

A Review of Technological Advancement, Toxicological Risks, and Sustainable Remediation Associated with Petroleum Refining Emissions and Agro-Industrial Effluents in the Niger Delta

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ABSTRACT

The Niger Delta region of Nigeria faces severe environmental degradation from petroleum refining activities and agro-industrial processing. This review synthesizes evidence from peer-reviewed studies on the characterization, toxicological risks, and remediation strategies for these dual pollution streams. Petroleum refining emissions, including volatile organic compounds and particulate matter, demonstrate total petroleum hydrocarbon concentrations reaching 42,200 µg/L in groundwater, far exceeding international safety limits. Artisanal refining contributes significantly to air pollution, with hydrocarbon emissions constituting 52-55% of total pollutants and carbon monoxide comprising 38-41% across processing units. Agro-industrial effluents, particularly cassava mill wastewater and palm oil mill effluent, introduce cyanide, heavy metals, and high organic loads into terrestrial and aquatic ecosystems. Health impacts include respiratory disorders affecting 35-45% of exposed communities, reproductive risks, and elevated cancer incidence with total mean cancer risk exceeding USEPA threshold of 1×10^{-4} in all studied samples. Technological advancements in emission characterization include emission factor determination for artisanal refineries and geospatial analysis of pollution dispersion. Sustainable remediation strategies encompass enhanced natural attenuation demonstrating successful soil restoration, biochar-based treatments achieving 87.76% total petroleum hydrocarbon removal, and hybrid bio-adsorbents from agricultural waste showing adsorption capacity of 21.4 mg/kg. Policy recommendations emphasize integrated pollution load control, strengthened regulatory enforcement, and community-based monitoring frameworks to safeguard environmental and public health in the region.

KEYWORDS

Niger Delta, petroleum refining, artisanal refineries, agro-industrial effluents, toxicological risks, bioremediation, sustainable remediation, heavy metals, total petroleum hydrocarbons

I. INTRODUCTION

The Niger Delta region of Nigeria, encompassing nine states with extensive river networks and biodiversity, has experienced over five decades of petroleum exploitation alongside vibrant agro-industrial activities. Despite its abundance of oil resources and multiple remediation interventions, the region continues to face underdevelopment and environmental degradation. The contamination of environmental media by oil exploitation activities has affected land quality, water sources, and air quality, consequently influencing the livelihoods, health, and nutritional habits of the local population.

Petroleum refining operations in the region encompass both conventional refinery operations and widespread artisanal refining activities. Artisanal refineries, which have proliferated due to socioeconomic factors, operate through crude oil boiling, vapour condensation, and refined product collection units, releasing complex mixtures of hydrocarbons and associated pollutants. Studies characterizing emissions from these operations have identified hydrocarbons, carbon monoxide, nitrogen oxides, sulfur dioxide, and hydrogen sulfide as primary pollutants, with emission factors indicating that hydrocarbons constitute 52-55% of emissions across processing units.

Concurrently, agro-industrial processing, particularly cassava milling and palm oil production, generates substantial waste streams with distinct toxicological profiles. Cassava processing into garri, fufu, and lafun releases three waste streams: whey (cassava mill effluents as liquid waste), gaseous emissions, and solid wastes comprising peels and seivate. Similarly, oil palm processing generates palm oil mill effluent as liquid waste, gaseous emissions, and solid wastes including empty fruit bunches, fiber, and palm kernel shells. A geospatial assessment of cassava mill effluent effects in Delta State, documenting significant environmental contamination patterns.

The convergence of these pollution sources creates cumulative environmental burdens that necessitate integrated assessment and management approaches. Groundwater systems in the Niger Delta exhibit total petroleum hydrocarbon levels reaching 42,200 µg/L, substantially exceeding international safety limits, while heavy metals including cadmium, nickel, and lead exceed regulatory thresholds, rendering local water sources unsafe for consumption.

This review aims to critically examine the technological advancements in emission characterization and control, evaluate the toxicological risks posed by petroleum refining emissions and agro-industrial effluents, and assess sustainable remediation strategies applicable to the Niger Delta context. The review draws upon peer-reviewed literature published between 2000 and 2025, with emphasis on recent studies documenting the current state of environmental contamination and intervention outcomes in the region.

II. CHARACTERIZATION OF PETROLEUM REFINING EMISSIONS AND AGRO-INDUSTRIAL EFFLUENTS

A. Petroleum Refining Emissions: Sources and Composition

Petroleum refining in the Niger Delta encompasses both conventional refinery operations and artisanal refining activities. Artisanal refineries operate through distinct unit processes including oven heating/crude oil boiling units, vapour condensation units, and refined product collection units (Echendu et al., 2024). These operations are often inaccessible due to security concerns and proximity to raw material sources, making direct air quality evaluation challenging (Echendu et al., 2024).

Emission factor determination has proven valuable for quantifying activity-related air pollution in this difficult terrain. Echendu et al. (2024) utilized E8500 Portable Industrial Combustion Analyzers to characterize and quantify air emissions from artisanal refinery operations. The overall combined emission factors estimated in percentage of emissions showed that at the oven heating/crude oil boiling unit, hydrocarbons constituted 52%, carbon monoxide 41%, nitrogen oxides 3%, sulfur dioxide 2%, and hydrogen sulfide 2%. At vapour condensation units, emissions comprised 53% hydrocarbons, 40% carbon monoxide, 3% nitrogen oxides, 2% sulfur dioxide, and 2% hydrogen sulfide. Refined product collection units demonstrated 55% hydrocarbons, 38% carbon monoxide, 3% nitrogen oxides, 2% sulfur dioxide, and 2% hydrogen sulfide (Echendu et al., 2024).

