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Review

A Systematic Review of Contaminants of Concern in Uganda: Occurrence, Sources, Potential Risks, and Removal Strategies

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Abstract: Contaminants of concern (CoCs) pose significant threats to Uganda's ecosystems and public health, particularly in the face of rapid urbanization, industrial expansion, and intensified agriculture. This systematic review comprehensively analyzed Uganda's CoC landscape, addressing imminent challenges that endanger the country's ecosystems and public health. CoCs, originating from urban, industrial, and agricultural activities, encompass a wide range of substances, including pharmaceuticals, personal care products, pesticides, industrial chemicals, heavy metals, radionuclides, biotoxins, disinfection byproducts, hydrocarbons, and microplastics. This review identified the major drivers of CoC dispersion, particularly wastewater and improper waste disposal practices. From an initial pool of 887 articles collected from reputable databases such as PubMed, African Journal Online (AJOL), Web of Science, Science Direct, and Google Scholar, 177 pertinent studies were extracted. The literature review pointed to the presence of 57 pharmaceutical residues and personal care products, along with 38 pesticide residues and 12 heavy metals, across various environmental matrices, such as wastewater, groundwater, seawater, rainwater, surface water, drinking water, and pharmaceutical effluents. CoC concentrations displayed significant levels exceeding established regulations, varying based on the specific locations, compounds, and matrices. This review underscores potential ecological and health consequences associated with CoCs, including antibiotic resistance, endocrine disruption, and carcinogenicity. Inefficiencies in traditional wastewater treatment methods, coupled with inadequate sanitation practices in certain areas, exacerbate the contamination of Uganda's aquatic environments, intensifying environmental and health concerns. To address these challenges, advanced oxidation processes (AOPs) emerge as promising and efficient alternatives for CoC degradation and the prevention of environmental pollution. Notably, no prior studies have explored the management and mitigation of these contaminants through AOP application within various aqueous matrices in Uganda. This review emphasizes the necessity of specific regulations, improved data collection, and public awareness campaigns, offering recommendations for advanced wastewater treatment implementation, the adoption of sustainable agricultural practices, and the enforcement of source control measures. Furthermore, it highlights the significance of further research to bridge knowledge gaps and devise effective policies and interventions. Ultimately, this comprehensive analysis equips readers, policymakers, and regulators with vital knowledge for informed decision-making, policy development, and the protection of public health and the environment.

Keywords: contaminants of concern; Uganda; ecological impacts; public health; legacy contaminants; sustainable agriculture; environmental management

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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 issue has escalated due to the rapid industrialization, urbanization, and modernization processes taking place across the world [1,2]. These processes have led to the release of a diverse array of pollutants into various environmental compartments, giving rise to the concept of "contaminants of concern (CoCs)" [5]. These CoCs, often originating from new technologies, industrial processes, and urban activities, have the potential to pose significant ecological and human health risks [6,7].

CoCs encompass a wide array of substances, including emerging contaminants (Ecs) and legacy contaminants, both raising heightened environmental and public health concerns. Ecs include previously unidentified or underrecognized substances, such as industrial byproducts, pharmaceutical residues, pesticides, personal care products, flame retardants, polycyclic aromatic hydrocarbons (PAHs), polychlorinated compounds (PCBs), mycotoxins, and microplastics, whose presence and potential environmental implications were not widely known, necessitating ongoing investigations [8–11]. In contrast, legacy contaminants are well-established and regulated, with documented adverse consequences for ecosystems and public health. This category comprises familiar contaminants such as heavy metals and persistent organic pollutants (POPs) [4,12–14].

Notably, many of these CoCs, particularly Ecs, currently lack established regulatory standards, demanding continuous monitoring due to their bioaccumulation potential, and persistence in various environmental compartments [15]. Understanding their presence, sources, distribution, and potential impacts is essential for sustainable environmental management and public health protection [16]. However, the scarcity of data regarding their occurrence, transport, and fate, and the absence of standardized detection methods are significant challenges. Advanced analytical chemistry and instrumentation have played a pivotal role in revealing these substances, with the ability to detect them at minute concentrations, often in parts per trillion (ppt) or even parts per quadrillion (ppq). These substances enter water bodies, soil, and the atmosphere through various pathways, including industrial discharges, agricultural runoff, improper waste disposal, and atmospheric deposition as illustrated in Figure 1, where they persist, accumulate in organisms, and potentially cause adverse effects [4,5,17–19].

Uganda, renowned for its rich biodiversity and stunning landscapes, faces mounting challenges with the rise of CoCs. These pose significant threats to the country's ecosystems, public health, and socio-economic development [4,20,21]. Uganda's contribution to the continent's overall contaminant pollution is estimated to be between 6–8%, primarily resulting from rapid urbanization, industrial growth, importation of electric waste, and intensified agricultural practices, all contributing to the release of various contaminants into the environment [21]. These developments have triggered concerns regarding the long-term sustainability of the region [21–23]. Furthermore, the status of ambient air quality in Uganda presents alarming figures, with $PM_{2.5}$ mass concentrations exceeding the US 24 h $PM_{2.5}$ National Ambient Air Quality Standards (NAAQS; 35 $\mu g/m^3$) and the WHO air quality guidelines (25 $\mu g/m^3$) by three to four times, highlighting a dangerous level of air pollution, particularly detrimental to susceptible populations such as children and the elderly [24]. The impacts of these contaminants can be profoundly detrimental to both the environment and human health. They have been associated with ecosystem disruption [25], biodiversity loss, hormonal imbalances in wildlife, and reproductive impairments [3,20,26,27]. 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 [28,29]. Despite considerable efforts to monitor and regulate legacy contaminants, the knowledge about different types of CoCs and their impact on Ugandan ecosystems and public health remains limited. The persistence and potential adverse effects of CoCs raise significant concerns as these substances are characterized by their diverse behavior and sources of production, making their detection and characterization challenging. Some CoCs, 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 [15]. The detection of these CoCs necessitates the use of sophisticated analytical techniques capable of detecting trace levels of these compounds in environmental matrices.

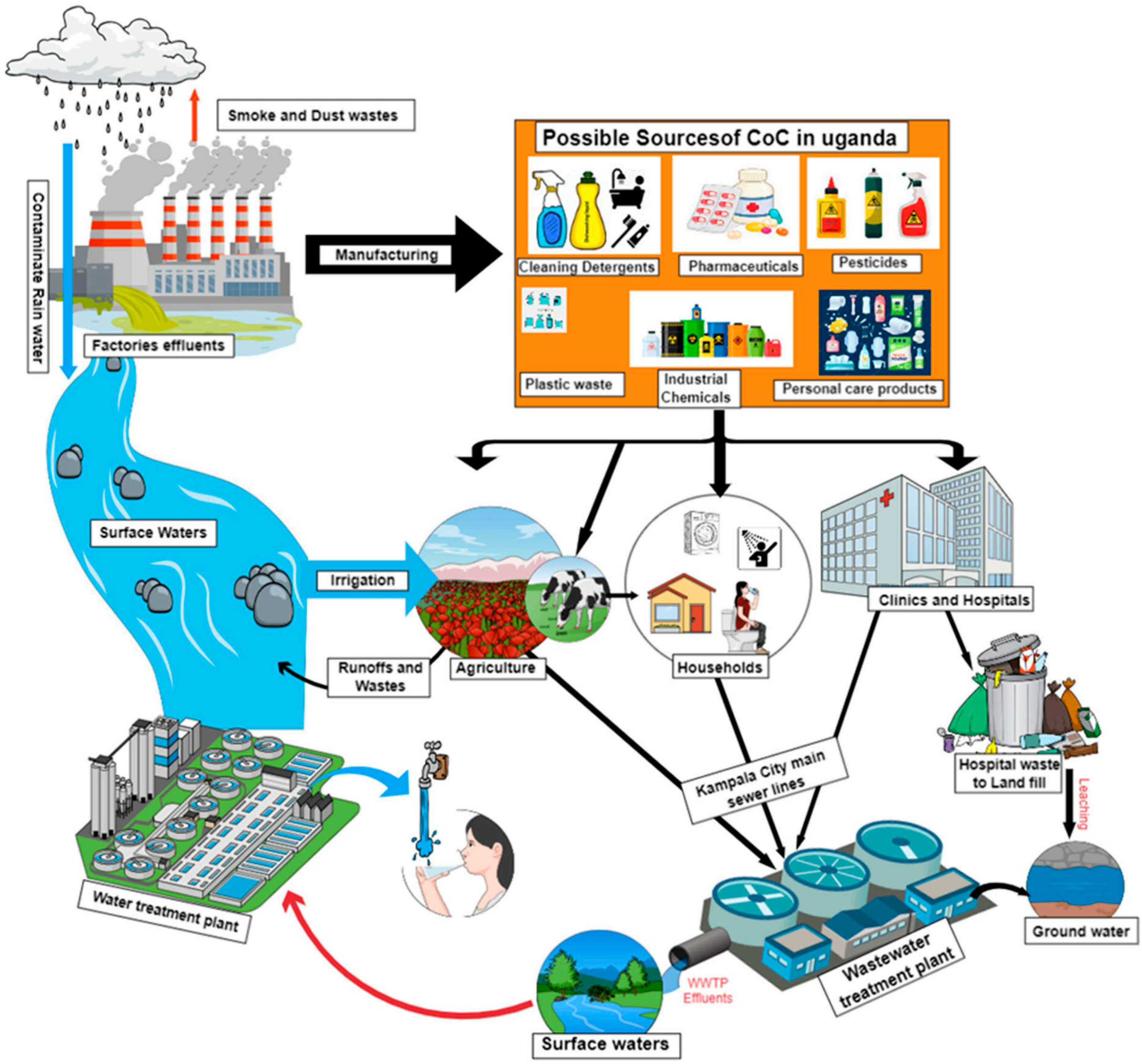

Figure 1. Sources, pathways, and distribution of CoCs in different environmental compartments in Uganda.

Several studies in Uganda have investigated the sources, presence, and concentrations of CoCs in various environmental systems, revealing a range of compounds, including pharmaceutical residues, personal care products, pesticides, industrial chemicals, microplastics, and heavy metals. However, concentrations vary depending on the sampling location, environmental matrix, and analytical techniques employed. Several 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 CoCs in different environmental compartments [30]. The diverse nature of CoCs necessitates a comprehensive investigation of their occurrence in various matrices, including surface water bodies (lakes, rivers, and wetlands), groundwater, sediments, soils, air, and biota (aquatic and terrestrial organisms). Understanding the distribution and concentrations of CoCs in various environmental compartments is crucial for assessing their potential risks and designing effective management strategies.

Several studies conducted in Uganda have investigated the sources, presence, and concentrations of CoCs in various environmental systems, including water bodies [31,32], sediments [31,33], surface waters [34–36], food crops [37,38], edible insects [39], breast-milk [40], and fish [34]. These studies have identified a range of compounds, including pharmaceutical residues like antibiotics and analgesics [30,41,42], personal care products like fragrances and UV filters [43], pesticides like herbicides and insecticides [31,39,44,45], industrial chemicals like flame retardants and plasticizers [40,43,46], microplastics, and heavy metals [32,47,48]. The reported concentrations of these CoCs exhibit variation depending on the sampling location, environmental matrix, and analytical techniques used. For example, antibiotics have been detected in surface waters at concentrations ranging from 1 ng/L to 5600 ng/L, highlighting the potential ecological impact of pharmaceutical pollution [30,42]. However, there is limited information on healthcare professionals' disposal methods and adherence to disposal guidelines in Uganda, particularly for pharmaceutical waste [42]. This lack of data, combined with the absence of robust national guidelines and low compliance with existing protocols, heightens the risk of environmental contamination and the ingestion of toxic pharmaceutical waste by humans and animals. Likewise, various chemicals, including pesticides [31,49], perfluorinated alkylated substances (PFAS) [50], personal care products [43], and persistent organic pollutants (POPs) [40], have been observed in surface waters, occasionally exceeding regulatory limits, indicating potential threats to agricultural productivity and human health [23,42,51]. The contamination of surface waters by these emerging contaminants poses a considerable public health concern, similar to the concerns raised in previous studies [42]. In addition, wastewater treatment plant (WWTP) effluents have been identified as significant sources of contamination in Uganda, with some compounds poorly degrading due to a lack of specific treatment methods for organic pollutants [41,42,51–53]. The role of hospitals and households in the pharmaceutical contamination of WWTPs is concerning [30,54]. Urban discharges, including separate or combined sewer overflows, can impact receiving waters in Uganda, similar to other regions. Urban stormwaters contain a variety of contaminants, such as polycyclic aromatic hydrocarbons (PAHs), alkylphenols, and pesticides, contributing to the pollution of surface waters in urban areas [21,41,42,50–52,55]. Furthermore, Uganda faces challenges related to the importation and management of electronic waste (E-waste) due to its poor recycling infrastructure, reliance on informal sectors with crude dismantling, and artisanal recycling techniques [56–59]. As a result, Uganda's soil, water, and air are contaminated with substances such as brominated flame retardants, non-dioxin-like polychlorinated biphenyls (PCBs), PAHs, polychlorinated dibenzo-p-dioxins (PCDDs), polychlorinated dibenzofurans (PBDFs), and dioxin-like polychlorinated biphenyls (DL-PCBs) [35,40,43,46,60,61]. The crude activities involved in E-waste management, including waste dumping in agricultural farmlands and water bodies, further exacerbate environmental pollution in Uganda [56,59].

