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Per- and Polyfluoroalkyl Substances and Waste Management in Nigeria: A Review

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Abstract: *Per- and polyfluoroalkyl substances (PFAS) are highly persistent synthetic contaminants increasingly classified as a global environmental and public health concern. This review examines PFAS within the specific context of Nigeria — Africa's most populous nation, generating an estimated 32 million tonnes of municipal solid waste annually, of which only 20-30% is formally managed, arguing that prevailing waste practices function as structural amplifiers of environmental release and human exposure. Drawing on empirical evidence from Nigerian environmental and biotic matrices, including surface waters and river sediments, sewage sludge from industrial treatment facilities, electronic waste contaminated soils, fish tissues from rivers, drinking water sources, and early-life matrices, the paper examines current occurrence data and critically evaluates substantial analytical, regulatory, and surveillance gaps. Nigeria's dependence on open dumping, informal recycling, unlined landfills, wastewater discharge, and uncontrolled burning creates interconnected PFAS exposure pathways through groundwater ingestion, aquatic food web bioaccumulation, occupational dermal and inhalation contact, and household dust exposure, with informal e-waste workers, women and children identified as vulnerable populations. A comparative assessment reveals that Nigeria lacks established analytical protocols, infrastructure, enforceable drinking water limits, and population-level biomonitoring, in contrast to high-income countries with regulatory frameworks. Remediation feasibility is evaluated under Nigeria's infrastructural constraints: while granulated activated carbon and lined landfill represent feasible management pathways, reverse osmosis and high-temperature incineration face significant energy and operational cost. The review concludes by proposing a phased, context-responsive national roadmap with prioritised actions spanning laboratory strengthening, hotspot surveillance and interim drinking water guideline values.*

Keywords: *PFAS; Environmental contamination; Human exposure; Waste management, Remediation; Public health risk*

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1.0 Introduction

Nigeria, Africa's most populous nation, generates approximately 32 million tonnes of municipal solid waste (MSW) annually, of which only 20-30% is formally collected and less than 10% is recycled (Ikeah, 2022; Ogunnaike, 2024). Open dumping, uncontrolled burning, and unlined landfills are common disposal practices for MSW. Furthermore, over 1.1 million tonnes of e-waste are generated locally, and Nigeria receives significant imports of used electrical and electronic equipment, either intentionally or unintentionally (Ideho, 2012; Ogunyemi & Marinho, 2025), with informal recycling releasing hazardous substances directly into

soils and water bodies (Nnorom and Osibanjo, 2008; Kikanme *et al.,* 2024). These structurally deficient waste management practices act as amplifiers of environmental PFAS release, yet the extent of contamination remains poorly quantified.

Per- and polyfluoroalkyl substances (PFAS) are a large group of synthetic chemicals in which one or more hydrogen atoms of carbon chains have been fully or partially replaced by fluorine, forming the perfluoroalkyl (C_nF_{2n+1}) or polyfluoroalkyl moieties (Buck *et al*., 2011; OECD, 2021). These fluorinated compounds contain at least one fully fluorinated methyl (-CF_3) or methylene (-CF_2-) group, excluding substances with halides/hydrogen (OECD, 2021). The extreme strength and thermal stability of the C-F bond confer resistance of PFAS to environmental degradation under normal conditions (Meng *et al*., 2021). However, the strong C-F bonds and chemical stability also lead to persistent environmental contamination, particularly in regions with poor waste management infrastructure (Aborode *et al*., 2024). Their persistence has led to their classification as "forever chemicals" (Kikanme *et al*., 2024).

There are thousands of PFAS, but there is increasing focus on four, including perfluorooctanoic acid (PFOA), perfluorooctane sulphonate (PFOS), perfluorononanoic acid (PFNA), and perfluorohexane sulphonic acid (PFHxS) (EFSA, 2020). Out of these four, PFOA and PFOS have attracted extensive attention, partly due to their potential for developmental toxicity and reproductive effects in laboratory-based animal models (Negri *et al*., 2017). Additionally, these two classes of PFAS exhibit bioaccumulation and biomagnification abilities (Conder *et al*., 2008), and relatively long half-lives in organisms (Ololade *et al*., 2018). They were also included in the Stockholm Convention list of Persistent Organic Pollutants (POPs) in 2009 (Stockholm Convention, 2009), while the European Union has suggested implementing restrictions on all varieties of PFAS by the year 2030 (European Environmental Bureau, 2022). In 2023, PFOA was classified as a human carcinogen and PFOS as a potential carcinogen (IARC Working Group, 2023). Toxicological studies have shown that exposure to PFAS is linked with a range of health disorders, including immune (Grandjean and Budtz-Jorgensen, 2013), developmental (Szilagyi *et al*., 2020), metabolic (Liu *et al*., 2018), reproductive (Zhou *et al*., 2016), etc.

