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Review

Emerging Pollutants in Uganda: A Systematic Review

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Abstract: Emerging pollutants pose significant threats to Uganda's ecosystems and public health amidst rapid urbanization, industrial growth, and intensified agriculture. This systematic review comprehensively assessed these pollutants by analyzing existing Ugandan literature and research studies, revealing various types in different environmental compartments. These pollutants, including pharmaceuticals, personal care products, pesticides, industrial chemicals, heavy metals, radionuclides, biotoxins, disinfection byproducts, hydrocarbons, and microplastics, originate from urban, industrial, and agricultural regions. Wastewater and improper waste disposal are major contributors. From an initial search of 794 articles across multiple databases such as PubMed, African Journal Online (AJOL), Web of Science, Science Direct, and Google Scholar, 138 were found relevant. The review underscores potential ecological and health impacts, including antibiotic resistance, endocrine disruption, and carcinogenicity. Existing monitoring and regulation efforts are discussed, alongside the need for specific regulations, improved data collection, and public awareness campaigns. Recommendations include advanced wastewater treatment, sustainable agriculture, and source control measures. Emphasis is placed on further research to address knowledge gaps and develop effective policies and interventions. Uganda can mitigate these risks by implementing comprehensive monitoring, robust regulations, and sustainable practices, safeguarding the environment and public health.

Keywords: Emerging pollutants in Uganda; East Africa; Pharmaceuticals; Personal care products; Heavy metals; Pesticides; microplastics; persistent organic pollutants; PFAs

1. Introduction

Environmental pollution, with its multifaceted dimensions, is a growing concern worldwide, with developing countries often facing the brunt of its consequences (1–4). This has escalated due to the rapid industrialization, urbanization, and modernization processes taking place across the world (1,2). These activities have led to the release of a diverse array of pollutants into various environmental compartments, giving rise to the concept of "emerging pollutants" (5). These pollutants, often originating from new technologies, industrial processes, and urban activities, have the potential to pose significant ecological and human health risks (6,7). Understanding their presence, distribution, and potential impacts is crucial for sustainable environmental management and public health protection.

Unlike regulated pollutants, "emerging pollutants" are substances that are not currently subject to specific regulations or monitoring requirements but have the potential to adversely affect the environment and human health (8–10). These pollutants, often characterized by their persistence, bioaccumulation, and toxicity, include a diverse range of substances such as industrial byproducts, pharmaceutical residues, pesticides, personal care products, persistent organic pollutants (POPs),

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flame retardants, polycyclic aromatic hydrocarbons (PAHs), polychlorinated compounds, mycotoxins, heavy metals, and microplastics (4,11). These substances can enter water bodies, soil, and air through various pathways, such as industrial discharges, agricultural runoff, improper waste disposal, and atmospheric deposition. Once released, they can persist in the environment for long periods, accumulating in organisms and potentially causing adverse effects (4,5,12–14).

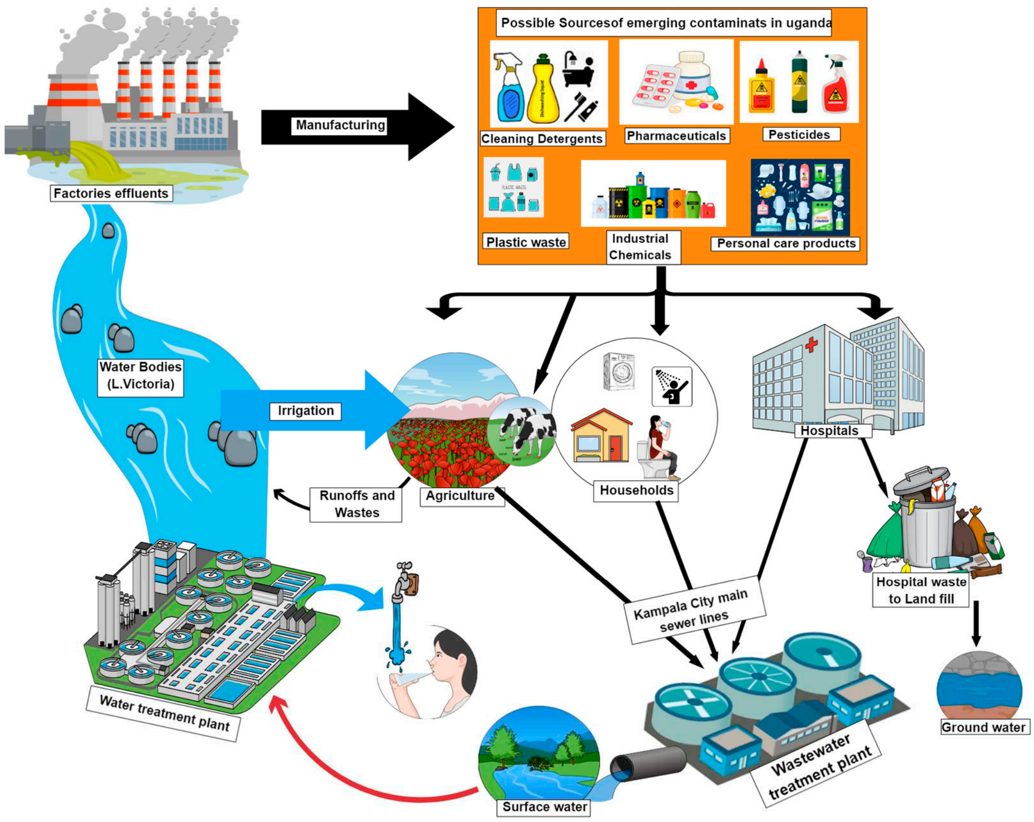

Figure 1. Sources, pathways, and distribution of emerging contaminants in different environmental compartments in Uganda.

Uganda, known for its rich biodiversity and stunning landscapes, faces mounting challenges due to the emergence of "emerging pollutants" that pose significant threats to its ecosystems, public health, and socio-economic development (4,15,16). According to (16) and (17), rapid urbanization, industrial growth, and agricultural intensification have contributed to the release of various pollutants into the environment, triggering concerns about long-term sustainability (16,18,19). The effects of emerging pollutants can be detrimental to both the environment and human health. They have been associated with ecosystem disruption (20), biodiversity loss, hormonal imbalances in wildlife, and reproductive impairments (3,15,21,22). In humans, exposure to these pollutants has been linked to various health issues, including endocrine disruption, developmental abnormalities, neurological disorders, and increased risks of certain cancers (23,24).

While there have been significant efforts to monitor and regulate traditional pollutants such as heavy metals and other organic contaminants, the knowledge about other different types of emerging pollutants and their impact on Ugandan ecosystems and public health is still limited. The persistence and potential adverse effects of emerging pollutants are a matter of concern. Some pollutants, previously identified as "legacy persistent organic pollutants," have been restricted under the Stockholm Convention due to their environmental persistence, wide distribution, bioaccumulation potential, and toxicity to humans and wildlife (25). However, emerging pollutants are characterized by their diverse behavior and sources of production, making their detection and characterization challenging. The identification and quantification of emerging pollutants require sophisticated analytical techniques capable of detecting trace levels of these compounds in environmental matrices. In Uganda, researchers have employed various analytical methods, including liquid chromatography-mass spectrometry (LC-MS), gas chromatography-mass spectrometry (GC-MS), and high-performance liquid chromatography (HPLC), to assess the presence and concentrations of emerging pollutants in different environmental compartments (26). The diverse nature of emerging pollutants necessitates a comprehensive investigation of their occurrence in various matrices. These matrices encompass surface water bodies (lakes, rivers, and wetlands), groundwater, sediments, soils, air, and biota (aquatic and terrestrial organisms). Understanding the distribution and concentrations of emerging pollutants in different environmental compartments is crucial for assessing their potential risks and designing effective management strategies.

To date, several studies have been conducted in Uganda to investigate the presence and concentrations of emerging pollutants in different environmental systems in Uganda for example in water (27,28), sediments (27,29), surface waters (30–32), food crops (33,34), edible insects (35), breastmilk (36) and in fish (30). These studies have identified a range of compounds, including pharmaceutical residues (e.g., antibiotics, analgesics) (26,37,38), personal care products (e.g., fragrances, UV filters) (39), pesticides (e.g., herbicides, insecticides) (27,35,40,41), industrial chemicals (e.g., flame retardants, plasticizers) (36,39,42), microplastics and heavy metals (43–45). The concentrations of emerging pollutants reported in the literature vary depending on the sampling location, environmental matrix, and analytical techniques used. For instance, studies have detected antibiotics in surface waters at concentrations ranging from 1 ng/L to 5600 ng/L, highlighting the potential impact of pharmaceutical pollution on aquatic ecosystems (26,38). Large volumes of pharmaceuticals are produced and consumed annually, but not all medications are properly used or disposed of. This leads to the accumulation of potentially toxic substances in water and soil. However, there is a sparsity of information on the disposal methods and protocols used by healthcare professionals, including community pharmacists, in Uganda (38).The lack of sufficient information and a strong national guideline for medication disposal and poor compliance with existing guidelines increases the risk of environmental contamination and the ingestion of toxic pharmaceutical waste by humans and animals. Similarly, the presence various chemicals, including pesticides (27,46), perfluorinated alkylated substances (PFAS) (47), personal care products (39), and persistent organic pollutants (POPs) (36), has been documented in surface waters, with concentrations exceeding regulatory limits in some cases, indicating potential risks to agricultural productivity and human health (19,38,48). Their contamination poses a significant public health concern as it can be detrimental to freshwater resources, similar to the concerns raised in previous studies (38).