Beyond the context of Uganda, various African regions, covering approximately 17 percent of the continent's countries, have also reported the presence of CoCs. Notably, 59 percent of these occurrences stem from studies conducted in South Africa, with contributions of 9 percent each from Tunisia and Nigeria, along with 7 percent from Kenya [62–65]. The documentation of CoCs extends throughout the African landscape, including sediments, sludge, treated drinking water, surface water, wastewater, groundwater, and solid deposits. However, limited knowledge about contaminant sources, pathways, properties, and analytical detection techniques hampers the systematic inclusion of CoCs in groundwater monitoring and protection policies. Improper disposal practices further exacerbate Uganda's CoC issues [28,53,58]. The improper disposal of expired medications and electronic waste presents additional risks to the environment and human health [58,66]. The indiscriminate disposal of pharmaceutical waste and the lack of adequate protocols for drug disposal contribute to potential water and soil contamination. The 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 [35,67].

This systematic review aimed to provide a holistic understanding of the status, sources, and impacts of CoCs in Uganda. It offers valuable insights for policymakers, researchers, and stakeholders, ultimately guiding the development of evidence-based interventions and fostering sustainable practices that protect Uganda's natural resources and promote a healthier environment for future generations. Importantly, this review article serves as a critical resource for raising awareness about the prevalence and implications of CoCs in Uganda. It underscores the urgency of addressing these pollutants' sources and effects, both in Uganda and across Africa. By shedding light on the multifaceted challenges posed by contaminants of emerging concern, this article equips readers with essential knowledge for implementing effective management and mitigation strategies. It provides a foundation for informed decision-making, the development of sustainable environmental policies, and the protection of public health, ecosystems, and the country's long-term socio-economic development.

2. Materials and Methods

2.1. Study Design

This review followed a comprehensive and structured approach to assess the state of CoCs 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 CoCs 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 such as "contaminants of concern, Uganda", "emerging contaminants in Uganda", or "Emerging pollutants in surface water, Uganda", "Emerging contaminants in soils, Uganda", or "Emerging contaminants in the air, Uganda", or "Emerging contaminants in wastewater, 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 CoC concentrations 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 CoCs in Uganda or lacked sufficient data were excluded.

2.4. Data Extraction

Data was 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 CoCs investigated, pollutant sources and concentrations, and any reported impacts or observations. The extracted data were organized comprehensively 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 was analyzed and synthesized to provide a comprehensive overview of the state of CoCs 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

The review had potential limitations including the inclusive consideration of English-language studies, which may introduce language bias. Additionally, the review was limited to the available literature only until September 2023, possibly overlooking newer studies. Challenges in data synthesis and comparison may arise due to variations in methodologies and data reporting across different studies. Notably, being a literature review, ethical approval was not required; however, all selected studies were conducted adhered to ethical guidelines, and obtained appropriate ethical clearance where applicable.

3. Results and Discussion

In this review, a comprehensive analysis of 177 articles was conducted to investigate the presence and concentrations of CoCs in Uganda. Employing the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flowchart facilitated the study selection process, providing a transparent overview of the search and screening procedure (see Figure 2) [68]. We initially identified 887 articles from various electronic databases. After the elimination of duplicate entries, 859 articles remained in the pool. Subsequently, we screened the titles and abstracts of these articles for relevance, leading to the exclusion of 214 articles that did not meet the inclusion criteria. Following the elimination of irrelevant articles, we sought the retrieval of the remaining 645 articles, while 305 articles could not be retrieved. We then carefully assessed the full texts of the remaining 340 articles for eligibility. After a meticulous evaluation, we excluded an additional 163 articles due to inadequate data or irrelevance, which ultimately resulted in the inclusion of 177 studies in the systematic review. A detailed summary of the characteristics of the included studies can be found in Table 1. This summary provides information such as author names, publication year, the classes of pollutants investigated, the areas of detection, sources, and concentrations in different environmental systems. The selected studies utilized a wide range of research approaches, including laboratory analyses, field studies, and monitoring programs.

This systematic review successfully identified more than 194 CoC in Uganda, which were subsequently categorized into 12 major classifications, as illustrated in Figure 3. These classifications encompass pharmaceuticals, pesticides, persistent organic pollutants (POPs), personal care products, heavy metals, hydrocarbon compounds, biotoxins, radionuclides, electromagnetic radiations, microplastics, disinfection byproducts, and particulates, with detailed information provided in Tables 1 and 2.

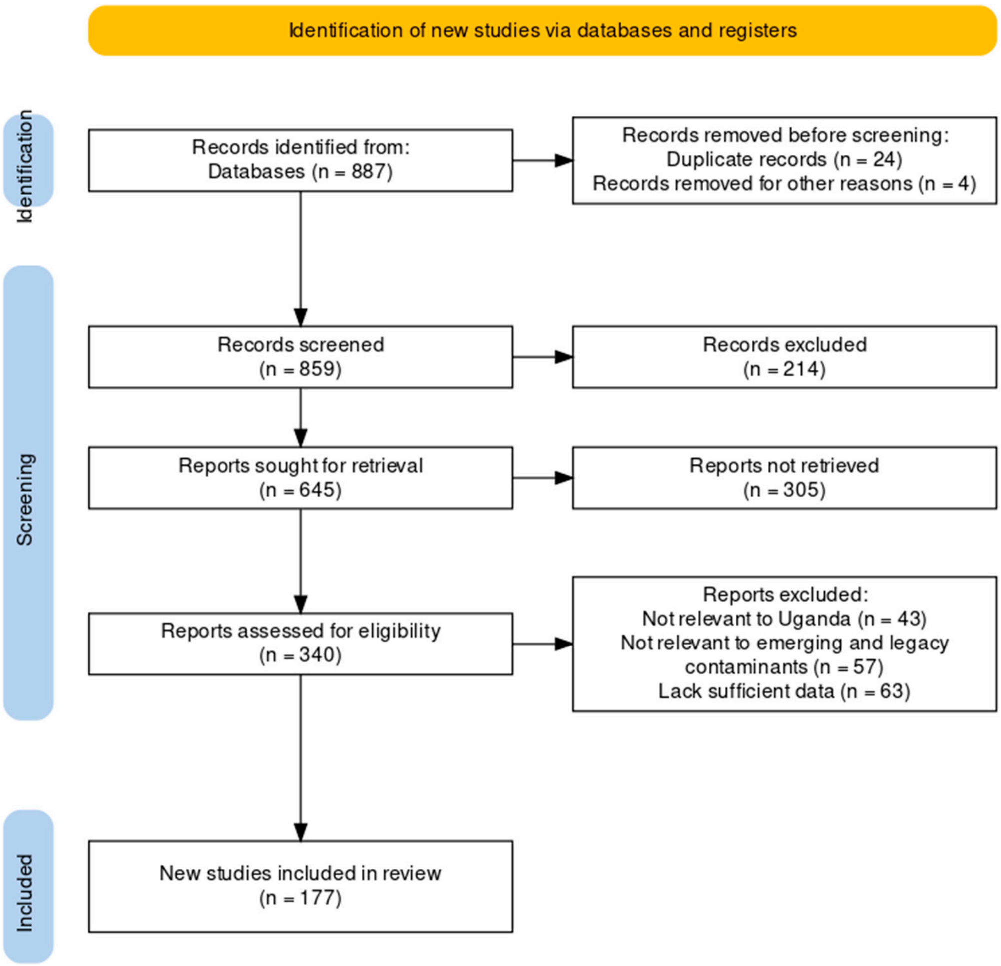

Figure 2. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram for the literature survey.

Table 1. Major groups of CoCs; their descriptions, components, and properties, detected in Ugandan environmental systems.

Category of CoC	Description	Components	Persistence and Bioaccumulation
Pharmaceuticals	Medicinal compounds, including prescription and over-the-counter drugs, enter the environment through human excretion and wastewater.	Antibiotics, Analgesics, Hormones, Antidepressants, Beta-Blockers, Diuretics, Antihypertensive, Fibrate, and Antiparasitic	Low to Medium Persistence, some are bioaccumulative in zoobenthos
Pesticides	Chemical substances used to control pests in agriculture can leach into soil and water, impacting non-target organisms.	Insecticides, Herbicides, Fungicides, and Rodenticides	Medium to High Persistence, some are bioaccumulative such as the cases of Dichlorodiphenyl-trichloroethane (DDT)
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, and Furans, among others	High persistence and Bioaccumulative

Table 1. *Cont.*

Category of CoC	Description	Components	Persistence and Bioaccumulation
Personal Care Products	Chemicals found in cosmetics, shampoos, soaps, and perfumes can be washed into water bodies and contribute to water pollution.	Fragrances, UV Filters, Preservatives, and Surfactants	Low to Medium Persistence
Heavy metals	Metallic elements like lead, mercury, cadmium, and chromium can accumulate in the environment and pose health risks to living organisms.	Lead (Pb), Mercury (Hg), Cadmium (Cd), Chromium (Cr), Nickle (Ni) among others	Medium to High Persistence, some are bioaccumulative
Hydrocarbon Compounds	Organic compounds derived from petroleum, including polycyclic aromatic hydrocarbons (PAHs), are often associated with oil spills.	Polycyclic Aromatic Hydrocarbons (PAHs), and Benzene	Low to Medium Persistence, Bioaccumulative
Biotoxins–Mycotoxins	Toxins are produced by organisms like fungi (mycotoxins) and harmful algae, which can contaminate water and food sources, posing health risks.	Aflatoxins, Ochratoxins, and Fusarium Toxins	Low Persistence, bioaccumulative in humans and animals
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,	Low to High persistence
Other Contaminants of concern	Various emerging contaminants, like flame retardants and nanomaterials, whose impacts on the environment and health are under investigation.	Flame Retardants, and Nanomaterials,	Persistent and highly Bioaccumulative, atmospheric deposition
Microplastics	Tiny plastic particles result from the breakdown of larger plastic waste, which can be ingested by organisms and enter the food chain.	Microplastic particles, and Microfibers,	Low to Medium Persistence, atmospheric deposition
Disinfection byproducts	Chemical compounds formed when disinfectants like chlorine react with organic matter in water, potentially leading to health risks.	Trihalomethanes (THMs)	Low to Medium Persistence
Particulates	Tiny solid particles or liquid droplets suspended in the air can have adverse health effects when inhaled by humans and animals.	$PM_{2.5}$ (Fine Particulate Matter), PM_{10} (Coarse Particulate Matter), Gases, Sulphur dioxide (SO_2), Ozone (O_3), and Nitrogen dioxide (NO_2)	Low Persistence

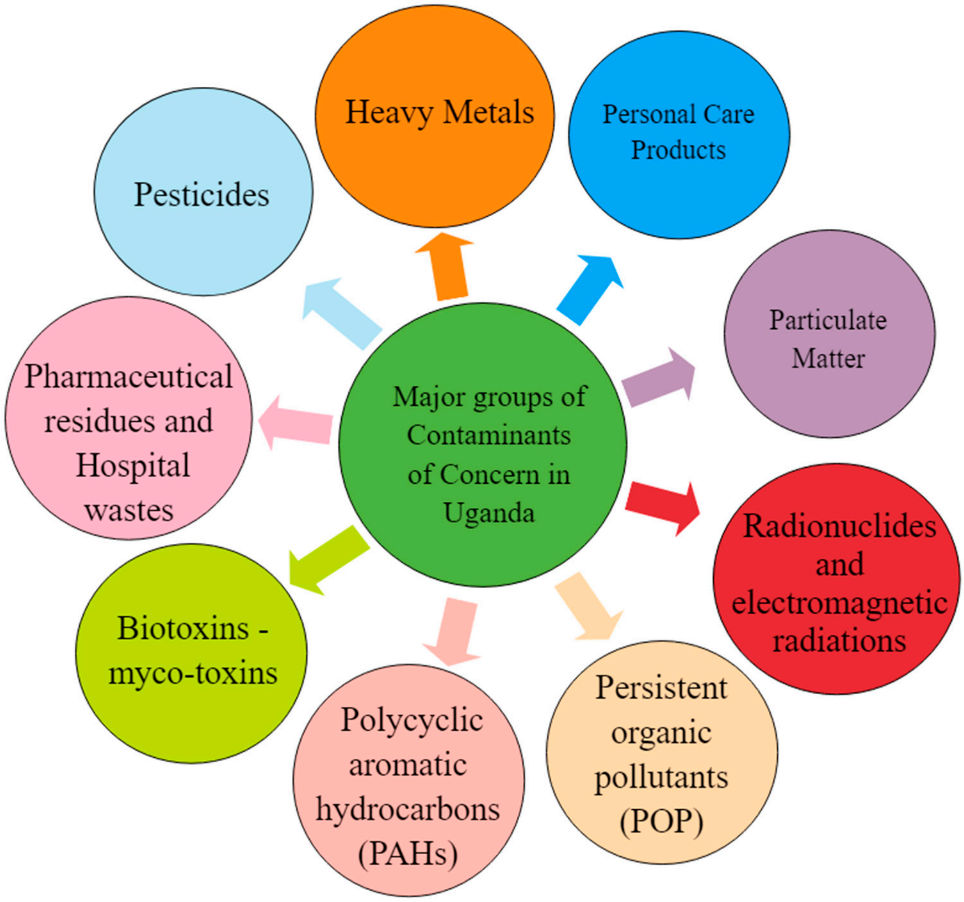

Figure 3. Major groups of CoCs detected in Ugandan environmental systems.