With Nigeria being the most populous country in Africa, a combination of rapid urbanization and industrial growth, with poor waste management infrastructure, creates ideal conditions for the accumulation and spread of PFAS (Popoola, 2023). The nation produces around 32 million tons of municipal solid waste each year, with only 20-30% being properly collected and disposed of (Ikeah, 2022; Moro, 2023). Additionally, Nigeria generates large quantities of various waste types, including municipal, industrial, electronic, medical etc. Open dumping and uncontrolled burning are common disposal practices in metropolitan and peri-urban regions, which pose a threat to public health and the environment. When landfills do exist, they are usually unlined and lack adequate mechanisms for collecting and treating leachate, which allows pollutants to seep into soil and groundwater (Iniaghe and Adie, 2015). With e-waste, the informal sector dominates collection and recycling, using crude techniques that can result in the release of PFAS (Kikanme *et al*., 2024). However, because of insufficient study and monitoring, the precise effect of these sources on Nigeria's PFAS load is still largely unknown (Kikanme *et al*., 2024). This review critically examines the current state of PFAS in the context of waste management in Nigeria, identifying critical knowledge gaps that hinder effective assessment and intervention. The objectives of

this review are: (1) Examine the physicochemical properties and environmental behaviour of PFAS; (2) analyse Nigeria's waste management system as a structural determinant of PFAS release and redistribution; (3) assess available empirical evidence of PFAS occurrence in Nigerian environmental and human matrices; (4) evaluate dominant exposure pathways and associated health implications; (5) identify analytical, infrastructural, and regulatory barriers limiting effective PFAS monitoring and risk assessment; and (6) propose a phased, implementable national strategic roadmap that integrates governance reform, monitoring expansion, source control, and institutional capacity development.

1.2 PFAS: Chemical Properties and Environmental Behaviour

1.2.1 Structural Characteristics and Persistence

PFAS typically contain an aliphatic carbon content in which fluorine molecules have entirely (prefix: per-) or partially (prefix: poly-) replaced hydrogen molecules, and are represented by the general chemical formula, C_nF_{2n+1}, where "n" is the number of carbon atoms. The strong and extremely polar carbon-fluorine bonds confers PFAS with unique qualities, including great stability, resistance to chemical and biological degradation, and resistance to heat, stains, and water (Kissa, 2001; Buck *et al*., 2011; Cordner *et al*., 2019; Gaines, 2023). They find useful applications in food packaging, firefighting foams, clothing, protective coatings for fabrics and carpets, electronics, and the production of fluoropolymers (USEPA, 2016; ATSDR, 2018; Cordner *et al*., 2019).

Perfluorooctanoic acid, $C_7F_{15}COOH$ (PFOA), and perfluorooctane sulphonic acid, $C_8F_{17}SO_3H$ (PFOS), are the two most often produced and found PFASs in the environment (Buck *et al*, 2011). Water, sediment organisms, and air have all been found to contain PFASs (Lake, 2015; Zareitalabad *et al*., 2013). Nigeria's tropical climate, which is marked by high temperatures and a variety of soil types, may cause PFAS behavior to diverge considerably from patterns observed in temperate regions where majority of studies have been conducted. According to preliminary studies, the sorption and retention characteristics of PFAS are significantly influenced by the mineral composition, organic matter content, and air-water interfaces (Evich *et al*., 2025; Fang *et al*., 2025; Hazrati *et al*., 2025).

In Nigeria, rapid urbanization, industrial growth, and inadequate waste management amplify the potential for PFAS accumulation in soils, water bodies, and food webs, underscoring the need for targeted environmental assessment and intervention.

1.2.2 Applications and Pathways of PFAS Release into the Environment

PFAS are discharged into the environment throughout their lifecycle, from production and processing to distribution, usage, and final disposal. Although thorough source apportionment studies are still lacking, PFAS enter the environment through a variety of routes. Inadequate waste management practices are a major cause of PFAS contamination of soils around solid waste disposal sites (Aborode *et al*., 2025). Nations like Nigeria remain susceptible to PFAS due to the global nature of production and dissemination of PFAS (Okudo & Nicholas, 2024). Important sources of PFAS include:

a. Industrial discharges: PFAS may be released from untreated effluents, but Nigeria does not have a systematic mechanism for monitoring PFAS industrial discharges (Kikanme *et al*., 2024). Manufacturing plants and industrial installations are important point sources of PFAS emissions. During production operations, these chemicals may be released

directly into the air or wastewater (European Environment Agency, 2023). Smaller factories frequently release their wastewater into municipal treatment plants, which allows PFAS to reach the public sewage system, even though larger industrial sites may have treatment plants (European Environment Agency, 2023). Certain industrial processes are known to contribute to the emission of PFAS, including the textile and leather sectors, as well as metal plating and finishing (Minnesota Pollution Control Agency, 2025).

b. Firefighting Activities: Airports, military installations, and industrial facilities have all made extensive use of aqueous film-forming foams (AFFF) containing PFAS (Michigan PFAS Action Response Team, n.d). This is because of their capacity to smother fires by forming a barrier between the fuel and the air. This is especially helpful in high-intensity fire situations where quick action is necessary to stop the fire from spreading, such as those in aircraft crashes, military environments, or industrial mishaps (Dauchy *et al*., 2017).