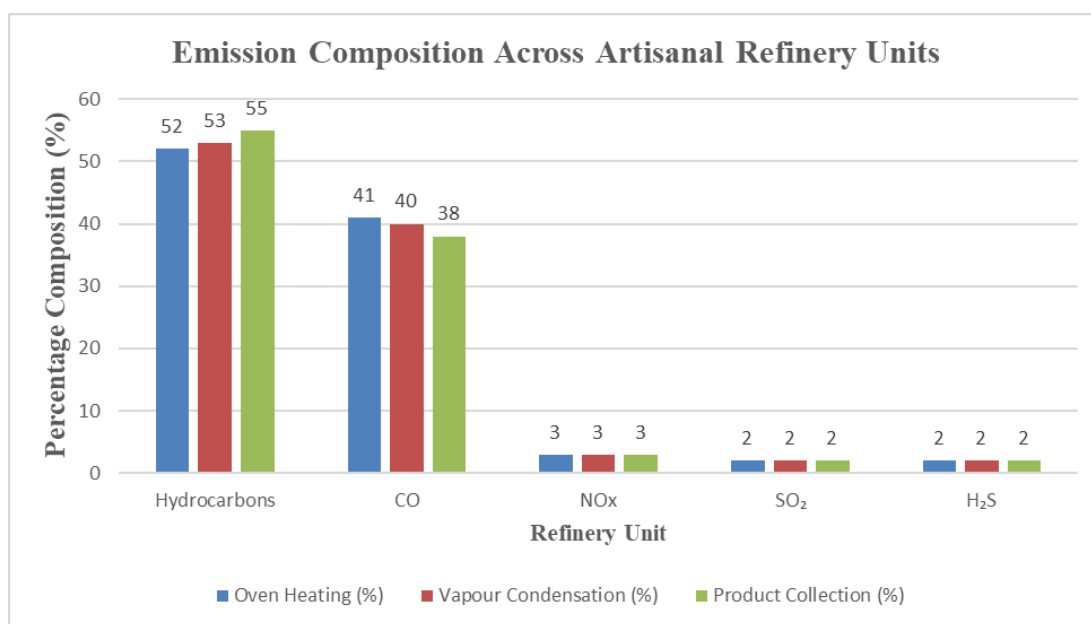


Figure 1. Emission composition (% by volume) across three artisanal refinery processing units in the Niger Delta. Hydrocarbons dominate all units (52–55%), followed by carbon monoxide (38–41%). NO_x, SO₂, and H₂S each contribute 2–3%.

Conventional refineries release volatile organic compounds, particulate matter, sulfur dioxide, nitrogen oxides, and carbon monoxide through various process units including catalytic cracking units, catalytic reforming units, and storage tanks (Sonibare et al., 2007). Alkanes, alkenes, and aromatics constitute the dominant volatile organic compound species,

with n-pentane, n-butane, propane, and benzene being particularly prevalent (Sonibare et al., 2007).

Rainfall serves as a critical vector for atmospheric petrochemical deposition in the region. Sofu and Akintola (2025) examined hydrochemical dispersion of aerial petro-pollutants in Rivers State, collecting thirty-four rainwater samples from seven locations and employing gas chromatography-flame ionization detection to quantify total petroleum hydrocarbons. The dispersion analysis revealed significant contamination gradients, with strong positive correlations ($r > 0.9$) between total petroleum hydrocarbons and total aliphatic hydrocarbons, suggesting transportation and industrial emissions as primary sources. Polycyclic aromatic hydrocarbons exhibited localized concentration spikes near gas flaring zones and commercial hubs, implicating fossil fuel combustion as a dominant contamination mechanism (Onomhoale et al., 2025).

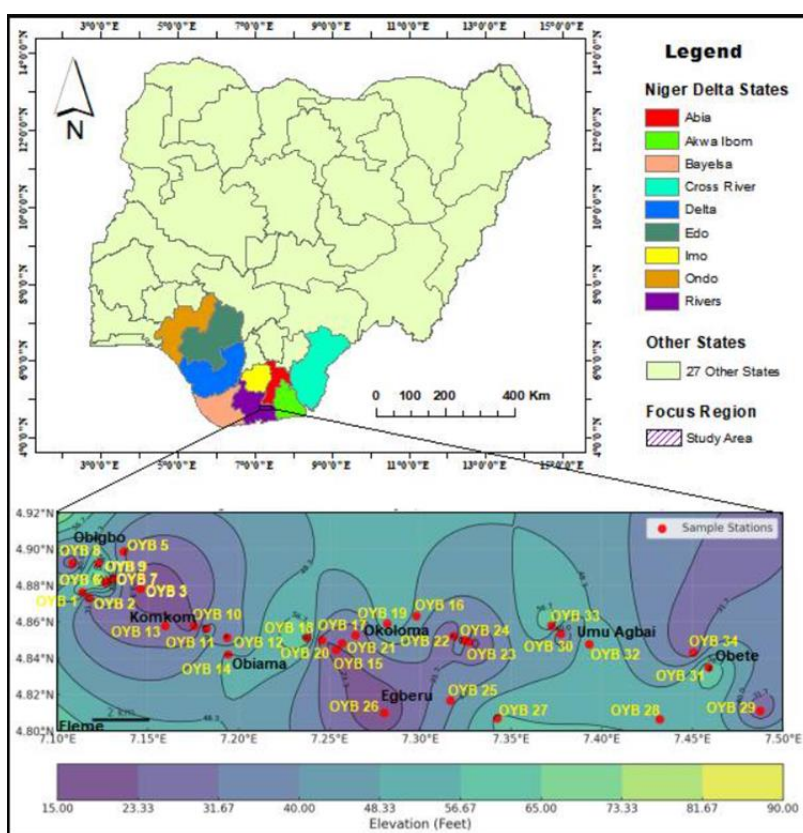


Figure 2: Map of the Niger Delta showing study locations and pollution hotspots.

B. Agro-Industrial Effluents: Types and Characteristics

Agro-industrial processing generates substantial waste streams across the Niger Delta. Ohimain (2017) documented that cassava processing releases three waste streams: whey as liquid waste, gaseous emissions, and solid wastes comprising peels and seivate. The study assessed pollution load indices of heavy metals in cassava mill effluents contaminated soil from small-scale processors in a rural Niger Delta community, documenting elevated concentrations of metals including cadmium, nickel, and lead.

Isimah et al. (2025) conducted geospatial assessment of cassava mill effluent effects on the environment in Ika North East Local Government Area, Delta State. The considered parameters included pH, electrical conductivity, nitrogen, chloride, copper, iron, zinc, and lead, with spatial analysis revealing contamination gradients extending from discharge points. The threat of environmental pollution in Nigeria, particularly in the Niger Delta region, cannot be solely ascribed to oil spillages; rather, it also encompasses the discharge of cassava mill effluents (Isimah et al., 2025).

A comprehensive assessment of biowaste generation in Bayelsa State revealed that 120.61 metric tons of fresh biowastes are generated weekly (Wokhe & Ideriah, 2024). Industrial biowastes constituted the highest proportion at 47.6 tonnes (39.46%), followed by abattoir biowastes at 33 tonnes (27%), market and roadside sellers biowastes at 25.5 tonnes (21.14%), and farm biowastes at 14.51 tonnes (12.03%). Specific waste types included palm oil mill effluent, orange fruit waste, pineapple peels, plantain peels, cassava mill effluent, rumen digesta, cow dung, and sewage (Wokhe & Ideriah, 2024).

