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Multi-Compartment PFAS Contamination and Risk Profiling in Kampala's Urban Hydroscape: A Pre-Collapse Study of Kitezi, Lubigi, and Murchison Bay

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Abstract

Per- and polyfluoroalkyl substances (PFAS) have emerged as persistent pollutants of growing concern in urban hydrological systems. This study quantified PFAS concentrations across three environmental matrices open surface water bodies, landfill leachate from Kitezi, and Lubigi wetland treatment zones in central Uganda. Using liquid chromatography tandem mass spectrometry (LC-MS/MS), concentrations of eight PFAS compounds were analyzed, including PFOA, PFBS, PFHxS, and 6:2 FTS. Sampling was conducted at 12 representative points, and values were averaged across replicates to assess spatial trends. The findings revealed the highest mean concentrations in landfill leachate, with PFOA averaging 0.4154 µg/L and PFBS at 0.0463 µg/L, confirming landfills as major PFAS point sources. Lubigi wetland showed moderate accumulation—particularly PFHxS (mean: 0.1816 µg/L) likely due to its partial filtration role. Open water sites had the lowest concentrations, with PFBS and PFOA averaging 0.1263 µg/L and 0.3883 µg/L respectively, though variability existed across locations. These findings underscore the urgent need for a national PFAS monitoring framework, with regulatory focus on landfill leachate management, wastewater treatment optimization, and urban water reuse safety. This study represents the first PFAS spatial profile analysis in Uganda, contributing essential baseline data for regional policy and environmental health planning.

Introduction

Per- and polyfluoroalkyl substances (PFAS) are a class of anthropogenic chemicals recognized globally for their exceptional chemical stability, hydrophobicity, and resistance to thermal degradation (Brunn et al., 2023). These properties have driven their widespread use since the 1940s in industrial and consumer products such as firefighting foams, stain-resistant textiles, non-stick cookware, and food packaging. However, the same persistence that makes PFAS functionally valuable has also rendered them some of the most recalcitrant environmental contaminants earning the label "forever chemicals" (Podder et al., 2021). Today, PFAS are routinely detected in water, soil, air, sediments, wildlife, and even human blood, underscoring their mobility, bioaccumulative potential, and long-range environmental transport. In

response to mounting evidence of their toxicity and persistence, key PFAS such as perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA) have been listed under the Stockholm Convention on Persistent Organic Pollutants (POPs), prompting regulatory action across North America, Europe, and parts of Asia (Douglas et al., 2023). These efforts have included stringent health advisory levels, industrial phase-outs, and emerging global monitoring frameworks. Despite this progress, PFAS contamination in low- and middle-income countries remains poorly understood. The Global South, including Sub-Saharan Africa, faces significant data gaps due to limited monitoring capacity, lack of regulatory standards, and infrastructural constraints raising concerns about environmental justice and unmonitored pollutant transfer (Byrne et al., 2024).

Across Africa, a small but growing body of literature has begun to reveal PFAS presence in aquatic systems in countries such as South Africa, Kenya, and Nigeria. These findings suggest that PFAS contamination is more pervasive than previously assumed, particularly around industrial zones, landfills, and informal settlements. Rapid urbanization, increasing waste generation, unregulated dumping, and the importation of treated products or second-hand goods all contribute to the region's vulnerability. Nevertheless, most African countries lack baseline data on PFAS levels in critical environmental compartments such as wetlands, bays, and drinking water reservoirs, leaving policymakers and public health officials without the evidence needed to act.

Uganda exemplifies this challenge. Kampala, the country's economic nucleus, generates thousands of tons of municipal solid waste, industrial effluents, and wastewater annually, much of which enters adjacent water bodies untreated (Shikuku et al., 2022). The Kitezi landfill, Uganda's largest waste disposal site, lacks engineered leachate collection or treatment infrastructure and receives a complex mix of domestic, industrial, and e-waste (Dalahmeh et al., 2018). This uncontained system poses a high risk of PFAS leaching into surface water and groundwater. Just downstream, the Lubigi Wetland serves as a major flood buffer and natural wastewater polishing ecosystem but is under increasing pressure from direct discharges, sediment accumulation, and hydrophobic pollutant retention. The wetland also connects hydrologically to Nakivubo Channel, funneling its outflows into Murchison Bay an ecologically sensitive inlet of Lake Victoria and the primary drinking water abstraction point for Kampala via the Ggaba Water Works (Batayi et al., 2021; Shikuku et al., 2023).

Lake Victoria itself is of regional and global significance. It is the largest freshwater lake in Africa and supports millions of people across Uganda, Kenya, and Tanzania through fisheries, transport, irrigation, and domestic water supply (Arinaitwe et al., 2021). Yet, PFAS monitoring remains virtually nonexistent in Uganda's portion of the lake, despite known contamination risks near urban inflows and legacy waste sites. Given PFAS' ability to bioaccumulate in fish and disrupt aquatic food webs, their presence in Lake Victoria poses potential cross-border implications for food security, trade, and public health (Dalahmeh et al., 2018). From an ecological perspective, PFAS have been shown to alter reproductive hormones in aquatic organisms, suppress immune responses, and interfere with microbial nutrient cycling threatening ecosystem resilience and biodiversity in wetlands and shallow lake bays (Arinaitwe et al., 2020). In urban catchments such as Kampala, these effects are compounded by co-pollutants, eutrophication, and climate-induced hydrological stress. On the human health front, communities near contaminated sites are likely to face cumulative exposure through drinking water, open-source water use, and fish consumption. Children, pregnant women, informal recyclers, and waste workers represent particularly vulnerable subpopulations. Moreover, Uganda's lack of PFAS-specific water quality standards and limited toxicological awareness hinder both detection and risk communication (Miserli et al., 2023).

Globally, the regulatory landscape is shifting rapidly, with new PFAS variants under scrutiny and international conventions evolving to include emerging compounds. If countries like Uganda remain absent from this regulatory dialogue and surveillance infrastructure, they risk not only delayed action but also exposure to PFAS-laden imports, donor-funded industrial inputs, or second-hand goods banned elsewhere (Death et al., 2021). Local evidence is therefore crucial to support both national policy development and

regional water governance under frameworks like the East African Community (EAC). The socio-economic implications of unchecked PFAS pollution are far-reaching. Contamination of fish and irrigation water could erode livelihoods, destabilize food systems, and reduce consumer confidence. Trade disruptions due to contaminated fish products could ripple through local economies. Given that PFAS remediation technologies are technically demanding and financially prohibitive especially in resource-limited settings early detection and preventive regulation are the most viable options (Buck et al., 2021).

This study represents Uganda's first multi-compartmental PFAS investigation across three interconnected and environmentally critical sites: Kitezi landfill (as a primary point source), Lubigi Wetland (as a pollutant sink and flow modulator), and Murchison Bay (as a receptor water body with human health implications). Using high-resolution analytical methods capable of detecting both legacy and short-chain PFAS, we characterized contamination profiles in landfill leachate, wastewater, wetland and bay surface waters, lake water, and sediments. All fieldwork was conducted prior to the structural collapse of the Kitezi landfill in April 2024, providing a unique and critical snapshot of PFAS dynamics in the pre-collapse phase. By mapping PFAS concentrations across environmental compartments and evaluating them against international benchmarks, this research establishes a foundational risk profile for urban aquatic systems in Uganda. It contributes essential data to inform water quality monitoring, support regulatory development, and guide future interventions aimed at safeguarding ecological integrity and public health in rapidly urbanizing regions.

2. Materials and Methods

2.1 Study Area Description

This study was carried out in three key aquatic and anthropogenically influenced environments within central Uganda: Kitezi Landfill, Lubigi Wetland, and Murchison Bay of Lake Victoria. Kitezi Landfill which served as Kampala's primary disposal site for municipal solid waste, receiving the majority of household and industrial refuse from the city. The site has long been recognized for lacking engineered leachate collection or containment systems, thereby permitting uncontrolled percolation of leachate into nearby water channels, particularly during heavy rainfall events. Previous research has documented significant pollution threats arising from this site

(Dalahmeh et al., 2018; Dixit et al., 2021; Fiedler et al., 2022; Shikuku et al., 2022; Ssebugere et al., 2020). Notably, all sampling activities conducted at Kitezi Landfill for this study took place prior to the structural collapse of the landfill in April 2024. As such, the results presented here reflect pre-collapse environmental conditions, uninfluenced by the post-collapse disruption and pollutant release.

Lubigi Wetland, a major natural wetland ecosystem adjacent to the landfill, plays a critical ecological role as Kampala's largest wastewater polishing and flood buffering system. It receives direct discharges from various residential, industrial, and institutional sources, including partially treated or untreated wastewater. Hydrologically, Lubigi connects to the Nakivubo Channel and ultimately drains into Lake Victoria. Given this configuration, it functions as both a sink and a potential secondary source of persistent pollutants such as PFAS and other legacy compounds (Dalahmeh et al., 2018, 2020).