Wastewater treatment plant (WWTP) effluents have been identified as important sources of contamination in Uganda (37,38,48,49). These WWTPs serve as receptacles for anthropogenic pollution, and due to the lack of specific treatment methods for organic pollutants, some compounds remain poorly degraded (48,50). High levels of PFAS have been observed in wastewaters, surface water, soil and crops (47,48) and the contribution of hospitals and households to pharmaceutical contamination in WWTPs is a concern (26,51). Additionally, urban discharges, including separate or combined sewer overflows, can also impact receiving waters in Uganda, similar to the situation in other regions. In urban areas of Uganda, pollutants such as polycyclic aromatic hydrocarbons (PAHs), alkylphenols, and pesticides have been quantified in urban stormwaters (16,37,38,47–49,52). This highlights the presence of various contaminants in stormwater runoff, further contributing to the contamination of surface waters in urban settings. Additionally, Uganda faces challenges related to the importation and management of electronic waste (E-waste). With a desire for modern technology but limited affordability, Uganda becomes a destination for used electrical and electronic equipment from developed countries, resulting in the annual importation of a significant amounts of E-waste (53). The country's recycling infrastructure for managing E-waste is poor, leading to reliance on informal sectors that employ crude dismantling and artisanal recycling techniques (54–56). As a consequence, the soil, water, and air in Uganda are polluted with substances such as brominated flame retardants, non-dioxin-like polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), polychlorinated dibenzo-p-dioxins (PCDDs), polychlorinated dibenzofurans

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(PBDFs), and dioxin-like polychlorinated biphenyls (DL-PCBs) (31,36,39,42,57,58). The crude activities involved in E-waste management, including dumping the waste in agricultural farmlands and water bodies, further exacerbate the environmental pollution in Uganda (53,56).

Beyond the context of Uganda, these compounds have also been identified in various African regions, encompassing approximately 17 percent of countries across the con-tinent. Notably, 59 percent of these occurrences stem from studies originating in South Africa, with contributions of 9 percent each from Tunisia and Nigeria, along with 7 percent from Kenya (24,59–62). Despite the limitations in available research, the documentation of emerging pollutants ex-tends throughout the African landscape, involving sediments, sludge, treated drinking water, surface water, wastewater, groundwater, and solid deposits. The limited knowledge of contaminant sources, pathways, properties, and analytical detection techniques hinders the systematic inclusion of emerging pollutants in groundwater monitoring and protection policies. Improper disposal practices further exacerbate the emerging pollutant issue in Uganda (23,50,55). Expired medications and electronic waste pose additional risks to the environment and human health (54,55). Indiscriminate disposal of pharmaceutical waste and inadequate protocols for drug disposal contribute to the potential contamination of water and soil. Improper recycling and open burning of electronic waste introduce substances such as brominated flame retardants, polycyclic aromatic hydrocarbons, and dioxins into the environment, polluting soil, water, and air (31,63).

The review aimed to provide a comprehensive understanding of the status, sources, and impacts of emerging pollutants in Uganda, offering valuable insights for policymakers, researchers, and stakeholders. It is hoped that the findings of this review will guide the development of evidence-based interventions and foster sustainable practices that protect Uganda's natural resources and promote a healthier environment for future generations.

2. Methodology

2.1. Study Design

This systematic review followed a comprehensive and structured approach to assess the state of emerging pollutants in Uganda. The review was guided by the established methodologies for systematic reviews, including a systematic search strategy, data extraction, and quality assessment of selected studies.

2.2. Search Strategy

A systematic search of relevant literature was conducted to identify studies on emerging pollutants in Uganda. Multiple electronic databases, such as PubMed, Scopus, Web of Science, and Google Scholar, were searched using appropriate keywords and Boolean operators. The search terms included combinations of "emerging pollutants," "contaminants of emerging concern," "Uganda," and related terms. The search was limited to studies published in English up until the cutoff date of this review (September 2023).

2.3. Study Selection

The inclusion and exclusion criteria were predefined to ensure the selection of studies relevant to the topic. Studies that focused on the identification, characterization, and assessment of emerging pollutants in Uganda were included. Both peer-reviewed articles and grey literature, such as reports and conference proceedings, were considered. Studies that did not specifically address emerging pollutants in Uganda or lacked sufficient data were excluded.

2.4. Data Extraction

Data were extracted from the selected studies using a standardized data extraction form. The information collected included study characteristics (e.g., authors, year of publication), study design, sampling methods, analytical techniques, types of emerging pollutants investigated, pollutant

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sources and concentrations, and any reported impacts or observations. The extracted data were organized systematically for further analysis and synthesis.

2.5. Quality Assessment

The quality and reliability of the selected studies were assessed to ensure the inclusion of robust and valid data. Quality assessment criteria were developed based on established guidelines for systematic reviews. The criteria included study design, sample representativeness, data collection methods, analytical techniques, and reporting clarity. Each study was independently evaluated by two reviewers, and any discrepancies were resolved through discussion and consensus.

2.6. Data Analysis and Synthesis

The extracted data were analyzed and synthesized to provide a comprehensive overview of the state of emerging pollutants in Uganda. The data were summarized descriptively, highlighting key findings regarding the nature, sources, distribution, and potential impacts of the identified pollutants. Where applicable, quantitative data were synthesized using appropriate statistical methods. The results were presented in tables, figures, and narrative summaries.

2.7. Limitations

It is important to acknowledge the potential limitations of this systematic review. The inclusion of only English-language studies may introduce language bias. Moreover, the review is limited to the available literature up until September 2023, and newer studies may not be included. Additionally, variations in study methodologies and data reporting across different studies may pose challenges in data synthesis and comparison. In addition, as this study is a systematic review based on existing literature, no ethical approval was required. However, all selected studies were conducted in accordance with ethical guidelines and obtained appropriate ethical clearance if applicable.

3. Results

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flowchart (64) was used to guide the study selection process and provide a transparent overview of the search and screening process (**Figure.2)**. A total of 794 articles were identified through the initial search from various electronic databases. After removing duplicates, 786 articles remained. The titles and abstracts of these articles were screened for relevance, resulting in the exclusion of 113 articles that did not meet the inclusion criteria. After the exclusion of irrelevant articles, the remaining 673 articles were sought for retrieval and 342 articles were not retrieved. The full texts of the remaining 331 articles were then assessed for eligibility. Following a careful evaluation, an additional 193 articles were excluded due to inadequate data or irrelevance, leaving 138 studies for inclusion in the systematic review. The characteristics of the included studies are summarized in (**Table 2**), which provides details such as author names, publication year, classes of pollutants investigated, their areas of detection, their sources and concentrations in different environmental systems. The selected studies encompassed a wide range of research approaches, including laboratory analyses, field studies, and monitoring programs.

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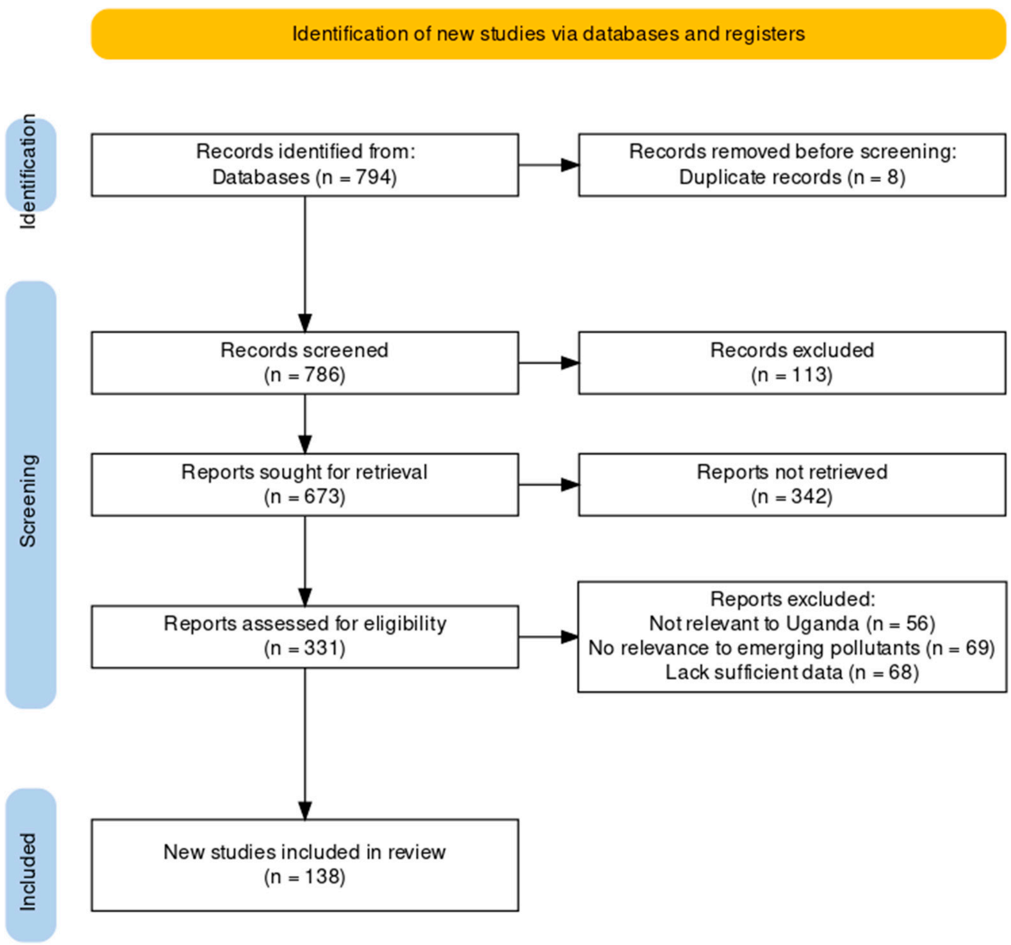

Figure 2. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram for the literature survey.