The findings from these studies yield valuable insights into the state of CoCs in Uganda, shedding light on their potential implications for both human and environmental health. This diversity underscores the complex nature of pollution sources, arising from urbanization, industrial activities, agricultural practices, and improper waste management, highlighting the pressing need for comprehensive monitoring and assessment programs to better understand their occurrence, behavior, and potential risks to the environment and human health. One prominent category revealed in the reviewed studies is the pharmaceutical compounds. 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, raising concerns about ecological impacts and antibiotic resistance [30,42].

Table 2. Sources and occurrence of different categories/classes of detected concentrations of CoCs in Ugandan environmental compartments.

Categories of CoC	Classes	CoC (s)	Use/Application	Sampling Matrix	Detected Levels	Place of Study	Detection Periods	References
Pharmaceuticals	Antibiotics	Sulfamethoxazole	Pharmaceutical	Wastewater Effluents, Sediments, Soil, Surface Waters	1–5600 ngL^{-1}	Murchison Bay on L. Victoria and Bugolobi wastewater treatment plant, Kampala, Uganda	2020–2022	[30,41,42]
		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}			
		Oxytetracycline	Pharmaceutical		17–300 ngL^{-1}			
		Tetracycline	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, Ground Water, Runoffs	1350 ngL^{-1}	Bwaise Wobulenzi city suburbs, Kampala, Uganda	2013–2022	[42,69,70]
		Chlortetracycline	Pharmaceutical		394 ngL^{-1}			
		Ciprofloxacin	Pharmaceutical		340 ngL^{-1}			
		Enrofloxacin	Pharmaceutical		17 ngL^{-1}			
		Metacycline	Pharmaceutical		17 ngL^{-1}			
		Nalidixic acid	Pharmaceutical		2340 ngL^{-1}			
		Oxytetracycline	Pharmaceutical		17 ngL^{-1}			
		Penicillin G (benzylpenicillin)	Pharmaceutical		800 ngL^{-1}			
		Sulfathiazole	Pharmaceutical		140 ngL^{-1}			
		Tetracycline	Pharmaceutical		47.3 ngL^{-1}			
	Analgesic/Anti-inflammatory	Ibuprofen	Pharmaceutical	Wastewater treatment plant (WWTP) Effluents, Runoffs, sewer channel wastewater	5.9–780 ngL^{-1}	Nakivubo sewer channel, Murchison Bay on L. Victoria and Bugolobi wastewater treatment plant, Uganda	2020	[30,41]
		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			

Table 2. *Cont.*

Categories of CoC	Classes	CoC (s)	Use/Application	Sampling Matrix	Detected Levels	Place of Study	Detection Periods	References
	Beta-Blockers	Atenolol	Pharmaceutical	Wastewater treatment plant (WWTP) Effluents, Runoffs, sewer channel wastewater	24–380 ngL^{-1}	Nakivubo sewer channel, Murchison Bay on L. Victoria and Bugolobi wastewater treatment plant, Uganda	2020	[30,41]
		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	Organochlorine pesticides (OCPs)	Endosulfan sulfate	Herbicide, insecticides and fungicides	Air, sediment, and surface water samples	0.82–5.62 µg kg^{-1} d.w. (Banned for all users in 2011)	Murchison, Waiya, Thurston Bays, and Napoleon Gulf on the Ugandan side of L. Victoria	2004–2022	[23,31,34,39,45,49,52,71–74]
		Aldrin	Herbicide, insecticide		0.22–15.96 µg kg^{-1} d.w (MRL = 0.1 mg kg^{-1}) (Banned for all users in 2001)			
		Dieldrin	Soil insecticide and for control of mosquitoes.		0.94–7.18 µg kg^{-1} d.w (MRL = 0.1 mg kg^{-1}) (Banned for all users in 2001)			
		Lindane	Insecticide		7–11.4 µg kg^{-1} d.w. (MRL = 0.5 mg kg^{-1})			
		Chlordane	Insecticide		3.82–35.6 pgm^{-3} (Banned for all users in 2001)			
		Hexachlorocyclohexanes	Insecticide		3.72–81.8 pg m^{-3} (Banned for all users in 2009)			
		Heptachlor	Insecticide		0.81 µg kg^{-1} d.w. (Banned for all users in 2001)			
		Heptachlor epoxide	Insecticide. Used for fire ant control in power transformers		3.19 µg kg^{-1} d.w. (Banned for all users in 2001)			
		p, p′-dichlorodiphenyldichloroethylene (DDE)	Insecticides		0.11–3.59 µg kg^{-1} d.w. (Banned for all users in			
		p, p′-DDD			0.38–4.02 µg kg^{-1} d.w. (Banned for all users in			
		p, p′-dichlorodiphenyltrichloroethane (DDT)			0.04–1.46 µg kg^{-1} d.w. (Banned for all users in			

Table 2. *Cont.*

Categories of CoC	Classes	CoC (s)	Use/Application	Sampling Matrix	Detected Levels	Place of Study	Detection Periods	References
Pesticides	Organochlorine pesticides (OCPs)	*o, p′*-DDE	Insecticides	Air, sediment, and surface water samples	0.07–2.72 µg kg^{-1} d.w.	Murchison, Waiya, Thurston Bays, and Napoleon Gulf on the Ugandan side of L. Victoria	2004–2022	[23,31,34,39,45,49,52,71–74]
		o, p′-DDT			0.01–1.63 µg kg^{-1} d.w.			
		Total Endosulfan	Isomer of Endosulfan. Insecticide and acaricide		12.3–282 pg m^{-3} (Banned for all users in 2011)	Air and water samples of Lake Victoria Northern shore watershed, areas of Kakira and Entebbe, Uganda	2006–2022	[31,45,49,69,72,73,75–78]
		Total DDT-related compounds	Insecticide used in agriculture		22.8–130 pg m^{-3} (Banned in 2001, production for the specific uses)			
		Endosulfan sulphate	Insecticide and acaricide		0.82–5.62 µg kg^{-1} d.w. (Banned for all users in 2011)			
		α-Endosulfan			7.59 and 6.00 µg kg^{-1} (MRL = 0.1 mg kg^{-1}) (Banned for all users 2011)	Napoleon Gulf on L. Victoria, Uganda	2004–2022	[34,49,73,79]
		p, p′-1,1-dichloro-2,2-bis-(4-chlorophenyl) ethylene (*p, p′*-DDE)	Insecticide	Air, Surface waters, Fish Tissues	6.10 and 3.44 µg kg^{-1}	Napoleon Gulf on L. Victoria, Uganda	2006–2010	[31,45,77]
		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	2020	[78]
		Endosulfans			1.55 µg kg^{-1} d.w. (Banned for all users in 2011)			
		*p, p′*DDE			125 mg/kg	Kampala and Iganga districts in Uganda	1996–2011	[44,80]
		Dieldrin			123 mg/kg			
		*p, p′*DDD			24 mg/kg			
		p, p′ DDT			13 mg/kg			
		*o, p′*DDT			23 mg/kg			
		α-hexachlorocyclohexane (HCH)			54 mg/kg (Banned for all users in 2009)			
		β-HCH			10 mg/kg (Banned for all users in 2009)			
		Total Dichlorodiphenyl-trichloroethane (ΣDDTs)			22.8–130 pg/m^3	Kakira and Entebbe, northern shore of L. Victoria, Uganda	2016	[73]
		Total hexachlorocyclohexanes (ΣHCHs)			3.72–81.8 pg/m^3			
		Total Endosulfan (ΣEndo)			12.3–282 pg/m^3			

Table 2. *Cont.*

Categories of CoC	Classes	CoC (s)	Use/Application	Sampling Matrix	Detected Levels	Place of Study	Detection Periods	References
Pesticides	Carbamates	Carbofuran	Insecticide	Air, Surface waters, Fish Tissues	83.3 pg/m^3	Air samples from Kakira and Entebbe, northern shore of L. Victoria, Uganda	2010–2019	[72,78,81]
	Organophosphates (OPPs)	Chlorpyrifos			93.5 ng/m^3			
		Chlorthalonil	Fungicide		<0.10–24.0 pg m^{-3}			
		Metribuzin	Herbicide		<0.02–0.53 ng m^{-3}			
		Trifluralin			0.02–0.32 pg m^{-3}			
		Malathion	Insecticide		<0.08–193 pg m^{-3}			
Persistent organic pollutants (POPs)	Brominated Flame Retardants	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 (Banned for all users in 2001)	Napoleon Gulf and Thurston Bay on the northern shore of L. Victoria, Uganda	2013	[46]
	Chlorinated Flame Retardants	Dioxin-like polychlorinated biphenyls (PCBs)			136 pg g^{-1} dw (Banned for all users in 2001)		2006–2021	[40,46,60,82]
		polychlorinated dibenzo-p-dioxins/furans (PCDD/Fs)			44.1 pg g^{-1} d.w. 0.07–5.53 pg Toxic Equivalent Factors (TEQ) g^{-1} d.w. (Banned for all users in 2001)		2006–2021	[40,60,82]
		polychlorinated dibenzofurans (PCDFs)			0.07–5.61 pg g^{-1} d.w. 0.01–0.23 pg TEQ g^{-1} d.w. (Banned for all users in 2001)		2006–2021	[40,60,82]
	Organochlorine pesticides	Pymetrozine	Pesticide	Edible Insects	0.02 pg g^{-1} d.w.	Ugandan districts	2022	[39]
		Methabenzthiazuron			0.08 pg g^{-1} d.w.			
		Metazachlor			1.4 ± 0.03 pg g^{-1} d.w.			
		Fenimorph			0.04 ± 0.03 pg g^{-1} d.w.			
		Fludioxonil	Fungicide		0.29 pg g^{-1} d.w.			
		Metalaxyl			0.01 ± 0.01 pg g^{-1} d.w.			
	Organophosphorus flame retardants (OPFRs)	Tricresyl phosphate	Used as a plasticizer	Waters, sediments, and soil samples	25–8100 ngL^{-1}	Napoleon gulf, Murchison, Waiya, Entebbe, and Thurston bays, Uganda	2006–2021	[31,43,44,49, 72,74,76–78]
		Tris-(2-chloroethyl) phosphate (TCEP)	Widely used as a plasticizer, fire retardant, and solvent		24–6500 ngL^{-1}			
		Triphenyl phosphate (TPP)			54–4300 ngL^{-1}			
		Tris-(2-ethylexyl) phosphate (TEHP)			4300 ngL^{-1}			
		2-Ethylhexyl diphenyl phosphate (EHDPP)			7.7–730 ngL^{-1}			
		Tricresyl phosphate (TCP)			8100 ngL^{-1}			