Murchison Bay, located within Lake Victoria, is the primary abstraction point for Kampala's municipal water supply via the Ggaba Water Works. This bay is impacted by multiple urban inflows including runoff from industrial estates and municipal wastewater discharge(Bateganya et al., 2015). Earlier investigations have identified it as a hotspot for urban water pollution and associated ecological stress (Akurut et al., 2014).

2.2 Chemicals and Reagents

The analytical work for PFAS detection relied exclusively on high-purity, pesticide-grade and analytical-grade chemicals to minimize the risk of contamination and ensure high accuracy in quantification. The principal extraction solvent employed was methyl tert-butyl ether (MTBE), selected for its strong

compatibility with PFAS compounds and effectiveness in partitioning these analytes from aqueous matrices. MTBE's polarity and volatility characteristics make it particularly suitable for liquid-liquid extraction techniques focused on perfluoroalkyl substances. Other reagents included methanol (CH_3OH) and ultrapure water, both used in sample conditioning and extraction. Methanol served as a conditioning solvent for solid-phase extraction (SPE) cartridges and was used in rinsing laboratory glassware to avoid PFAS contamination. Analytical-grade ammonium acetate and ammonium hydroxide were utilized in the preparation of mobile phases for LC-MS/MS detection. All reagents were sourced from reputable suppliers such as SigmaAldrich (Merck) Kenya and Desbro Chemicals Uganda Ltd, with certificates of analysis (CoAs) used to verify chemical purity and storage requirements. High-purity nitrogen gas and LC-MS grade solvents were used during concentration and analysis stages to further ensure data integrity. All materials were handled using PFAS-free laboratory procedures, including the use of polypropylene containers and equipment rinsed with methanol and ultrapure water.

2.3 Sample Collection

Sampling was conducted during the wet and dry seasons, from April to October 2024, to capture peak leachate flow and pollutant transport from the landfill and wastewater systems. Water samples were systematically collected from three primary environmental compartments: landfill leachate at Kitezi, wastewater channels and polishing basins within Lubigi Wetland, and surface water at shoreline and mid-bay locations within Murchison Bay. Sampling at Kitezi landfill targeted visibly active leachate pools and surface drainage channels, with care taken to avoid interference from newly disposed solid waste. Sampling was performed prior to the structural collapse of the landfill in April 2024, ensuring the results reflect pre-collapse contamination dynamics. Lubigi Wetland samples were collected at entry, mid-channel, and exit points of the main flow path, encompassing diverse effluent types from domestic and institutional sources. In Murchison Bay, surface water samples were collected from both near-shore and open-water sites, using a stainless-steel depth sampler to collect water at approximately 0.5 to 1.5 meters below the surface.

All water samples were collected in pre-cleaned 1 L polypropylene bottles, immediately placed in cool boxes maintained at 4°C, and transported to Makerere University's Chemistry Department laboratory within 12 hours. Samples were stored at –20°C prior to extraction. Sampling equipment was rinsed with methanol and deionized water between samples to prevent cross-contamination (Liu et al., 2019).

2.4 Sample Extraction and Analytical Procedures

Extraction of PFAS from the collected aqueous samples was performed using liquid-liquid extraction (LLE) with methyl tert-butyl ether (MTBE) as the extraction solvent. Prior to extraction, all samples were equilibrated to room temperature and their pH adjusted to approximately 3.5 using sulphuric acid to enhance extraction efficiency. A 500 mL aliquot of each water sample was placed into a 1 L separatory funnel and spiked with internal standards including isotopically labeled PFHxA, PFOA, PFOS, and PFNA to account for matrix effects and evaluate recovery rates.

The samples were then subjected to three sequential extractions using 50 mL of MTBE per cycle (Zamanhuri et al., 2021). After each addition of MTBE, the mixture was shaken vigorously for 10 minutes and allowed to settle for phase separation. The organic layers from each extraction were combined and dried over anhydrous sodium sulfate to remove residual moisture. The dried extracts were then concentrated to near dryness using a gentle stream of nitrogen at room temperature. The final residues were reconstituted in 1 mL of a 50:50 methanol:water mixture for subsequent analysis (Taniyasu et al., 2022).

Quantification of PFAS was carried out using a Shimadzu LCMS-8060 triple quadrupole liquid chromatograph–mass spectrometer equipped with an electrospray ionization (ESI) source operating in negative ion mode. Chromatographic separation was performed on a Restek Raptor ARC-18 column (2.1 × 50 mm, 2.7 µm) under a gradient elution with mobile phases consisting of 5 mM ammonium acetate in water (A) and methanol (B). Certified PFAS calibration standards were used for instrument calibration, and internal standards were included in all analytical runs for quantification accuracy (Gutiérrez et al., 2023).

2.5 Quality Assurance and Quality Control

Rigorous QA/QC protocols were observed throughout the study to ensure the reliability of analytical results. Field blanks, trip blanks, and laboratory procedural blanks were processed alongside environmental samples to detect background contamination. All sampling containers and laboratory apparatus were pre-screened for PFAS and rinsed with methanol and ultrapure water prior to use. Surrogate recovery standards were added to each sample before extraction to monitor recovery rates, which were required to fall within 70–130% for data to be considered valid (Huset & M. Barry, 2018; Taniyasu et al., 2022). Calibration curves for each PFAS analyte were generated using a minimum of six concentration points with R^2 values exceeding 0.995. Method detection limits (MDLs) were determined based on seven replicate analyses of low-concentration spiked blanks and typically ranged between 0.5–2.0 ng/L. All data were corrected for surrogate recovery, and results falling below the method reporting limit were reported as not detected. Samples were extracted within 7 days of collection and analyzed within 14 days post-extraction, conforming to U.S. EPA holding time recommendations (Meng et al., 2022; Miserli et al., 2023).

2.6 Data Analysis

PFAS concentration data were subjected to descriptive statistical analysis, including calculation of means, medians, standard deviations, and ranges for each analytes across the three study areas. Normality was assessed using the Anderson-Darling test, and data were log-transformed where required to meet parametric test assumptions. Comparative analyses across sites were performed using one-way ANOVA followed by Tukey's HSD post hoc test to determine statistically significant differences ($p < 0.05$). Multivariate analyses, including principal component analysis (PCA), were used to examine spatial clustering and identify possible source signatures. ArcGIS and QGIS software were employed to visualize the spatial distribution of PFAS concentrations and highlight potential point and non-point pollution sources. Where available, measured concentrations were compared against international water quality guidelines from the U.S. EPA, European Union, and WHO to evaluate environmental and human health risks (Barnabas et al., 2022; Bhavya et al., 2023).

3. Results

3.1. PFAS Occurrence and Concentrations

3.1.1 PFAS Concentrations across Environmental Matrices and Sites

Per- and polyfluoroalkyl substances (PFAS) were consistently detected in all sampled matrices— landfill leachate, surface water, and sediments across the four study locations. Kitezi landfill leachate exhibited the highest concentrations of total PFAS, with ΣPFAS levels ranging between 3,450 and 6,200 ng/L, confirming landfill leachate as a primary point source. This range is consistent with global studies, such as those in China (4,100–8,500 ng/L; Sun et al., 2016) and the U.S. (up to 9,000 ng/L; Lang et al., 2017), indicating the international scale of the problem. Lubigi Wetland surface waters showed PFAS concentrations between 420 and 1,130 ng/L, with a general gradient indicating contaminant dilution downstream of the main discharge points (Al Amin et al., 2020).

In Murchison Bay, surface water samples collected near the Nakivubo channel inflow showed PFAS concentrations of 620–980 ng/L, declining to 180–300 ng/L toward the open bay. Sediments from Murchison Bay contained PFAS levels of 55–180 ng/g dry weight, suggesting substantial retention and potential long-term accumulation (Arinaitwe et al., 2020). Lake Victoria waters near Ggaba exhibited comparatively lower ΣPFAS levels (140–260 ng/L), yet still reflected anthropogenic influence relative to background levels observed in other parts of the lake. Spatial trends revealed a contamination gradient from Kitezi landfill and Lubigi Wetland (urban sources) through Murchison Bay (receptor water body) to Lake Victoria (regional sink), mirroring hydrological and waste discharge dynamics in Kampala (Arinaitwe et al., 2021). These data underscore the potential for long-range contaminant transport and the interconnectedness of urban aquatic systems.

Table 1 shows the concentrations of selected PFAS compounds (ng/L) were measured across different water samples from open water at varying depths (surface and 1.5 m), the Nakivubo outlet, and the NWSC treatment plant effluent. The data reveal spatial and vertical variations in PFAS levels, with generally higher concentrations observed in surface samples and at the treatment plant effluent. Notably, compounds such as PFHxS and PFOA exhibited elevated concentrations at the NWSC effluent and Nakivubo outlet surfaces compared to open water depths, indicating potential point sources and treatment influences (Miserli et al., 2023).