c. Sporting Activities and Household Furniture: Since PFAS repel oil and water, they are employed in the manufacture of sportswear (European Environment Agency, 2024). These substances are used on textiles to provide a barrier that keeps water out. As a result, PFAS are perfect for usage in performance and outdoor clothing where comfort and water resistance are both sought (Gilchrist, 2023). For the same reasons, PFAS are frequently utilized in the furniture sector, thereby extending the furniture's lifespan by keepomg liquids from seeping into the cloth (Brandon, 2023).

d. Consumer Products: Certain PFAS are intentionally added as ingredients to consumer products such as lipstick, eye shadows, nail polish and cleansers, as well as om cosmetics to condition and smooth the skin and hair, giving them shiny appearances, making them long-lasting or water-resistant (Teles, 2021; Whitehead *et al*., 2021; U.S FDA, n.d). Some varieties of dental floss also contain PFAS to improve durability and glide (Subbaraman, 2019). PFAS may be added to lotions and creams to give them a smoother texture and improve their ability to withstand perspiration and water (Bui, 2017). Every day, PFAS-containing items including food packaging, waterproof clothes, and nonstick cookware find their way into the municipal waste stream. These items probably contribute significantly to environmental PFAS loading due to the lack of adequate recycling infrastructure and the prevalence of informal trash processing (Moro, 2023).

e. Agricultural Inputs: PFAS contamination of irrigation water and biosolids is a possible route for agricultural soil contamination, as observed in reports from other areas (Kikanme *et al.*, 2024).

f. Industrial Activities

PFAS are used in the manufacture of several paint kinds. PFAS are useful additions in paint products because of their special qualities, which include their resistance to heat, chemicals, and oil as well as their capacity to provide a smooth, long-lasting finish (DeLuca, 2023). The strength and endurance needed to endure harsh circumstances in airplane paints are greatly enhanced by PFAS, as they aid in the formation of a shield that is impervious to UV rays and the mechanical strains of flight (Cahuas, 2022; Santiago *et al*., 2023).

g. Food Industry

Since PFAS can withstand water, oil, and grease, they are employed as ingredients in fast food packaging. By keeping grease from fast food items like pizzas, fries, and burgers from seeping through the packaging, the PFAS coating preserves the integrity and cleanliness of the package and, consequently, the surface it sits on (Schwartz-Narbonne *et al*., 2023).

Figure 1 is a schematic diagram of PFAS sources in the environment.

1.3 Nigerian Waste System as PFAS Amplifier

Nigeria generates an estimated 32 million tonnes of municipal solid waste annually, yet only 20–30% is formally collected and disposed of (Moro, 2023; Umar *et al*., 2024). Per capita waste generation ranges from 0.45 kg/day nationally to 0.72 kg/day in Lagos, 0.66 kg/day in Abuja, and 1.34 kg/day in Uyo, a figure projected to rise 40% within a decade (Bassey *et al*., 2024). Urban waste is projected to grow from 66,828 to 125,473 tonnes per day by 2040 (Ezeudu *et al*., 2021; Agbo, 2023). The composition is dominated by organics (27–47%), plastics (2.5 million tonnes/year), paper, and textiles, with recyclables comprising over 45–51% in some cities (Eneh, 2025; Bassey *et al*., 2024).