Table 2. *Cont.*

Categories of CoC	Classes	CoC (s)	Use/Application	Sampling Matrix	Detected Levels	Place of Study	Detection Periods	References
Persistent organic pollutants (POPs)		Tris-(2-chloroisopropyl) phosphate (TCPPi)	Used as plasticizers and antifoam agents	Waters, sediments, and soil samples	25–600 ngL^{-1}	Napoleon gulf, Murchison, Waiya, Entebbe, and Thurston bays, Uganda	2006–2021	[31,43,44,49,72,74,76–78]
		Tributyl phosphate (TBP)			29 ngL^{-1}			
		Triethyl phosphate (TEP)			9.6–500 ngL^{-1}			
	Phthalate ester plasticizers (PEP)	Dibutyl phthalate (DBP)	Are added to polymers to ease processing and to enhance flexibility and toughness of the final product	Waters, sediments, and soil samples	350–16,000 ngL^{-1}	Napoleon gulf, Murchison, Waiya, Entebbe, and Thurston bays, Uganda	2021	[43]
		Bis-(2-ethylhexyl) phthalate (DEHP)			210–23,000 ngL^{-1}			
		Dimethyl phthalate			6.8–400 ngL^{-1}			
		Diethyl phthalate (DEP)			38–1100 ngL^{-1}			
		N-butyl benzenesulfonamide (NBBS)			7.5–200 ngL^{-1}			
		Bis-(2-ethylhexyl) adipate (DEHA)			12–6100 ngL^{-1}			
Personal Care Products	Antimicrobial	Triclosan	Antibiotics in soaps, toothpaste, detergents	Wastewater Effluents	89–1400 ngL^{-1}	Napoleon gulf, Murchison, Waiya, Entebbe, and Thurston bays, Uganda	2021	[43]
	Organic sunscreens	Benzophenone	Protect the products from UV light		36–1300 ngL^{-1}			
		4-methylbenzylidine camphor	Organic UV filters		21–1500 ngL^{-1}			
	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, 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}			
	Masking agent	Acetophenone	Covers the unpleasant scents of other ingredients		2.2–100 ngL^{-1}			
		3-methylindole	It is 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}			

Table 2. *Cont.*

Categories of CoC	Classes	CoC (s)	Use/Application	Sampling Matrix	Detected Levels	Place of Study	Detection Periods	References
Personal Care Products	Preservatives	3-tert-butyl-4-hydroxy anisole	Is used as an antioxidant and preservative	Wastewater Effluents	7.3–100 ngL^{-1}	Napoleon gulf, Murchison, Waiya, Entebbe, and Thurston bays, Uganda	2021	[43]
	Antioxidant	2,6-di-tert-butyl-phenol	They are used as stabilizers, free-radical scavengers, and antioxidants		66 ngL^{-1}			
Heavy metals	Post-transition metals	Pb	Battery assembling, in gasoline	Water, sediments, dairy, and beef product samples	79–138.18 mg/kg	Nakivubo channelized stream sediments and in Kampala markets, Uganda	2009–2021	[32,34,47,48, 83–94]
	Transition metals	Cd	Find applications in batteries, alloys, coatings (electroplating), solar cells, plastic stabilizers, and pigments	Water, sediments, Roadside soils, surface films, and selected vegetable weeds	0.84–1.04 mg/kg			
	Transition metals	Cu	Find applications in electrical wiring, roofing, plumbing, and industrial machinery.	Sludge waste, dairy and beef products, soil, food crops, groundwater, Industrial effluents, Herbal medicine, rainwater, sediments, food items, 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	2006–2021	[32,33,36,47, 86–90,94–102]
	Trace element	Zn	Smelting and galvanization	Roadside soils, surface films, and selected vegetable weeds	177.89–442.40 mg/kg	Kampala city roads, Uganda	2017–2022	[47,83,89,101, 102]
	Transition metals	Mn	Welding, making structural alloys	Food crops,	363.47 mg/kg	Kampala City, Uganda	2004–2019	[33,48,52,71]
	Transition metal	Fe	Making alloy steels	Groundwater, soils, stream sediments, and food crops.	30,085.33–5835.00 mg/kg	Nakivubo stream, Kilembe copper mines, southwestern Uganda areas	2004–2021	[33,91,92,95, 99,103]
	Transition metal	Ni	Use in alloying such as in armor plating	Soils, surface water, herbal medicines, and food items	2.2–9.40 ppm	Jinja steel rolling mills, areas of southwestern Uganda, and Kampala markets	2015–2020	[87,98,99]
	Metalloid	As	Used as an allowing agent as well as in making glass, pigments, textiles, and both metal and wood adhesives	Up and Downstream waters, soil, surface water, and plant tissues	0.5–4.6 ppm	Roofings rolling mills, steel and tube industries in Nakawa Industrial area and areas of Kilembe copper mines, Uganda	2007–2022	[47,87,91,92]

Table 2. *Cont.*

Categories of CoC	Classes	CoC (s)	Use/Application	Sampling Matrix	Detected Levels	Place of Study	Detection Periods	References
Heavy metals	Transition metals	Co	Making alloys, find applications in magnets and is also used as a catalyst in petroleum industries.	Surface water, vegetables, and medicinal herbal samples	0.233 g/mL	River Nyamwamba areas in Kasese, southwestern Uganda parts, and Soroti district	2010–2020	[33,86,98]
	Transition metals	Hg	Find applications in gold extraction and also used in manometers	Soils, Food samples, Surface waters	0.05 ± 0.01 ppm	Kampala, Wakiso and Busia districts, Uganda	2009–2022	[34,47,103]
	Transition metals	Cr	Applied in the manufacture of steel as well as hardening steel	Soils, Dairy products, Herbal samples, Food samples	156.9 ppm	Steel and Tube industrial area, Roofings rolling mills area, Kampala and Soroti districts, Uganda	2010–2022	[32,104]
	Transition metal	Fe	Making alloy steels	Sediments, Soils, Surface Waters,	64.05–147.40 mg/Kg	Industrial effluents in Kampala and Soroti districts, Nakivubo stream, and Osukuru phosphate mines areas, Uganda	2007–2022	[87,91,92]
Hydrocarbon Compounds	High and Low molecular Polycyclic aromatic hydrocarbons (PAHs)	Acenaphthene	Used to prepare naphthalene dicarboxylic anhydride, which is a precursor to dyes	Leachates and Groundwater samples	1020 ng/L	Bwaise and Wobulenzi towns in Kampala district, Uganda	2013–2021	[67,69,105]
		Acenaphthylene	Used to make electrically conductive polymers		92 ng/L			
		Anthracene	Used in the manufacture of red dye alizarin, wood preservation, insecticide, coating of material		340 ng/L			
		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			

Table 2. *Cont.*

Categories of CoC	Classes	CoC (s)	Use/Application	Sampling Matrix	Detected Levels	Place of Study	Detection Periods	References
Hydrocarbon Compounds	High and Low molecular Polycyclic aromatic hydrocarbons (PAHs)	Naphthalene	Industrial solvent	Leachates and Groundwater samples	570 ng/L 258 ng/L	Bwaise and Wobulenzi towns in Kampala district, Uganda	2013–2021	[67,69,105]
		Phenanthrene	Used to make dyes, plastics and pesticides, explosives and drugs		220 ng/L 1050 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			
	Low and High Molecular Polycyclic aromatic hydrocarbons (PAHs)	Naphthalene	Naphthalene	Sediments and Fish tissues	184–239 ng g^{-1} d.w.	The White Nile environment near melt oil fields, South Sudan, Uganda Napoleon Gulf, and Murchison Bays	2017–2021	[67,105,106]
		Acenaphthylene	Used to make electrically conductive polymers		16–20.5 ng g^{-1} d.w.			
		Fluorene	Used to make dyes, plastics, and pesticides.		148–156 ng g^{-1} d.w.			
		Anthracene	Used in the artificial manufacture of red dye alizarin, wood preservation, insecticide, coating of material		79.3–112 ng g^{-1} d.w.			
		Fluoranthene	No found uses and is said to be produced by some plants.		2.46–8.73 ng g^{-1} d.w.			
		Pyrene	Used to produce dyes, plastics, and pesticides.		2.09–5.7 ng g^{-1} d.w.			
		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} d.w.			
		Chrysene	Used to make some dyes.		8.4–25 ng g^{-1} d.w.			
		Benzo[b]fluoranthene	Research purpose		2.7–9.3 ng g^{-1} d.w.			
		Benzo[k]fluoranthene	Research purpose		0.6–6.5 ng g^{-1} d.w.			
		Benzo[a]pyrene	No known use		0.02–1.06 ng g^{-1} d.w.			
		Dibenzo [a, h] anthracene	Is used only for research purposes to induce tumorigenesis		1.0–1.9 ng g^{-1} d.w.			

Table 2. *Cont.*

Categories of CoC	Classes	CoC (s)	Use/Application	Sampling Matrix	Detected Levels	Place of Study	Detection Periods	References
Hydrocarbon Compounds	Chlorinated aromatic chemicals	Polychlorinated dibenzo-*p*-dioxins (PCDDs)	Applicable in chemicals, notably herbicides	Sediments	44.1 pg g^{-1} dry weight (d.w.)	Napoleon Gulf and Thurston Bay on the northern shore of L. Victoria, Uganda	2017–2021	[67,105,106]
		Polychlorinated dibenzofurans (PCDFs)			5.61 pg g^{-1} dry weight (d.w.)			
		Dioxin-like Polychlorinated biphenyls (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	Food Samples	16.0 ± 3.6 µg/kg	Kitgum district	2006–2010	[107–110]
					1.9 ± 0.9 µg/kg	Kitgum and Lamwo districts, Uganda	2021–2022	[101,110–113]
					2.9 ± 1.2 µg/kg			
					4.3 ±1.5 µg/kg			
					2.4 ± 1.1 µg/kg			
					3.5 ± 2.9 µg/kg			
					16.0 ± 3.6 µg/kg			
				Fish Tissues	148 ± 46.9 µg/kg	Lake Victoria Basin, Uganda		
				Fish Tissues	110 ± 39.9 µg/kg	Lake Victoria Basin, Uganda	2006–2016	[107,108]
		Aflatoxin B2 (AFB2)		Food Samples	0–540 µg/kg	Mubende, Uganda	2006–2016	[107,108]
					10.5 ± 6.15 µg/kg	Iganga markets, Uganda		
					7.3 ± 4.98 µg/kg	Mayuge markets, Uganda		
					11.5 ± 0.43 µg/kg	Southwestern Uganda markets	2010–2021	[110,114]
				Food Samples	15.2 ± 0.20 µg/kg	Southwestern Uganda markets	2016–2018	[86,108]
					14.0 ± 1.22 µg/kg	Southwestern Uganda markets	2010	[110]
		Aflatoxin G1 [AFG1]			16.0 ± 1.66 µg/kg	Southwestern Uganda	2010–2016	[108,110]
					18.6 ± 2.40 (µg/kg)	Southwestern Uganda		[110]
					0–540 µg/kg	Kampala markets, Uganda		[101,107]
					9.6 ± 4.20 µg/kg	Mubende markets, Uganda		[110,114]
					10.1 ± 3.10 µg/kg	Ibanda markets, Uganda	2010–2020	[108,113,115]
					9.1 ± 4.35 µg/kg	Jinja markets, Uganda	2010–2020	
					11.0 ± 3.01 µg/kg	Hoima markets, Uganda		

Table 2. *Cont.*

Categories of CoC	Classes	CoC (s)	Use/Application	Sampling Matrix	Detected Levels	Place of Study	Detection Periods	References
Biotoxins–Mycotoxins	Aflatoxins	Aflatoxin G2 (AFG2)	Exert inhibitory effects on biological processes including DNA synthesis, DNA-dependent RNA synthesis, DNA repair, and protein synthesis	Food Samples	10.6 ± 1.63 μg/kg	Mayuge markets, Uganda	2010–2020	[108,113,115]
					6.5 ± 0.60 μg/kg	Buikwe markets, Uganda		
					3.8 ± 1.30 μg/kg	Mpigi markets, Uganda		
					7.2 ± 1.99 μg/kg	Masindi markets, Uganda		
					8.5 ± 2.56 μg/kg	Bugiri markets, Uganda	2021	[114]
		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	Food Samples	60.3 ± 27.99 μg/kg	Kalerwe markets, Uganda	2010–2017	[101,110]
					40.5 ± 12.82 μg/kg	Bukoto markets, Uganda		
					10.3 ± 3.54 μg/kg	Nakawa markets, Uganda	2010–2017	[101,115]
					143.1 μg/kg	Owino markets, Uganda	2017	[101]
					5.8 ± 12.3 μg/kg	Bugiri markets, Uganda	2010	[115]
				Food Samples	2.9 ± 6 μg/kg	Bulambuli markets, Uganda	2010	[115]
					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		
				Food Samples	6.87 μg/kg	Northern Uganda	2010–2020	[108,112,113,115]
					6.77 μg/kg	Northern Uganda		
					1.46 μg/kg	Northern Uganda		
					10.24 μg/kg	Northern Uganda		