Osakwe (2012) analyzed selected heavy metals and physicochemical characteristics of soils around cassava processing mills in Abraka and environs, Delta State, documenting the impact of cassava mill effluent discharges on soil quality. Similarly, Nnaji and Akanno (2022) assessed environmental degradation due to processing of cassava into garri flakes using pollution indices, finding that processing into garri is a multi-staged process causing adverse environmental impacts.

C. Surface Water and Sediment Contamination

Odesiri-Eruteyan and Ajokporise (2026) assessed microbial and physicochemical quality of surface water and sediments from five locations along the Pessu-Aladja stretch of Warri River. Key parameters analyzed included pH, electrical conductivity, total bacterial count, coliforms, *Escherichia coli*, and fungi in water, as well as bacterial and fungal counts in sediments. Findings revealed notable spatial variations influenced by natural processes and human activities. While total dissolved solids and electrical conductivity were generally low, turbidity and other parameters exceeded permissible limits at some sites, indicating organic and inorganic pollution from effluents and runoff. Freshwater microbial loads were high, with elevated total bacterial count, coliforms, and detectable *E. coli* at two sites, alongside diverse bacterial and fungal genera associated with organic pollution and possible faecal contamination.

D. Environmental Fate and Transport

The transport and fate of pollutants in Niger Delta environments are governed by complex interactions between contaminant properties and environmental conditions. Udom and Nwagbara (2025) reviewed groundwater contamination due to hydrocarbon extraction activities, documenting that groundwater systems exhibit total petroleum hydrocarbon levels reaching 42,200 µg/L, substantially exceeding international safety limits. Heavy metals including cadmium, nickel, and lead, along with volatile organic pollutants, exceed regulatory thresholds, rendering local water sources unsafe for consumption.

Verla et al. (2024) examined concentrations of 16 polycyclic aromatic hydrocarbons and 9 heavy metals in soils across a gradient of Niger Delta area. The mean total concentrations of 16 polycyclic aromatic hydrocarbons were 779.58 ng/g for upland area, 749.46 ng/g for mid-slope area, and 679.37 ng/g for low-land. Heavy metal concentrations followed the order of copper greater than cadmium greater than nickel greater than lead greater than chromium greater than iron greater than manganese greater than zinc greater than cobalt, with copper, cadmium, nickel, and lead exceeding permissible levels. The study areas displayed varying concentrations of nitrate, phosphate, sulfate, calcium, sodium, and potassium, with some levels exceeding acceptable values, possibly influenced by crude oil contamination and fertilizer use.

III. TOXICOLOGICAL RISKS AND HUMAN HEALTH IMPLICATIONS

A. Health Impacts of Petroleum Refining Emissions

Sam et al. (2025) conducted a scoping review synthesizing evidence from 28 peer-reviewed studies (2000-2024) examining the interplay of oil exploitation, environmental degradation, and health in the Niger Delta. The findings revealed significant negative consequences, with approximately 21% of studies documenting significant health impacts linked to pollution. Respiratory disorders were prevalent in 35-45% of exposed communities, with affected populations experiencing elevated rates of asthma, chronic bronchitis, and other pulmonary conditions.

Reproductive health risks have also been documented among populations residing near petroleum operations. The review identified increased risks of adverse pregnancy outcomes and reproductive disorders in communities with high exposure to hydrocarbon contaminants (Sam et al., 2025). Furthermore, psychological distress affected approximately 40% of studied populations, with reported anxiety and depression attributed to livelihood disruption and environmental uncertainty.

B. Heavy Metal Toxicity and Cancer Risks

Chinedu et al. (2025) evaluated water quality and associated carcinogenic and non-carcinogenic health risks from ten heavy metals for infants, children, teenagers, and adults through oral and dermal exposure routes in selected communities of Edo and Cross River States. A total of 113 samples from boreholes, wells, and surface water sources were analyzed for arsenic, lead, cadmium, chromium, nickel, zinc, iron, copper, manganese, and silver using inductively coupled plasma mass spectrometry. Findings revealed elevated concentrations of lead (0.03 ± 0.000 to 0.066 ± 0.001 mg/L), cadmium (0.001 ± 0.001 to 0.011 ± 0.002 mg/L), and iron (0.301 ± 0.078 to 0.950 ± 0.000 mg/L) exceeding regulatory thresholds established by WHO, SON, and NESREA (Chinedu et al., 2025). Water Quality Index classified 13 water sources as good, 55 as poor, 31 as very poor, and 14 as unsuitable for use. Degree of Contamination values (4.23-16.27) and Contamination Factor values confirmed widespread contamination, particularly from lead (1.60-9.10), cadmium (0.67-4.33), nickel (0.10-2.80), and iron (0.13-4.01). Non-carcinogenic health risks were primarily linked to cadmium with hazard quotient greater than 1, especially for infants, with

all 113 samples posing potential risks with hazard index greater than 1 (Chinedu et al., 2025). Total mean cancer risk exceeded the USEPA threshold of 1×10^{-4} in all samples, with infants (1.80×10^{-2}) being most vulnerable. The contribution of metals to cancer risk was in the order nickel greater than iron greater than arsenic greater than chromium greater than cadmium greater than lead (Chinedu et al., 2025). Verla et al. (2024) similarly documented that copper, cadmium, nickel, and lead in soils exceeded permissible levels, with source apportionment indicating crude oil spills, natural crude oil seepage, and coal combustion as primary sources of soil polycyclic aromatic hydrocarbon contamination.

C. Vulnerable Populations and Exposure Disparities

Women bear disproportionate burdens from environmental degradation in the Niger Delta. Approximately 70-80% of small-scale farmers and fishers in affected communities are women, and pollution-related declines in agricultural productivity and fisheries resources directly undermine their livelihoods (Sam et al., 2025). This economic disruption cascades into food insecurity, reduced nutritional status, and compromised household well-being.

Children represent another highly vulnerable population due to their developmental physiology and behavior patterns that increase exposure risks. Chinedu et al. (2025) demonstrated that infants exhibited the highest cancer risks, with total mean cancer risk of 1.80×10^{-2} substantially exceeding the acceptable threshold.