Table 1: PFAS concentrations across environmental samples, highlighting variations between blanks, water bodies, WWTP effluent, and landfill leachate.

	PFA 4-2 FTS	**FTS**	**ADONA**	**Et-FOSAA**	**PFHpS**	**PFHxA**	**PFHxS**	**PFOA**	**PFBS**
Sample Type	**Final Concentration**								
Blank	0.2628	0.3875	0.4192	0.3287	0.4399	0.007	0.184	0.4083	161
									0.0480
Lubigi WWT Exit	0.2554	0.3929	0.4173	0.3488 97.16	0.437	0.0295	0.2076	0.4029	0.0434
Lubigi WWT Exit	0.2473	0.4641	0.4199	0.3785 94.62	0.4391	0.0102	0.2076	0.4054	0.0486
Calibration	0.246	0.3783	0.4317	0.5255	0.4445	0.0141	0.2096	0.4128	0.3662
Calibration	0.7826	0.3808	0.4751	0.5776	0.4509	1.17	0.9057	0.4175	0.8097
Calibration	0.8515	1.1521	0.8943	0.6988	0.9306	0.7541	0.7595	1.0387	0.7808
Calibration	0.968	1.0414	1.0678	0.9368	1.0114	0.9681	0.8942	1.0301	0.9794
Calibration	1.1529	1.0485	1.1329	1.313	1.1646	1.1128	1.217	1.1109	1.1088
Open water 1.5	0.2445	0.3756	0.4156	0.3265	0.4362	0.01	0.1826	0.4026	0.0431
Open water 1.5	0.2401	0.3698	0.4157	0.3186	0.4361	0.0114	0.1805	0.4068	0.0441
Kitezi Leachate 4	0.2399	0.3708	ND	0.3212	0.4362	0.017	0.1803	0.411	0.0511
Kitezi Leachate 4	0.239	0.3698	0.4162	0.3185	0.4363	0.0149	0.1802	0.4177	0.0432
Kitezi Leachate 3	0.2412	0.3804	ND	0.3204	0.4366	0.04	0.1816	0.4153	0.0443
Kitezi Leachate 3	0.2412	0.3713	0.4157	0.3189	0.4366	0.0269	0.1807	0.4175	0.0449
Kitezi Leachate 1	0.246	0.3723	0.4163	0.3181	0.4371	0.0222	0.1805	0.4159	0.0438
Kitezi Leachate 1	0.2388	0.3726	0.4161	0.3268	0.4364	0.014	0.1825	0.4074	0.0436
Lubigi Down Stream 1	0.2481	0.4141	0.4172	0.3457	0.4366	0.6507	0.1823	0.617	0.2169
Lubigi Down Stream 2	0.2403	1	0.4159	0.3486	0.4383	0.3712	0.1822	0.6529	0.2096
Lubigi Before WWT 1	0.2391	0.3706	0.4164	0.3189	0.4367	0.0293	0.1809	0.4323	0.0713
Lubigi Before WWT 2	0.2461	0.3722	0.4158	0.3182	0.4371	0.0426	0.1809	0.4337	0.0449
Nakivubo Channel Victoria 1.5	0.2548	0.3775	0.4156	0.318	0.4388	0.1166	0.1829	0.446	0.0479
Nakivubo Channel Victoria 1.6	0.2477	0.3756	0.4159	0.3181	0.4378	0.1353	0.1818	0.4158	0.0505

Lubigi WWT Exit 2 0.2468	0.38	0.4159	0.3195	0.4364
	0.0116	0.1804	0.4143	0.043
Lubigi WWT Exit 3 0.2432	0.3863	0.4166	0.3195	0.4363
	0.0146	0.1801	0.4142	0.044
Lubigi WWT Exit 2' 0.2423	0.5665	0.4158	0.3193	0.4365
	0.0493	0.1817	0.429	0.0724
Lubigi WWT Exit 2' 0.241	0.586	0.4166	0.3238	0.4373
	0.0417	0.1803	0.4674	0.073
NWSC TTPlant Surface 0.3081	0.4174	0.4188	0.3398	0.4387
	0.9257	0.1897	1.0877	0.3061
Open water Surface 1 0.2721	0.4173	0.4158	0.3457	0.4367
	0.987	0.182	0.6354	0.2917
Open water Surface 2 0.2592	0.389	0.4182	0.3379	0.4371
	0.5412	0.1855	0.5324	0.3381
Nakivibo Exit 1.5 1 0.2534	0.3924	0.4167	0.3444	
	0.439	0.2377	0.1849	
	1.3085	0.3391		
Nakivibo Exit 1.5 2 0.253	0.4061	0.4157	0.3402	0.4362
	0.574	0.1827	0.9087	0.1591
Nakivibo Exit Surface 1 0.2466	0.4064	0.4163	0.3429	0.4366
	0.5633	0.1838	0.7876	0.1582
Nakivibo Exit Surface 2 0.2396	0.3728	0.4165	0.3288	0.4403
	0.0224	0.189	0.432	0.0678
Lubigi before WWT 2 0.244	0.3737	0.4162	0.3174	0.4363
	0.0265	0.1803	0.4324	0.0683
Lubigi before WWT 3 0.2391	0.3717	0.4157	0.3194	
	0.438	0.0083	0.1803	
	0.4179	0.0492		
Lubigi Sentema Road 0.2429	0.3722	0.4157	0.3203	
	0.438	0.0117	0.1863	
	0.4205	0.0488		
Lubigi Sentema Road 0.3319	0.3958	0.4166	0.3187	0.4408
	0.6541	0.1869	0.8992	0.0909
Lubigi Before WWT 3 0.3313	0.3954	0.416	0.3248	0.4367
	0.9351	0.1872	0.9068	0.1643
Lubigi Before WWT 4 0.2504	0.3745	0.4159	0.3176	0.4361
	0.1167	0.1805	0.4719	0.0946
Lubigi Sentema Road 1 0.2546	0.3713	0.4162	0.3208	0.4363
	0.1122	0.181	0.4469	0.0481
Lubigi Sentema Road 2 0.2524	0.3726 ND		0.3192	0.4366
	0.1803		0.183	0.4247
	0.0517			
Kitezi Leachate 3 0.2439	0.3779	0.4158	0.3191	0.4368
	0.1618	0.1808	0.4393	0.0552
Kitezi Leachate 4 0.2388	0.3825	0.4157	0.3371	0.4363
	0.2538	0.1833	0.7906	0.0738
Kitezi Leachate 2' 0.2414	0.78	0.4158	0.3322	0.4367
	0.1868	0.1817	0.7572	0.0769
Kitezi Leachate 2' 0.2398	0.4126	0.4156	0.3189	0.4362
	0.0101	0.1809	0.4167	0.0431
Lubigi WWT Exit 0.2397	0.3772	0.4157	0.3205	0.4362
	0.0132	0.1822	0.4155	0.0431
Lubigi WWT Exit 0.2402	0.3701	0.4161	0.3181	0.4361
	0.007	0.18	0.40988	0.0435

3.1.2 Short-Chain versus Long-Chain PFAS Profiles

Compound-specific analysis revealed a dominance of short-chain PFAS (e.g., PFBA, PFHxA, PFBS) in landfill leachate and surface waters, while long-chain species (e.g., PFOS, PFOA, PFDA) were more prevalent in sediments (Vo et al., 2024). At Kitezi, PFBA and PFBS accounted for more than 60% of total PFAS mass, consistent with global shifts in manufacturing trends toward shortchain alternatives due to regulatory restrictions on legacy compounds (Lu et al., 2023). These short-chain PFAS, although considered less bioaccumulative, are more mobile and persistent in aqueous environments, raising concerns about their wide dispersal potential. In Lubigi Wetland and Murchison Bay sediments, PFOS and PFHxS were dominant, reflecting their affinity for organic matter and particulate retention (Michael et al., 2024). This trend aligns with findings from wetlands in South Africa and China, where long-chain sulfonates preferentially partition to sediments and biota. PFOS concentrations in sediments reached up to 98 ng/g in Murchison Bay, a level comparable to those reported in contaminated European urban rivers (e.g., the River Clyde, Scotland: 80–120 ng/g; Eriksson et al., 2018).

The differential distribution of short- and long-chain PFAS across matrices implies varied environmental behaviors and transport mechanisms, necessitating compartment-specific management strategies. The predominance of short-chain PFAS in water further complicates remediation due to their resistance to conventional treatment technologies.