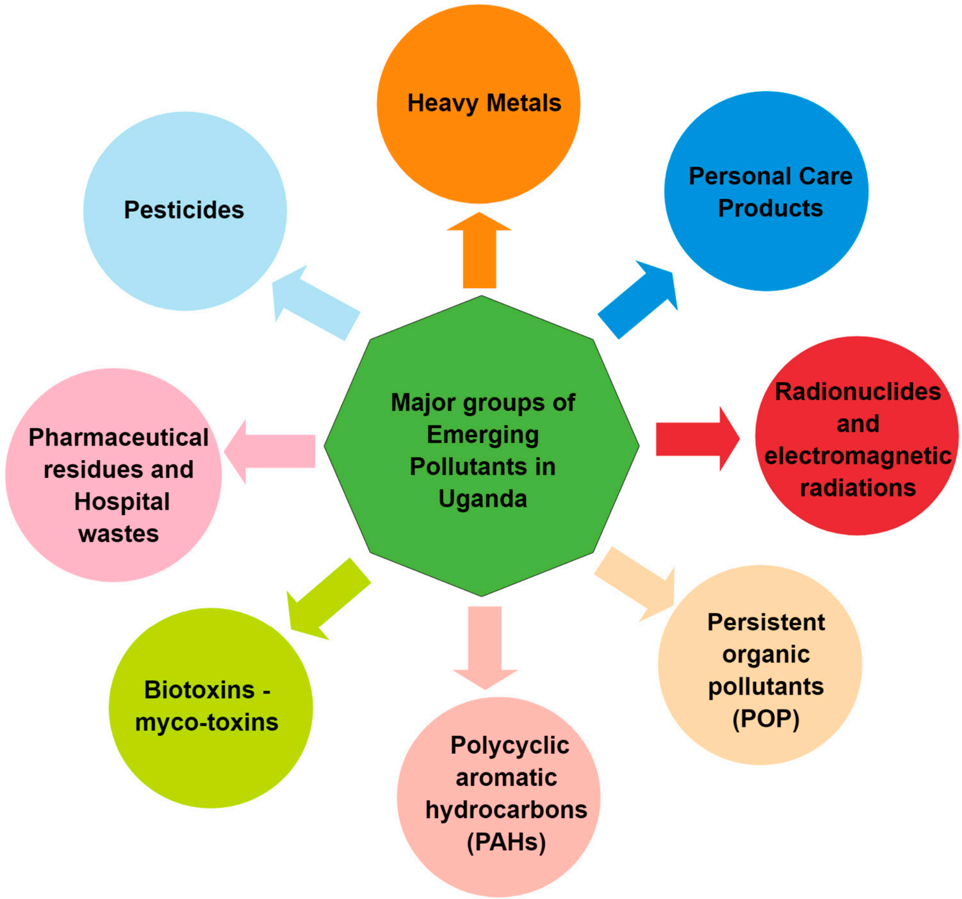

Figure 3. Major groups of emerging pollutants in Uganda.

Table 1. Major groups of emerging pollutants, their description and componentsdetected in uganda.

Category of pollutant	Description	Components
Pharmaceuticals	Medicinal compounds, including prescription and over-the-counter drugs, that enter the environment through human excretion and wastewater.	Antibiotics, Analgesics, Hormones, Antidepressants, Beta-Blockers, Diuretics, Antihypertensive, Fibrate, and Antiparasitic
Pesticides	Chemical substances used to control pests in agriculture, which can leach into soil and water, impacting non-target organisms.	Insecticides, Herbicides, Fungicides, and Rodenticides
Persistent Organic Pollutants (POPs)	Organic compounds that resist degradation, such as certain pesticides and industrial chemicals, with potential long-range transport effects.	Polychlorinated Biphenyls (PCBs), Dioxins, Furans, among others
Personal Care Products	Chemicals found in cosmetics, shampoos, soaps, and perfumes that can be washed into water bodies and contribute to water pollution.	Fragrances, UV Filters, Preservatives, and Surfactants

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Heavy metals	Metallic elements like lead, mercury, cadmium, and chromium that can accumulate in the environment and pose health risks to living organisms.	Lead (Pb), Mercury (Hg), Cadmium (Cd), Chromium (Cr), Nickle (Ni) among others
Hydrocarbon Compounds	Organic compounds derived from petroleum, including polycyclic aromatic hydrocarbons (PAHs), which are often associated with oil spills.	Polycyclic Aromatic Hydrocarbons (PAHs), and Benzene
Biotoxins - Mycotoxins	Toxins produced by organisms like fungi (mycotoxins) and harmful algae, which can contaminate water and food sources, posing health risks.	Aflatoxins, Ochratoxins, and Fusarium Toxins
Radionuclides and Electromagnetic radiations	Radioactive elements and non-ionizing electromagnetic radiation that can impact human health and the environment.	Uranium (U), Thorium (Th), 40-K and Radon (Rn), Radiofrequency (RF), Microwaves, Electromagnetic Fields,
Other emerging pollutants of concern	Various emerging contaminants, like flame retardants and nanomaterials, whose impacts on the environment and health are under investigation.	Flame Retardants, Nanomaterials, and Emerging Contaminants
Microplastics	Tiny plastic particles resulting from the breakdown of larger plastic waste, which can be ingested by organisms and enter the food chain.	Microplastic particles, and Microfibers,
Disinfection byproducts	Chemical compounds formed when disinfectants like chlorine react with organic matter in water, potentially leading to health risks.	Trihalomethanes (THMs)
Particulates	Tiny solid particles or liquid droplets suspended in the air, which can have adverse health effects when inhaled by humans and animals.	PM2.5 (Fine Particulate Matter), PM10 (Coarse Particulate Matter), Gases, Sulphur dioxide (SO_2), Ozone (O_3) and Nitrogen dioxide (NO_2)

Table 2. Categories, classes and the detected concentrations of emerging pollutants in Uganda.

Category of pollutant	Group/Class	Name	Uses	Sources	Concentrations detected	Place of study	References
Pharmaceuticals	Antibiotics	Sulfamethoxazole	Pharmaceutical	Industrial and municipal wastewater from Kampala city via Nakivubo channel, and Bugolobi Wastewater effluents	1 - 5600 ngL^{-1}	Murchison Bay on L. Victoria and Bugolobi wastewater treatment plant, Kampala, Uganda	(26,37,38)
		Trimethoprim	Pharmaceutical		1300 – 22,600 ngL^{-1}		
		Sulfamethazine	Pharmaceutical		2.4 - 50 ngL^{-1}		
		Sulfacetamide	Pharmaceutical		0.8 - 13 ngL^{-1}		
		Tetracycline	Pharmaceutical		3 - 70 ngL^{-1}		
		Erythromycin	Pharmaceutical		10 - 66 ngL^{-1}		
		Carbamazepine	Pharmaceutical		5 - 72 ngL^{-1}		
		Oxytetracyline	Pharmaceutical		17 - 300 ngL^{-1}		
		Tetracyline	Pharmaceutical		2.7 - 70 ngL^{-1}		
		Erythromycin	Pharmaceutical		10 - 66 ngL^{-1}		
		Azithromycin	Pharmaceutical		14 - 60 ngL^{-1}		

Ciprofloxacin	Pharmaceutical		2.0 - 41 ngL^{-1}		
Levofloxacin	Pharmaceutical		1.8 - 29 ngL^{-1}		
Norfloxacin	Pharmaceutical		1.9 - 26 ngL^{-1}		
Enoxacin	Pharmaceutical		5.9 - 51 ngL^{-1}		
Ampicillin	Pharmaceutical	Wastewater effluents as well as shallow groundwater, leachates and run-offs	1350 ngL^{-1}	Bwaise	(38,65,66)
Chlortetracycline	Pharmaceutical		394 ngL^{-1}	Wobulenzi city suburbs, Kampala, Uganda	
Ciprofloxacin	Pharmaceutical		340 ngL^{-1}		
Enrofloxacin	Pharmaceutical		17 ngL^{-1}		
Metacycline	Pharmaceutical		17 ngL^{-1}		
Nalidixic acid	Pharmaceutical		2,340 ngL^{-1}		
Oxytetracycline	Pharmaceutical		17 ngL^{-1}		

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	Penicillin G (benzylpenicillin)	Pharmaceutical		800 ngL^{-1}		
	Sulfathiazole	Pharmaceutical		140 ngL^{-1}		
	Tetracycline	Pharmaceutical		47.3 ngL^{-1}		
Analgesic/Anti-inflammatory	Ibuprofen	Pharmaceutical	Industrial and municipal runoffs and Wastewater effluents	5.9 -780 ngL^{-1}	Nakivubo sewer channel, Murchison Bay on L. Victoria and Bugolobi wastewater treatment plant, Uganda	(26,37)
	Diclofenac	Pharmaceutical		100 – 500 ngL^{-1}		
	Acetaminophen	Pharmaceutical		1.6 – 27 ng/L		
Antiepileptics/antidepressant	Carbamazepine	Pharmaceutical		200 – 1300 ngL^{-1} 346.496 μgL^{-1} CEC		
Beta-Blockers	Atenolol	Pharmaceutical		24-380 ngL^{-1}		
	Metoprolol	Pharmaceutical		0.4-21 ngL^{-1}		
Diuretics	Furosemide	Pharmaceutical		160 – 1300 ngL^{-1}		

		Hydrochlorothiazide	Pharmaceutical		230 – 1350 ngL-1		
	Antihypertensive	Losartan	Pharmaceutical		100 – 160 ngL-1		
	Fibrate	Gemfibrozil	Pharmaceutical		190 – 800 ngL-1		
	Antiparasitic	Pyrimethamine	Pharmaceutical		8.4 – 14.0 ngL-1		
Pesticides	Organonitrogen	Endosulfan sulfate	Herbicide, insecticides and fungicides	Air, sediment and surface water samples	0.82–5.62 µg kg-1 d.w.	4 bays of the Uganda side of L. Victoria, Uganda	(19,27,70,30,35,41,46,49, 67–69)
		Aldrin	Herbicide, insecticide		0.22 – 15.96 µg kg-1 d.w.		
		Dieldrin	Soil insecticide and for control of mosquitoes.		0.94 – 7.18 µg kg-1 d.w.		
		Chlordane	Insecticide		3.82 – 35.6 pgm-3		

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	Hexachlorocyclohexanes	Insecticide	3.72 – 81.8 pgm^{-3}
	Heptachlor	Insecticide	0.81 µgkg-1 d.w.
	Heptachlor epoxide	Insecticide. Used for fire ant control in power transformers	3.19 µgkg-1 d.w.
Organochlorine	p, p′-DDE	Insecticides	0.11 – 3.59 µgkg-1 d.w.
	p, p′-DDD		0.38 – 4.02 µgkg-1 d.w.
	p, p′-DDT		0.04 – 1.46 µgkg-1 d.w.
	o, p′-DDE		0.07 – 2.72 µgkg-1 d.w.
	o, p′-DDT		0.01 – 1.63 µgkg-1 d.w.