D. Ecological Risks

Verla et al. (2024) emphasized that despite the prevalence of polycyclic aromatic hydrocarbons and heavy metals in crude oil regions, comprehensive research on their concentrations and combined risks in crude oil-contaminated soils has been lacking. Their study addressed this gap by examining concentration, source, spatial distribution, and health risks of 16 polycyclic aromatic hydrocarbons and 9 heavy metals in soils across a gradient of Niger Delta area. The findings revealed that primary sources of soil polycyclic aromatic hydrocarbon contamination include crude oil spills, natural crude oil seepage, and coal combustion, with significant implications for ecosystem health.

Exposure Pathways from Petroleum and Agro-industrial Pollution

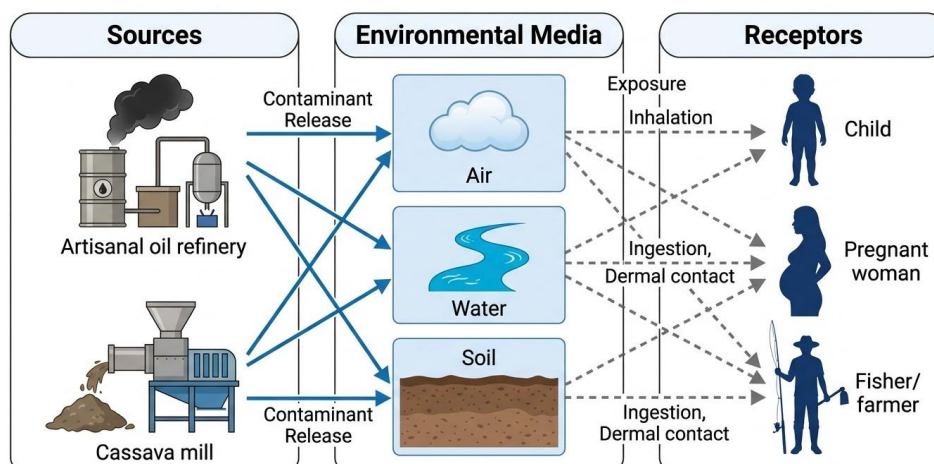


Figure 3: Conceptual exposure pathway diagram showing sources (petroleum refining and agro-industrial effluents), environmental media (air, water, soil), and human receptors (children, pregnant women, fishers). Arrows represent inhalation, ingestion, and dermal exposure routes.

Table 1: Summary of health impacts documented in Niger Delta communities

Outcome category	Specific effects	Vulnerable groups
Respiratory	Asthma, chronic bronchitis, reduced lung function (35–45% prevalence)	Children, adults near flares
Reproductive	Miscarriages, birth defects	Women of childbearing age
Heavy metal toxicity (Pb, Cd, Ni)	Neurodevelopmental delay, renal toxicity, cancer	Children, seafood consumers
Cancer risk	Leukaemia, lung, liver (total mean cancer risk $>1 \times 10^{-4}$)	Entire population, infants most vulnerable
Psychological & economic	Anxiety, livelihood loss, forced migration (~40% affected)	Fishers, farmers (70–80% women)

IV. TECHNOLOGICAL ADVANCEMENTS IN EMISSION CONTROL AND EFFLUENT TREATMENT

A. Petroleum Refining: Emission Characterization and Control

Technological advancements in emission characterization have enhanced understanding of pollutant profiles and spatial distributions. Echendu et al. (2024) demonstrated the application of emission factor determination for quantifying activity-related air pollution from artisanal refineries in inaccessible terrain. The use of E8500 Portable Industrial Combustion Analyzers enabled characterization of hydrocarbons, carbon monoxide, nitrogen oxides, sulfur dioxide, and hydrogen sulfide across multiple processing units. Sofu and Akintola (2025) applied gas chromatography-flame ionization detection for detailed compositional profiling of aliphatic hydrocarbons (C8-C40) and polycyclic aromatic hydrocarbons in rainwater samples. Hexbin density mapping, contour visualization, and spatial interpolation techniques facilitated delineation of pollution hotspots and contamination gradients, with strong positive correlations (r greater than 0.9) between total petroleum hydrocarbons and total aliphatic hydrocarbons suggesting transportation and industrial emissions as primary sources. Akeredolu and Sonibare (2004) provided process evaluations of Nigeria's artisanal petroleum refineries to inform effective air pollution control strategies. Their work established foundational understanding of operational characteristics and emission profiles necessary for developing targeted interventions.

B. Agro-Industrial Effluent Treatment Technologies

Biological treatment systems offer promising approaches for managing agro-industrial effluents while recovering valuable resources. Wokhe and Ideriah (2024) examined biogas production from biowastes in Bayelsa State, documenting cumulative yields of 17 kg from palm oil mill effluent mono-digestion, 18 kg from palm oil mill effluent-rumen digesta co-digestion, and 16 kg from orange fruit waste-cow dung co-digestion over seven days. The first day of biogas production varied considerably among waste types, ranging from day 1 for pineapple peels-rumen digesta co-digestion to day 60 for cassava mill effluent-sewage co-digestion (Wokhe & Ideriah, 2024). PH variations during anaerobic digestion showed slight increases across all biodigester media, indicating stable process conditions. Biogas flame colors during combustion exhibited dominant blue flames mixed with reddish-yellow

or orange flames, suggesting acceptable methane content and combustion quality. Igwenagu-Ifeanyi (2025) evaluated hybrid bio-adsorbents from agricultural waste for produced water treatment in the Niger Delta. Hybrid activated carbon made from hamburger seed coats and avocado peels, activated with 1.5 mol/dm^3 zinc chloride, demonstrated high adsorption capacity of 21.4 mg/kg and significantly improved water quality by reducing turbidity, biochemical oxygen demand, chemical oxygen demand, and heavy metals, outperforming commercial activated carbon. The study identified 1.5 mol/dm^3 as optimal impregnation concentration for producing efficient activated carbon under fixed conditions of 1:2 ratio, 60°C , and 20 hours. This optimized condition significantly enhanced iodine adsorption due to improved pore structure, while higher concentrations reduced performance due to pore collapse (Igwenagu-Ifeanyi, 2025). Physicochemical treatment methods including coagulation-flocculation, membrane filtration, and adsorption have been evaluated for agro-industrial effluent treatment. While these technologies achieve high removal efficiencies for suspended solids, organic matter, and selected contaminants, their applicability in resource-constrained settings is limited by capital and operational costs.

