentation	<i>Pseudomonas</i> spp., <i>Bacillus</i> spp.	Heavy metals, hydrocarbons	High – indigenous isolates available	Competition with native flora
Biostimulation	Native microbial consortia	Petroleum, organochlorines	Moderate – nutrient cost	Potential eutrophication

Phytoremediation	Constructed wetland flora	Nutrients, heavy metals	High – low-cost, low-tech	Slow, large land area required
Mycoremediation	Aspergillus niger, white-rot fungi	Dyes, heavy metals	Moderate – fungal biomass available	pH sensitivity, scaling challenges
Algal bioremediation	Chlorella spp., Spirulina	Nutrients, CO ₂ , heavy metals	High – abundant sunlight, biomass	Requires nutrient balance
Bioelectrochemical (MFC)	Shewanella oneidensis, Geobacter	Organics + energy generation	Low – high capital cost	Limited scale-up in SSA

Pollutant Removal Efficiencies of Three Treatment Approaches

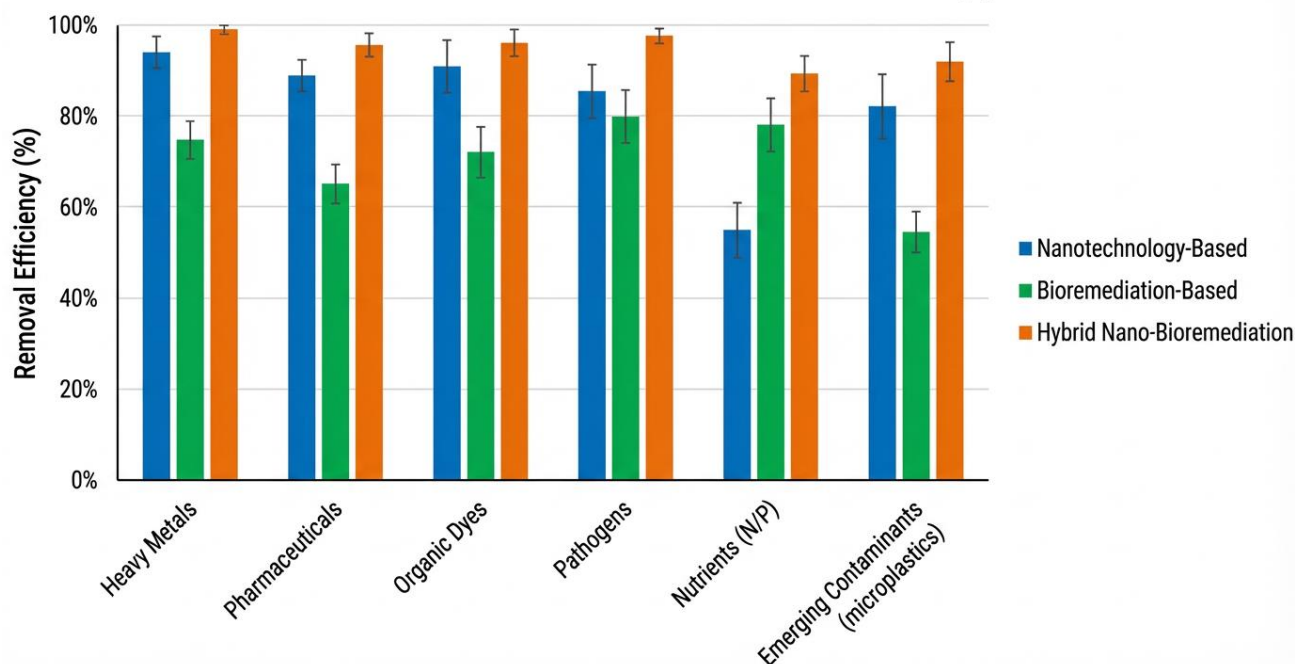


Figure 3. Comparative bar chart showing pollutant removal efficiencies (%) of nanotechnology-based versus bioremediation-based versus hybrid nano-bioremediation systems across six pollutant categories: heavy metals, pharmaceutical compounds, organic dyes, pathogens, nutrients (N/P), and emerging contaminants (microplastics, endocrine disruptors).