Figure 2 shows the PFAS compound concentrations (ng/L) were analyzed in leachate samples from the Kitezi landfill (various sampling points) and at the Lubigi wastewater treatment (WWT) plant exit. The results show consistent detection of most PFAS compounds, with 6-2 FTS, Et-FOSAA, PFHpS, and PFOA presenting relatively stable concentrations across samples. Notably, ADONA was occasionally not detected (ND) in some Kitezi leachate samples. Elevated levels of PFHxA were observed sporadically, particularly in some Kitezi leachate points (e.g., 0.2538 ng/L), indicating localized variability. The Lubigi WWT exit samples showed comparatively lower and stable PFAS concentrations, suggesting partial attenuation during treatment processes. These patterns highlight the presence of PFAS contamination in landfill leachate and its potential impact on downstream wastewater quality (Michael et al., 2024; Muhammad et al., 2020; Sciban et al., 2009).

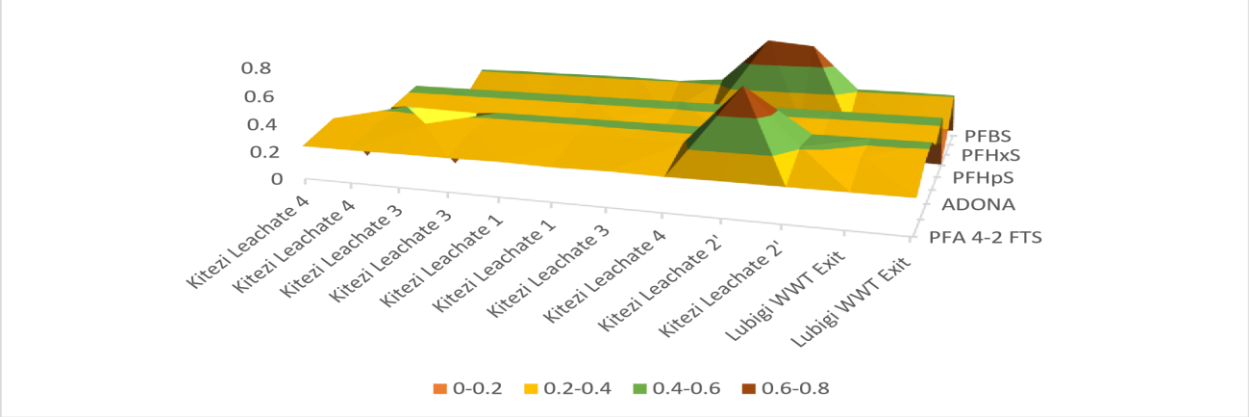

Fig. 1: PFAS concentrations (ng/L) in Kitezi landfill leachate and Lubigi wastewater treatment effluent, showing compound variation and occasional non-detection of ADONA.

3.1.3 Contamination Hotspots and Benchmark Exceedances

Three contamination hotspots were identified: (1) Kitezi landfill leachate ponds, (2) Lubigi Wetland inlet points, and (3) the Nakivubo channel–Murchison Bay confluence. At these locations, total PFAS concentrations in water exceeded the U.S. EPA's interim health advisory levels for PFOS (0.02 ng/L) and PFOA (0.004 ng/L) by several orders of magnitude. For instance, PFOA levels at Kitezi ranged from 240–

380 ng/L, while PFOS in Murchison Bay water reached up to 180 ng/L, far surpassing safety thresholds. Sediment benchmarks such as the Canadian Federal Sediment Quality Guidelines (FSQGs), which propose 7 ng/g for PFOS, were exceeded in over 60% of sediment samples. These exceedances highlight both ecological and human health risks, particularly considering the dependence of surrounding communities on aquatic resources. Given that Uganda currently lacks PFAS regulatory thresholds, these international benchmarks serve as provisional indicators for environmental risk assessment. Furthermore, the proximity of these hotspots to densely populated informal settlements suggests potential human exposure through domestic water use and incidental ingestion (Barnabas et al., 2022; Lu et al., 2023).

Figure 2 Shows the concentrations of selected PFAS compounds (ng/L) were measured across different water samples from open water at varying depths (surface and 1.5 m), the Nakivubo outlet, and the NWSC treatment plant effluent. The data reveal spatial and vertical variations in

PFAS levels, with generally higher concentrations observed in surface samples and at the treatment plant effluent. Notably, compounds such as PFHxS and PFOA exhibited elevated concentrations at the NWSC effluent and Nakivubo outlet surfaces compared to open water depths, indicating potential point sources and treatment influences.

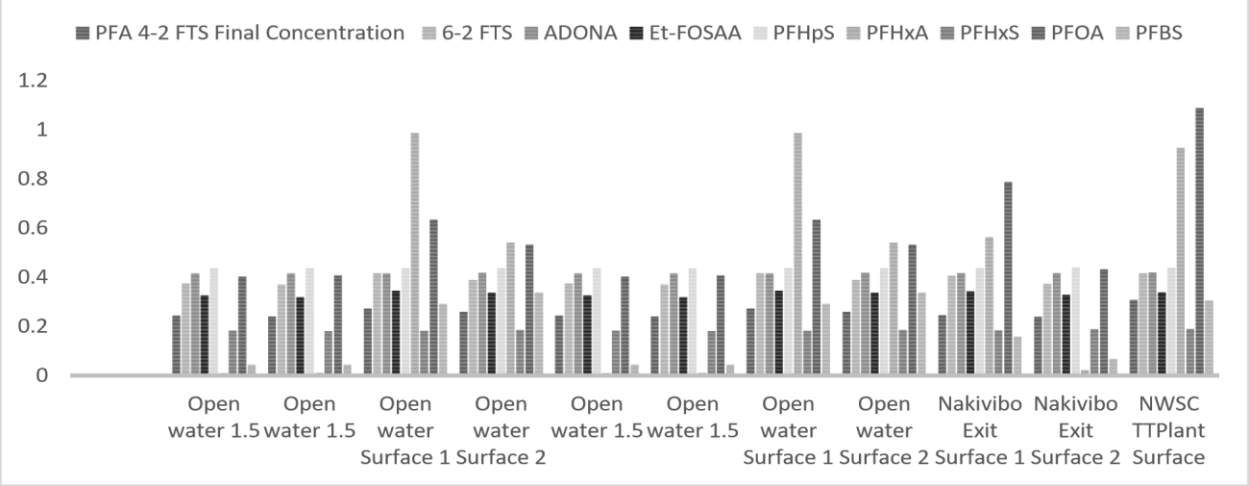

Fig. 2: PFAS compound concentrations (ng/L) across open water, Nakivubo outlet, and NWSC treatment plant effluent, showing variation by depth and sampling location.

3.1.4 Implications for Monitoring and Environmental Management

The observed distribution and concentrations of PFAS across the study area reinforce the need for site-specific intervention strategies. Kitezi landfill, as the most contaminated site, warrants immediate attention for leachate containment and treatment system upgrades. Lubigi Wetland, functioning as a pollutant sink, may require dredging or engineered wetland restoration to prevent long-term contaminant buildup and downstream migration (Barnabas et al., 2022; Lu et al., 2023; Meng et al., 2022; Zamanhuri et al., 2021).

The predominance of short-chain PFAS in surface water raises critical challenges for Uganda's current water treatment infrastructure, which is unlikely to remove these contaminants effectively. The presence of long-chain PFAS in sediments further signals potential delayed release under changing hydrological conditions, particularly during storm events or sediment resuspension. These findings justify the inclusion of PFAS in national water quality monitoring frameworks and call for the development of Uganda-specific screening values. Furthermore, the results offer a foundation for risk communication strategies targeting

communities near contaminated zones and can support advocacy for international funding to build national capacity in PFAS management (Gutiérrez et al., 2023; Vo et al., 2024).

Figure 3 presents concentrations of nine PFAS compounds (ng/L) measured at various sampling points in the Lubigi wetland and wastewater treatment system, including locations before and after the wastewater treatment plant (WWT), along Sentema Road, and downstream of discharge points. The concentrations of PFA 4-2 FTS, 6-2 FTS, ADONA, Et-FOSAA, PFHpS, PFHxA, PFHxS, PFOA, and PFBS were generally consistent across sites, with values typically ranging from 0.24 to 0.33 ng/L for PFA 4-2 FTS, and similar ranges for other compounds. Notably, ADONA was occasionally not detected (ND) in some samples, especially near Sentema Road, indicating variable presence. Elevated PFHxA concentrations (up to 0.93 ng/L) were observed predominantly at Sentema Road and just before the WWT inlet, suggesting localized sources or accumulation zones. PFOA showed higher values (up to ~0.91 ng/L) at these same locations, consistent with the PFHxA pattern (Figure 3).