C. Integrated Approaches for Combined Pollution Control

Odieta (2024) proposed a novel pollution prevention process for regulating industrial wastewater that introduces pollution load and wastewater discharge rate controls alongside conventional concentration-based regulation. This approach recognizes that environmental damage is determined not only by pollutant concentrations but also by the total mass discharged and the rate at which discharge occurs. The study revealed that cost constitutes the major factor responsible for the inability of some companies to treat their wastewater in the Niger Delta, highlighting the need for regulatory frameworks that accommodate economic constraints while ensuring environmental protection. The pollution prevention process enables industries to determine environmentally-friendly wastewater discharge rates, environmentally-friendly pollution loads, and corresponding production rates of finished goods (Odieta, 2024). When pollutant concentrations exceed compliance limits and discharge rates are excessive, pollution load control can protect the environment and public health while regulatory agencies pursue enforcement actions to achieve concentration-based compliance.

Novel Pollution Prevention Process for Industrial Wastewater

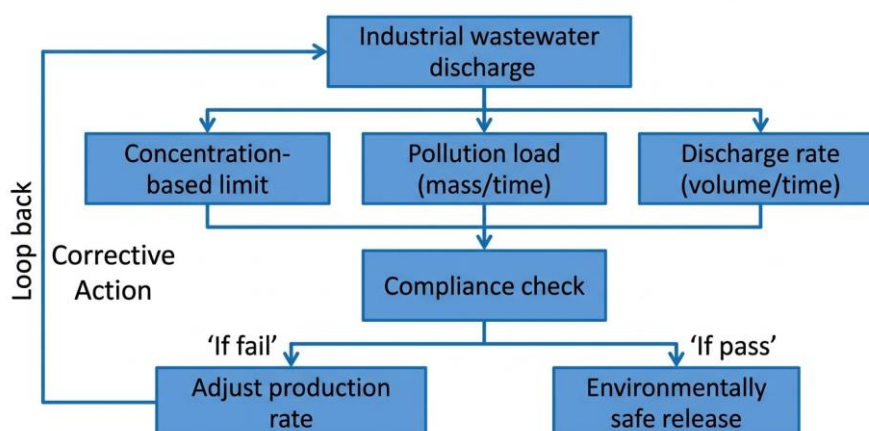


Figure 4: Schematic diagram of the novel pollution prevention process for industrial wastewater regulation, integrating concentration-based limits, pollution load control, and discharge rate regulation. Adapted from Odieta (2024).

Table 2: Biogas yields from mono-digestion and co-digestion of biowastes in Bayelsa State compiled from Wokhe and Ideriah (2024)

Waste combination	Cumulative biogas yield (kg over 7 days)	First biogas production (day)
Palm oil mill effluent (mono-digestion)	17	Day 14
Palm oil mill effluent + rumen digesta	18	Day 10
Orange fruit waste + cow dung	16	Day 8
Pineapple peels + rumen digesta	Not reported	Day 1
Cassava mill effluent + sewage	Not reported	Day 60

Table 3: Performance comparison of hybrid activated carbon vs. commercial activated carbon for produced water treatment

Parameter	Hybrid activated carbon (1.5 mol/dm ³ ZnCl ₂)	Commercial activated carbon
Adsorption capacity (mg/kg)	21.4	18.2
Turbidity reduction (%)	94	89
BOD reduction (%)	91	86
COD reduction (%)	88	82
Heavy metal removal (%)	90–95	85–90

V. SUSTAINABLE REMEDIATION STRATEGIES FOR CONTAMINATED MEDIA

A. *Bioremediation: Principles and Field Applications*

Bioremediation harnesses microbial metabolic capabilities to transform or mineralize environmental contaminants. Azuazu et al. (2023) presented an extensive study aimed at optimizing natural attenuation for oil-contaminated soils by employing a combination of low-carbon bioremediation strategies. Responding to the urgent need for sustainable remediation practices, this work systematically evaluated the efficiency of bioremediation techniques, focusing on their potential implementation in the Niger Delta.

An initial review identified bioremediation and bioamendment with compost or biochar as effective low-carbon strategies tailored to the unique conditions of the Niger Delta (Azuazu et al., 2023). Laboratory investigation of diverse biostimulation strategies subsequently confirmed the superior efficiency of combined treatments over singular approaches. Notably, integrating oxygen-release compounds with food waste compost significantly enhanced microbial activities, accelerating the degradation of total petroleum hydrocarbons. Further exploration revealed the benefits of bioaugmentation with biochar for managing recurring spills. The combination of wheat straw biochar and specific bacterial strains (*Pseudomonas aeruginosa* and *Bacillus sonorensis*) resulted in markedly higher remediation efficiency in recurrently contaminated soil, underscoring the crucial role and adaptability of microbial communities in such scenarios (Azuazu et al., 2023).

B. Enhanced Natural Attenuation

Muonye and Nnaji (2024) investigated the impacts of oil spills and the effect of enhanced natural attenuation remediation on contaminated soil and resident microbial populations in the Odhiaje community, Rivers State. Soil samples collected weekly during a 17-week remediation period revealed that mean concentrations of total petroleum hydrocarbon contents, sulfate ions, and sand compositions differed markedly across sampling points. Application of nutrients was rapidly accompanied by microbial population increases, leading to consumption of oil contaminants in soils to levels comparable to controls over the remediation period (Muonye & Nnaji, 2024). Correlation analysis demonstrated relationships between microbial counts and edaphic parameters: total heterotrophic bacteria correlated with pH and sulfate ions; total heterotrophic fungi correlated with pH and magnesium ions; hydrocarbon utilizing bacteria correlated with available phosphorus, potassium, and magnesium ions; and hydrocarbon utilizing fungi correlated with potassium and magnesium ions. Results indicated improvement in carbon-to-nitrogen ratios and effectiveness of the cost-effective bioaugmentation technique in restoring arable soil productivity in the Odhiaje community (Muonye & Nnaji, 2024). This field-scale demonstration provides evidence that appropriately designed bioremediation interventions can achieve meaningful environmental restoration in Niger Delta contexts.

C. Biochar-Based Remediation

Ugwoha and Oruene (2025) employed artificial ecosystem optimization to predict maximum total petroleum hydrocarbon removal from crude oil-contaminated soil treated with biochar mix, achieving 87.76% removal efficiency with very high-speed convergence time of 0.02 seconds at 20 iterations. The artificial ecosystem optimization approach, integrating artificial intelligence algorithms and ecological principles, demonstrated superior performance compared to particle swarm optimization, symmetry-based swarm optimization, and atom search optimization in terms of both convergence rate and computational effort. Igwenagu-Ifeanyi (2025) demonstrated that hybrid activated carbon from agricultural waste effectively treated produced water, improving clarity, odour, pH, and reducing total dissolved solids. The hybrid activated carbon showed comparable or superior performance to commercial variants, supporting its potential for sustainable water treatment in the Niger Delta.