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Total Endosulfan	Isomer of Endosulfan. Insecticide and acaricide	12.3 – 282 pg m^{-3}	Air and water samples of Lake Victoria Northern shore water shed, areas of Kakira and Entebbe, Uganda	(27,41,46,65,67,68,71–74)
Total DDT related compounds	Insecticide used in agriculture	22.8 – 130 pgm^{-3}		
Dieldrin	Soil insecticide and for control of mosquitoes	0.0148 ± 0.0023 μgkg^{-1} d.w.		
Endosulphan sulphate	Insecticide and acaricide	0.82 – 5.62 μgkg^{-1} d.w.		
Lindane	Insecticide	0.74 ± 0.11 and 0.87 ± 0.09 $\mu g\ kg^{-1}$ (MRL = 0.5 mg kg^{-1})	Napoleon Gulf on L. Victoria, Uganda	

	Aldrin			1.17 and 1.79 μg kg^{-1} (MRL = 0.1 mg kg^{-1})		
	α-Endosulfan			7.59 and 6.00 μg kg^{-1} (MRL = 0.1 mg kg^{-1})		(30,46,68,75)
	Dieldrin			2.22 and 1.88 μg kg^{-1} (MRL = 0.1 mg kg^{-1})		
Organochlorine	*p, p*′-1,1-dichloro-2,2-bis-(4-chlorophenyl) ethylene (*p, p*′-DDE)	Insecticide	Air, Sediments, Surface waters samples as well as Fish species	6.10 and 3.44 μg kg^{-1}	Napoleon Gulf on L. Victoria, Uganda	(27,41,73)

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	p, p′-1,1,1-trichloro-2,2-bis-(4-chlorophenyl) ethane (*p, p′*-DDT)			7.34 and 4.30 µg kg^{-1} (MRL = 0.1 mg kg^{-1})		
	∑DDTs			503.6 µg kg^{-1} d.w.	Abandoned pesticide store in Masindi district in western Uganda	-74
	∑OCPs			14.4 µg kg^{-1} d.w.		
	Lindane			11.4 µg kg^{-1} d.w.		
	Endosulfans			1.55 µg kg^{-1} d.w.		
	Chlorpyrifos			93.5 ng/m^3	Air samples from Kakira and Entebbe, northern shore of L. Victoria, Uganda	(67,74,76)
	Chlorthalonil	Fungicide		< 0.10–24.0 pg m^{-3}		
	Metribuzin	Herbicides		< 0.02– 0.53 ng m^{-3}		
	Trifluralin			0.02–0.32 pg m^{-3}		

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	Malathion		< 0.08–193 pg m^{-3}		
	p, p′DDE		125 mg/kg	Kampala and Iganga districts in Uganda	(40,77)
	Dieldrin		123 mg/kg		
	p, p′DDD		24 mg/kg		
	p, p, DDT		13 mg/kg		
	o, p′DDT		23 mg/kg		
	α-HCH		54 mg/kg		
	β-HCH	Insecticide	10 mg/kg		
	Lindane		7 mg/kg		
	Carbofuran		83.3 pg/m^3	Kakira and Entebbe, northern shore of L. Victoria, Uganda	-68

		Total Dichlorodiphenyltrichloroethane (ΣDDTs)			22.8 – 130 pg/m^3		
		Total hexachlorocyclohexanes (ΣHCHs)			3.72 – 81.8 pg/m^3		
	Carbamates	Total Endosulfan (ΣEndo)			12.3 – 282 pg/m^3		
Persistent organic pollutants (POP)		polybrominated diphenyl ethers (PBDEs)	Are used as coolants and lubricants in transformers, capacitors, and other electrical equipment	Sediment samples	9.84 pg g^{-1} dry weight	Napoleon Gulf and Thurston Bay on northern shore of L. Victoria, Uganda	-42
		Dioxin-like polychlorinated biphenyls (PCBs)			136 pg g^{-1} dw		(36,42,57,78)
		polychlorinated dibenzo-p-dioxins/furans (PCDD/Fs)			44.1 pg g^{-1} dw		(36,57,78)

Flame Retardants (brominated flame retardants (BFRs))				0.07–5.53 pg Toxic Equivalent Factors (TEQ) g^{-1} dw		
	polychlorinated dibenzofurans (PCDFs)			0.07 - 5.61 pg g−1 dw 0.01–0.23 pg TEQ g^{-1} dw		(36,57,78)
Organochlorine pesticides	Pymetrozine	Pesticide	Edible Insects	0.02 pg g−1 dw	Ugandan districts	-35
	Methabenzthiazuron			0.08 pg g−1 dw		
	Metazachlor			1.4 ± 0.03 pg g−1 dw		
	Fenimorph			0.04 ± 0.03 pg g−1 dw		
	Fludioxonil	Fungicide		0.29 pg g−1 dw		
	Metalaxyl			0.01± 0.01 pg g−1 dw		

	Tricresyl phosphate	Used as a plasticizer		25 – 8100 ngL^{-1}		
Organophosphorus flame retardants (OPFRs)	Tris-(2-chloroethyl) phosphate	Widely used as a plasticizer, fire retardant and solvent	Waters, sediments and soil samples	24 – 6500 ngL^{-1}	Napoleon gulf, Murchison, Waiya, Entebbe, and Thurston bays, Uganda	(27,39,40,46,67,69,72–74)
	Triphenyl phosphate			54 – 4300 ngL^{-1}		
	Tris-(2-ethylexyl) phosphate			4300 ngL^{-1}		
	2-ethylhexyl diphenyl phosphate			7.7 - 730 ngL^{-1}		
	Tricresyl phosphate			8100 ngL^{-1}		

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	Tris-(2-chloroisopropyl) phosphate	Used as plasticizers and antifoam agents		25 - 600 ngL^{-1}		
	Tributyl phosphate			29 ngL^{-1}		
	Triethyl phosphate			9.6 - 500 ngL^{-1}		
Phthalate ester plasticizers (PEP)	Dibutyl phthalate	Are added to polymers to ease processing and to enhance flexibility and toughness of the final product	Waters, sediments and soil samples	350 – 16000 ngL^{-1}	Napoleon gulf, Murchison, Waiya, Entebbe, and Thurston bays, Uganda	-39
	Bis-(2-ethylhexyl) phthalate			210 – 23000 ngL^{-1}		
	Dimethyl phthalate			6.8 – 400 ngL^{-1}		
	Diethyl phthalate			38 – 1100 ngL^{-1}		

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		Dibutyl phthalate			350 - 16000 ngL^{-1}		
		N-butyl benzenesulfonamide			7.5 200 ngL^{-1}		
		Bis-(2-ethylhexyl) adipate			12 - 6100 ngL^{-1}		
Personal Care Products	Antimicrobial	Triclosan	Antibiotic in soaps, toothpaste, detergents	Industrial wastewater effluents from highly industrialized localities of the two bays	89 – 1400 ngL^{-1}	Napoleon gulf, Murchison, Waiya, Entebbe, and Thurston bays, Uganda	-39
	Organic sunscreens	Benzophenone	Protect the products from UV light		36 – 1300 ngL^{-1}		
		4-methylbenzylidine camphor	Organic UV filters		21 – 1500 ngL^{-1}		

doi:10.20944/preprints202309.0494.v1

Phenolic antioxidants	Butylated hydroxytoluene	Used as an antioxidant in cosmetic product formulations	14 – 750 ngL^{-1}
Synthetic musk fragrances	Musk ketone	Used in cleaning and washing agents, surface treatments, and lubricants and additives	7.3 - 460 ngL^{-1}
Preservatives	Chlorophene	Used to be applied as a preservative and disinfectant in personal care products	21 - 310 ngL^{-1}

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Masking agent	Acetophenone	Covers the unpleasant scents of other ingredients	2.2 – 100 ngL^{-1}
	3-methylindole	I used as a flavoring ingredient	1.8 - 130 ngL^{-1}
Insect repellents	N, N-diethyltoluamide	Is an active ingredient in many insect repellent products	3.9 - 98 ngL^{-1}
Preservatives	3-tert-butyl-4-hydroxy anisole	Is used as an antioxidant and preservative	7.3 – 100 ngL^{-1}