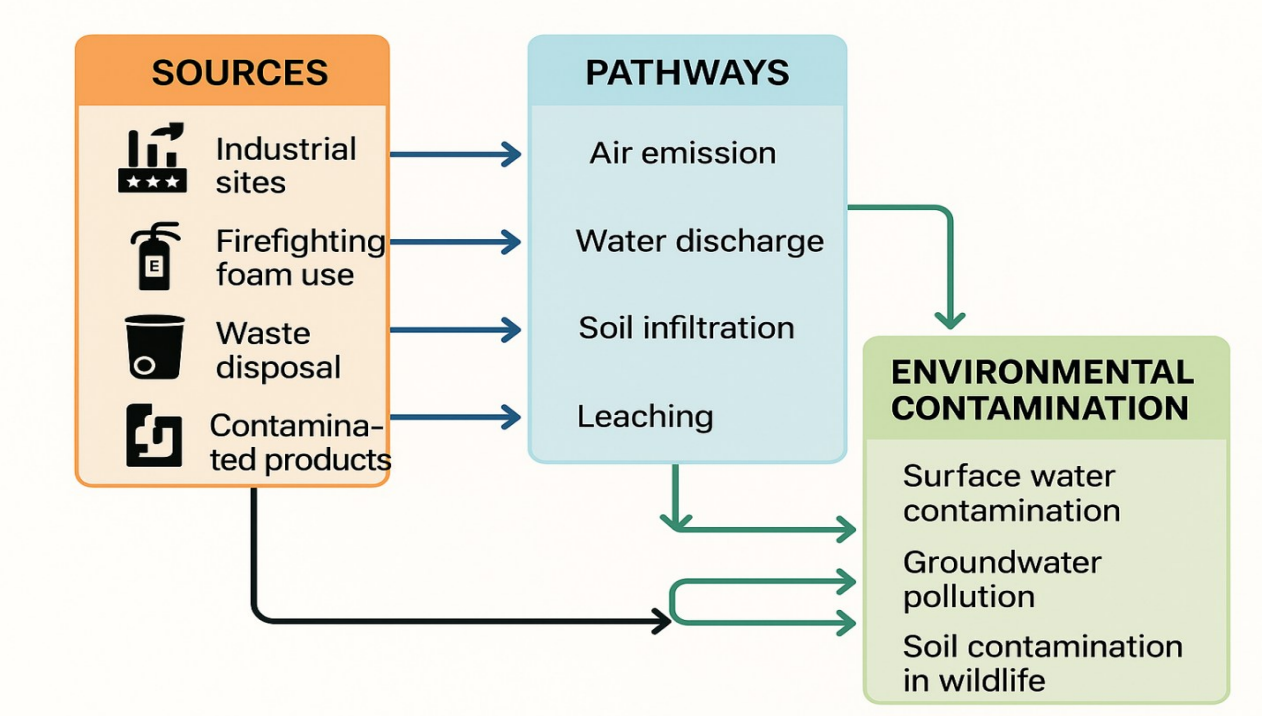

Fig. 1. Sources, Pathways, and Environmental Contamination of PFAS

Inadequate infrastructure, poor funding, and weak regulatory enforcement mean that open dumping and uncontrolled burning remain the dominant disposal practices (Aborode *et al*., 2024; Ukala *et al*., 2020). Existing landfills are mostly unlined and lack leachate collection, enabling direct migration of contaminants into soil and groundwater (Tewogbola, 2024).

MSW is the primary vector through which PFAS-containing consumer products (including food packaging, textiles, nonstick cookware, and personal care products) enter Nigeria's waste stream. Without adequate sorting or recycling infrastructure, these materials end up in unlined dumps or are burned openly, mobilising PFAS into soil, air, and water (Moro, 2023).

Electronic waste (E-waste) represents another important waste stream. Nigeria receives over 1.1 million tonnes of e-waste annually, with an estimated 400,000 used computers entering through Lagos port alone each month, with 25–75% being non-functional (Nnorom & Osibanjo, 2008; Odeyingbo *et al*., 2025). Similarly, informal recycling involving open burning and acid stripping of circuit boards releases PFAS and other hazardous substances directly into soils and drainage channels (Kikanme *et al*., 2024; Puckett *et al*., 2005). The dominant waste practices and their

corresponding PFAS exposure pathways are summarised in Table 1. These systemic waste management deficiencies create multiple pathways for PFAS release, which are subsequently documented in surface water, sediments, soils, and biotic matrices as outlined in Section 1.4.

1.4 Evidence of PFAS in Nigeria

Although studies have detected PFAS in environmental and human matrices across Nigeria, the data remain sparse, geographically uneven, and mostly limited to legacy compounds such as PFOS and PFOA. The synthesis of empirical data on PFAS occurrence in Nigeria across environmental and human matrices is displayed in Table 2

Table 1: Waste management practices and exposure pathways for PFAS

Waste Practice	Environmental Impact	Exposure Pathway
Open dumping	Leachate formation	Groundwater ingestion
Unlined landfills	Vertical PFAS migration	Borehole contamination
Open burning	Redistribution of particulates	Inhalation (workers & residents)
Informal e-waste recycling	Soil/dust contamination	Occupational + household dust
Wastewater discharge	River contamination	Fish consumption

1.5 Exposure Pathways and Associated Health Risks within Nigeria's Waste Management Framework

Nigeria's environmental exposure landscape is shaped by open dumping, informal recycling, uncontrolled burning, unlined landfills, and decentralized groundwater dependence, in contrast to designed landfills, modern wastewater treatment, and regulated hazardous waste disposal. Drinking water, food consumption (particularly fish), and occupational contact are the main sources of PFAS exposure worldwide (ATSDR, 2024; Sunderland *et al*., 2019).

Understanding the major exposure pathways, via water, food, occupational contact, and vulnerable populations, is critical for assessing the public health impact of PFAS within Nigeria's unique waste management context.

1.5.1 Drinking Water Exposure: Groundwater Vulnerability and Waste Leachate Pathways

Contaminated drinking water represent one of the major causes of PFAS exposure at the population level, especially in the vicinity of contaminated sites (IARC, 2023). Dependency on shallow aquifers and boreholes makes Nigeria more vulnerable.