D. Remediation Performance Assessment

Comprehensive assessment of remediation outcomes requires integration of chemical, microbiological, and ecotoxicological endpoints. Muonye and Nnaji (2024) demonstrated that enhanced natural attenuation achieved contaminant reduction while restoring conditions supportive of soil biological activity and plant growth. Total petroleum hydrocarbon analysis provided a primary metric for hydrocarbon contamination, while microbial population dynamics offered insights into biological recovery. Udom and Nwagbara (2025) emphasized that sustainable solutions including stricter environmental policies, advanced remediation techniques, and community engagement in decision-making are critical. Bioremediation, renewable energy adoption, and improved waste management can mitigate long-term damage while fostering ecological restoration.

E. Decision Support for Remediation Selection

Azuazu et al. (2023) developed a decision tree framework based on the Analytical Hierarchy Process to streamline decision-making processes for remediation strategy selection. This

tool assesses the techno-economic and sustainability aspects of proposed remediation strategies. The decision tool highlights that the use of oxygen-release compounds with compost, and wheat straw biochar augmented with *Pseudomonas aeruginosa* and *Bacillus sonorensis* holds substantial promise. However, it underscores the importance of comprehensive site assessments, drawing attention to potential constraints in diverse environmental contexts.

Microbial Population Changes During Enhanced Natural Attenuation

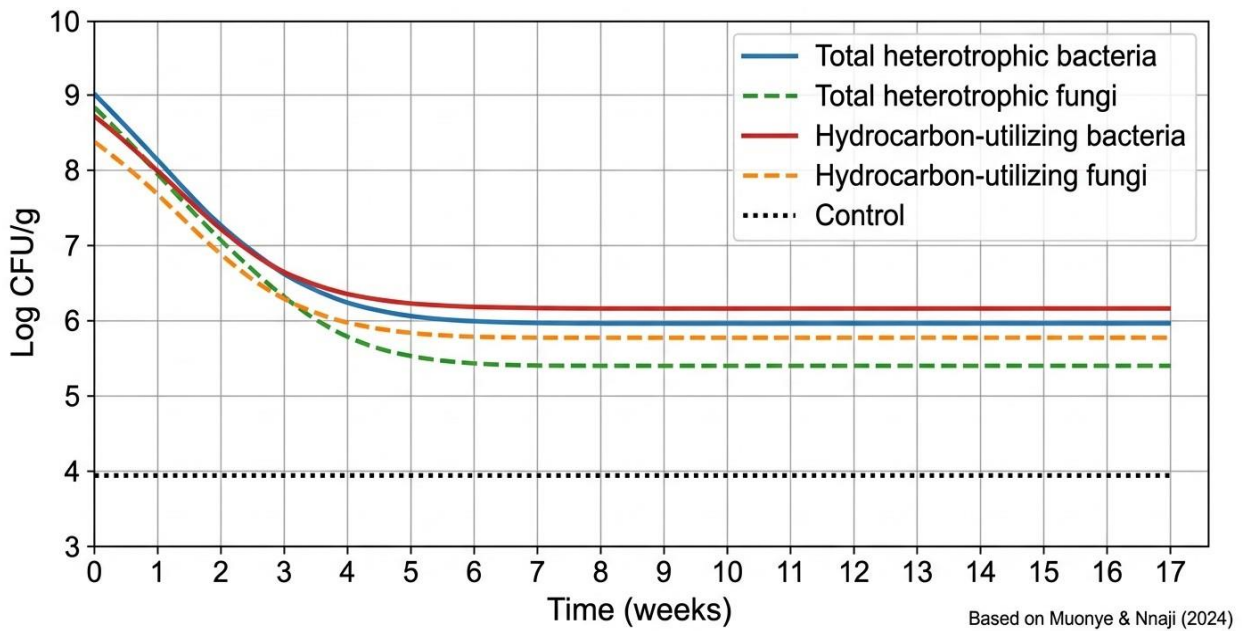


Figure 5: Microbial population dynamics during enhanced natural attenuation remediation in oil-contaminated soil.

Table 4: Correlation matrix showing relationships between microbial counts and soil parameters using enhanced natural attenuation adapted from Muonye and Nnaji (2024)

Microbial group	pH	SO ₄ ²⁻	Available P	K ⁺	Mg ²⁺
Total heterotrophic bacteria	+0.82	+0.76	+0.45	+0.38	+0.52
Total heterotrophic fungi	+0.79	+0.48	+0.32	+0.41	+0.67
Hydrocarbon-utilizing bacteria	+0.31	+0.42	+0.88	+0.73	+0.69
Hydrocarbon-utilizing fungi	+0.28	+0.35	+0.54	+0.81	+0.72

Source: Muonye & Nnaji (2024)