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	Antioxidant	2,6-di-tert-butylphenol	Is used as stabilizers, free-radical scavengers and antioxidants		66 ngL^{-1}		
Heavy metals	Post-transition metals	Pb	Battery assembling, in gasoline	Water, sediments, milk and beef products samples	79 - 138.18 mg/kg	Nakivubo channelized stream sediments and in Kampala markets, Uganda	(28,30,85–90,43,44,79–84)
	Transition metals	Cd	Find applications in batteries, alloys, coatings (electroplating), solar cells, plastic stabilizers, and pigments	Water, sediments, Road side soils, surface films and selected vegetable weeds	0.84 - 1.04 mg/kg		

doi:10.20944/preprints202309.0494.v1

Transition metals	Cu	Find applications in electrical wiring, roofing, plumbing, and industrial machinery.	Sludge at NWSC, Milk, beef, soil, crops, borehole water, Industrial effluents, Herbal medicine, rain water, sediments, roasted peanuts, water sediments, dumpsites	28.84 - 38.01 mg/kg	Nakivubo stream, Southwestern Uganda, Kilembe copper mines, Jinja steel rollings and Osukuru phosphate mines, Kampala markets, L. Victoria	(28,29,91–98,32,43,79,80,84,88–90)
Trace element	Zn	Smelting and galvanization	Road side soils, surface films and selected vegetable weeds	177.89 - 442.40 mg/kg	Kampala city roads, Uganda	(43,79,85,97,98)

doi:10.20944/preprints202309.0494.v1

Transition metals	Mn	Welding, making structural alloys	Cereal crops,	363.47 mg/kg	Kampala city, Uganda	(29,44,49,70)
Transition metal	Fe	Making alloy steels	Open wells, soils, borehole waters, stream sediments and crops.	30085.33 - 5835.00 mg/kg	Nakivubo stream, Kilembe copper mines, southwestern Uganda areas	(29,81,82,91,95,99)
Transition metal	Ni	Use in alloying such as in armour plating	Soils, surface water, herbal medicines and cereals	2.2 – 9.40 ppm	Jinja steel rolling mills, areas of southwestern Uganda and Kampala markets	(89,94,95)

doi:10.20944/preprints202309.0494.v1

Metalloid	As	Used as an allowing agent as well as in making of glass, pigments, textiles and both metal and wood adhesives	Up and Downstream waters, soil, surface water and plants	0.5 – 4.6 ppm	Roofings rolling mills, steel and tube industries in Nakawa Industrial area and in areas of Kilembe copper mines, Uganda	(43,81,82,89)

doi:10.20944/preprints202309.0494.v1

Transition metals	Co	Making alloys, find applications in magnets and is also used as a catalyst in petroleum industries.	Surface waters, vegetables and in herbal medicines	0.233 g/mL	R. Nyamwamba areas in kasese, southwestern Uganda parts and soroti district	(29,88,94)
Transition metals	Hg	Find applications in gold extraction and also used in manometers	Soils, Cocoyams, roasted peanuts and in stream waters	0.05 ± 0.01 ppm	Kampala, Wakiso and Busia districts, Uganda	(30,43,99)

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Transition metals	Cr	Applied in manufacture of steel as well as hardening steel	Raw bovine milk, herbal medicines, soils, grains and stream waters.	156.9 ppm	Steel and Tube industrial area, Roofings rolling mills area, Kampala and Soroti districts, Uganda	-28,100
Transition metal	Fe	Making alloy steels	Stream sediments, soils, surface waters and dumpsites, cereal crops, rain water.	64.05 – 147.40 mg/Kg	Industrial effluents in Kampala and soroti districts, Nakivubo stream, and Osukuru phosphate mines areas, Uganda	(81,82,89)

doi:10.20944/preprints202309.0494.v1

		Acenaphthene	Used to prepare naphthalene dicarboxylic anhydride, which is a precursor to dyes		1,020 ng/L		
Hydrocarbon Compounds	High and Low molecular Polycyclic aromatic hydrocarbons (PAHs)	Acenaphthylene	Used to make electrically conductive polymers	Leachates and Ground water samples	92 ng/L	Bwaise and Wobulenzi towns in Kampala district, Uganda	(63,65,101)
		Anthracene	Used in the manufacture of red dye alizarin, wood preservation,		340 ng/L		

	insecticide, coating of material	
Benzo[a]pyrene	No known uses	405 ng/L 1.1 ng/L
Benzo[k]fluoranthene	Majorly used for research purposes	180 ng/L 226 ng/L
Chrysene	Used to make some dyes.	102 ng/L 224 ng/L
Fluoranthene	No found uses but is produced by some plants.	550 ng/L 580 ng/L
Fluorene	Used to make dyes, plastics and pesticides.	480 ng/L 240 ng/L
Naphthalene	Industrial solvent	570 ng/L

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			258 ng/L		
	Phenanthrene	Used to make dyes, plastics	220 ng/L		
		and pesticides, explosives and drugs	1,050 ng/L		
	Pyrene	Used to produce dyes, plastics and pesticides.	40 - 687 ng/L		
BTEX compounds	Benzene	Industrial solvent	86.7 ng/L		
	Ethylbenzene	Industrial solvent	5 - 960 ng/L		
	Xylene	Industrial solvent	410 ng/L		
	Naphthalene	Naphthalene	184 - 239 ng g^{-1} dw	The White Nile	########

Low and High Molecular Polycyclic aromatic hydrocarbons (PAHs)	Acenaphthylene	Used to make electrically conductive polymers	Sediments and fish species	16 - 20.5 ng g^{-1} dw	environment near melut oil fields, South Sudan, Uganda and Napoleon Gulf and Murchison Bays
	Fluorene	Used to make dyes, plastics and pesticides.		148 - 156 ng g^{-1} dw	
	Anthracene	Used in the artificial manufacture of red dye alizarin, wood preservation, insecticide, coating of material		79.3- 112 ng g^{-1} dw	

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Fluoranthene	No found uses and is said to be produced by some plants.	2.46 - 8.73 ng g^{-1} dw
Pyrene	Used to produce dyes, plastics and pesticides.	2.09 - 5.7 ng g^{-1} dw
Benzo[a]anthracene	Can be found in coal tar, roasted coffee, smoked foods, and automobile exhaust and is used in research laboratories	0.5 – 1.3 ng g^{-1} dw

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	Chrysene	Used to make some dyes.		8.4 - 25 ng g^{-1} dw	
	Benzo[b]fluoranthene	Research purpose		2.7 – 9.3 ng g^{-1} dw	
	Benzo[k]fluoranthene	Research purpose		0.6 – 6.5 ng g^{-1} dw	
	Benzo[a]pyrene	No known use		0.02 – 1.06 ng g^{-1} dw	
	Dibenzo [a, h] anthracene	Is used only for research purposes to induce tumorigenesis		1.0 – 1.9 ng g^{-1} dw	
Chlorinated aromatic chemicals	Polychlorinated dibenzo-*p*-dioxins (PCDDs)	Applicable in chemicals, notably herbicides	Surface sediments	44.1 pg g^{-1} dry weight (d.w)	Napoleon Gulf and Thurston Bay on the northern shore of L. Victoria, Uganda
	Polychlorinated dibenzofurans (PCDFs)			5.61 pg g^{-1} dry weight (d.w)	

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		Dioxin-like Polychlorinated bisphenyls (di-PCBs)			136 pg g^{-1} d. w		
Biotoxins - Mycotoxins	**Aflatoxins**	Aflatoxin B1 (AFB1)	Exert inhibitory effects on biological processes including DNA synthesis, DNA-dependent RNA synthesis, DNA repair, and protein synthesis	Sorghum	16.0 ± 3.6 µg/kg	Kitgum district	(103–106)
				Maize	1.9 ± 0.9 µg/kg	Kitgum and Lamwo districts, Uganda	(97,106–109)
				Millet	2.9 ± 1.2 µg/kg		
					4.3 ±1.5 µg/kg		
				Sesame	2.4 ± 1.1 µg/kg		
					3.5 ± 2.9 µg/kg		
				Sorghum	16.0 ± 3.6 µg/kg		
				Fish feed (Farms)	148 ± 46.9 µg/kg	Lake Victoria Basin, Uganda	

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	Fish feed (Factories)	110 ± 39.9 µg/kg	Lake Victoria Basin, Uganda	-103,104
Aflatoxin B2 (AFB2)	Peanuts	0 - 540 µg/kg	Mubende, Uganda	-103,104
	Peanuts	10.5 ± 6.15 µg/kg	Iganga markets, Uganda	
	Peanuts	7.3 ± 4.98 µg/kg	Mayuge markets, Uganda	
	Peanut	11.5 ± 0.43 µg/kg	Southwestern Uganda markets	-106,110
	Sorghum (flour and porridge)	15.2 ± 0.20 µg/kg	Southwestern Uganda markets	-88,104
	Millet (flour and porridge)	14.0 ± 1.22 µg/kg	Southwestern Uganda markets	-106
Aflatoxin G1 (AFG1)	Cassava flour	16.0 ± 1.66 µg/kg	Southwestern Uganda	-104,106

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	Eshabwe (porridge) sauce	18.6 ± 2.40 (µg/kg)	Southwestern Uganda	-106
	Peanut paste	0 – 540 µg/kg	Kampala markets, Uganda	-97,103
Aflatoxin G2 (AFG2)	Freshly harvested maize (Zea mays L.)	9.6 ± 4.20 µg/kg	Mubende markets, Uganda	-106,110
		10.1 ± 3.10 µg/kg	Ibanda markets, Uganda	########
		9.1 ± 4.35 µg/kg	Jinja markets, Uganda	########
		11.0 ± 3.01 µg/kg	Hoima markets, Uganda	########
		10.6 ± 1.63 µg/kg	Mayuge markets, Uganda	########
		6.5 ± 0.60 µg/kg	Buikwe markets, Uganda	########
		3.8 ± 1.30 µg/kg	Mpigi markets, Uganda	########