Rainfall infiltration in unlined landfill systems can produce PFAS-loaded leachate. Evidence unique to Nigeria verifies the presence of PFAS in matrices connected to water. Ololade *et al*. (2018) found PFOS and PFOA in a few Nigerian rivers, indicating water-phase persistence and environmental mobility. Multiple PFAS were found in sewage sludge from residential, commercial, and hospital wastewater treatment facilities (Sindiku *et al*., 2013), suggesting that wastewater systems are significant sources. Because of Nigeria's heavy reliance on groundwater, drinking water continues to be a priority exposure pathway that needs immediate monitoring (Ogbuewu *et al*., 2024).

1.5.2 Food Chain Exposure: Aquatic Bioaccumulation and Dietary Risk

PFAS can biomagnify in aquatic food webs and bioaccumulate in tissues high in protein (Sunderland *et al*., 2019). one of the primary evidences of trophic transfer currently available in Nigeria is the Ologe Lagoon: Ibor *et al*. (2025) showed that PFAS were present in fish species consumed by residents.

Table 2: Empirical Evidence on PFAS Occurrence in Nigeria Across Environmental and Human Matrices

Evidence area	Matrix	Nigeria location	What has been shown	Main limitation
Rivers	Surface water + sediment	Selected Nigerian rivers	PFOS/PFOA detected; sediment–water distribution assessed	Limited sites; few timepoints (Ololade *et al.,* 2018)
Wastewater residues	Sewage sludge	SW Nigeria WWTPs (industrial/domestic/hospital)	Multiple PFAS present; concentration ranges reported; recoveries provided	Not connected to downstream exposure pathways (Sindiku *et al.,* 2013)
Informal recycling	E-waste soils	Nigeria included in West African e-waste soil study	PFAS-relevant contaminant mixtures in e-waste soils; hotspots indicated	Nigeria-only PFAS congener often not prominent (Eze *et al.,* 2023)
Food webs	Fish + sediment + invertebrates	Ologe Lagoon	Biomagnification evidence; precursor diSAMPAP; trophic differences	Limited ecosystem coverage nationally (Ibor *et al* 2025)
Freshwater fish	Fish gills	Eleyele Lake	Congener patterns linked to niche/microhabitat	Single-lake study (Adeogun *et al.,* 2024)
Drinking water	Borehole/tap/sachet/bottled	Abakaliki	Targeted PFAS screening reported	Method comparability uncertainty (Ogbuewu *et al.,* 2024)
Human biomonitoring	Breast milk + infant stool	Nigerian mother–infant pairs	Early-life exposome signals; feasibility for PFAS-related screening	Not always targeted PFAS quantification (Oesterle *et al.,* 2024)

The authors demonstrated that exposure is not restricted to legacy PFOS/PFOA by identifying precursor molecules and reporting biomagnification trends. Similarly, Adeogun *et al*. (2024) reported the presence of PFAS in fish gill tissues from Eleyele Lake, demonstrating species-specific variations impacted by microhabitat and ecological niche.

These investigations confirm the incorporation of PFAS into Nigerian freshwater food webs, despite the lack of data on edible muscle tissue. Chronic dietary exposure is conceivable because fish is a significant source of protein in many Nigerian communities, particularly in coastal and riverine areas. However, there are still unknowns because there is limited information on PFAS concentrations by tissue (liver vs. muscle), rates of regional consumption of seafood, seasonal fluctuations, and the impact of cooking on the concentration of PFAS.

1.5.3 Occupational Exposure: Waste Workers and Informal Recycling

There is a sizable informal industry in Nigeria's trash economy: contaminated goods are often handled by landfill workers and unofficial e-waste recyclers without the use of personal protective equipment. Mechanisms of occupational PFAS exposure include dermal contact with packaging, electronics, and treated textiles; inhaling polluted dust while disassembling and burning, and hand-to-mouth transfer ingestion

E-waste processing environments are linked to PFAS exposure hazards, including higher levels in exposed worker populations in worldwide settings (Tansel, 2022). Environmental measurements from sludge (Sindiku *et al*., 2013) and aquatic systems (Ololade *et al*., 2018; Ibor *et al*., 2025) reveal environmental reservoirs that can transfer into occupational contact. However, given the paucity of occupational health surveillance systems in Nigeria, this aspect of occupational exposure is particularly worrisome.

1.5.4 Women and Children: Heightened Biological Vulnerability

According to epidemiological data (IARC 2023 and ATSDR 2024), exposure to PFAS is linked to preeclampsia and hypertension brought about by pregnancy, lower birth weight, effects on children's immune systems, decreased antibody response to certain vaccinations, and effects on development and hormones.

The feasibility of identifying various chemical exposures, including PFAS-related chemicals, in breast milk and newborn biological samples is demonstrated by emerging exposomic research in Nigerian mother-infant pairs (Oesterle *et al*., 2024). The authors demonstrated that early-life exposure assessment infrastructure can be built, even though there is currently no national PFAS biomonitoring programme.

2.0 Analytical and Monitoring Barriers

The efficient handling of PFAS is largely dependent on strong analytical capabilities and organized monitoring systems. However, substantial technological, infrastructure, financial, and legal constraints make it difficult to accurately detect, quantify, and monitor PFAS in biological and environmental matrices in Nigeria (Kikanme *et al*., 2024; Aborode *et al*., 2025). These obstacles make it increasingly difficult to identify contamination hotspots, measure exposure, apply risk-based guidelines, and assess the efficacy of interventions.