Sources: Data compiled from included studies [7,10,13,14,16,18].

3.4 Hybrid Nano-Bioremediation Systems: The Synergistic Frontier

The convergence of nanotechnology and bioremediation into integrated hybrid systems represents the most scientifically advanced and operationally promising frontier for SSA wastewater treatment [13,19]. These hybrid approaches exploit complementary mechanisms: nanomaterials provide rapid, high-capacity pollutant concentration and photocatalytic pre-treatment, while biological agents achieve mineralisation, selective biodegradation, and effluent polishing at low operational cost.

Nano-bioaugmentation systems combining ZnO nanoparticles with *Pseudomonas* consortia demonstrate 15–30% higher removal efficiency than nanomaterials alone, attributed to nano-enabled membrane permeabilisation that enhances microbial pollutant uptake [13]. Magnetic nano-biofilms – where Fe₃O₄ nanoparticles are incorporated into microbial biofilm matrices – achieve >98% heavy metal removal while enabling simple magnetic regeneration and multi-cycle reuse [14,15]. Perhaps most promising for SSA is the green synthesis of IONPs from *Aspergillus niger* biomass ('myco-IONPs'), which combines fungal bioremediation with nanoparticle formation in a single bioprocess using locally available fungal strains [16]. Table 4 summarises hybrid nano-bioremediation systems with SSA-specific advantages.

Table 4. Hybrid nano-bioremediation systems: components, performance, and Sub-Saharan Africa contextual advantages

Hybrid System	Components	Efficiency Gain	SSA Advantage	Reference
Nano-bioaugmentation	ZnO NPs + <i>Pseudomonas</i> consortium	15–30% over NP alone	Low-cost NP synthesis from local plants	[13]
Magnetic nano-biofilm	Fe ₃ O ₄ NPs + immobilized biofilm	>98% heavy metal removal	Reusable, magnetically separable	[14,15]
Green-synthesized IONPs + fungi	Myco-IONPs (<i>Aspergillus niger</i>)	Cd, Pb, Cr >95% removed	Fungal isolates common in SSA soil	[16]
Nano-constructed wetlands	Nano-biochar + <i>Phragmites</i> spp.	Improved N/P removal by 40%	Leverages existing wetland practice	[17]
Photocatalytic-biofilm reactor	TiO ₂ + activated sludge	Disinfection + organics removal	Solar-driven in high-irradiance zones	[10,18]

Sources: Data compiled from references [13–19]

4. DISCUSSION

4.1 SSA-Contextual Adaptation of Nanomaterials

While nanotechnology promises transformative advances in wastewater treatment, several challenges constrain its deployment in SSA. The cost of high-purity nanomaterial synthesis using conventional physico-chemical methods (sol-gel, co-precipitation, chemical vapour deposition) remains prohibitive for most African municipalities and research institutions [4,7]. However, a paradigm shift towards green synthesis, exploiting abundant African botanical resources such as *Moringa oleifera* leaf extract, Neem (*Azadirachta indica*), and Aloe vera gel as bio-reducing agents, offers a pathway to low-cost, eco-compatible nanomaterial production with demonstrated pollutant removal efficacy [20,21]. Sub-Saharan Africa's extraordinary biodiversity of medicinal and agricultural plants constitutes an untapped biorefinery for nanotechnology feedstocks.

Solar-powered photocatalytic reactors using ZnO or TiO₂ nanoparticles are particularly appropriate for SSA, which receives 5–7 kWh/m² of solar irradiation daily, far exceeding the requirements for catalytic activation [10]. Pilot-scale solar photocatalytic systems have demonstrated effective disinfection and pharmaceutical degradation in South Africa and Kenya, offering a proof-of-concept for scale-up. Regulatory gaps around nanomaterial environmental release, ecotoxicity, and worker exposure remain a critical concern; SSA lacks dedicated nanotechnology governance frameworks, creating both a risk and an opportunity for prospective, evidence-based policy development [22,23].