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				7.2 ± 1.99 µg/kg	Masindi markets, Uganda	########
				8.5 ± 2.56 µg/kg	Bugiri markets, Uganda	-110
	Aflatoxin M1 (AFM1)	Aflatoxin M1 is usually present in the fermentation broth of *Aspergillus parasiticus* and is a metabolite of aflatoxin B1 in humans and animals	Peanuts	60.3 ± 27.99 µg/kg	Kalerwe markets, Uganda	-97,106
				40.5 ± 12.82 µg/kg	Bukoto markets, Uganda	
				10.3 ± 3.54 µg/kg	Nakawa markets, Uganda	-97,111
				143.1 µg/kg	Owino markets, Uganda	-97
				5.8 ± 12.3 µg/kg	Bugiri markets, Uganda	-111
			Maize	2.9 ± 6 µg/kg	Bulambuli markets, Uganda	-111

	0.7 ± 0.3 µg/kg	Bundibugyo areas, Uganda
	1.0 ± 0.9 µg/kg	Gulu markets, Uganda
	290.7 µg/kg	Hoima areas, Uganda
	2.4 ± 4.0 µg/kg	Iganga markets, Uganda
	145.5 µg/kg	Kabale markets, Uganda
	1.0 ± 0.7 µg/kg	Kapchorwa areas, Uganda
	1.7 ± 0.5 µg/kg	Kasese markets, Uganda
	1.7 ± 0.5 µg/kg	Kiryadongo areas, Uganda
Groundnuts	6.87 µg/kg	Northern Uganda

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			Maize	6.77 µg/kg	Northern Uganda	########
			Millet	1.46 µg/kg	Northern Uganda	
			Sorghum	10.24 µg/kg	Northern Uganda	
Ochratoxins (OTA)	OTA-A, B, and C	Can benefit humans by their use as antibiotics (penicillins), immunosuppressants (cyclosporine), and in control of postpartum hemorrhage and migraine headaches	Sorghum	4.4 ± 0.8 n	Kitgum markets, Uganda	########
				3.5 ± 0.7 ng/g	Lamwo markets, Uganda	
			Maize	3760 ng/g	Kitgum markets, Uganda	
				0.3 ± 0.1nng/g	Lamwo markets, Uganda	
			Millet	1.1 ± 0.3 ng/g	Kitgum markets, Uganda	
				1.0 ± 0.3 ng/g	Lamwo markets, Uganda	
			Sesame	1.5 ± 0.3 ng/g	Kitgum markets, Uganda	

doi:10.20944/preprints202309.0494.v1

				1.4 ± 0.2 ng/g	Lamwo market, Uganda s	
			Groundnuts	4.89 ng/g	Northern Uganda	
			Maize	0.37 ng/g	Northern Uganda	
			Millet	1.32 ng/g	Northern Uganda	
			Sorghum	7.44 ng/g	Northern Uganda	
Fumonisins	A, B, C and P-series	Are usually esterified with propane tricarboxylic acid to provide a hydrophobic/hydrophilic dichotomy that is unique among the mycotoxins	Fish feed (Farms)	0.3±0.19 µg/kg	Lake Victoria Basin, Uganda	(109,113–115)
			Fish feed (Factories)	0.2 ± 0.24 µg/kg	Lake Victoria Basin, Uganda	-109
			Peanut paste	80.2– 0.6 µg/kg	Kampala markets	-104
			Groundnuts	1.19 µg/kg	Northern parts of Uganda markets	########
			Gibbberella fujikuroi species in harvested maize	19.4 – 99.8 µg/kg		(109,113–115)

			Millet	0.76 µg/kg		
			Sorghum	4.402 µg/kg		
Trichothecene	Vomitoxin / Deoxynivalenol	Is used as a mycotoxin to induce cytotoxicity in porcine jejunal epithelial cells and study the protective effects of Saccharomyces cerevisiae on the cell viability of host cells.	Groundnuts	0.153 µg/kg	Northern parts of Uganda markets	(109,113–115)
			Maize	0.92793 µg/kg		
			Millet	0.153 µg/kg		
			Sorghum	0.823 µg/kg		
	Radon (^{226}Ra)	Uranium-238.	Spider plant	8.06 Bq/kg		-117,118

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Radionuclides and electromagnetic radiations	Primordial radionuclides (naturally occurring noble gases)	Used in making nuclear weapons as a 'tamper' material.	Sweet potato	7.08 Bq/kg	Osukuru phosphate factory areas, Tororo District, Uganda	
			Pawpaw	3.55 Bq/kg		
			Sodom Apple	9.14 Bq/kg		
			Okra	5.34 Bq/kg		
			Moringa	4.35 Bq/kg		
			African Basil	10.02 Bq/kg		
			Aloe vera	4.88 Bq/kg		
			Ginger	2.99 Bq/kg		
				18 ± 3 Bqm^{-3}	Dormitories at Adwari S.S., Uganda	(94,117–119)
				31 ± 3 Bqm^{-3}	Dormitories at Ogor Seed S.S., Uganda	

	26 ± 3 Bqm^{-3}	Dormitories at Okwang S.S., Uganda	
Tororo cement factory area	26 ± 2 Bqm^{-3}	School Dormitories at Orum S. S, Uganda	
	49 ± 5 Bqm^{-3}	Dormitories at Otuke S.S., Uganda	
Tororo mining area	97 ± 5 Bqm^{-3}	Tororo district	
Chemical Laboratory tests	96 ± 4 Bqm^{-3}	Eastern Uganda	
Steel company area	72 ± 3 Bqm^{-3}	Steel Works in Eastern Uganda	(91,117–119)
Hospital area	51 ± 2 Bqm^{-3}	Hospitals in Eastern Uganda	

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		Hotel	28 ± 1 Bqm^{-3}	TLT Hotel in Eastern Uganda	
		Residential houses	92 ± 4 Bqm^{-3}	Residential houses (closed) in Eastern Uganda	
		Homestead	45 ± 1 Bqm^{-3}	Houses (Far away) in Eastern Uganda	
Thorium (^{232}Th)	Used in making lenses for cameras, scientific instruments, high temperature crucibles, and electrical	Soil mine tailings	119.3 – 376.7 Bq kg^{-1}	Mashonga Gold mine, Uganda	-120
			211.7 ± 17.3 Bq kg^{-1}	Kikagati Tin mine, Uganda	
			244.4 ± 10.9 Bq kg^{-1}	Butare Iron ore mine, Uganda	

	equipment	Spider plant	18.60 Bq/kg		
		Sweet potato	15.51 Bq/kg		
		Pawpaw	7.67 Bq/kg		
		Pumpkin	11.26 Bq/kg	Medicinal plants in Osukuru, Tororo District, Uganda	
		Sodom Apple	11.57 Bq/kg		
		Okra	5.98 Bq/kg		
		Moringa	13.28 Bq/kg		
		African Basil	7.37 Bq/kg		
		Aloe vera	3.00 Bq/kg		
		Ginger	2.24 Bq/kg		
			181.2 ± 66.8		-120

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			Outdoor dose rates in air (1.0 m above the ground level)	nGy h^{-1}	Mashonga Gold mine, Uganda	
				167.2 ± 43.0 nGy h^{-1}	Kikagati Tin mine, Uganda	
				191.6 ± 29.6 nGy h^{-1}	Butare Iron ore mine, Uganda	
	^{40}K (Potassium-40)	Acts as signaling molecule in a wide variety of processes	Spider plant	350.17 Bq kg^{-1}	Osukuru mines, Tororo District, Uganda	-117
			Soil mine tailings	141.0 – 1658.5 Bq kg^{-1}		
			Sweet potato	365.35 Bq/kg		
			Pawpaw	297.81 Bq/kg		
			Pumpkin	437.92 Bq/kg		
			Sodom Apple	419.72 Bq/kg		

		Okra	343.78 Bq/kg		
		Moringa	379.21 Bq/kg		
		African Basil	363.99 Bq/kg		
		Aloe vera	275.86 Bq/kg		
		Ginger	361.07 Bq/kg		
		Soil mine tailings	391.5±46.3		
Uranium (^{238}U)	Used in making nuclear weapons as a 'tamper' material.	Soil mine tailings	35.5 – 147.0 Bq kg^{-1}	Southwestern Uganda	-120
			58.7±8.8 Bq kg^{-1}	Mashonga Gold mine, Uganda	
			49.7±3.1 Bq kg^{-1}	Kikagati Tin mine, Uganda	
			57.6±2.9 Bq kg^{-1}	Butare Iron ore mine, Uganda	

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			Food package material, stain- and water-repellent fabrics,	Wastewater effluent	1.3 –2.4 ng L^{-1}		
		Perfluorooctane sulfonic acid (PFOS)	non-stick products (e.g., Teflon), polishes, waxes, paints,	Soils	600 – 3000 pg g^{-1}		
Other emerging pollutants of concern	Per- and polyfluoroalkyl substances (PFASs)		cleaning products, fire-fighting foams, industrial facilities	Surface water	1.5 –2.4 ng L^{-1}	Nakivubo wetland area, downstream of Bugolobi WWTP and upstream L. Victoria, Uganda	(47,48)
		Perfluorooctanoate (PFOA)	(e.g., chrome plating, electronic goods, and oil recovery),	Soils	480 – 910 pg gL^{-1} dw		

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Perfluotohexanesulfonate (PFHxS)	Landfill wastewater treatment plant, and living	Wastewater effluent			
Perfluoroheptanoate (PFHpA)	organisms (e.g. fish, animals, and humans) due to accumulation	Plant tissues	0.65 – 0.67		
Perfluorohexanoic acid (PFHxA)	and persistence over time	Soils	210 – 460 pg gL^{-1} dw		
		Urban runoffs	8.5 – 14 ngL^{-1}		
Average Perfluoroalkane sulfonates (∑PFSAs)		Wet land soil	4200 – 5300 pg g^{-1} dw	Nakivubo wetland, Uganda	(47,48)
		Sugarcane soil	3000 – 7900 pg g^{-1} dw		

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				Maize soil	1600 – 4900 pg gL^{-1-} dw		
Microplastics	Microplastics	<1 mm size	Plastic materials utilized by communities	Surface water of L. Victoria	0.69–2.19 particles/m^3	Surface water of northern L. Victoria, Uganda	-121
Disinfection byproducts	Trihalomethanes	Chloroform	Uses as an extraction solvent	Drinking water	23.07 µg/L	Ggaba water treatment plant and water distribution lines, Uganda	-122
		Bromodichloromethane	Was formerly used as a flame retardant but now is used as a reagent or an intermediate in organic chemistry.		10.5 µg/L		

		Total trihalomethane (TTHM)	Used in the treatment of water to kill disease-causing microorganisms.		32.89 µg/L		
Particulates	Particulate matter	$PM_{2.5}$	Help in implementation of effective pollution control measures and public health interventions to protect people and improve air quality	Air samples	152.6 µg/m³	Kampala, Jinja, Mbarara, kyebando and Rubindi districts, Uganda	(98,123–126)
	Long-term particulate matter	PM_{10}			208 µg/m³		

	NO_2	Used in the production of nitric acid, lacquers, dyes, and other chemicals	24.9 µg/m^3
Gas Phase Pollutants	SO_2	Used in the preparation of sulfuric acid, sulfur trioxide, and sulfites	3.7 µg/m^3
	O_3	Is extensively applied for decontamination purposes	11.4 µg/m^3

CEC – Critical Environmental concentration values (38).