2.1 Instrumentation and Technical Capacity Constraints

High-resolution analytical platforms like liquid chromatography coupled with tandem mass spectrometry (LC–MS/MS), in particular triple quadrupole systems that can detect PFAS at ng/L (parts per trillion) levels in water and ng/g levels in solid matrices, are usually needed for PFAS quantification in environmental media (Post *et al*., 2012; OECD, 2021). High-purity solvents, a steady power source, climate-controlled lab settings, skilled analytical

chemists, and substantial investment are all necessary for this equipment. The lack of coordinated monitoring programmes and inadequate analytical infrastructure contributes to the paucity of PFAS research output in Nigeria (Kikanme *et al.,* 2024). Environmental PFAS assessments depend mainly on outside laboratory collaborations. Moreso, since fluoropolymer-containing products (such as PTFE tubing) are common in laboratory settings, these substances provide a danger of false positives and background contamination (Richards, 2025). To guarantee data dependability, standardized quality assurance/quality control (QA/QC) procedures, such as isotope-labelled internal standards, method blanks, field blanks, and matrix spikes, are crucial (EPA, 2024; OECD, 2021).

2.2 Narrow Chemical Scope and Emerging Compounds

Although there are thousands of molecules that make up PFAS, many environmental assessments in developing monitoring contexts concentrate on a small number of legacy compounds, like PFOS and PFOA. Despite their historical significance and toxicological relevance (IARC, 2023), short-chain PFAS and precursor chemicals have become more prevalent in worldwide production (Glüge *et al*., 2020).

2.3 Absence of Systematic Monitoring Networks

The lack of organised national monitoring programmes restricts the production of representative data. Presently, Nigeria lacks a systematic strategy for PFAS surveillance that includes systems for drinking water, leachate from landfills, wastewater effluents, surface waters that receive discharge from municipalities and occupationally exposed groups.

2.4 Financial and Logistical Barriers

Monitoring of PFAS is not cost-effective. High cost results from internal standards tagged with isotopes and analytical standards, SPE consumables and cartridges, calibration and maintenance of instruments, training for skilled personnel, transporting and preserving samples. Sustained PFAS monitoring is financially difficult for many Nigerian universities, with little support for research. Additionally, there may be substantial procurement costs and regulatory delays associated with importing approved standards and reference materials.

2.5 Regulatory and Governance Gaps

There are currently no legal thresholds related to PFAS in Nigeria, which lessens institutional incentives for systematic testing (Aborode *et al*., 2024; Kikanme *et al*., 2024). This results in a vicious cycle whereby insufficient monitoring generates insufficient data, which in turn erodes the need for regulation (Grandjean and Budtz-Jorgensen, 2013), and the lack of regulation further diminishes the incentives for monitoring.

2.6 Implications for Risk Assessment and Policy Development

Barriers to monitoring and analysis directly affect risk assessment. Without trustworthy concentration data, calculations of estimated daily intake are predicated on conjecture, and models of cancer risk and the hazard quotient might not have any empirical support (ATSDR, 2024; US EPA, 2024).

2.7 Comparative Analytical and Monitoring Capacity: High-Income Countries vs Nigeria

Sustained surveillance systems, regulatory incentives, and analytical infrastructure are necessary for effective PFAS monitoring. The gap between Nigeria and high-income countries (HICs) is a result of systemic variations in funding, standardization, laboratory capacity, and regulatory enforcement. The comparative analytical and monitoring hurdles are displayed in Table 3.

3.0 Remediation and Treatment Options: Feasibility in Nigeria

Because of their remarkable chemical stability, resistance to biodegradation, and strong carbon–fluorine linkages, PFAS pose major scientific and infrastructure issues worldwide (Buck *et al*., 2011). Remedial techniques must either immobilize, concentrate, or degrade PFAS using advanced treatment technologies, as these compounds are resistant to natural attenuation due to their strong carbon–fluorine bonds. (Ross *et al*., 2018; OESD, 2021).

3.1 Drinking Water Treatment Technologies

3.1.1 Granular Activated Carbon (GAC)

One of the most popular PFAS remediation methods for drinking water is granular activated carbon: adsorption is the main method by which GAC eliminates PFAS; long-chain PFAS, such as PFOS and PFOA, are more effectively removed than short-chain compounds (Rahman *et al*., 2014). GAC is frequently used at municipal water treatment facilities in high-income nations, especially in response to regulatory requirements like the U.S. EPA's 2024 drinking water limitations (U.S. EPA, 2024).

In Nigeria, GAC systems might work at sizable urban water treatment facilities with centralized treatment infrastructure, such those in Lagos and Abuja. However, scalability is limited by the extensive use of decentralised boreholes. Pilot studies are recommended to determine optimum bed depth, contact time, and replacement schedules under local water chemistry conditions. Operational challenges however, persist, including frequent carbon replacement, high installation cost, and limited technical capacity for routine monitoring and system optimisation.