Table 2. *Cont.*

Categories of CoC	Classes	CoC (s)	Use/Application	Sampling Matrix	Detected Levels	Place of Study	Detection Periods	References
Biotoxins–Mycotoxins	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	Food Samples	4.4 ± 0.8 n	Kitgum markets, Uganda	2019–2021	[112,113,115,116]
					3.5 ± 0.7 ng/g	Lamwo Markets, Uganda	2010–2020	
					3760 ng/g	Kitgum markets, Uganda		
					0.3 ± 0.1ng/g	Lamwo Markets, Uganda		
					1.1 ± 0.3 ng/g	Kitgum markets, Uganda		
					1.0 ± 0.3 ng/g	Lamwo Markets, Uganda		
					1.5 ± 0.3 ng/g	Kitgum markets, Uganda		
					1.4 ± 0.2 ng/g	Lamwo market, Uganda s		
					4.89 ng/g	Northern Uganda		
					0.37 ng/g	Northern Uganda		
					1.32 ng/g	Northern Uganda		
					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 Tissues	0.3 ± 0.19 µg/kg	Lake Victoria Basin, Uganda	2011–2021	[113,117–119]
					0.2 ± 0.24 µg/kg	Lake Victoria Basin, Uganda	2021	[113]
				Food Samples	80.2–0.6 µg/kg	Kampala markets	2016	[108]
					1.19 µg/kg	Northern parts of Uganda's markets	2000–2021	[113,115,120]
					19.4–99.8 µg/kg		2011–2021	[113,117–119]
					0.76 µg/kg			
					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.	Food Samples	0.153 µg/kg	Northern parts of Uganda's markets	2011–2021	[113,117–119]
					0.92793 µg/kg			
					0.153 µg/kg			
					0.823 µg/kg			

Table 2. *Cont.*

Categories of CoC	Classes	CoC (s)	Use/Application	Sampling Matrix	Detected Levels	Place of Study	Detection Periods	References
Radionuclides and electro-magnetic radiation	Primordial radionuclides (naturally occurring noble gases)	Radon (^{226}Ra)	Uranium-238. Used in making nuclear weapons as a 'tamper' material.	Plant Tissues and Food samples	8.06 Bq/kg	Osukuru phosphate factory areas, Tororo District, Uganda	2020–2021	[121,122]
					7.08 Bq/kg			
					3.55 Bq/kg			
					9.14 Bq/kg			
					5.34 Bq/kg			
					4.35 Bq/kg			
					10.02 Bq/kg			
					4.88 Bq/kg			
					2.99 Bq/kg			
				Tororo cement factory area	18 ± 3 Bqm^{-3}	Dormitories at Adwari S.S., Uganda	2014–2020	[98,121–123]
					31 ± 3 Bqm^{-3}	Dormitories at Ogor Seed S.S., Uganda		
					26 ± 3 Bqm^{-3}	Dormitories at Okwang S.S., Uganda		
					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	2014–2022	[95,121–123]
				Steel company area	72 ± 3 Bqm^{-3}	Steel Works in Eastern Uganda		
				Hospital area	51 ± 2 Bqm^{-3}	Hospitals in Eastern Uganda		
				Hotel	28 ± 1 Bqm^{-3}	TLT Hotel in Eastern Uganda		
				Residential houses	92 ± 4 Bqm^{-3}	Residential houses (closed) in Eastern Uganda		
				Homesteads	45 ± 1 Bqm^{-3}	Houses (Far away) in Eastern Uganda		

Table 2. *Cont.*

Categories of CoC	Classes	CoC (s)	Use/Application	Sampling Matrix	Detected Levels	Place of Study	Detection Periods	References
Radionuclides and electro-magnetic radiation	Primordial radionuclides (naturally occurring noble gases)	Thorium (^{232}Th)	Used in making lenses for cameras, scientific instruments, high-temperature crucibles, and electrical equipment	Soil mine tailings	119.3–376.7 Bq kg^{-1}	Mashonga Gold Mine, Uganda	2016	[124]
					211.7 ± 17.3 Bq kg^{-1}	Kikagati Tin mine, Uganda		
					244.4 ± 10.9 Bq kg^{-1}	Butare Iron ore mine, Uganda		
				Food Samples	18.60 Bq/kg	Medicinal plants in Osukuru, Tororo District, Uganda		
					15.51 Bq/kg			
					7.67 Bq/kg			
					11.26 Bq/kg			
					11.57 Bq/kg			
					5.98 Bq/kg			
					13.28 Bq/kg			
					7.37 Bq/kg			
					3.00 Bq/kg			
					2.24 Bq/kg			
				Air	181.2 ± 66.8 nGy h^{-1}	Mashonga Gold Mine, Uganda	2016	[124]
					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 a signaling molecule in a wide variety of processes	Food Samples	350.17 Bq kg^{-1}	Osukuru mines, Tororo District, Uganda	2021	[121]
					141.0–1658.5 Bq kg^{-1}			
					365.35 Bq/kg			
					297.81 Bq/kg			
					437.92 Bq/kg			
					419.72 Bq/kg			
					343.78 Bq/kg			
					379.21 Bq/kg			
					363.99 Bq/kg			

Table 2. *Cont.*

Categories of CoC	Classes	CoC (s)	Use/Application	Sampling Matrix	Detected Levels	Place of Study	Detection Periods	References
Radionuclides and electro-magnetic radiation	Primordial radionuclides (naturally occurring noble gases)	^{40}K (Potassium-40)	Acts as a signaling molecule in a wide variety of processes	Food Samples	275.86 Bq/kg	Osukuru mines, Tororo District, Uganda	2021	[121]
					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	2016	[124]
					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		
Other emerging CoC	Per- and poly-fluoroalkyl substances (PFASs)	Perfluorooctane sulfonic acid (PFOS)	Food package material, stain- and water-repellent fabrics, non-stick products (e.g., Teflon), polishes, waxes, paints, cleaning products, fire-fighting foams, industrial facilities (e.g., chrome plating, electronic goods, and oil recovery), Landfill wastewater treatment plant, and living organisms (e.g., fish, animals, and humans) due to the accumulation and persistence over time	Wastewater effluent	1.3–2.4 ng L^{-1}	Nakivubo wetland area, downstream of Bugolobi WWTP and upstream of L. Victoria, Uganda	2018–2021	[50,51]
				Soils	600–3000 pg g^{-1} (Banned in 2009, production for specified uses)			
		Perfluorooctanoate (PFOA)		Surface water	1.5–2.4 ng L^{-1}			
				Soils	480–910 pg gL^{-1} d.w. (Banned in 2019, production for specified uses)			
		Perfluoroheptanoate (PFHpA)		Plant tissues	0.65–0.67 pg gL^{-1} d.w.			
		Perfluorohexanoic acid (PFHxA)		Soils	210–460 pg gL^{-1} d.w. (Banned in 2022 for all users)			
		Average Perfluoroalkane sulfonates (∑PFSAs)		Urban runoffs	8.5–14 ngL^{-1}			
				Wetland soil	4200–5300 pg g^{-1} d.w.	Nakivubo Wetland, Uganda	2018–2021	[50,51]
				Sugarcane soil	3000–7900 pg g^{-1} d.w.			
				Maize soil	1600–4900 pg gL^{-1-} d.w.			
Microplastics	Microplastics	<1 mm size	Plastic materials utilized by communities	Surface water	0.69–2.19 particles/m^3	Surface water of northern L. Victoria, Uganda	2020	[125]
Disinfection byproducts	Trihalomethanes	Chloroform	Uses as an extraction solvent	Drinking water	23.07 µg/L	Ggaba water treatment plant and water distribution lines, Uganda	2022	[126]
		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			

Table 2. *Cont.*

Categories of CoC	Classes	CoC (s)	Use/Application	Sampling Matrix	Detected Levels	Place of Study	Detection Periods	References
Particulates	Particulate matter	$PM_{2.5}$	Help in the implementation of effective pollution control measures and public health interventions to protect people and improve air quality	Air samples	152.6 μg/m^3	Kampala, Jinja, Mbarara, kyebando, and Rubindi districts, Uganda	2010–2022	[24,102,127–129]
	Long-term particulate matter	PM_{10}			208 μg/m^3			
	Gas Phase Pollutants	NO_2	Used in the production of nitric acid, lacquers, dyes, and other chemicals		24.9 μg/m^3			
		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 [42]. MRL—Maximum residue limits.

4. Challenges of CoCs in Uganda

4.1. Sources, Occurrence, Fate, and Transport of CoCs in Uganda

Several studies conducted in Uganda have identified and quantified various classes of CoCs in different environmental matrices, including WWTP and industrial effluents, surface and groundwater, food items, air, sediments, edible insects, and soil. Surface waters were identified with the highest pollution levels (58%) for all the detected CoC in Uganda as illustrated in Figure 4. In addition, pharmaceutical residues, pesticides and POPs were the mostly detected CoC in all the available literature as illustrated in Figure 5. Furthermore, this review unveiled the distribution patterns and sources of CoCs in Uganda, shedding light on areas with substantial pollution loads. Urban areas, industrial zones, and agricultural regions emerged as the most prominent sources of both legacy and ECs in Uganda. Rapid urbanization sweeping across the country, coupled with inadequate waste management practices, are identified as the biggest contributors of most CoC that find their way into various environmental compartments in Uganda, contaminating both surface and groundwater resources [28,71,130]. Industrial activities on the other hand, are identified as the biggest contributors of multitudes of chemical byproducts into the various environmental matrices [41,48,50,87], followed by agricultural practices characterized by the application of pesticides and fertilizers, leading to significant soil and water pollution [69,77,78,81]. Additionally, the uncontrolled municipal waste disposal, WWTP effluents, and urban center runoffs are identified as the main drivers for the presence of most CoC in different matrices.

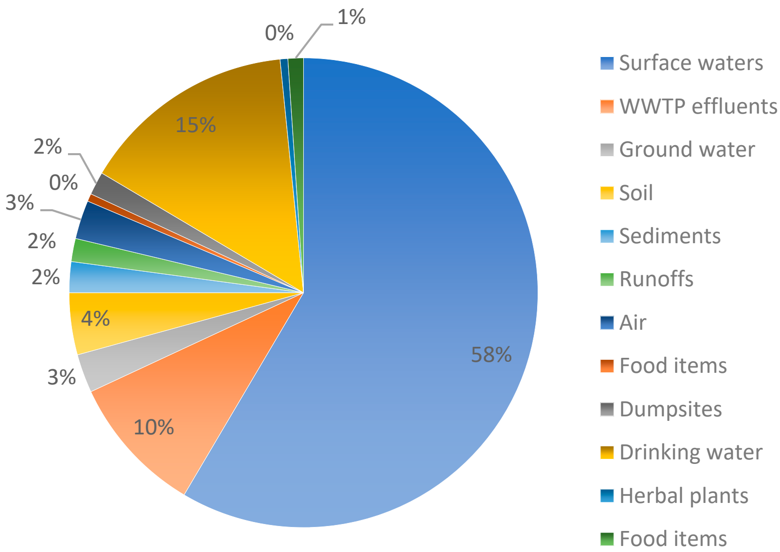

Figure 4. Percentage contaminations of different matrices from the conducted studies in Uganda.

Considering all the 82 articles related to the occurrence of CoCs in Uganda out of 177 articles selected for this study, a total of 194 contaminants were detected in 121 districts out of the 136 in the five regions of the country and in different environmental matrices. Central Uganda which hosts the country's capital city—Kampala emerged with the greatest pollution indices, attributed to the industrial growth and urban activities, this is followed by eastern Uganda where most of the industrial parks are located, then western Uganda renowned for agricultural activities, southern, and finally northern parts of Uganda with the least pollution indices as illustrated in Figure 6a.