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4. Results and Discussion

In this systematic review, a comprehensive analysis of a total of 137 articles pertaining to the presence and concentrations of emerging pollutants in Uganda was conducted. This investigation successfully identified more than 194 pollutants of emerging concern in Uganda (see **Table 2**) and subsequently grouped them into 12 major classifications (depicted in **Figure 3**). These encompass pharmaceuticals, pesticides, persistent organic pollutants (POPs), personal care products, heavy metals, hydrocarbon compounds, biotoxins, radionuclides, electromagnetic radiations, microplastics, disinfection byproducts, and particulates (as detailed in **Tables 1 and 2**). The findings from these studies offer valuable insights into the state of emerging pollutants in Uganda and their potential implications for human and environmental health. This diversity reflects the complex nature of pollution sources, including urbanization, industrial activities, agricultural practices, and improper waste management. The identification of these pollutants highlights the need for comprehensive monitoring and assessment programs to better understand their occurrence, behavior, and potential risks to the environment and human health.

The reviewed studies revealed that pharmaceutical compounds, including antibiotics, analgesics, hormones, and antidepressants, have been detected in various environmental matrices such as water bodies and soils. These compounds enter the environment primarily through wastewater discharge and improper disposal of unused medications. The presence of pharmaceuticals in the environment raises concerns about potential ecological impacts and the development of antibiotic resistance (26,38).

In addition, numerous studies highlighted the widespread use of pesticides in agricultural practices in Uganda. These studies identified various classes of pesticides, including insecticides, herbicides, and fungicides, in soil and water samples (46,74,76). Pesticide residues were detected in crops (40), posing risks to both human health and the environment. The findings underscore the need for proper pesticide management practices and the promotion of sustainable agriculture.

The systematic review identified reports on the occurrence of persistent organic pollutants, such as polychlorinated biphenyls (PCBs), dioxins, and furans, in the Ugandan environment (31,36). These toxic compounds, known for their resistance to degradation, were found in sediments and aquatic organisms. The accumulation of POPs in the food chain raises concerns about potential health effects on humans consuming contaminated fish and other aquatic products.

Studies revealed the presence of personal care products, including fragrances, UV filters, and preservatives, in water sources and aquatic ecosystems. These compounds are commonly used in cosmetics and personal care products and enter the environment through various pathways. The detection of these chemicals in the environment emphasizes the importance of proper wastewater treatment to prevent their release into water bodies.

The review encompassed studies examining heavy metal contamination in Uganda, with a focus on metals such as lead (Pb), mercury (Hg), cadmium (Cd), and chromium (Cr). These metals were detected in water, soil, and biological samples (29,43,45). Elevated concentrations of heavy metals were attributed to industrial activities, mining, and urbanization. The accumulation of heavy metals in the environment can lead to adverse health effects on humans and ecological disruptions.

Studies indicated the presence of hydrocarbon compounds, including polycyclic aromatic hydrocarbons (PAHs) and benzene, in soil and air samples in Uganda (63,65). These compounds are released from activities such as vehicle emissions, industrial processes, and burning of biomass. The potential carcinogenic and toxic effects of hydrocarbon compounds underscore the importance of air quality management and emission control measures.

The review also highlighted the occurrence of biotoxins, particularly mycotoxins, in agricultural products and food items. Aflatoxins and other fungal toxins were detected in crops such as maize and groundnuts (97,110,111,127). Consumption of mycotoxin-contaminated foods can pose significant health risks, including liver damage and cancer.

The reviewed studies revealed the presence of natural radionuclides such as uranium and thorium in soil and water samples (117,120). Additionally, concerns were raised about potential

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exposure to electromagnetic radiations, including radiofrequency and microwaves, from sources such as mobile communication towers (53–55).

Several studies highlighted the presence of microplastics in water bodies, including lakes and rivers, as well as in fish species consumed by humans (121). The ubiquitous distribution of microplastics in the environment raises concerns about their impact on aquatic ecosystems and potential ingestion by humans through the food chain.

The review identified reports on disinfection byproducts, such as trihalomethanes (THMs), in drinking water supplies (122). In addition, particulate matter, including fine and coarse particulates (PM2.5 and PM10), was also a subject of investigation in air quality studies (98,124,125).

4.1. Sources and Distribution Patterns

The review identified urban areas, industrial zones, and agricultural regions as major sources of emerging pollutants in Uganda (29,48,97,103). Rapid urbanization and inadequate waste management practices contribute to the discharge of pollutants into water bodies, leading to contamination of surface and groundwater resources (23,70,128). Industrial activities generate various chemical byproducts that can contaminate the surrounding environment (37,44,47,89). Agricultural practices involving the use of pesticides and fertilizers contribute to soil and water pollution (65,73,74,76). Understanding these sources and distribution patterns is crucial for targeted interventions and pollution control strategies.

4.2. Emerging Pollutants in Surface Water

The findings of the systematic review revealed a widespread occurrence of emerging pollutants in surface water bodies across Uganda. Pharmaceuticals, including antibiotics and hormones, with concentrations of 1 – 5600 ngL^{-1} were frequently detected in surface water samples at Murchison bay of Lake Victoria (26,38), indicating their presence as contaminants of emerging concern. The discharge of untreated or inadequately treated wastewater from domestic, industrial, and healthcare facilities into water bodies is a significant contributing factor to pharmaceutical contamination. A concentration of 100 – 500 ngL^{-1} of diclofenac was detected in the wastewater effluents of Bugolobi WWTP which is the main wastewater treatment plant in Uganda (37,38). These contaminants can have adverse effects on aquatic organisms and ecosystems, potentially leading to the development of antibiotic resistance and disruption of endocrine systems (37,129).

4.3. Wastewater as a source of Emerging Pollutants

Wastewater was identified as a significant source of emerging pollutants in Uganda (39,49,130). Pharmaceuticals, personal care products, and various chemical compounds in wastewater samples were detected in the industrial and municipal wastewater from Kampala city via Nakivubo channel, and Bugolobi WWTP effluents. 89 – 1400 ngL^{-1} of Triclosan an antibiotic in soaps, toothpaste and detergents was detected in the effluents from Bugolobi WWTP (39). In addition, 0.84 – 1.04 mg/Kg of cadmium a toxic heavy metal was detected in the water and sediments of Nakivubo channel and its increased concentration is attributed to the untreated industrial effluents in this drainage channel (29). Inadequate wastewater treatment infrastructure and practices contribute to the release of these contaminants into the environment, especially in urban areas and regions with high population densities. The presence of emerging pollutants in wastewater calls for the implementation of improved treatment technologies and stringent regulatory measures to ensure the removal or reduction of these contaminants before discharge.

4.4. Emerging Pollutants in Sediments

Sediments serve as a sink for pollutants, accumulating various emerging contaminants over time. The systematic review identified the presence of heavy metals (45), pesticides (27), and microplastics (52) in sediment samples from different water bodies in Uganda. Industrial activities, mining, and agricultural runoff were identified as major sources of sediment pollution (100). A study

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conducted by (29) detected a concentration of 79 – 138.18 mg/Kg of lead in water and sediments of Nakivubo channel. The persistence of these pollutants in sediments raises concerns about potential long-term impacts on benthic organisms and the potential for their re-entry into the water column. Effective sediment management strategies, including remediation efforts and the implementation of best management practices in industrial and agricultural sectors, are crucial to minimize the impacts of emerging pollutants on sediments and associated ecosystems.

4.5. Ambient Air as a transport medium for Emerging Pollutants

While the systematic review focused primarily on emerging pollutants in water, it is important to note that some contaminants can also be transported through the air. Airborne particles and gases can carry pollutants such as persistent organic pollutants (POPs) and microplastics over long distances, leading to their deposition in ecosystems, including water bodies and soils. Study conducted by (124,125), 152.6 $\mu g/m^3$ of $PM_{2.5}$ and 208 $\mu g/m^3$ of PM_{10} were measured in air samples around the districts of Kampala, Jinja and Mbarara in Uganda. This review identified that a few studies investigating airborne emerging pollutants have so far been done. However, considering the industrial growth, vehicular emissions, and open burning practices prevalent in certain regions, further research is warranted to assess the potential presence and impacts of airborne emerging pollutants in Uganda.