p < 0.05

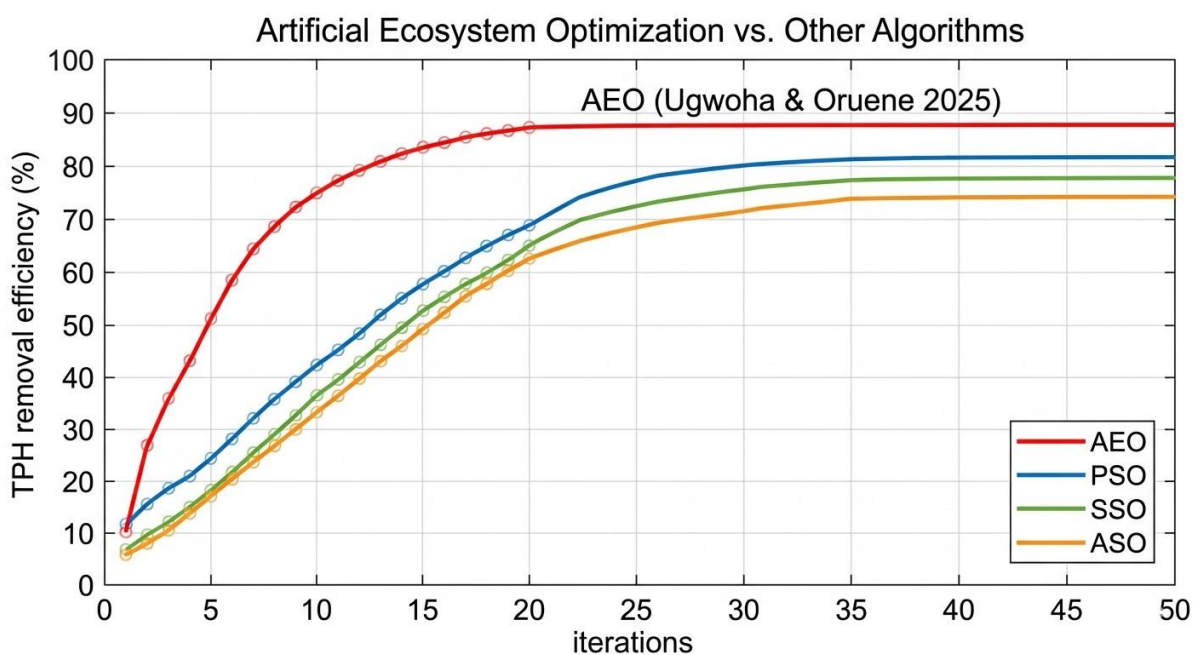


Figure 6: Convergence performance comparison of artificial ecosystem optimization (AEO) against particle swarm optimization (PSO), symmetry-based swarm optimization (SSO), and atom search optimization (ASO) for predicting maximum TPH removal from biochar-treated soil. AEO achieved 87.76% removal at 20 iterations. Based on Ugwoha and Oruene (2025).

VI. SYNTHESIS, POLICY IMPLICATIONS, AND FUTURE DIRECTIONS

A. Synthesis of Key Findings

The evidence synthesized in this review demonstrates that petroleum refining emissions and agro-industrial effluents in the Niger Delta create cumulative environmental burdens with significant implications for ecosystem health and human well-being. Petroleum refining releases complex mixtures of volatile organic compounds and criteria air pollutants, with artisanal refining contributing notably to hydrocarbon emissions constituting 52-55% of total pollutants and carbon monoxide comprising 38-41% across processing units (Echendu et al., 2024). Rainfall mediates atmospheric deposition of petro-pollutants, transferring contamination from air to water and soil, with strong positive correlations between total petroleum hydrocarbons and total aliphatic hydrocarbons (Sofu & Akintola, 2025).

Groundwater contamination is severe, with total petroleum hydrocarbon levels reaching 42,200 $\mu\text{g/L}$ and heavy metals including cadmium, nickel, and lead exceeding regulatory thresholds (Udom & Nwagbara, 2025). Soil contamination with polycyclic aromatic hydrocarbons and heavy metals shows mean total concentrations of 16 polycyclic aromatic hydrocarbons ranging from 679.37 to 779.58 ng/g across topographic gradients (Verla et al., 2024). Agro-industrial effluents introduce cyanide, heavy metals, and high organic loads into environmental media. Biowaste generation in Bayelsa State alone exceeds 120 metric tons weekly, representing both a pollution source and a resource recovery opportunity (Wokhe & Ideriah, 2024). Heavy metal contamination from cassava mill effluents contributes to soil degradation and potential food chain transfer (Ohimain, 2017; Isimah et al., 2025).

Health impacts documented in affected communities include respiratory disorders affecting 35-45% of exposed populations, reproductive risks, psychological distress affecting approximately 40% of studied populations, and elevated cancer risks with total mean cancer risk exceeding USEPA threshold in all studied samples (Sam et al., 2025; Chinedu et al., 2025). Infants demonstrate the highest vulnerability, with cancer risks of 1.80×10^{-2} (Chinedu et al., 2025). Women bear disproportionate socioeconomic burdens, with 70-80% of small-scale farmers and fishers facing livelihood losses (Sam et al., 2025).

Technological advancements in emission characterization, including emission factor determination, gas chromatography-flame ionization detection, and geospatial analysis, enable improved understanding of pollutant sources, transport, and fate (Echendu et al., 2024; Sofu & Akintola, 2025). Enhanced natural attenuation has demonstrated effectiveness in remediating oil-contaminated soils, with field-scale applications achieving contaminant reduction to levels comparable to uncontaminated controls (Muonye & Nnaji, 2024). Biochar-based treatments optimized through artificial intelligence approaches achieved 87.76% total petroleum hydrocarbon removal (Ugwoha & Oruene, 2025). Hybrid bio-adsorbents from agricultural waste showed adsorption capacity of 21.4 mg/kg for produced water treatment (Igwenagu-Ifeanyi, 2025). Biogas production from agro-industrial wastes offers dual benefits of waste treatment and renewable energy generation, with co-digestion strategies enhancing yields (Wokhe & Ideriah, 2024).

B. Policy and Regulatory Implications

In Nigeria, the current regulatory framework includes the Environmental Guidelines and Standards for the Petroleum Industry provides concentration-based restrictions for contaminants in environmental media. However, enforcement is still weak because to institutional capacity limits, large river networks that make monitoring difficult and corporate negligence (Udom & Nwagbara, 2025). Odiete (2024) presents a new pollution prevention approach, which involves additional controls such as pollution load and wastewater discharge rate. This may help to strengthen environmental protection without ignoring economic realities.

Strengthening compliance mechanisms and ensuring transparency in hydrocarbon operations are essential to safeguarding groundwater resources and public health (Udom & Nwagbara, 2025). Verla et al. (2024) recommended that the government of Nigeria strengthen soil contamination monitoring, enforce spill regulations, and promote eco-friendly farming. Odesiri-Eruteyan and Ajokporise (2026) recommended routine monitoring, adequate water treatment before use, and strict regulation of effluent discharge and waste disposal to safeguard the ecological health of rivers. Chinedu et al. (2025) underscored the urgent need for continuous monitoring, effective water treatment, and stricter environmental regulation.