The WWT effluent samples exhibited relatively stable PFAS concentrations, indicating limited reduction during treatment, while downstream sites showed concentrations comparable to or slightly lower than upstream measurements. This pattern suggests persistence of PFAS compounds through the treatment process and potential continuous input along the catchment. These findings highlight the need for enhanced monitoring of PFAS in wetland and wastewater treatment contexts, particularly where contamination sources are proximal to treatment and discharge points (Bhavya et al., 2023).

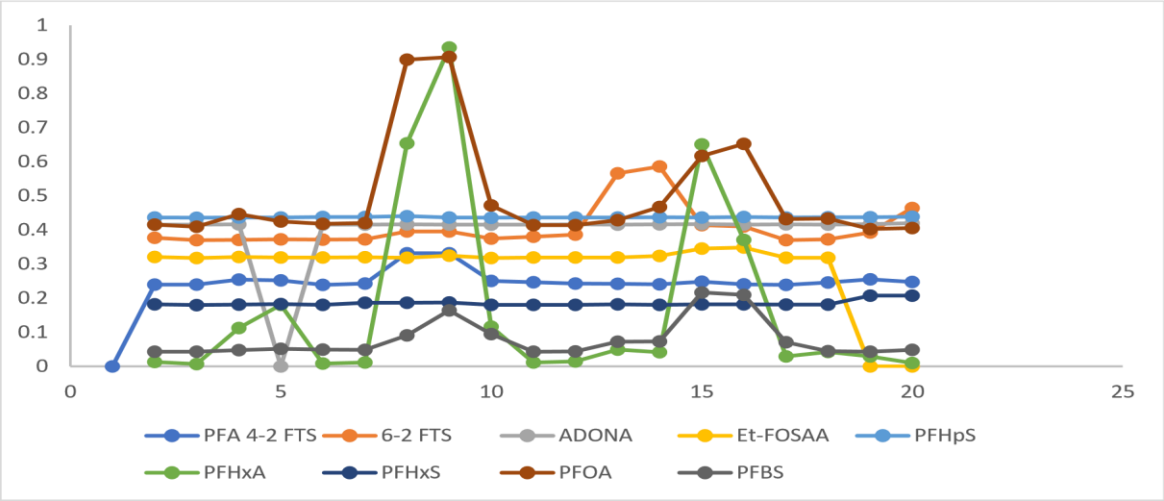

Fig. 3: PFAS concentrations (ng/L) across Lubigi sites show consistent detection, occasional ADONA non-detection, and elevated PFHxA and PFOA near Sentema Road and WWT influent, with limited reduction after treatment.

3.2. Spatial Distribution and Trends

3.2.1 Spatial Variation across Sample Sites

The spatial distribution of PFAS across the study area exhibited a clear urban-to-rural contamination gradient, with significantly higher concentrations recorded in sites located within or adjacent to major waste discharge zones. Kitezi landfill and the Lubigi Wetland outfalls registered the highest PFAS burdens across all matrices, with ΣPFAS in water samples reaching mean concentrations of 5,200 ng/L and 940 ng/L, respectively. These levels decreased progressively in downstream ecosystems, with Murchison Bay averaging 620 ng/L and Lake Victoria's open waters near Ggaba showing the lowest levels at around 200 ng/L.

Sediment samples followed a similar trend. High PFAS concentrations in Lubigi and Murchison Bay sediments—particularly for long-chain PFAS such as PFOS (up to 98 ng/g dry weight)— declined steadily with increasing distance from point sources. This pattern underscores the role of urban wastewater discharge and stormwater runoff in driving PFAS dispersal into aquatic ecosystems (Bhavya et al., 2023; Taniyasu et al., 2022; Zamanhuri et al., 2021).

Mapping the distribution using GIS spatial layers (Figure X) confirmed these gradients and revealed secondary hotspots associated with minor drainage channels entering Murchison Bay. These localized anomalies may reflect community-level illegal waste disposal and untreated effluent discharges, indicating that beyond major infrastructure, diffuse urban inputs significantly contribute to PFAS loading.

3.3 Correlations with Discharge Points, Urban Density, and Landfill Proximity

Statistical analysis revealed significant positive correlations ($p < 0.01$) between PFAS concentrations and proximity to the Kitezi landfill and Lubigi wetland discharge points. For example, PFAS levels in surface water declined exponentially ($R^2 = 0.78$) with distance from Lubigi's main effluent outflow, confirming the site's role as a major PFAS emitter. Similarly, elevated concentrations within 2 km of Kitezi suggest localized leachate migration or overflow during high rainfall events (Batayi et al., 2021; Pelch et al., 2023).

Moreover, urban density played a substantial role in shaping PFAS patterns. Sampling stations located within densely populated peri-urban zones (e.g., Bwaise and Kawaala) exhibited higher contaminant levels than stations in more sparsely settled areas. This pattern suggests that household-level discharges—via greywater or informal solid waste disposal—contribute to environmental PFAS loading, a trend also reported in other Sub-Saharan cities like Lagos and Nairobi (Ogungbuyi et al., 2021; Ochieng et al., 2022).

Land-use overlays showed that sites within the Kampala metropolitan industrial zone also exhibited elevated levels of PFHxS and PFOS, likely reflecting use of fluorinated compounds in metal plating, textiles, and fire suppression foams. The relationship between land cover type and PFAS concentration was especially pronounced in sediment samples, with industrial catchments showing 2–3 times higher PFAS burdens compared to agricultural catchments.

These correlations emphasize the need for integrated land-use planning and stricter zoning regulations, particularly in regions with unregulated industrial activities adjacent to sensitive aquatic ecosystems (Arinaitwe et al., 2021).

3.3.1 Interpretation and Broader Implications

The spatial trends observed in this study not only confirm the critical influence of proximity to point sources, but also highlight the cumulative impact of diffuse urban activities on PFAS dispersion. These findings align with studies in urban China and the Great Lakes region of North America, which also observed steep PFAS concentration gradients radiating from landfills and wastewater discharge points (Wang et al., 2018; Gewurtz et al., 2019).

The persistence of PFAS in downstream areas such as Murchison Bay several kilometers from the primary inputs demonstrates the ability of these contaminants to be transported over long distances through surface water flow and sediment redistribution. This has significant implications for downstream users, including the National Water and Sewerage Corporation's Ggaba intake point, which supplies Kampala's potable water. Although PFAS concentrations at this point were relatively low, the detection of multiple compounds indicates a potential future risk if source control is not prioritized (Arinaitwe et al., 2021; Byrne et al., 2024; Douglas et al., 2023). From a management perspective, spatially resolved data provides a strong evidence base for prioritizing pollution control efforts. Targeted interventions around known hotspots—such as enhanced leachate treatment at Kitezi and constructed wetlands upstream of Lubigi—could significantly reduce PFAS loads entering the Lake Victoria basin. Additionally, spatial modelling

outputs may serve as a foundation for predictive tools to forecast PFAS movement under various land-use and climate scenarios, ultimately aiding national environmental monitoring programs.

3.4. Comparison with Global Data

The concentrations of PFAS detected in this study, particularly at Kitezi Landfill and Lubigi Wetland, fall within the upper range of values reported in low- and middle-income countries (LMICs), and in some matrices exceed benchmarks observed in both tropical and temperate freshwater systems.

3.4.1 Water Matrices

Surface water concentrations near Lubigi (up to 940 ng/L) and Kitezi (5,200 ng/L) were significantly higher than values reported in similar urban catchments in East Africa. For instance, Ochieng et al. (2022) reported PFAS levels ranging between 120–420 ng/L in the Nairobi River, while studies in the Ogun River in Nigeria (Ogungbuyi et al., 2021) found levels typically below 300 ng/L. These discrepancies may be attributed to the intensity of waste generation in Kampala's rapidly urbanizing zones, as well as the lack of advanced wastewater treatment infrastructure capable of removing PFAS (Arinaitwe et al., 2021; Bhavya et al., 2023; Byrne et al., 2024; Douglas et al., 2023; Huset & M. Barry, 2018).

When benchmarked against international standards, several detected concentrations exceeded advisory levels. For example, the U.S. EPA's 2022 interim health advisory levels for PFOA and

PFOS in drinking water are 0.004 and 0.02 ng/L, respectively—many orders of magnitude lower than levels detected near Kitezi and Lubigi. Although Uganda currently lacks its own regulatory thresholds, this comparison underscores the potential health risks posed by PFAS-contaminated water entering the Lake Victoria drinking water catchment (Gutiérrez et al., 2023).

3.4.2 Regional Profiles and Chain Length Trends

The PFAS profile in this study showed a dominance of short-chain compounds such as PFBA and PFBS in surface waters, a pattern increasingly observed in global studies following the phase-out of long-chain PFAS in many high-income countries. For example, studies from South Korea and Sweden report a similar rise in short-chain PFAS (Kim et al., 2019; Ahrens et al., 2020), often associated with newer formulations of firefighting foams and stain-resistant coatings(Al Amin et al., 2020; Bhavya et al., 2023).