3.1.2 Ion Exchange Resins

Ion exchange (IX) resins frequently outperform GAC in specific applications and show good removal efficiency for both short-chain and long-chain PFAS (Appleman *et al*., 2014). Although technically efficient, IX systems are more expensive than GAC and necessitate expert operation as well as adherence to resin regeneration and disposal procedures. In Nigeria, inadequate regular water quality monitoring, improper handling or disposal of spent resins could lead to secondary PFAS contamination, highlighting the need for strict operational protocols.

3.1.3 Reverse Osmosis (RO) and Nanofiltration

Reverse osmosis and nanofiltration are two membrane-based methods that have significant PFAS removal efficiency (>90%) for a variety of substances (Tang *et al*., 2007). These systems use charge interactions and size exclusion to physically separate pollutants. Because RO systems use a lot of energy, they need a steady supply of electricity, membrane replacement, and technical know-how.

Widespread deployment in rural or peri-urban areas is unlikely without significant infrastructure investment; however, RO and nanofiltration may be feasible in high-income residential settings or for bottled water production.

3.2 Wastewater and Sludge Treatment

PFAS partition into effluent or concentrate in sludge because wastewater treatment plants (WWTPs) are not built to break them down (Benskin *et al*., 2012). Concerns over downstream contamination have been raised by a Nigerian study that confirmed the presence of PFAS in sewage sludge from hospital and industrial sources (Sindiku *et al*., 2013).

3.2.1 Thermal Destruction and Incineration

PFAS can be broken down by high-temperature incineration (>1,100°C) (OECD, 2021). However, due to limited studies on emissions of fluorinated and mixed halogenated compounds, definitive conclusions on safety cannot yet be established (Weitz *et al*., 2024; Kovacs *et al*., 2025). In Nigeria, majority of waste facilities use open burning or uncontrolled combustion techniques, which may release pollutants into the air and ash, but do not reach the temperatures required to destroy PFAS.

Table 3: Comparative Analytical and Monitoring Barriers: High-Income Countries vs Nigeria

Dimension	High-Income Countries (e.g., US, EU)	Nigeria	Implication for Risk Assessment
Analytical Instrumentation	Widespread availability of LC–MS/MS (triple quadrupole and high-resolution systems); validated EPA and ISO methods	Few LC–MS/MS platforms exist, often limited to university or private laboratories, with variable access and capacity	Limited instrumentation reduces detection coverage and may lead to underestimation of PFAS contamination, particularly for short-chain and emerging compounds." **Location:** Implication column, Analytical Instrumentation row.
Standardized Methods	EPA Methods 533 & 537.1 (U.S.); EU harmonized methods under REACH; ISO standards	No nationally endorsed PFAS analytical protocol	Limited comparability across studies
Detection Limits	Routine detection at sub-ng/L (ppt) levels in drinking water	Detection limits are inconsistent, and many laboratories cannot reliably quantify PFAS at sub-ng/L (ppt) levels in water or trace levels in solid matrices." **Location:** Nigeria column, Detection Limits row	Variable detection limits create uncertainty in estimating low-level population exposure and hinder risk assessment for sensitive groups." **Location:** Implication column, Detection Limits row
Target Compound Scope	Expanded panels (20–40+ PFAS); inclusion of short-chain PFAS and precursors	Often limited to PFOS/PFOA or small compound lists	Emerging PFAS may remain undetected

Quality Assurance (QA/QC)	Mandatory isotope-labeled standards, field blanks, method validation, proficiency testing	QA/QC practices inconsistent; limited inter-laboratory benchmarking	Greater analytical uncertainty
Monitoring Programmes	National surveillance networks (e.g., UCMR in U.S.); routine drinking water testing	No national PFAS monitoring program	Lack of representative national exposure data
Human Biomonitoring	Population-level serum monitoring (e.g., NHANES in U.S.)	No national PFAS biomonitoring programme	Limited linkage between environmental levels and health outcomes
Regulatory Drivers	Enforceable drinking water limits (US EPA, 2024); EU restriction proposals (German Federal Institute for Risk Assessment, 2023)	No PFAS-specific drinking water standards	Weak compliance incentive for routine testing
Funding & Research Investment	Dedicated environmental health research funding streams	Limited sustained funding for PFAS surveillance	Episodic, site-specific studies only
Data Transparency & Reporting	Public databases and regulatory reporting requirements	Fragmented academic publications; no centralized PFAS database	Reduced policy integration