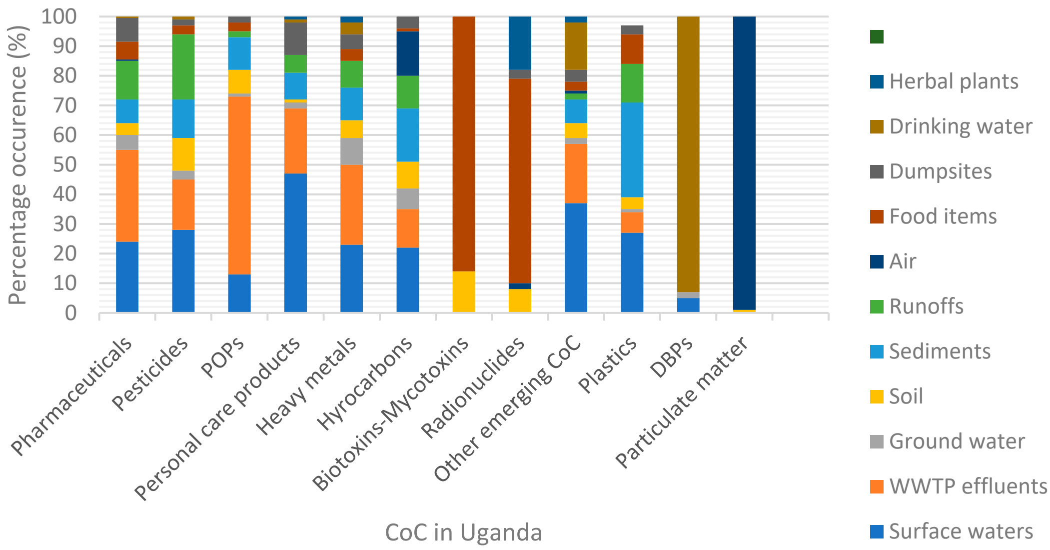

Figure 5. Percentage occurrences of CoCs in different matrices in Uganda.

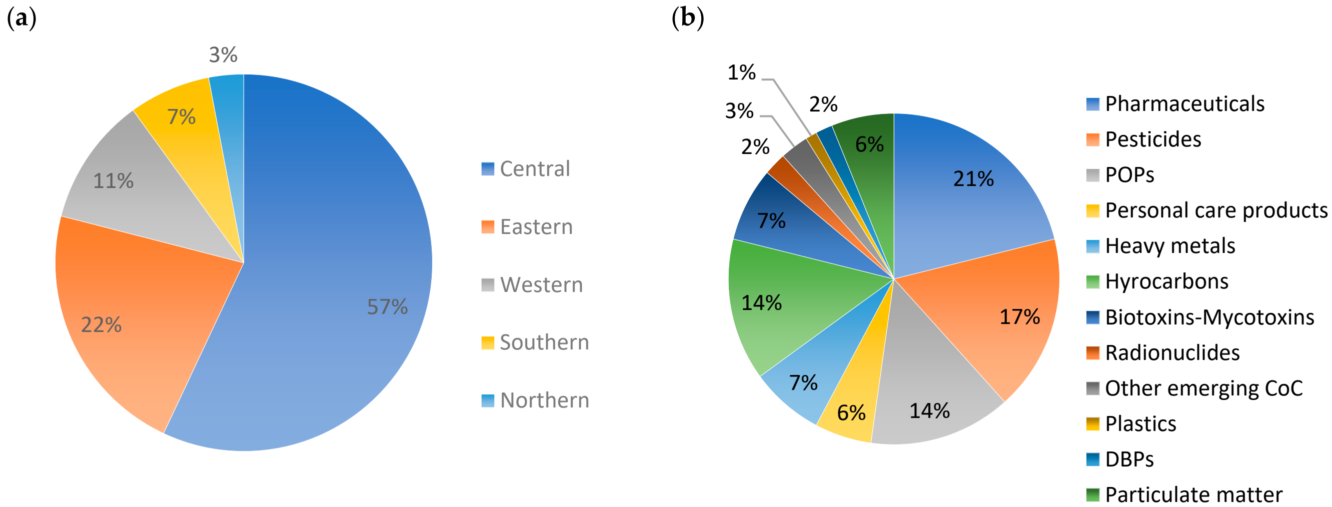

Figure 6. (**a**) Percentage numbers of CoCs investigated in the available literature in Uganda; (**b**) percentage levels of CoCs in different regions of Uganda from the conducted studies.

Furthermore, these CoCs from different sources eventually find their way into various environmental compartments, including soil, rivers, lakes, air, and even drinking water where they accumulate. Pharmaceutical residues have the highest accumulation rate (21%), followed by the pesticides (17%) and the least is observed in microplastics from the available literature as illustrated in Figure 6b [131,132]. The introductions and accumulation of these compounds can have detrimental consequences for ecosystems and eventually humans. The fate and persistence of these contaminants are strongly influenced by the physicochemical properties of the environmental compartments they interact with as illustrated in Figure 7. The primary processes that dictate the fate of CoCs in the environment include their biodegradation rate, photodegradation rate, and sorption kinetics [4,133]. Humans and animals may consume these contaminants for diverse reasons, such as for medical or recreational purposes, including veterinary drugs in the case of animals or pesticides and herbicides used in agriculture. Upon ingestion, biotransformation processes occur, leading to the release of drug residues and metabolites into the environment. These substances, which can end up in water bodies or sewage systems, can adversely affect various organisms, from humans to large mammals and other life forms [134,135].

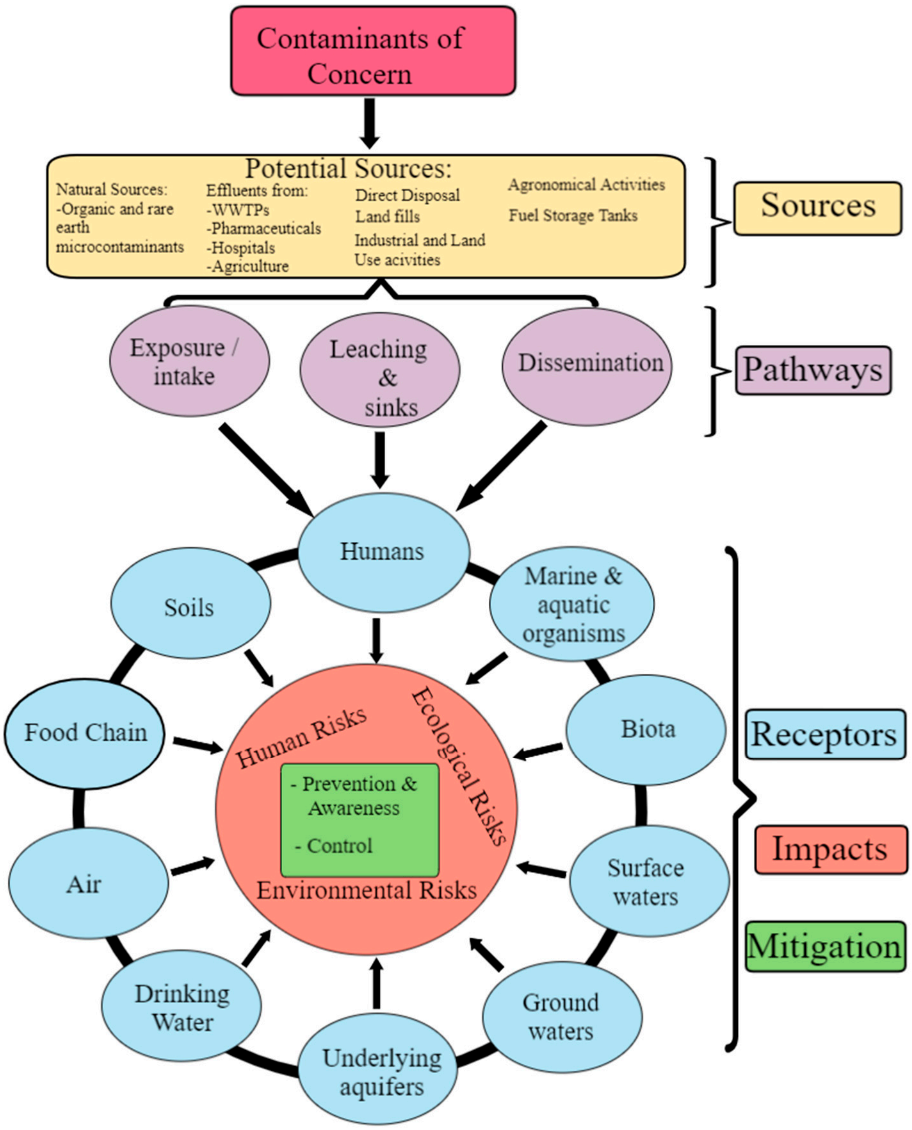

Figure 7. Flow of CoCs across various environmental compartments, following their introduction; these substances transform, giving rise to secondary contaminants that have the potential to impact human health. This dynamic interplay suggests that human beings play a dual role as both sources and recipients of these contaminants.

Sewage, which contains waste from residential, industrial, and clinical sources, is usually mixed in waste stabilization ponds, contributing to the chemical burden. This water is then reused in agriculture and aquaculture, and sludge, laden with active chemicals, is used as fertilizer. This reinserts active chemicals into the soil, ultimately leading to their presence in food crops. The consequence of this cycle is that active chemicals find their way into the food chain, taken up by plants and algae, leading to bioaccumulation in aquatic ecosystems. This can subsequently result in bioconcentration and biomagnification as they move through the food chain, as established by previous studies. This dynamic interaction between active chemicals, ecosystems, and human consumption highlights the need for comprehensive monitoring and assessment programs to understand their occurrence, behavior, and potential risks. Additionally, it underscores the importance of adopting measures to manage and mitigate the introduction and proliferation of these contaminants throughout the environment. The coalescence of these findings provides a holistic view of the sources and environmental fate of CoCs in Uganda, emphasizing the urgency of regulatory measures and sustainable practices to safeguard both ecosystems and human health.

4.1.1. CoCs in Ugandan Surface Waters

From the available literature, this review identified that about 58% of the surface waters are contaminated with a widespread CoC across Uganda. One prominent category revealed in the reviewed studies is the pharmaceutical compounds. Antibiotics, analgesics, hormones, and antidepressants, have been detected within various environmental matrices, particularly within water bodies. The concentration levels, for instance, ranging from 1–5600 ngL^{-1} in surface water samples at Murchison Bay of Lake Victoria strongly underscore their classification as CoC [30,42]. These compounds carry the potential for detrimental effects on aquatic organisms and ecosystems, with implications extending to the development of antibiotic resistance and disruption of endocrine systems [41,136].

Furthermore, numerous studies highlighted the widespread use of pesticides in Ugandan agriculture. These studies have identified multiple classes of pesticides, including insecticides, herbicides, and fungicides, in soil and water samples [49,78,81]. The detection of pesticide residues not only poses risks to human health but also bears environmental consequences, thus emphasizing the critical importance of adhering to proper pesticide management practices and promoting the adoption of sustainable agricultural methods [44]. Moreover, the presence of microplastics within various water bodies, including lakes and rivers, and their occurrence within fish species consumed by humans, has been emphasized by several studies [125]. The ubiquitous distribution of microplastics in the environment raises concerns about their impact on aquatic ecosystems, further raising concerns about human ingestion through the food chain.

In addition to pharmaceuticals, pesticides, and microplastics, the presence of personal care products within water sources and aquatic ecosystems has been noted in multiple studies [30,73,77]. These products, which often contain substances like fragrances, UV filters, and preservatives, are commonly used in cosmetics and personal care items and find their way into the environment through various pathways. Detecting these chemicals in the environment highlights the imperative role of rigorous wastewater treatment practices, which are vital for preventing their release into water bodies. The potential consequences of these substances finding their way into water bodies include ecological impacts and potential human health concerns, making proper wastewater treatment a priority for mitigating these effects.

4.1.2. Urban Runoffs and Wastewater Treatment Plants (WWTP) Effluents as Sources of CoCs

Wastewater has emerged as a significant source of CoCs in Uganda [43,52,137]. In WWTP effluents, a troubling array of substances, including pharmaceuticals, personal care products, and various chemical compounds, has been identified. Specifically, industrial and municipal wastewater originating from Kampala city, coursing through the Nakivubo channel, and emanating from the Bugolobi WWTP, have exhibited notable contamination [43]. A compelling example of this contamination includes the presence of 89–1400 ngL^{-1} of triclosan, an antibiotic found in soaps, toothpastes, and detergents detected in the effluents from Bugolobi WWTP [43]. Furthermore, the detection of 0.84–1.04 mg/kg of cadmium, a toxic heavy metal, in both the water and sediments of the Nakivubo channel, points to the detrimental impact of untreated industrial effluents on this drainage channel [33]. This worrisome trend can be attributed to inadequate wastewater treatment infrastructure and practices, especially prevalent in urban areas and regions characterized by high population densities. The presence of these emerging CoCs in wastewater underscores the immediate necessity for improved treatment technologies and the implementation of stringent regulatory measures. These measures are imperative to ensure the removal or reduction of these contaminants before their discharge into the environment, thereby preventing further pollution and safeguarding aquatic ecosystems. Additionally, the effluents from the Bugolobi Wastewater Treatment Plant have been found to contain a concentration of 100–500 ngL^{-1} of diclofenac, a common pharmaceutical compound [41,42]. The presence of such pharmaceutical compounds within wastewater effluents is typically a result of improper disposal of unused medications and their discharge into the wastewater systems. This situation raises serious concerns about the potential ecological impacts and the development of antibiotic resistance, as well as the disruption of endocrine systems [30,42]. It is crucial to recognize that these contaminants, once present in wastewater, ultimately enter aquatic environments and ecosystems. In such environments, these substances can have adverse effects on aquatic organisms and ecosystems, potentially leading to the development of antibiotic resistance and disruption of endocrine systems, further emphasizing the urgency of addressing this issue comprehensively and effectively [41,136].