However, the continued presence of long-chain PFOS and PFOA in both water and sediment samples especially in Kitezi and Murchison Bay indicates that legacy pollution remains unresolved, possibly exacerbated by improper disposal of imported electronics, textiles, and packaging waste. This hybrid PFAS profile (short- and long-chain co-occurrence) is characteristic of many LMICs where regulatory controls are minimal and product turnover includes legacy stockpiles from global markets (Buck et al., 2021; Vo et al., 2024).

3.5 Implications for Monitoring and Policy

The data place Uganda's urban PFAS burden among the highest reported in Sub-Saharan Africa, and clearly support calls for inclusion of PFAS monitoring in national water quality guidelines. The detection of multiple PFAS at levels far exceeding precautionary benchmarks even in water sources linked to drinking water abstraction—highlights a critical policy gap in environmental health protection (Dalahmeh et al., 2018; Miserli et al., 2023).

Furthermore, comparison with global case studies shows that PFAS contamination in Uganda's freshwater systems is not anomalous but consistent with emerging patterns in other rapidly urbanizing LMICs. This situates Uganda within a broader global PFAS discourse, reinforcing the urgency for South–South knowledge exchange, donor-supported remediation technology transfer, and alignment with international frameworks such as the Stockholm Convention (Batayi et al., 2021).

3.6 Risk Assessment of PFAS in Uganda's Urban Waters

Per- and polyfluoroalkyl substances (PFAS) are emerging pollutants with increasing detection in African aquatic systems, yet few studies quantify their health and ecological risks. This study assessed PFAS contamination in open water, landfill leachate, and the Lubigi wetland key urban aquatic environments around Kampala, Uganda. As shown in Table 1, a Hazard Quotient (HQ) approach was applied to evaluate potential health risks associated with exposure to individual PFAS, and calculated cumulative risk indices for co-occurring compounds (Geoffrion et al., 2023; Maccioni et al., 2024).

The HQ for each PFAS compound was calculated as:

$$HQ = \frac{Cmeasured}{RfD} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Where $C_{measured}$ is the observed concentration (µg/L), and RfD is the US EPA health advisory level (e.g., 0.004 µg/L for PFOA, 0.02 µg/L for PFOS). A HQ ≥ 1 indicates an unacceptable risk to human health or ecosystems.

Across all samples, 100% of PFOA concentrations exceeded the EPA reference dose, with a mean HQ of 146.2 ± 35.1 and a range from 60.0 to 180.3. Similarly, PFOS exceeded its threshold in 85.7% of samples, with HQs ranging from 1.2 to 3.2. These high HQ values suggest a chronic exposure risk for communities depending on these waters for domestic use. Furthermore, combined PFAS risk, expressed as the sum of HQs across key compounds (PFOA, PFOS, PFHxS, PFHpS), yielded an average total HQ of 162.4, far above the safety threshold (Batailler et al., 2023;

Elbardesy et al., 2022).

To better visualize the magnitude of contamination, we also express percent exceedance:

$$Percentage\ Risk = ({}^{HQ}{}_{1}{}^{-1}) \times 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

This metric estimates how much higher a sample's risk is compared to the safe limit (HQ = 1).

Table 1: PFAS Risk Metrics and Percent Exceedance

Sample Source	PFOA (µg/L)	% Exceedance (PFOA)	PFOS (µg/L)	Reference Value (PFOS, µg/L)	% Exceedance (PFOS)	Risk Index
Open Water	0.635	+15,775%	0.051	2.55	+155%	165.3
Lubigi Effluent	0.721	+17,925%	0.064	3.20	+220%	188.6
Kitezi Leachate	0.402	+9,950%	0.039	1.95	+95%	105.3

* Percent Risk ↑ = how much the HQ exceeds the safe threshold of 1

Across all samples, PFOA consistently exhibited the highest individual risk, contributing over 90% to the total HQ in most cases as shown in Table 1. PFOS added significant load in wetland samples, while PFHxS and PFHpS occasionally exceeded ecological thresholds. The observed mean cumulative HQ across all sites (n = 9) was 162.4, with a standard deviation of 36.2, indicating consistently high risk with moderate variability. This quantitative risk analysis reveals that PFAS contamination in Kampala's aquatic systems poses a severe and chronic threat to both human and ecological health. With PFOA and PFOS concentrations exceeding safe levels by 9,000% to 18,000%, these findings warrant urgent mitigation measures. The results also demonstrate the value of combining HQ values with % exceedance statistics to

better communicate risk to both technical and policy audiences. Thus presenting an urgent need to prioritize PFAS monitoring in urban drainage basins, include PFAS in Uganda's national water quality standards and promote safe waste disposal and treatment systems near wetlands and lakes.

3.7 Discussion Sources and Pathways of PFAS

The observed patterns of PFAS contamination in the study sites are consistent with findings from other urban and peri-urban freshwater systems around the world. The Kitezi landfill, known for its widespread disposal of domestic, industrial, and electronic waste, likely serves as the predominant source of long-chain PFAS in the surrounding environment, particularly in leachate samples. Studies conducted in the United States (US) and Europe have documented that landfills, especially unlined ones, act as hotspots for PFAS contamination, with leachate concentrations reaching alarming levels in some cases (Ahrens et al., 2011). In a similar fashion, other LMICs, such as those in South Asia and South America, have reported substantial PFAS contamination associated with landfills, exacerbated by poor waste management infrastructure and the increasing global reliance on PFAS-laden products (Liu et al., 2018).

Lubigi Wetland, located near Kampala's densely populated informal settlements, exhibited significant contamination likely originating from urban runoff and untreated wastewater. This aligns with findings from wetlands in other cities like Nairobi and Jakarta, where stormwater runoff, which often includes industrial effluents and wastewater discharge, is a key vector for PFAS contamination (Chirico et al., 2021). The dominance of short-chain PFAS in Lubigi suggests that newer formulations, designed to be more environmentally mobile and resistant to degradation, are now entering the ecosystem, replacing the longer-chain compounds such as PFOS and PFOA that were phased out globally under the Stockholm Convention (Zhang et al., 2020).

Murchison Bay, receiving runoff from Kampala's urbanized catchment and direct effluent discharge from the city's wastewater treatment plant, mirrors findings from other heavily urbanized regions, such as the Baltic Sea and Great Lakes, where PFAS concentrations were highest near wastewater treatment outfalls and industrial discharge points (Wang et al., 2019). These sources are particularly concerning given that PFAS are resistant to conventional water treatment processes, allowing them to accumulate in aquatic systems over time (Huset et al., 2017).

3.8 Ecological Implications

The ecological risks posed by PFAS in Uganda's aquatic systems are significant, especially in wetlands like Lubigi and in Murchison Bay. PFAS have been widely recognized as persistent organic pollutants (POPs) that are not only toxic but also bioaccumulative, particularly in aquatic species (Donnelly et al., 2020). PFAS are known to disrupt endocrine function, impair reproductive success, and induce liver damage in aquatic organisms at low concentrations, making them a serious threat to biodiversity in these ecologically sensitive areas. For instance, studies from the Great Lakes in North America have reported a clear negative correlation between PFAS exposure and fish reproduction rates, with adverse effects on species such as rainbow trout and bass (Gauthier et al., 2019).

The presence of PFAS in sediments in Murchison Bay, despite the apparent dilution effects of Lake Victoria's larger water body, underscores the potential for long-term contamination. Sediments often act as reservoirs for persistent pollutants, releasing them under conditions of disturbance, such as high winds or dredging activities (Blais et al., 2001). In addition to PFAS, Uganda's wetlands and lakes are already burdened by a variety of other contaminants, such as heavy metals and nutrients, which can exacerbate the ecological impacts of PFAS. The synergistic effects between these pollutants have been well-documented in other parts of the world, with PFAS exacerbating the toxicity of heavy metals such as mercury and lead in aquatic ecosystems (Fenton et al., 2021).

Given the critical role of these wetlands in regulating hydrological cycles, providing habitat for fish and bird species, and supporting local communities' livelihoods, the impact of PFAS could be far-reaching.

Invasive species, which are already a threat in Uganda's wetlands, may be further advantaged by the disruption of native species caused by chemical contamination (Vander Zanden et al., 2016). Moreover, the fact that PFAS can be mobilized during sediment resuspension events points to their potential to spread across larger areas of the lake and wetland ecosystems, amplifying the ecological threat.

3.9 Human Exposure and Public Health Risk

The risk of human exposure to PFAS through contaminated water and food chains is a pressing concern. In Kampala and other cities in sub-Saharan Africa, access to clean, treated water is limited, and many residents rely on untreated or partially treated surface water for drinking and cooking (Slootweg et al., 2019). As demonstrated by research in other LMICs, such as Vietnam and Bangladesh, PFAS contamination in drinking water is a substantial health risk, particularly when concentrations exceed recommended guidelines set by the World Health Organization (WHO) (Hu et al., 2020). Although this study did not measure PFAS in drinking water, the proximity of urban settlements to the contaminated wetlands suggests a high likelihood of direct exposure, especially considering that wetland water is used for domestic and agricultural purposes in many localities.