Table 4: Implementation Matrix for Nigeria's PFAS Strategic Roadmap

Action	Lead Agency	Timeline	Key Indicators of Progress
Establish National PFAS Taskforce	Federal Ministry of Environment (FME)	0–6 months	Formal taskforce constituted; terms of reference published
Develop Interim Drinking Water Guideline Values	Standards Organisation of Nigeria (SON), FME	6–12 months	Interim guidance document issued
Hotspot Monitoring (airports, dumpsites, WWTPs)	NESREA + State Environmental Agencies	6–18 months	≥10 priority sites screened
Establish 2–3 Regional PFAS Reference Laboratories	FME + Tertiary Institutions	12–24 months	LC–MS/MS operational; QA/QC protocol adopted
Landfill Upgrading Pilot (liners + leachate control)	State Governments	18–36 months	At least 2 engineered containment upgrades completed
Installation of GAC Treatment in Urban Utilities	State Water Corporations	18–36 months	PFAS reduction documented at pilot utilities
Draft and Adopt Enforceable PFAS Standards	National Assembly + FME	24–36 months	Regulatory framework gazetted
Targeted Biomonitoring (Women, Children, Workers)	Federal Ministry of Health	24–48 months	Baseline serum dataset established
Develop National PFAS Database	FME + Research Institutions	36–60 months	Public-access monitoring portal launched
Restrict Non-Essential PFAS Uses	FME + Trade Authorities	3–7 years	Import controls implemented

3.3 Soil and Landfill Remediation

3.3.1 Containment and Landfill Upgrading

PFAS migration can be considerably reduced by installing groundwater monitoring wells, leachate collection systems, and landfill liners. While advanced chemical treatments remain inaccessible in Nigeria due to cost and infrastructure constraint, upgrading specific high-risk dumpsites (particularly those close to urban boreholes) may offer a more cost-effective mitigation strategy, despite the substantial initial construction expenses.

3.3.2 Soil Stabilization and Immobilization

By increasing sorption capacity, soil amendments like activated carbon and biochar have been demonstrated to decrease the mobility and leaching of organic contaminants PFAS in contaminated soils, thereby reducing the potential for groundwater contamination. Activated carbon, in particular, has demonstrated a long-lasting reduction of PFAS leachability, while the efficacy of biochar may depend on its production conditions and soil organic matter content (Navarro *et al*., 2023; Bui *et al*., 2024).

3.4 Strategic Roadmap for Nigeria

The strategic PFAS plan for Nigeria should begin with achievable actions—screening, hotspot management, and interim standards—while progressively moving toward full regulation and implementation of advanced remediation technologies A possible PFAS strategic roadmap implementation matrix is shown in Table 4.

4.0 Conclusion and Recommendations

This review advances a systems-based understanding of PFAS contamination in Nigeria. Rather than treating PFAS occurrence as isolated findings, it demonstrates how prevailing waste practices—open dumping, informal e-waste recycling, unlined landfills, and wastewater discharge—create structured exposure pathways. By integrating empirical data, exposure assessments, analytical constraints, remediation feasibility, and governance gaps, this work provides a translational foundation for policy development.

Empirical evidence confirms PFAS presence across multiple Nigerian matrices: PFOS and PFOA in surface waters and sediments; multiple congeners in sewage sludge from industrial, domestic, and hospital sources in south-western Nigeria; PFAS in e-waste soils; and biomagnification in the food web of Ologe Lagoon. PFAS contamination has also been detected in drinking water sources in Abakaliki and in early-life exposomes of mother–infant pairs. However, evidence is largely limited to southern and south-western Nigeria, preventing comprehensive population-level risk assessment.

Effective PFAS monitoring is challenged by limited LC–MS/MS availability, absence of nationally endorsed analytical protocols, lack of enforceable drinking water standards, and absence of a national biomonitoring programme. For remediation, granular activated carbon and targeted landfill upgrades are the most feasible near-term interventions, whereas reverse osmosis, high-temperature incineration, and advanced ion exchange remain constrained by energy, cost, and technical expertise.”The novelty of this review lies in explicitly linking PFAS contamination risk to the institutional and infrastructural realities of Nigeria's waste management system, thereby clarifying not only where contamination is occurring but why surveillance gaps persist and how they may be strategically addressed.

Immediate national priorities must include: hotspot-targeted PFAS screening at airports, industrial zones, landfills, and urban wastewater treatment plants; the development of interim drinking water guideline values; investment in LC–MS/MS reference laboratories; and targeted biomonitoring of women of reproductive age, children near waste facilities, and informal sector workers to establish baseline dataset. Addressing these

gaps will require sustained interdisciplinary collaboration between environmental chemists, public health researchers, waste management engineers, and regulatory bodies, supported by adequate domestic research funding and international technical partnerships.

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Declaration

Consent for publication

Not Applicable

Availability of data and materials

The publisher has the right to make the data public

Conflict of Interest

The authors declared no conflict of interest

Ethical Considerations

Not applicable

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Authors' Contribution

Paschal O. Iniaghe conceptualized the study, conducted extensive literature synthesis, analyzed Nigerian waste management frameworks, and drafted the manuscript. Chimere Ezekwe contributed to data interpretation, critical review of PFAS occurrence and exposure pathways, refinement of methodological perspectives, and manuscript editing. Both authors jointly developed the national roadmap recommendations and approved the final version for publication.