4.1.3. CoCs in Sediments

Sediments serve as a sink for pollutants, accumulating various contaminants of concern over time. The comprehensive review identified the presence of heavy metals [32], pesticides [31], and microplastics [55] in sediment samples from different water bodies in Uganda. The sources of sediment pollution were traced back to industrial activities, mining, and runoff from agricultural operations [104]. Of note, a study conducted by [33] detected substantial concentrations of lead, ranging from 79 to 138.18 mg/kg within both the water and sediments of the Nakivubo channel. The persistence of these contaminants in sediments raises significant concerns regarding potential long-term impacts on benthic organisms and the potential for their re-entry into the water column. Consequently, the implementation of effective sediment management strategies, including remediation efforts and the adoption of best management practices within industrial and agricultural sectors, becomes vital. Such measures are critical for minimizing the consequences of emerging CoCs on sediments and the ecosystems they are a part of.

Moreover, the systematic review unveiled reports detailing the occurrence of persistent organic pollutants, such as polychlorinated biphenyls (PCBs), dioxins, and furans, in the Ugandan environment [35,40]. These toxic compounds, renowned for their resistance to degradation, were identified within both sediments and aquatic organisms, raising considerable concerns regarding potential health effects on humans consuming contaminated fish and other aquatic products.

In another context of this systematic review, there was a focus on the examination of heavy metal contamination in Uganda, focusing on metals like lead (Pb), mercury (Hg), cadmium (Cd), and chromium (Cr) [32,33,47]. Elevated concentrations of heavy metals were attributed to industrial activities, mining, and urbanization. The accumulation of heavy metals within the environment can lead to adverse health effects on humans and contribute to ecological disruptions.

4.1.4. Ambient Air as a Transport Medium for CoCs in Uganda

Hydrocarbon compounds, including polycyclic aromatic hydrocarbons (PAHs) and benzene, were detected in soil and air samples across Uganda [67,69]. These compounds originate from various sources such as vehicle emissions, industrial processes, and the burning of biomass, highlighting the potential carcinogenic and toxic effects of hydrocarbon compounds. This emphasizes the importance of robust air quality management and the implementation of emission control measures.

Furthermore, the systematic review brought to light 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 [101,114,115,138]. Consuming mycotoxin-contaminated foods can pose significant health risks, including liver damage and cancer.

The review also identified reports on natural radionuclides such as uranium and thorium in soil and water samples [121,124]. Additionally, concerns were raised regarding potential exposure to electromagnetic radiations, including radiofrequency and microwaves, emanating from sources like mobile communication towers [56,58,66]. It is important to note that some CoCs can also be transported through the air. Airborne particles and gases can carry pollutants, including persistent organic pollutants (POPs) and microplastics, over long distances, leading to their deposition in ecosystems, including water bodies and soils. For instance, a study conducted by [24,128] measured 152.6 $\mu g/m^3$ of $PM_{2.5}$ and 208 $\mu g/m^3$ of PM_{10} in air samples around the districts of Kampala, Jinja, and Mbarara in Uganda. Despite limited research on airborne emerging contaminants of concern, it is essential to consider the industrial growth, vehicular emissions, and open burning practices prevalent in specific regions, warranting further investigation into the potential presence and impacts of such contaminants in Uganda.

The review identified reports on disinfection byproducts, such as trihalomethanes (THMs), in drinking water supplies [126]. In addition, particulate matter, including fine and coarse particulates ($PM_{2.5}$ and PM_{10}), was also a subject of investigation in air quality studies [24,102,128].

4.1.5. CoCs Detected in Various Food Items Grown in Uganda

Although this comprehensive review primarily focused on the distribution of CoCs in various environmental matrices, it is crucial to address the potential transfer of these CoCs into the food chain. Contaminated water, soil, and sediments can contribute to the accumulation of contaminants in crops, aquatic organisms, and livestock. For example, processed peanuts contained 0.5–4.6 ppm of arsenic [101], and raw bovine milk and herbal medicines in the Kampala and Wakiso districts in Uganda were found to have 156.9 ppm of chromium. Such contamination poses risks to human health through the consumption of tainted food products, potentially leading to various health issues. 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. To ensure food safety and minimize consumers' exposure to these emerging contaminants of concern, the implementation of robust monitoring programs and adherence to good agricultural practices are imperative. This systematic review provides valuable insights into the nature, sources, distribution, and potential impacts of these contaminants in the country. The discussion of the results delves into key findings, and their implications, and offers recommendations for future research and policy interventions. The transfer of these contaminants into food crops and the subsequent effects on human health should be a subject of ongoing research to comprehensively address the broader implications of emerging pollutants in Uganda. Understanding the pathways and consequences of these contaminants in the food chain is vital for developing strategies to ensure food safety and protect human health.

The reviewed studies underscore the environmental impact of CoCs 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 both human and aquatic organisms as shown in Figure 7. They have the potential to disrupt endocrine systems and reproductive processes Figure 8 [30,32,33,42,61]. Pesticide residues in soils can adversely affect soil health, microbial communities, and non-target organisms, contributing to ecological imbalances, as shown in [73,77].

Waterborne exposure to CoCs through drinking water sources can have lasting consequences, including antibiotic resistance and endocrine disruption [30,40,42]. Contaminants accumulating in biota can propagate risks through the food chain, potentially causing acute toxicity, chronic health conditions, and further endocrine disruption [4,32,139]. Moreover, occupational exposure to these contaminants, particularly among workers in agriculture and waste management sectors, has been linked to various acute and chronic health effects.

In addition to these well-documented health effects, it is critical to consider the potential association of CoCs with cancer risks in Uganda. Emerging evidence from epidemiological studies suggests a concerning link between environmental exposures to CoCs and cancer incidence rates in Uganda, estimated to be around 109.9 and 99.9 per 100,000 in males and females [140]. Specifically, certain CoCs, such as persistent organic pollutants (POPs), heavy metals, and specific pesticides, have been implicated in increasing the risk of cancer among exposed populations as illustrated in Table 3. Prolonged exposure to these substances through contaminated water sources, agricultural practices, and other routes could potentially elevate the cancer risk within the Ugandan population, emphasizing the urgency of comprehensive risk assessment and mitigation strategies. The complex interplay between CoCs and cancer risks requires further research and attention to safeguard the well-being of Ugandan communities.

Table 3. Toxic effects of different categories of CoCs, and their ecological and human health effects.

Category of CoC	Ecological Effect	Human Health Effects
Pharmaceuticals	Altered aquatic ecosystems due to bioaccumulation of pharmaceutical residues.	Antibiotic resistance, endocrine disruption
Pesticides	Soil health and microbial community disruption, non-target organism harm, ecological imbalances	Acute and chronic toxicity, reproductive and endocrine disruption, carcinogenicity
Persistent Organic Pollutants (POPs)	Bioaccumulation, endocrine disruption, harm to aquatic life, disruption of food chains.	Cancer, developmental and reproductive disorders, immunotoxicity, neurotoxicity
Personal Care Products	Environmental toxicity to aquatic organisms, ecological disruption, contamination of water resources	Skin and eye irritation, allergies, hormonal disruptions
Heavy metals	Soil and water contamination, impact on aquatic life, potential bioaccumulation, disruption of aquatic food chains	Potential health issues from exposure include: neurological damage, kidney damage, cardiovascular issues, developmental problems, cancer risks
Perfluorinated compounds	Bioaccumulation in fish and fish products	Accumulates primarily in the serum, kidney, and liver, potentially diverse effects on developmental, and reproductive systems and other damaging outcomes.
Biotoxins–Mycotoxins	Harm to aquatic organisms, food chain disruption, and ecological imbalance.	Acute poisoning, mycotoxicosis, neurotoxicity
Radionuclides and Electromagnetic radiations	Genetic and ecological impacts due to radiation exposure, potential harm to organisms and ecosystems	Increased cancer risk, radiation sickness, tissue damage, genetic mutations
Engineered nanoparticles	Toxicity in plants, fish, earthworms, and bacteria (growth, mortality, reproduction, gene expression)	Cytotoxicity, oxidative stress, inflammatory effects in lungs, genotoxicity, carcinogenic effects, granulomas, thickening of alveolar walls, and augmented intestinal collagen staining
Microplastics	Accumulation in ecosystems, potential harm to marine life, potential disruption of the food chain	Health effects from potential ingestion, respiratory problems, skin irritation, potential carcinogenicity
Disinfection byproducts	Potential harm to aquatic life, impact on water quality, aquatic ecosystem disruption	Carcinogenic risk, skin and eye irritation, potential reproductive and developmental effects
Particulates	Air quality deterioration, potential harm to the respiratory health of ecosystem organisms	Respiratory issues, cardiovascular diseases, decreased lung function, cancer risks

The presence of pharmaceuticals and personal care products in Lake Victoria, a primary source of drinking water in Uganda, raises concerns about antibiotic resistance development and water resource contamination [30,73,77]. 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 [31,73,77]. Urban areas have reported the presence of microplastics in various environmental compartments, including water bodies, soils, and the air, suggesting potential impacts on human health and the environment [125]. Addressing these emerging CoCs is essential to safeguard ecosystems, biodiversity, and human health in Uganda. These risks are not confined to aquatic environments. Airborne emerging contaminants of concern, including 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 [3,4,17,141].

Waterborne CoCs, primarily stemming from agricultural, industrial, and domestic activities, can contaminate surface water, groundwater, municipal wastewater, and drinking water sources [5,17]. Microplastics, a notable emerging pollutant in water, accumulate various contaminants as they traverse the food chain, amplifying the risk [5,55,125,142]. The contamination of surface waters, including rivers and lakes, with CoCs 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, CoCs 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 to groundwater protection.

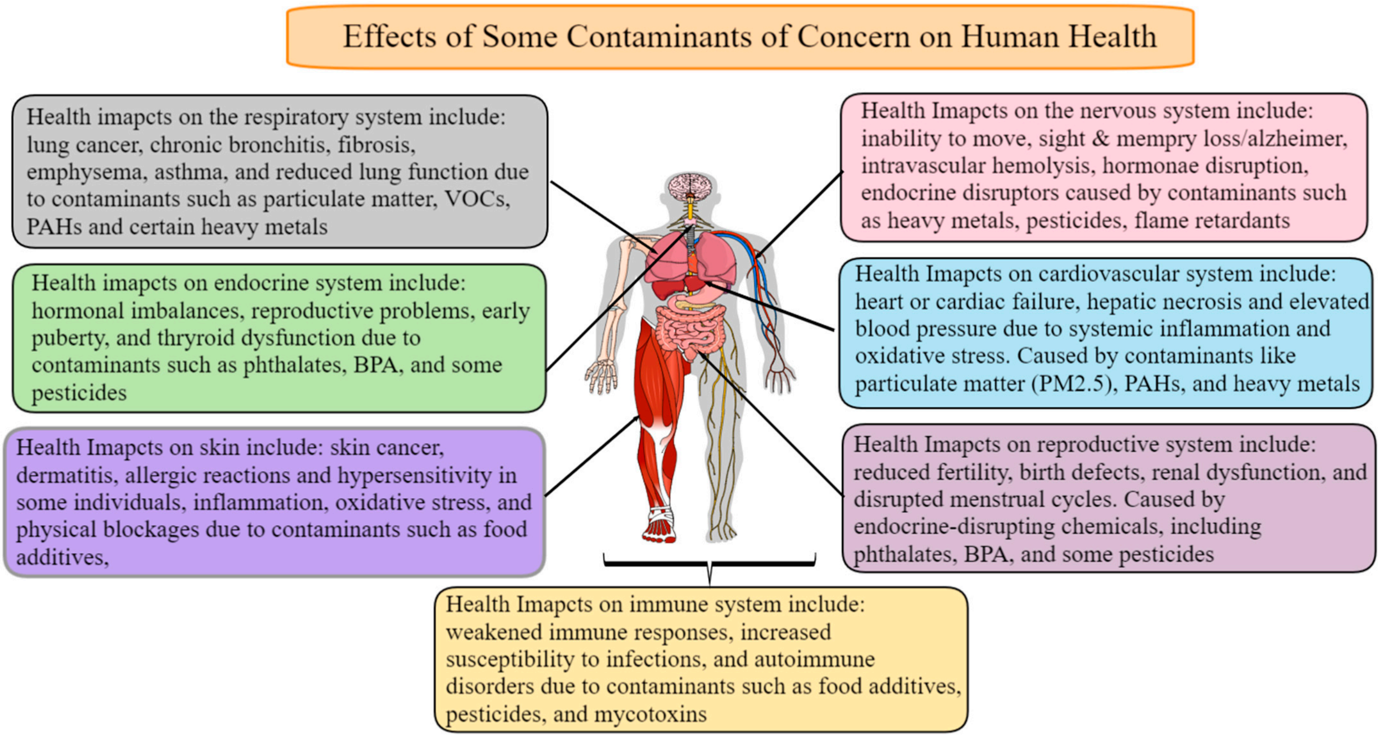

Figure 8. Health effects of some CoCs on human body systems (adapted from [143]).