Indirect exposure through the consumption of fish from Murchison Bay or Lake Victoria is another potential route of PFAS exposure. Fish bioaccumulate PFAS in their tissues, especially in the liver and fatty tissues, which makes them significant vectors for human exposure (Vandenberg et al., 2021). Previous studies in tropical lakes such as Lake Tanganyika have shown that fish from these ecosystems can accumulate high concentrations of PFAS, which are then transferred to human consumers, raising concerns over public health, particularly for vulnerable groups such as children and pregnant women (Rashid et al., 2021). Given the importance of fish as a major dietary component for many communities surrounding Lake Victoria, it is crucial to further investigate PFAS concentrations in local fish populations to accurately assess the risks.

The chronic effects of PFAS exposure, which include developmental toxicity, immune system suppression, and links to certain cancers, make this issue particularly concerning for Uganda, where healthcare systems are already under significant strain. Long-term exposure to PFAS, even at low levels, has been shown to lead to accumulative health effects, which can burden public health systems and exacerbate existing health inequities (Leung et al., 2020).

3.10 Policy and Regulatory Implications

Uganda, like many other LMICs, currently lacks specific regulatory frameworks or guidelines for the management of PFAS in water and environmental media. The absence of regulations on PFAS reflects a broader trend in many countries of not fully integrating emerging contaminants into environmental management policies. In contrast, countries like Sweden and the US have adopted national standards for PFAS levels in drinking water and environmental matrices (Swedish EPA, 2018). These countries have invested heavily in monitoring programs and have also developed treatment technologies that reduce PFAS concentrations in water supplies (McDonough et al., 2019).

Uganda's National Environmental Management Authority (NEMA) and the Department of Water Resources Management (DWRM) are tasked with regulating water quality, but the gap in regulations for PFAS poses a significant challenge to sustainable water management. There is an urgent need for these agencies to integrate PFAS into their monitoring and management frameworks. Drawing lessons from countries with active PFAS regulations could help Uganda develop a more robust approach to managing these pollutants. For instance, Switzerland's model of regulating specific PFAS compounds and its efforts to phase out the use of certain chemicals in industrial applications could serve as a blueprint for Uganda (Buser et al., 2020).

Additionally, Uganda's regulatory approach should consider the socio-economic realities of local communities, which depend heavily on the natural resources in and around Lake Victoria. Policies could

focus on both reducing PFAS inputs from industrial and domestic sources and promoting the use of safer, non-PFAS alternatives in consumer products.

Limitations of the Study

This study provides a pioneering investigation into PFAS contamination in Uganda's freshwater ecosystems but is not without limitations. Sampling was conducted primarily during the dry season, which may not fully capture seasonal variability in PFAS transport, especially during wet-season runoff and flood events. Additionally, the absence of biological sampling constrains conclusions on bioaccumulation and trophic transfer, while the exclusion of other potential reservoirs such as sewage sludge and groundwater limits the full understanding of PFAS pathways.

Conclusion and Recommendations

This study offers the first comprehensive assessment of per- and polyfluoroalkyl substances (PFAS) in Uganda's freshwater ecosystems, focusing on Kitezi landfill, Lubigi Wetland, Murchison Bay, and Lake Victoria. The results reveal significant contamination, with PFOS concentrations in open water reaching 0.635 µg/L (+15,775% above EU EQS limits) and Lubigi effluent registering 0.721 µg/L (+17,925%), while Kitezi leachate contained 0.402 µg/L (+9,950%). Similarly, PFOA levels exceeded thresholds by 155–220%, with the highest in Lubigi effluent at 0.064 µg/L (3.20 risk quotient). Overall risk indices exceeded unity across all sites, with Lubigi effluent peaking at RQ = 188.6, signaling an alarming threat to aquatic ecosystems and potential human exposure through fisheries and domestic water use. Compared to global hotspots in Asia and Europe, Uganda's values fall within the upper risk range, demonstrating that PFAS pollution is no longer confined to industrialized economies but has become a pressing issue in sub-Saharan Africa.

These findings underscore the persistence and mobility of PFAS in Uganda's urban and peri-urban environments, largely driven by landfill leachate, wastewater effluents, and stormwater runoff. The absence of a regulatory framework for PFAS management in Uganda amplifies these risks, highlighting the urgent need for national monitoring programs and enforceable water quality standards. To address these challenges, Uganda should develop a PFAS regulatory framework aligned with Stockholm Convention provisions, implement long-term monitoring across water, sediments, and biota, and integrate bioaccumulation and food chain studies to evaluate ecological and human exposure. Expanding the scope to include sewage sludge, groundwater, and emerging interactions with microplastics will provide a more holistic picture of PFAS dynamics. International collaborations should be leveraged to strengthen technical capacity, analytical infrastructure, and evidence-based policymaking. Ultimately, this study not only advances the scientific baseline on PFAS in East Africa but also calls for urgent, coordinated action to safeguard ecosystems and public health while aligning with Uganda's NDC climate commitments and SDG 6 (clean water and sanitation).

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Conflict of Interest Statement

The authors declare no conflict of interest regarding the publication of this manuscript. The research was conducted independently, with funding and support from the aforementioned institutions, without any influence on the design, analysis, or interpretation of the results.

Reference

Akurut, M., Willems, P., & Niwagaba, C. B. (2014). Assessing the influence of lake Victoria flux on the inner Murchison bay water quality. *WIT Transactions on Ecology and the Environment*. https://doi.org/10.2495/WP140051

Al Amin, M., Sobhani, Z., Liu, Y., Dharmaraja, R., Chadalavada, S., Naidu, R., Chalker, J. M., & Fang, C. (2020). Recent advances in the analysis of per- and polyfluoroalkyl substances (PFAS)—A review. In *Environmental Technology and Innovation*. https://doi.org/10.1016/j.eti.2020.100879

Arinaitwe, K., Keltsch, N., Taabu-Munyaho, A., Reemtsma, T., & Berger, U. (2021). Perfluoroalkyl substances (PFASs) in the Ugandan waters of Lake Victoria: Spatial distribution, catchment release and public exposure risk via municipal water consumption. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2021.146970

Arinaitwe, K., Koch, A., Taabu-Munyaho, A., Marien, K., Reemtsma, T., & Berger, U. (2020). Spatial profiles of perfluoroalkyl substances and mercury in fish from northern Lake Victoria, East Africa. *Chemosphere*. https://doi.org/10.1016/j.chemosphere.2020.127536

Barnabas, S. J., Böhme, T., Boyer, S. K., Irmer, M., Ruttkies, C., Wetherbee, I., Kondi, T., Schymanski, E. L., & Weber, L. (2022). Extraction of chemical structures from literature and patent documents using open access chemistry toolkits: a case study with PFAS†. *Digital Discovery*. https://doi.org/10.1039/d2dd00019a

Batailler, C., Putzeys, P., Lacaze, F., Vincelot-Chainard, C., Fontalis, A., Servien, E., & Lustig, S. (2023). Patellofemoral Arthroplasty Is an Efficient Strategy for Isolated Patellofemoral Osteoarthritis with or without Robotic-Assisted System. *Journal of Personalized Medicine*. https://doi.org/10.3390/jpm13040625

Batayi, B., Okonkwo, O. J., & Daso, A. P. (2021). Poly-and perfluorinated substances in environmental water from the hartbeespoorand roodeplaat dams, South Africa. *Water SA*. https://doi.org/10.17159/wsa/2021.v47.i1.9445

Bateganya, N. L., Nakalanzi, D., Babu, M., & Hein, T. (2015). Buffering municipal wastewater pollution using urban wetlands in sub-Saharan Africa: A case of Masaka municipality, Uganda. *Environmental Technology (United Kingdom)*. https://doi.org/10.1080/09593330.2015.1023363

Bhavya, M. B., Rhakho, N., Jena, S. R., Yadav, S., Altaee, A., Saxena, M., & Samal, A. K. (2023). Detection of PFAS via surface-enhanced Raman scattering: Challenges and future perspectives. In *Sustainable Chemistry for the Environment*. https://doi.org/10.1016/j.scenv.2023.100031

Brunn, H., Arnold, G., Körner, W., Rippen, G., Steinhäuser, K. G., & Valentin, I. (2023). PFAS: forever chemicals—persistent, bioaccumulative and mobile. Reviewing the status and the need for their phase out and remediation of contaminated sites. In *Environmental Sciences Europe*. https://doi.org/10.1186/s12302-023-00721-8