4.2 Scaling Bioremediation within SSA Realities

Bioremediation's greatest strength in SSA is its alignment with existing ecological and human capital. Indigenous microbial consortia, cultured from local wastewater effluents, are already adapted to the specific pollutant matrices and climatic conditions of their geographic contexts [5,14]. Constructed wetlands leveraging native macrophytes require minimal capital investment, create ecological co-benefits (habitat, carbon sequestration), and have been successfully deployed at the community scale in francophone West Africa and southern Africa [3,18]. The integration of bioremediation into informal settlements and peri-urban communities, where small-scale, decentralised treatment is the only feasible option, represents a critical but under-researched application domain.

The deployment of microbial fuel cells (MFCs) for simultaneous wastewater treatment and bioelectricity generation offers a compelling dual-benefit proposition for energy-deficient SSA communities, though high capital costs and complexity currently limit scale-up [6]. Algal photobioreactors, capitalising on SSA's abundant sunlight and freshwater algal biodiversity, simultaneously address nutrient removal (eutrophication prevention), heavy metal recovery, and biomass production for biofuel and animal feed, a circular economy model with multi-sectoral development impact [5,13].

4.3 Barriers, Enablers, and the Road Ahead

This review identifies seven cross-cutting barriers to scaling nanotechnology and bioremediation in SSA: high synthesis costs; absent nanomaterial regulation; limited trained workforce; power intermittency; overdependence on external donor financing; nanomaterial ecotoxicity data gaps;

and sparse water quality monitoring infrastructure [1,2,22,23]. Corresponding strategies for each barrier are outlined in Table 5.

Critically, the transition from laboratory promise to field deployment requires a fundamentally different innovation philosophy: solutions must be co-designed with communities, built from locally available materials, operated sustainably in off-grid conditions, and governed by African regulatory systems tailored to African realities. The role of African universities, including emerging research hubs pioneering nano-environmental science in Nigeria, South Africa, and Ethiopia, is indispensable for generating context-specific evidence and training the next generation of water scientists. Table 5. Presents the Barriers to the adoption of nanotechnology and bioremediation in Sub-Saharan Africa and recommended strategies, while Figure 4 shows the proposed roadmap for the scaled deployment of hybrid nano-bioremediation systems in Sub-Saharan Africa.

Table 5. Barriers to the adoption of nanotechnology and bioremediation in Sub-Saharan Africa and recommended strategies. Sources: Compiled from references [1–3,22,23]

Domain	Current Barrier	Recommended Strategy	Priority Level
Technology	High cost of nanomaterial synthesis	Green synthesis from local plant extracts (e.g., Neem, Moringa)	High
Regulation	Absent/weak nanomaterial governance	Harmonised regional nanotechnology policy framework (AU)	High
Capacity	Limited trained nano/biotechnology workforce	University–industry partnerships; research hubs	High
Infrastructure	Power intermittency limiting reactor operation	Solar-powered nano-photocatalytic systems; low-tech constructed wetlands	Medium
Funding	Overdependence on donor financing	Green bonds, blended finance, public-private partnerships	High
Environmental Safety	Nanomaterial ecotoxicity data gaps	Long-term ecotoxicological monitoring programs; life cycle assessment	Medium
Data Systems	Sparse WW quality monitoring	AI-enabled IoT sensor networks for real-time	Medium