5. Current Monitoring and Regulation Efforts in Uganda

In Uganda, a concerted effort has been made to monitor and assess emerging contaminants of concern, seeking to understand their presence, concentrations, and potential risks to the environment and public health. Collaborative initiatives with institutions like the National Environment Management Authority (NEMA) have played a crucial role in environmental management and hotspot identification [144]. The Ministry of Water and Environment, particularly the Directorate of Water Resources Management, conducts routine water quality assessments, extending their scope to encompass emerging CoCs in surface waters, groundwater, and drinking water sources. Furthermore, academic and research institutions, including universities and research centers, actively contribute to monitoring by evaluating these contaminants in various environmental compartments and providing valuable scientific insights to inform policymaking.

While Uganda has made significant progress in monitoring contaminants of concern, challenges persist in their effective regulation and management. Existing regulatory mechanisms, spearheaded by NEMA, establish a foundation for addressing these pollutants through environmental regulations, guidelines, and standards [144,145]. However, opportunities for improvement exist, particularly in the formulation of comprehensive, targeted regulations dedicated to CoCs and improved data collection and accessibility. Constraints in monitoring capacity and resource availability hinder the implementation of comprehensive, routine monitoring programs. Therefore, there is a pressing need to expand research efforts to deepen our understanding of the prevalence, fate, and impacts of contaminants of concern. Access to comprehensive data is pivotal for the development of effective mitigation strategies.

It is imperative to strengthen technical expertise and monitoring capabilities regarding CoCs, necessitating the use of advanced analytical techniques and fostering collaboration between research institutions and regulatory bodies. Additionally, refining regulatory frameworks to specifically address CoCs, including the formulation of guidelines and standards, is vital. Raising awareness among the public, policymakers, and industries is also imperative and can be achieved through educational and outreach programs that promote responsible practices and sustainable alternatives. By addressing these gaps and challenges, Uganda can significantly enhance its monitoring, regulation, and management of contaminants of concern.

6. Mitigation Strategies and Future Directions for Addressing Risks Posed by CoCs

Addressing the risks posed by CoCs, both in Uganda and on a global scale, is a complex challenge requiring effective approaches and advanced technologies. In the Ugandan context, upgrading wastewater treatment systems is paramount, and this can be achieved through the implementation of advanced technologies such as advanced oxidation, activated carbon adsorption, and membrane filtration, which have demonstrated their effectiveness in removing a wide range of CoCs, including pharmaceuticals, personal care products, and other emerging pollutants [4,146–148]. Furthermore, promoting sustainable agricultural practices is essential in mitigating CoC risks. Techniques like integrated pest management (IPM) and organic farming offer promising avenues to reduce pesticide usage, a common source of contamination. Implementing source control measures and improving waste management practices can effectively prevent the release of CoCs. Encouraging the adoption of green chemistry principles and developing eco-friendly alternatives are key steps in minimizing the generation and release of CoCs. While these strategies are well-established globally, it is noteworthy that there has been a lack of studies conducted in Uganda regarding the mitigation, prevention, or remediation of CoCs. However, based on the removal efficiencies provided in Table 4, AOPs stand out as the most promising option, with treatment efficiencies ranging from 95 to 99%.

On a global scale, the management of CoCs also presents a multifaceted challenge due to its diverse sources and potential ecological and human health risks [5,149]. To mitigate these concerns, different efficient treatment and removal strategies have been explored of which some have shown promising results in elimination. CoCs often found in industrial and municipal wastewater are resistant to conventional treatment methods, necessitating the application of advanced treatment technologies. Among the explored methods, include physicochemical and biological processes, such as sand and media filtration, chlorination, advanced oxidation processes (AOPs), adsorption using granular activated carbon, zeolite, hydrolysis processes, constructed wetlands, membrane bioreactors, phytoremediation, and biosorption, all of which offer distinct advantages in treating effluents contaminated with CoCs, as illustrated in Table 4 [150,151]. Biological processes, in particular, have played a crucial role in addressing the challenge of CoCs in wastewater [152,153]. Constructed wetlands have shown promise, offering low-energy, cost-effective, and efficient treatment of organics and nutrients. While much of the research on CoC removal in constructed wetlands has been conducted on a small scale, there is potential for larger-scale implementation. Biological membrane reactors (MBRs) have proven effective for CoC removal, achieving substantial efficiency, especially when combined with other treatment methods like ozonation and activated carbon. Anaerobic MBRs, with their biogas generation and high-efficiency biodegradation of emerging pollutants, are gaining traction. Additionally, biosorption, a biological treatment technology that utilizes various materials from biomass as adsorbents, has emerged as an eco-friendly option. It offers low costs due to the abundance of biomass, possibilities for regeneration, and high selectivity [154]. This method has demonstrated its effectiveness in the removal of emerging pollutants from secondary and tertiary effluents, particularly pharmaceuticals, personal care products, and other persistent pollutants [155,156].

Table 4. Advantages, challenges, removal efficacies, and treatment efficiencies of different technologies in the removal of contaminants of concern.

Treatment Method	Advantages	Challenges	Contaminants Removed	Treatment Efficiency (%)	References
		Conventional Methods			
Coagulation	Effective for suspended particles and some heavy metals with relatively low operational costs	Chemical costs Sludge disposal can be problematic	Pesticides, heavy metals	80–95%	[157,158]
Flocculation	Effective for particulate matter	Chemical usage and residual disposal	Heavy metals,		[157,158]
Sedimentation	Cost-effective and reduces suspended solids	Inefficient for dissolved contaminants Large space requirements	Suspended solids, radionuclides	60–90%	[159]
Filtration (Sand/Granular Media)	Effective for removing a wide range of contaminants	Clogging and frequent backwashing	Turbidity, bacteria, protozoa, microplastics	95–99%	[157,160]
		Unconventional			
Membrane Filtration,	Robust against variations in water	fouling and scaling issues in membranes	Microplastics, pharmaceuticals	4–56%	[157,161]
Activated Carbon Adsorption)	Removes most contaminants	Energy intensive for preparation of activated carbon	Personal care products, hydrocarbons, persistent organic pollutants, biotoxins, and mycotoxins	99.7%	[162,163]
Membrane bioreactors (MBR)	Sustainable and breaks down organic matter	Slower treatment compared to other methods	Organic compounds, pharmaceuticals	70–90%	[164,165]
Constructed wetlands	Cost-effective natural system, effective for wastewater	Seasonal performance variability, limited removal of some contaminants	Pathogens, heavy metals, organic compounds, pharmaceutical residues	74–99%	[164,165]
		Chemical processes			
Advanced Oxidation Processes [AOP]	Effective for breaking down organic compounds	High operational costs	Organic compounds, pesticides, pharmaceuticals	95–99%	[166,167]
Chemical extraction/Solvent extraction	Effective for the removal of heavy metals, applicable to a wide range of contaminant removal	High operational costs, potential risks associated with solvents	Model pollutants, bromocresol green, and phenols, oil-based drilling cuttings	99%	[168,169]
Fenton and Photo-Fenton oxidation	Degradation and mineralization of persistent organic compounds	Difficult to treat large volumes of wastewater	Organic pollutants in cosmetic water	95%	[170,171]
Photocatalysis (TiO_2)	High reaction rates upon using a catalyst	Cost associated with artificial UV lamps and electricity	Pharmaceuticals, volatile organic compounds, synthetic dyes, and biocides	90%	[172,173]
		Physical processes			
Ultraviolet (UV) Disinfection	No chemical addition Effective for disinfection and low energy consumption	Ineffectiveness against organic contaminants	Persistent organic pollutants, pharmaceuticals	91.1%	[174]
Filtration (Membrane)	Effective for removing microorganisms and nanoparticles	Membrane fouling High operational costs	Microorganisms, nanoparticles	90–99%	[175,176]
Micro or Ultrafiltration	Effective removal of pathogens	Not fully effective in removing some EPs as pore sizes vary from 100 to 1000 times, larger than the micropollutants, membrane fouling	Micro- and nano-plastics for particles larger than 100 µm	86.5–99.9%	[177]
Reverse Osmosis	Removes a wide range of contaminants, including salts	High energy requirements, membrane fouling	Dissolved salts, particles, colloids, organic compounds, bacteria, and pyrogens	90–99%	[178,179]

To facilitate effective monitoring, regulation, and enforcement of CoCs in Uganda, it is crucial to establish dedicated regulations accompanied by guidelines, standards, and monitoring requirements. Increasing funding and resources for monitoring programs, coupled with the capacity building for regulatory agencies and research institutions, will strengthen oversight and enforcement. Improving data collection and sharing mechanisms will enhance our understanding of the presence and distribution of CoCs. Conducting public awareness campaigns is a valuable tool to educate the public about emerging pollutants, specifically CoCs, and promote responsible practices and sustainable alternatives. These policy recommendations will contribute to the effective monitoring, regulation, and management of emerging pollutants in Uganda.

Research gaps regarding the occurrence, impact, ecological effects, presence in food crops and livestock, fate and transport mechanisms, and potential health risks associated with exposure to CoCs need to be bridged. Addressing these gaps will provide a better understanding of emerging pollutants and inform the development of effective policies and interventions aimed at minimizing their environmental and health effects, safeguarding natural resources, and securing the well-being of the population.

7. Conclusions and Recommendations

In this comprehensive review, we conducted a thorough assessment of CoCs in Uganda, highlighting their sources, distribution, and potential impacts. Our findings reveal the pervasive presence of a diverse array of these contaminants, including pharmaceuticals, personal care products, pesticides, industrial chemicals, and microplastics, across various environmental compartments in Uganda. Notably, higher concentrations are observed in urban, agricultural, and industrial areas. The primary drivers of CoC release are rapid urbanization, inadequate waste management, industrial activities, and prevailing agricultural practices.

The implications of these findings are profound, with the potential to harm ecosystems, biodiversity, and human health. To effectively address these challenges, it is imperative to establish robust policies and regulations. Strengthening waste management practices, promoting sustainable agriculture, and implementing pollution control measures are critical steps in reducing the impact of CoCs. Moreover, comprehensive and continuous monitoring programs should be established to track pollutant levels and assess their long-term impacts.

To effectively address the challenges posed by CoCs in Uganda, several recommendations are proposed. Firstly, further research is crucial to fill existing knowledge gaps, particularly in assessing ecological effects, the presence of contaminants in the air, understanding their fate and transport mechanisms, and comprehensively studying their long-term impacts on human health. Strengthening monitoring programs, enhancing technical capabilities, and promoting data sharing and accessibility are essential to track pollutant levels and assess their enduring effects. Additionally, it is imperative to improve regulatory frameworks with a specific focus on contaminants of concern. This includes setting guidelines, standards, and monitoring requirements. Public awareness campaigns should be initiated to educate the community on responsible practices and sustainable alternatives. The promotion of sustainable practices across various sectors in Uganda and Africa is essential. Collaboration among government agencies, research institutions, industries, and the public is paramount. By prioritizing research, implementing effective mitigation strategies, and refining regulatory frameworks, Uganda can work towards minimizing the release and impact of contaminants of concern. This concerted effort will contribute to sustainable environmental management, the protection of ecosystems and biodiversity, and the reduction of risks to public health, ensuring a cleaner and healthier environment for present and future generations.

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