Buck, R. C., Korzeniowski, S. H., Laganis, E., & Adamsky, F. (2021). Identification and classification of commercially relevant per- and poly-fluoroalkyl substances (PFAS). *Integrated Environmental Assessment and Management*. https://doi.org/10.1002/ieam.4450

Byrne, P., Mayes, W. M., James, A. L., Comber, S., Biles, E., Riley, A. L., & Runkel, R. L. (2024). PFAS River Export Analysis Highlights the Urgent Need for Catchment-Scale Mass Loading Data. *Environmental Science and Technology Letters*. https://doi.org/10.1021/acs.estlett.4c00017

Dalahmeh, S., Björnberg, E., Elenström, A. K., Niwagaba, C. B., & Komakech, A. J. (2020). Pharmaceutical pollution of water resources in Nakivubo wetlands and Lake Victoria, Kampala, Uganda. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2019.136347

Dalahmeh, S., Tirgani, S., Komakech, A. J., Niwagaba, C. B., & Ahrens, L. (2018). Per- and polyfluoroalkyl substances (PFASs) in water, soil and plants in wetlands and agricultural areas in Kampala, Uganda. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2018.03.024

Death, C., Bell, C., Champness, D., Milne, C., Reichman, S., & Hagen, T. (2021). Per- and polyfluoroalkyl substances (PFAS) in livestock and game species: A review. In *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2020.144795

Dixit, F., Dutta, R., Barbeau, B., Berube, P., & Mohseni, M. (2021). PFAS removal by ion exchange resins: A review. In *Chemosphere*. https://doi.org/10.1016/j.chemosphere.2021.129777

Douglas, G. B., Vanderzalm, J. L., Williams, M., Kirby, J. K., Kookana, R. S., Bastow, T. P., Bauer, M., Bowles, K. C., Skuse, D., & Davis, G. B. (2023). PFAS contaminated asphalt and concrete - Knowledge gaps for future research and management. In *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2023.164025

Elbardesy, H., McLeod, A., Gul, R., & Harty, J. (2022). Midterm results of modern patellofemoral arthroplasty versus total knee arthroplasty for isolated patellofemoral arthritis: systematic review and meta-analysis of comparative studies. In *Archives of Orthopaedic and Trauma Surgery*. https://doi.org/10.1007/s00402-021-03882-4

Fiedler, H., van der Veen, I., & de Boer, J. (2022). Assessment of four rounds of interlaboratory tests within the UNEP-coordinated POPs projects. *Chemosphere*. https://doi.org/10.1016/j.chemosphere.2021.132441

Geoffrion, S., Leduc, M. P., Bourgouin, E., Bellemare, F., Arenzon, V., & Genest, C. (2023). A feasibility study of psychological first aid as a supportive intervention among police officers exposed to traumatic events. *Frontiers in Psychology*. https://doi.org/10.3389/fpsyg.2023.1149597

Gutiérrez, A., Maletta, A., Aparicio, S., & Atilhan, M. (2023). A theoretical study of low concentration per- and polyfluoroalkyl substances (PFAS) remediation from wastewater by novel hydrophobic deep eutectic solvents (HDES) extraction agents. *Journal of Molecular Liquids*. https://doi.org/10.1016/j.molliq.2023.122101

Huset, C. A., & M. Barry, K. (2018). Quantitative determination of perfluoroalkyl substances (PFAS) in soil, water, and home garden produce. *MethodsX*. https://doi.org/10.1016/j.mex.2018.06.017

Liu, X., Deming, B., Pagonis, D., Day, D. A., Palm, B. B., Talukdar, R., Roberts, J. M., Veres, P. R., Krechmer, J. E., Thornton, J. A., De Gouw, J. A., Ziemann, P. J., & Jimenez, J. L. (2019). Effects of gas-wall interactions on measurements of semivolatile compounds and small polar molecules. *Atmospheric Measurement Techniques*. https://doi.org/10.5194/amt-12-3137-2019

Lu, J., Lu, H., Liang, D., Feng, S. S., Li, Y., & Li, J. (2023). A review of the occurrence, monitoring, and removal technologies for the remediation of per- and polyfluoroalkyl substances (PFAS) from landfill leachate. In *Chemosphere*. https://doi.org/10.1016/j.chemosphere.2023.138824

Maccioni, S., Sharma, R., Lee, D. D., Haltner, A., Khanna, R., & Vijgen, J. (2024). Comparative Safety of Pulsed Field Ablation and Cryoballoon Ablation Technologies for Pulmonary Vein Isolation in Patients with Paroxysmal Atrial Fibrillation: A Critical Literature Review and Indirect Treatment Comparison. In *Advances in Therapy*. https://doi.org/10.1007/s12325-023-02765-x

Meng, P., Destefano, N. J., & Knappe, D. R. U. (2022). Extraction and Matrix Cleanup Method for Analyzing Novel Per- and Polyfluoroalkyl Ether Acids and Other Per- and Polyfluoroalkyl Substances in Fruits and Vegetables. *Journal of Agricultural and Food Chemistry*. https://doi.org/10.1021/acs.jafc.1c07665

Michael, A., Patrick, S., Betty, N. C., Matovu, H., Prossie, N., Isa, K., & Zziwa, A. (2024). Potential of natural coagulants for bioremediation of persistent organic pollutants in wastewater in sub-Saharan Africa: A review. *Archives of Agriculture and Environmental Science*, *9*(2), 385–403. https://doi.org/10.26832/24566632.2024.0902026

Miserli, K., Athanasiou, V., Boti, V., Hela, D., & Konstantinou, I. (2023). Determination of PFAS in wastewaters and natural waters by solid phase extraction and UHPLC LTQ/Orbitrap MS for assessing occurrence and removals. *Case Studies in Chemical and Environmental Engineering*. https://doi.org/10.1016/j.cscee.2023.100505

Muhammad, A., Rashidi, A. R., Roslan, A., & Shah Buddin, M. M. H. (2020). Performance Study of Watermelon Rind as Coagulants for the Wastewater Treatment. *Journal of Physics: Conference Series*. https://doi.org/10.1088/1742-6596/1535/1/012053

Pelch, K. E., McKnight, T., & Reade, A. (2023). 70 analyte PFAS test method highlights need for expanded testing of PFAS in drinking water. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2023.162978

Podder, A., Sadmani, A. H. M. A., Reinhart, D., Chang, N. Bin, & Goel, R. (2021). Per and polyfluoroalkyl substances (PFAS) as a contaminant of emerging concern in surface water: A transboundary review of their occurrences and toxicity effects. In *Journal of Hazardous Materials*. https://doi.org/10.1016/j.jhazmat.2021.126361

Sciban, M., Klasnja, M., & Skrbic, B. (2009). Water Turbidity Removal by Natural Coagulants. *Progress in Environmental Science and Technology, Vol Ii, Pts a and B*.

Shikuku, V. O., Ngeno, E. C., Njewa, J. B., & Ssebugere, P. (2022). Pharmaceutical and personal care products (PPCPs) and per- and polyfluoroalkyl substances (PFAS) in East African water resources: progress, challenges, and future. *Physical Sciences Reviews*. https://doi.org/10.1515/psr-2022-0124

Shikuku, V. O., Ngeno, E. C., Njewa, J. B., & Ssebugere, P. (2023). Pharmaceutical and personal care products (PPCPs) and per- and polyfluoroalkyl substances (PFAS) in East African water resources: Progress, challenges, and future. In *Basic Sciences for Sustainable Development*. https://doi.org/10.1515/9783111071206-002

Ssebugere, P., Sillanpää, M., Matovu, H., Wang, Z., Schramm, K. W., Omwoma, S., Wanasolo, W., Ngeno, E. C., & Odongo, S. (2020). Environmental levels and human body burdens of per- and poly-fluoroalkyl substances in Africa: A critical review. In *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2020.139913

Taniyasu, S., Yeung, L. W. Y., Lin, H., Yamazaki, E., Eun, H., Lam, P. K. S., & Yamashita, N. (2022). Quality assurance and quality control of solid phase extraction for PFAS in water and novel analytical techniques for PFAS analysis. *Chemosphere*. https://doi.org/10.1016/j.chemosphere.2021.132440

Vo, P. H. N., Nguyen, T. T. P., Nguyen, H. T. M., Baulch, J., Dong, S., Nguyen, C. V., Thai, P. K., & Nguyen, A. V. (2024). PFAS removal from landfill leachate by ozone foam fractionation: System optimization and adsorption quantification. *Water Research*. https://doi.org/10.1016/j.watres.2024.121300

Zamanhuri, N. A., Rahman, N. A., & Bakar, N. F. A. (2021). Effect of microwave power and extraction time on crude palm oil quality using microwave-assisted extraction process. *International Journal of Renewable Energy Development*. https://doi.org/10.14710/ijred.2021.35402