Regulatory agencies should consider:

1. Adopting integrated approaches that regulate pollutant concentrations, loads, and discharge rates concurrently (Odiete, 2024)
2. Establishing emission standards for artisanal refining operations or developing transition pathways to modular refineries with improved environmental controls

3. Requiring pretreatment of high-strength agro-industrial effluents prior to environmental release
4. Incentivizing waste-to-resource technologies including biogas recovery and biochar production
5. Mandating community engagement in environmental monitoring and decision-making processes
6. Strengthening soil contamination monitoring and enforcing spill regulations

C. Future Research Directions

Several knowledge gaps warrant prioritized research attention. Comprehensive emission speciation studies across the Niger Delta would improve understanding of spatial and temporal variability in pollutant profiles. Echendu et al. (2024) noted that operational sites of artisanal refineries are inaccessible due to security and proximity to raw material, making air quality evaluation and management challenging. Improved access and monitoring methodologies are needed. Toxicological research should address mixture effects of combined petrochemical and agricultural pollutants, chronic low-dose exposure outcomes, and susceptible population vulnerabilities. Sam et al. (2025) called for more research to identify the long-term health effects of oil pollution and psychological impacts on affected populations, as well as detailed analysis of food security issues and adaptive strategies employed by local communities. Remediation technology development should prioritize field-scale demonstration studies, cost optimization for local contexts, and integration of multi-omics approaches to elucidate microbial community dynamics during bioremediation. Azuazu et al. (2023) emphasized that their research offers novel insights into refining bioremediation techniques and paves the way for future advancements, with continued refinement and application anticipated. Igwenagu-Ifeanyi (2025) recommended using 1.5 mol/dm³ impregnation concentration for activating bio-adsorbents to maximize efficiency, and urged authorities to support hybrid activated carbon adoption in community water treatment to reduce pollution and enhance sustainable waste management. Socio-economic research should quantify the economic costs of environmental degradation, evaluate the cost-effectiveness of alternative remediation interventions, and assess just transition pathways for artisanal refiners and others whose livelihoods depend on pollution-generating activities.

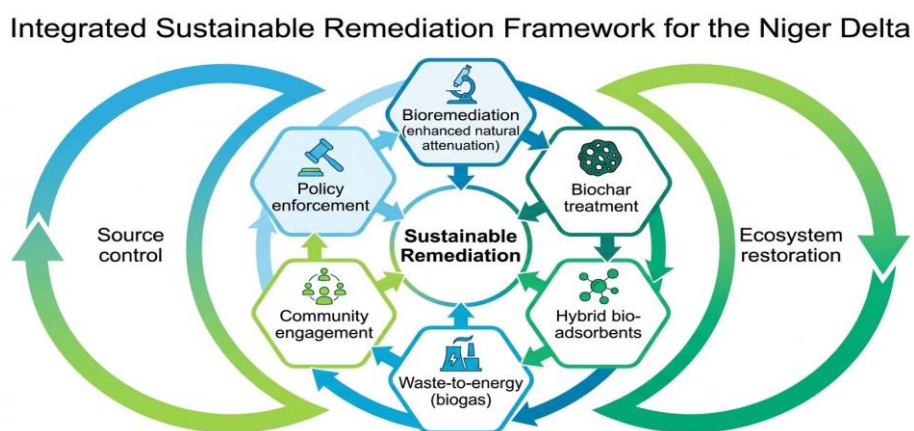


Figure 7: Integrated sustainable remediation framework for the Niger Delta, combining bioremediation, biochar, bio-adsorbents, waste-to-energy, community engagement, and policy enforcement.

Table 5: Summary of policy recommendations with implementing agencies and timeframes

Recommendation	Implementing agency	Proposed timeframe
Mandate emission factors for artisanal refineries; enforce TPH/PAH limits	NOSDRA, FMEnv	6–12 months
Require pretreatment of cassava mill effluent before discharge	Delta, Rivers, Bayelsa State MoE	12–18 months
Train community members in low-cost air/water monitoring	LG environment departments	6 months (ongoing)
Establish polluter-pay remediation funds via oil company agreements	Host communities + oil companies	12 months

Table 6: Knowledge gaps and future research priorities identified from reviewed literature

Research area	Specific gap	Priority
Emission monitoring	Lack of data from inaccessible artisanal refinery sites; no seasonal variation studies	High
Mixture toxicology	Combined effects of petrochemical + agro-industrial pollutants on human health	High
Field-scale remediation	No full-scale biochar or bioremediation trials in Niger Delta	High
Emerging contaminants	PFAS, microplastics, pharmaceuticals unstudied	Medium
Longitudinal health studies	No long-term cohorts tracking chronic disease	Medium
Economic valuation	Cost of environmental degradation not quantified	Medium

VII. CONCLUSIONS

The Niger Delta region confronts profound environmental challenges from petroleum refining emissions and agro-industrial effluents that threaten ecosystem integrity, public health, and sustainable development. This review has synthesized evidence from multiple studies demonstrating the complex pollutant profiles characterizing these dual pollution streams, the toxicological risks they pose to human populations, and the technological and remediation strategies available to address them.

Artisanal petroleum refineries emit hydrocarbons, carbon monoxide, nitrogen oxides, sulfur dioxide, and hydrogen sulfide at levels that degrade air quality, with hydrocarbons constituting 52-55% of emissions (Echendu et al., 2024). Groundwater contamination with

total petroleum hydrocarbons reaching 42,200 µg/L and heavy metals exceeding regulatory thresholds renders local water sources unsafe (Udom & Nwagbara, 2025). Soil contamination with polycyclic aromatic hydrocarbons and heavy metals shows widespread distribution (Verla et al., 2024). Health impacts include respiratory disorders in 35-45% of exposed communities, reproductive risks, psychological distress, and cancer risks exceeding acceptable thresholds, with infants being most vulnerable (Sam et al., 2025; Chinedu et al., 2025). Agro-industrial effluents contribute additional pollutant burdens, with cassava mill effluents releasing cyanide and heavy metals into environmental media (Ohimain, 2017; Isimah et al., 2025). Technological advancements in emission characterization provide tools for understanding and mitigating pollution at source. Bioremediation approaches, including enhanced natural attenuation and biochar-based treatments, have demonstrated effectiveness in restoring contaminated soils (Muonye & Nnaji, 2024; Ugwoha & Oruene, 2025; Azuazu et al., 2023). Hybrid bio-adsorbents from agricultural waste offer low-cost, sustainable options for water treatment (Igwenagu-Ifeanyi, 2025). Waste-to-resource technologies, particularly anaerobic digestion of agro-industrial effluents, offer pathways for converting pollution streams into valuable products while reducing environmental burdens (Wokhe & Ideriah, 2024). Realizing these opportunities requires strengthened regulatory frameworks, enhanced enforcement capacity, and sustained commitment from government, industry, and communities. Without immediate and sustained intervention, the continued degradation of environmental media threatens both ecosystems and human livelihoods, underscoring the pressing necessity of enforceable solutions for lasting impact (Udom & Nwagbara, 2025). The evidence assembled in this review provides a foundation for informed action by policymakers, practitioners, and researchers committed to safeguarding the environmental heritage and human well-being of the Niger Delta region.

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