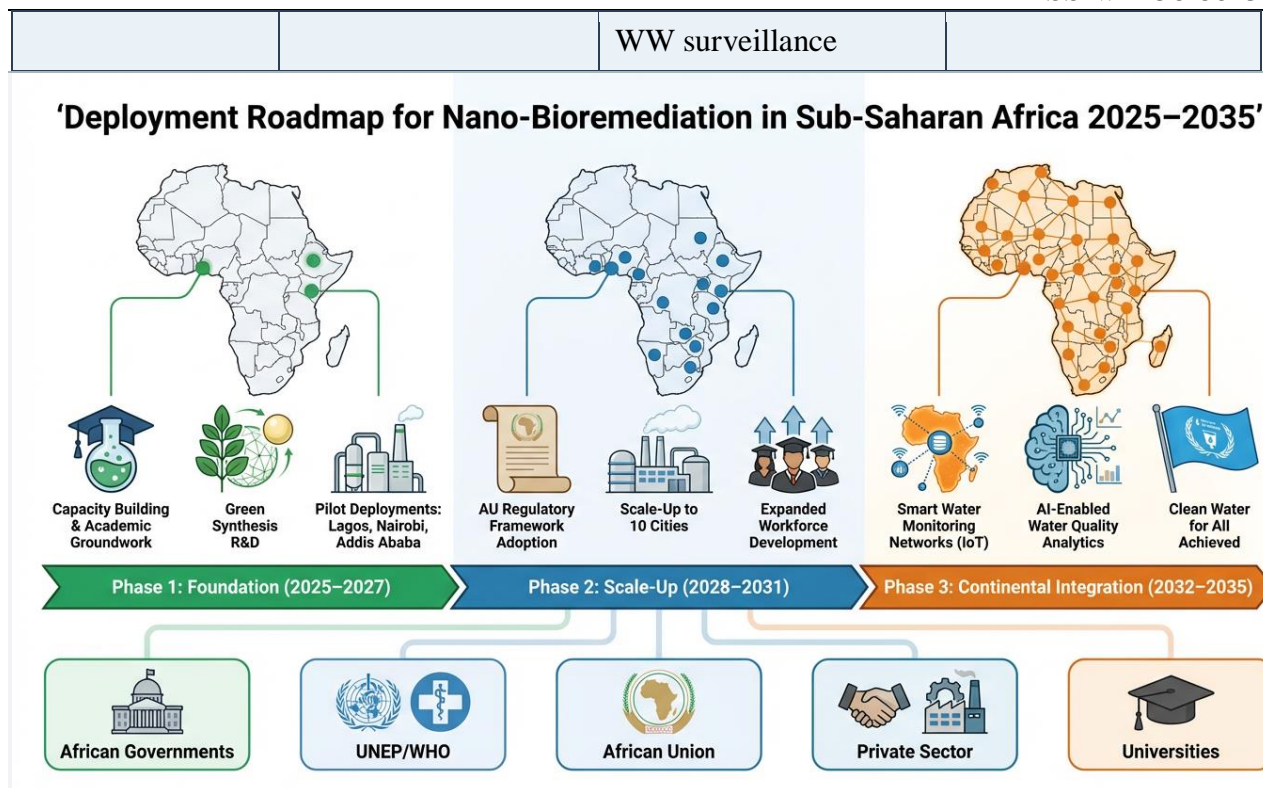


Figure 4. Proposed roadmap for the scaled deployment of hybrid nano-bioremediation systems in Sub-Saharan Africa (2025–2035), organised by three implementation phases: (Phase 1, 2025–2027) capacity building, green synthesis research, and pilot deployment; (Phase 2, 2028–2031) regulatory framework development, scale-up in priority urban centres; (Phase 3, 2032–2035) continental harmonisation, AI-IoT integration, and SDG 6 review milestones. Key stakeholders and funding mechanisms are identified per phase.

5. CONCLUSION

Sub-Saharan Africa's wastewater treatment deficit is both a humanitarian crisis and a scientific opportunity. This systematic review demonstrates that nanotechnology and bioremediation, individually and synergistically, offer technically viable, environmentally appropriate, and potentially cost-effective pathways to address the continent's treatment gap. Iron oxide nanoparticles, solar-driven photocatalytic systems, microbial bioaugmentation, algal bioremediation, and hybrid nano-bioremediation systems each offer compelling attributes for contextually relevant deployment.

However, the transition from laboratory proof-of-concept to community-scale implementation demands more than scientific innovation. It requires political will to fund and regulate the water sector, institutional investment in African research and educational capacity, community co-design of appropriate technologies, and the development of harmonised continental regulatory frameworks for nanomaterials and biotechnologies. The African continent's extraordinary natural assets – solar energy, botanical biodiversity, microbiological richness – position it uniquely to become a global leader in sustainable, nature-inspired water treatment innovation.