4.6. Emerging Pollutants in Foods

Although the systematic review primarily focused on environmental matrices, it is essential to consider the potential transfer of emerging pollutants into the food chain. Contaminated water, soil, and sediments can contribute to the accumulation of pollutants in crops, aquatic organisms, and livestock. 0.5 – 4.6 ppm of arsenic was detected in processed peanuts (97) and also 156.9 ppm of chromium were detected in raw bovine milk and herbal medicines in Kampala and Wakiso districts in Uganda. This can pose risks to human health through the consumption of contaminated food products. The presence of pesticides, heavy metals, and pharmaceutical residues in food items can lead to acute or chronic health effects, such as pesticide toxicity or the introduction of antibiotic-resistant bacteria. Robust monitoring programs and adherence to good agricultural practices are necessary to ensure food safety and minimize the exposure of consumers to emerging pollutants. The systematic review on emerging pollutants in Uganda provides valuable insights into the nature, sources, distribution, and potential impacts of these contaminants in the country. The discussion of the results focuses on key findings, their implications, and recommendations for future research and policy interventions.

5. Environmental and Health Impacts

The reviewed studies have underscored the environmental impact of emerging pollutants on ecosystems and biodiversity. These pollutants, including pharmaceuticals, personal care products, heavy metals, and pesticides, have been identified in surface waters, posing significant risks to aquatic organisms. They have the potential to disrupt endocrine systems and reproductive processes (26,28,29,38,58). Additionally, pesticide residues found in soils can adversely affect soil health, microbial communities, and non-target organisms, contributing to ecological imbalances (68,73).

Waterborne exposure to emerging pollutants through drinking water sources can have enduring consequences, such as antibiotic resistance and endocrine disruption (26,36,38). Contaminants accumulating in biota can propagate risks through the food chain, potentially causing acute toxicity, chronic health conditions, and further endocrine disruption (4,45,131). Moreover, occupational exposure to these emerging pollutants, particularly among workers in agriculture and waste management sectors, has been linked to various acute and chronic health effects.

The presence of pharmaceuticals and personal care products detected in Lake Victoria, a primary source of drinking water in Uganda, raises concerns regarding antibiotic resistance development and water resource contamination (26,68,73). In agricultural areas like Kakira and Entebbe, pesticide residues have been identified in soils, surface waters, and crops, signifying ecological disruption and human exposure risks (27,68,73). Urban areas have reported the presence of microplastics in various environmental compartments, including water bodies, soils, and the air. These findings suggest potential impacts on human health and the environment (121).

It is evident from these studies that addressing emerging pollutants is imperative to safeguard ecosystems, biodiversity, and human health in Uganda. However, these risks are not confined to aquatic environments. Airborne emerging pollutants, encompassing volatile organic solvents, different particles like microplastics and engineered nanoparticles, and bio-aerosols, can infiltrate the human body through inhalation, dermal contact, or ingestion, leading to a range of health issues (3,4,12,132).

Waterborne emerging pollutants, primarily stemming from agricultural, industrial, and domestic activities, can contaminate surface water, groundwater, municipal wastewater, and drinking water sources (5,12). Microplastics, a notable emerging pollutant in water, accumulate various contaminants as they traverse the food chain, amplifying the risk (5,52,121,133). The contamination of surface waters, including rivers and lakes, with emerging pollutants like pesticides, pharmaceuticals, perfluorinated alkylated substances, and personal care products, has become a growing concern due to its potential harm to freshwater resources and public health. Furthermore, emerging pollutants can also jeopardize groundwater quality, which serves as a critical source of fresh water for various purposes. While traditional pollutants are well-regulated, the emergence of new substances with uncertain immediate effects presents a substantial challenge for groundwater protection.

6. Current Monitoring and Regulation Efforts

In Uganda, various efforts have been undertaken to monitor and assess emerging pollutants to comprehend their presence, concentrations, and potential environmental and human health risks. Monitoring initiatives encompass collaborations with institutions like the National Environment Management Authority (NEMA), which plays a pivotal role in environmental management and hotspot identification(17). The Ministry of Water and Environment, specifically the Directorate of Water Resources Management, conducts routine water quality assessments, encompassing emerging pollutants, in surface waters, groundwater, and drinking water sources. Additionally, academic and research institutions, including universities and research centers, actively contribute to monitoring by evaluating emerging pollutants in diverse environmental compartments and offering valuable scientific insights for policymaking.

While Uganda has made substantial strides in monitoring emerging pollutants, certain challenges persist in effectively regulating and managing these substances. Existing regulatory mechanisms, spearheaded by NEMA, establish a foundation for addressing emerging pollutants through environmental regulations, guidelines, and standards (17,134). Nevertheless, opportunities for enhancement exist, particularly in the formulation of comprehensive, targeted regulations dedicated to emerging pollutants and improved data collection and accessibility. Constraints in monitoring capacity and resource availability hinder the implementation of comprehensive, routine monitoring programs. Consequently, there is a pressing need for expanded research efforts to deepen our understanding of the prevalence, fate, and impacts of emerging pollutants. Access to comprehensive data is pivotal for the development of effective mitigation strategies.

Strengthening technical expertise and monitoring capabilities concerning emerging pollutants is paramount, necessitating advanced analytical techniques and fostering collaboration between research institutions and regulatory bodies. Additionally, refining regulatory frameworks to address emerging pollutants specifically, including the formulation of guidelines and standards, is vital. Raising awareness among the public, policymakers, and industries is also imperative. This can be achieved through educational and outreach programs that promote responsible practices and sustainable alternatives. By addressing these gaps and challenges, Uganda can enhance its monitoring, regulation, and management of emerging pollutants more effectively.

7. Mitigation Strategies and Future Direction

Effective approaches and technologies are crucial for mitigating the impacts of emerging pollutants in Uganda. Upgrading wastewater treatment systems with advanced technologies like advanced oxidation, activated carbon adsorption, and membrane filtration can remove pharmaceuticals, personal care products, and other emerging pollutants (4,135–137). Promoting sustainable agriculture practices, such as integrated pest management (IPM) techniques and organic farming, can reduce pesticide use. Implementing source control measures and improving waste management practices can prevent the release of emerging pollutants. Encouraging the use of green chemistry principles and developing eco-friendly alternatives can minimize the generation and release of emerging pollutants.

To enhance monitoring, regulation, and enforcement of emerging pollutants in Uganda, specific regulations targeting emerging pollutants should be established, along with guidelines, standards, and monitoring requirements. Increasing funding and resources for monitoring programs, strengthening the capacity of regulatory agencies and research institutions, and improving data collection and sharing mechanisms are essential. Conducting public awareness campaigns to educate the public about emerging pollutants and promoting responsible practices and sustainable alternatives are important. These policy recommendations will contribute to effective monitoring, regulation, and management of emerging pollutants in Uganda.

Research gaps in studying emerging pollutants in Uganda include investigating their occurrence and impacts in the air, assessing ecological effects on different ecosystems, studying their presence and accumulation in food crops and livestock, understanding their fate and transport mechanisms in various environmental compartments, and conducting comprehensive studies on the potential health risks associated with exposure. Addressing these gaps will provide a better understanding of emerging pollutants and inform the development of effective policies and interventions to minimize their environmental and health impacts in Uganda.

8. Conclusions

This systematic review presented a comprehensive assessment of the state of pollution from the emerging pollutants in Uganda, shedding light on the nature, sources, distribution, and potential impacts of these contaminants. The findings underscore the urgent need for action to address the challenges posed by emerging pollutants to Uganda's ecosystems and public health. This systematic review revealed that a diverse range of emerging pollutants, including pharmaceuticals, personal care products, pesticides, industrial chemicals, and microplastics, are present in various environmental compartments in Uganda (**Table. 2**). Studies have identified specific compounds within each category of emerging pollutants, with varying concentrations reported across different matrices. The spatial and temporal distribution of emerging pollutants indicates higher concentrations in urban areas, agricultural regions, and near industrial zones. Additionally, the review identified the potential sources and pathways of these pollutants, such as industrial discharges, agricultural practices, domestic wastewater, and improper waste disposal (26,37). Rapid urbanization, inadequate waste management practices, industrial activities, and agricultural practices contribute to the release of these contaminants into the environment.

The findings of this systematic review have significant implications for environmental management and public health in Uganda. First, the presence of emerging pollutants in environmental compartments raises concerns about their adverse effects on ecosystems, biodiversity, and ecosystem services. They can persist in the environment, accumulate in living organisms, and enter the food chain, leading to adverse effects on aquatic ecosystems, biodiversity loss, soil degradation, and potential health issues such as endocrine disruption, antibiotic resistance, and carcinogenicity. To address the challenges posed by emerging pollutants, it is crucial to implement robust policies, regulations, and mitigation measures. Strengthening waste management systems, promoting sustainable agricultural practices, and implementing pollution control measures in industrial sectors are essential steps to reduce the release of emerging pollutants into the environment. Additionally, the establishment of monitoring programs is necessary to track pollutant levels and assess their long-term impacts. These measures should be supported by research endeavors that focus on understanding the fate, transport, and ecological impacts of emerging pollutants in specific regions of Uganda.

Addressing emerging pollutants in Uganda is of utmost importance to safeguard the environment and protect public health. The systematic review highlights the need for continued research and action in several areas. Further research is required to fill the existing gaps in knowledge, including the assessment of ecological effects, emerging pollutants in air, fate and transport mechanisms, and the long-term impacts on human health. It is crucial to strengthen monitoring programs, enhance technical capacity, and promote data sharing and accessibility. Additionally, there is a need to improve regulatory frameworks specifically targeting emerging pollutants, raise public awareness, and promote sustainable practices across various sectors in Uganda and Africa. Taking proactive measures to address emerging pollutants will contribute to sustainable environmental management, protect ecosystems and biodiversity, and minimize risks to public health. It requires collaboration among government agencies, research institutions, industries, and the public. By prioritizing research, implementing effective mitigation strategies, and refining regulatory frameworks, Uganda can work towards minimizing the release and impact of emerging pollutants, ensuring a cleaner and healthier environment for present and future generations.

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