Future research should prioritise: life cycle assessment of hybrid nano-bioremediation systems under SSA field conditions; long-term ecotoxicological monitoring of nanomaterial discharge into African aquatic environments; techno-economic analyses of decentralised solar-nano-bio treatment modules; and multi-country clinical/epidemiological studies on health outcomes from treated versus untreated wastewater exposure. Meeting SDG 6 in SSA is not optional – it is the foundation upon which human development, economic growth, and ecological sustainability depend.

Conflicts Of Interest

The authors declare no conflicts of interest.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data Availability

All data supporting the conclusions of this review are available within the cited peer-reviewed literature.

REFERENCES

1. Onu MA, Ayeleru OO, Oboirien B, Olubambi PA. Challenges of wastewater generation and management in sub-Saharan Africa: a Review. *Environ Chall.* 2023;11:100686. doi:10.1016/j.envc.2023.100686
2. Ali AF, Gujiba UK. Household wastewater management in sub-Saharan Africa: a review. *Discov Water.* 2024;4(1):6. doi:10.1007/s43832-024-00060-6
3. Omohwovo EJ. Wastewater management in Africa: challenges and recommendations. *Environ Health Insights.* 2024;18:11786302241289681. doi:10.1177/11786302241289681
4. Jain K, Patel AS, Pardhi VP, Flora SJS. Nanotechnology in wastewater management: a new paradigm towards wastewater treatment. *Molecules.* 2021;26(6):1797. doi:10.3390/molecules26061797
5. Ogundolie FA, Babalola OO, Adetunji CO, Aruwa CE, Manjia JN, Muftaudeen TK. A review on bioremediation by microbial immobilization – an effective alternative for wastewater treatment. *AIMS Environ Sci.* 2024;11(6):918-939. doi:10.3934/environsci.2024046
6. Madondo NI, Rathilal S, Bakare BF, Tetteh EK. Application of bioelectrochemical systems and anaerobic additives in wastewater treatment: a conceptual review. *Int J Mol Sci.* 2023;24(5):4753. doi:10.3390/ijms24054753
7. Yadav D, Rangabhashiyam S, Verma P, Singh P, Devi P, Kumar P, et al. Environmental and health impacts of contaminants of emerging concerns: recent treatment challenges and approaches. *Chemosphere.* 2021;272:129492. doi:10.1016/j.chemosphere.2020.129492
8. Sosun, Ali A, Mannan A, Khalid Z, Latif M. Removal of toxic metal ions (Ni²⁺ and Cd²⁺) from wastewater by using TOPO decorated iron oxide nanoparticles. *Appl Water Sci.* 2022;12:86. doi:10.1007/s13201-022-01588-5
9. Jjagwe J, Olupot PW, Carrara S. Iron oxide nanoparticles/nanocomposites derived from steel and iron wastes for water treatment: a review. *J Environ Manag.* 2023;343:118236. doi:10.1016/j.jenvman.2023.118236
10. *Frontiers Environmental Science.* Recent advances in the effective removal of hazardous pollutants from wastewater by using nanomaterials: a review. *Front Environ Sci.* 2023;11:1226101. doi:10.3389/fenvs.2023.1226101

11. Al-Hazmi HE, Śniatała B, Esmaili A, Habibzadeh S, Joseph TM. Nanoparticles and nanofiltration for wastewater treatment: from polluted to fresh water. *Environ Res.* 2023;238:117114. doi:10.1016/j.envres.2023.117114
12. Goci MC, Leudjo Taka A, Martin L, Klink MJ. Chitosan-based polymer nanocomposites for environmental remediation of mercury pollution. *Polymers.* 2023;15(3):482. doi:10.3390/polym15030482
13. Bhatt P, Pandey SC, Joshi S, Chaudhary P, Pathak VM, Huang Y, et al. Nanobioremediation: a sustainable approach for the removal of toxic pollutants from the environment. *J Hazard Mater.* 2022;427:128033. doi:10.1016/j.jhazmat.2021.128033
14. Pande V, Pandey SC, Sati D, Bhatt P, Samant M. Microbial interventions in bioremediation of heavy metal contaminants in agroecosystem. *Front Microbiol.* 2022;13:824084. doi:10.3389/fmicb.2022.824084
15. Abo-Alkasem MI, Hassan NH, Abo Elsouid MM. Microbial bioremediation as a tool for the removal of heavy metals. *Bull Natl Res Cent.* 2023;47:31. doi:10.1186/s42269-023-01012-9
16. Hashem AH, Al-Askar AA. Nano-bioremediation of metal-polluted industrial wastewater using myco-synthesized iron oxide nanoparticles derived from *Aspergillus niger* AUMC 16028. *Sci Rep.* 2025;15:19925. doi:10.1038/s41598-025-19925-4
17. Vaksmaa A, Guerrero-Cruz S, Ghosh P, Zeghal E, Hernando-Morales V, Niemann H. Role of fungi in bioremediation of emerging pollutants. *Front Mar Sci.* 2023;10:1070905. doi:10.3389/fmars.2023.1070905
18. Torrens A, de la Varga D, Ndiaye AK, Mane R, Diallo J, Puigagut J. Innovative multistage constructed wetland for municipal wastewater treatment and reuse for agriculture in Senegal. *Water.* 2020;12:3139. doi:10.3390/w12113139
19. *Frontiers Nanotechnology.* Metal and metal oxide nanomaterials for heavy metal remediation: novel approaches for selective, regenerative, and scalable water treatment. *Front Nanotechnol.* 2024;6:1466721. doi:10.3389/fnano.2024.1466721
20. Rahman MM, Ahmed L, Anika F, Riya AA, Kali SK, Rauf A, Sharma R. Bioinorganic nanoparticles for the remediation of environmental pollution: critical appraisal and potential avenues. *Bioinorg Chem Appl.* 2023;2023:2409642. doi:10.1155/2023/2409642
21. Alshahrani AA. Function of nanomaterials in removing heavy metals for water and wastewater remediation: a review. *Environments.* 2022;9(10):123. doi:10.3390/environments9100123
22. Sikhwivhilu K, Gumbi N, Nxumalo E. Nanotechnology innovations and commercial opportunities for water and sanitation management: a South African perspective. *S Afr J Sci.* 2023;119(1-2). doi:10.17159/sajs.2023/11657
23. Nyiwul L. Demand for water innovation: evidence on wastewater technology adoption in thirteen African countries. *Econ Change Restruct.* 2023;56:3383-3410. doi:10.1007/s10644-023-09493-8
24. Swapnil P, Singh LA, Mandal C, Chauhan S, Varma S. Functional characterization of microbes and their association with unwanted substance for wastewater treatment processes. *J Water Process Eng.* 2023;54:103983. doi:10.1016/j.jwpe.2023.103983
25. Nnaji ND, Onyeaka H, Miri T, Ugwa C. Bioaccumulation for heavy metal removal: a review. *SN Appl Sci.* 2023;5:125. doi:10.1007/s42452-023-05329-9
26. Shah BA, Malhotra H, Papade SE, Dhamale T, Ingale OP, Kasarlwar ST, Phale PS. Microbial degradation of contaminants of emerging concern: metabolic, genetic and omics

-
- insights for enhanced bioremediation. *Front Bioeng Biotechnol.* 2024;12:1470522. doi:10.3389/fbioe.2024.1470522
27. Pratap B, Rathore P, Singh G, Bhatt P. Wastewater generation and treatment by various eco-friendly technologies: possible health hazards and further reuse for environmental safety. *Chemosphere.* 2023;313:137547. doi:10.1016/j.chemosphere.2022.137547
28. *Frontiers Agronomy.* Bioremediation of environmental wastes: the role of microorganisms. *Front Agron.* 2023;5:1183691. doi:10.3389/fagro.2023.1183691
29. Bakare BF, Adeyinka GC. Evaluating the potential health risks of selected heavy metals across four wastewater treatment works in Durban, South Africa. *Toxics.* 2022;10:340. doi:10.3390/toxics10060340
30. *AIMS Microbiology.* Bioremediation and waste valorisation strategies: current perspectives and prospects. *AIMS Microbiol.* 2024;10(3):723-755. doi:10.3934/microbiol.2024033