Environmental Nanotechnology, Monitoring & Management 22 (2024) 100962

Contents lists available at ScienceDirect

Environmental Nanotechnology, Monitoring & Management

journal homepage: www.elsevier.com/locate/enmm

# Temporal trends of water quality parameters, heavy metals, microplastics, and emerging organic pollutants in Lake Victoria and its basin: knowns, knowledge gaps, and future directions

Ivan Oyege [a,b,*], Richard Katwesigye [b,c], Moses Kiwanuka [a,d], Hosea Eridadi Mutanda [d,e], John Bosco Niyomukiza [d,f], Dafrosa John Kataraihya [a,g], Solomon Kica [h], Moses Egor [b,*]

[a] Department of Earth and Environment, Florida International University, Miami, FL, USA
[b] Department of Chemistry, Busitema University, Tororo, P.O Box 236, Tororo, Uganda
[c] Department of Chemistry, Makerere University, Kampala, P.O Box 7062, Kampala, Uganda
[d] Department of Civil Engineering, Ndejje University, Kampala, P.O Box 7080, Kampala, Uganda
[e] Department of Civil and Building Engineering, Mbarara University of Science and Technology, P.O Box 1410, Mbarara, Uganda
[f] School of Civil Engineering and Technology, Sirindhorn International Institute of Technology, Thammasat University, Pathum Thani, Thailand
[g] Department of Geospatial Science and Technology, Ardhi University, Dar es Salaam, P.O Box 35176, Dar es Salaam, Tanzania
[h] Department of Earth, Marine and Environmental Sciences, University of North Carolina at Chapel Hill, Chapel Hill, USA

ARTICLE INFO

*Keywords:*
Lake Victoria
East Africa
Contaminants of emerging concern
Water quality
Heavy metals
Organic pollutants
Microplastics

ABSTRACT

The deteriorating water quality and increasing pollution of Lake Victoria, Africa's most important and world's second-largest freshwater lake, is threatening the critical resource within East Africa, which has profound ecological and socio-economic significance. This comprehensive review investigates the environmental dynamics of the lake, exploring temporal trends in water quality, heavy metals, microplastics, and emerging organic pollutants in Kenyan, Tanzanian, and Ugandan waters. Assessing the period from January 2000 to December 2022, the analysis integrates research findings from Lake Victoria and its basin. A complex interaction between natural processes and human activity causes fluctuations in the water quality of Lake Victoria. The study reveals substantial variations in key parameters, reflecting the impacts of industrial discharges, agricultural practices, urbanization, and wastewater inputs. Noteworthy among these variations are heavy metal concentrations, with lead consistently surpassing the acceptable levels in Kenyan and Ugandan waters. Zinc concentrations showed varying patterns, and chromium levels in sediments raise concerns by surpassing EPA guidelines in specific locations. The investigation of organic pollutants identified over 170 contaminants, highlighting the dominance of dichlorodiphenyltrichloroethane (DDT) and its derivatives. Microplastics, recognized in the guts of vital fish species and surface water, merge as a growing concern, posing risks to the aquatic ecosystem. This review illuminates the nature of pollutants in Lake Victoria and identifies knowledge gaps in research attention, especially in the northwestern, western, and southwestern lake basins, and the islands of Lake Victoria, overlooked for more than two decades. Scrutinizing existing research, it serves as a compass, pointing towards areas necessitating further investigation and thereby charting future directions in the research community.

## 1. Introduction

Lake Victoria is the second-largest freshwater lake globally and a vital resource shared by Kenya, Uganda, and Tanzania; it holds immense ecological and socio-economic significance within the East African Rift System (Britannica, 2023). Covering an area of 69,484 km$^2$, the lake touches the lives of over 42 million people, serving as a fundamental resource for food, employment, and clean drinking water (Andama, 2012; Pavur and Lakshmi, 2023; Wang et al., 2012).

The expansive Lake Victoria basin, covering over 238,901 km$^2$, with over 30 million people calling the basin home, plays a pivotal role in various economic activities, including fishing, transportation, agriculture, and tourism (Nyamweya et al., 2023; Oryiema, 2022; Virts and Goodman, 2020). However, rapid socio-economic transformations and

* Corresponding authors at: Department of Earth and Environment, Florida International University, Miami, FL, USA.
*E-mail addresses:* ioyeg002@fiu.edu (I. Oyege), megor.sci@busitema.ac.ug (M. Egor).

https://doi.org/10.1016/j.enmm.2024.100962
Received 24 January 2024; Received in revised form 22 March 2024; Accepted 9 May 2024
Available online 10 May 2024
2215-1532/© 2024 Elsevier B.V. All rights are reserved, including those for text and data mining, AI training, and similar technologies.

increasing population growth in the East African region have led to increased urbanization, industrial activities, and agricultural practices, exerting anthropogenic pressures on the lake (Newton et al., 2020; Okello et al., 2015). These pressures have resulted in the discharge of different pollutants into Lake Victoria, including pesticides, pharmaceuticals, heavy metals, plastics, and industrial byproducts, and have greatly influenced the water quality, which has led to eutrophication, high turbidity, and increased concentrations of nutrients, iron, and chemical oxygen demand in Lake Victoria (Juma et al., 2014; Oguttu et al., 2008).

The analysis of sediments and lake water can reveal the identities and quantities of these pollutants and is essential for a comprehensive understanding of the aquatic ecosystem's health. Sediment cores act as historical archives, preserving information about pollutant inputs over time and identifying long-term trends (Kang et al., 2022; Owens, 2020). Analyzing pollutants in both sediments and water helps assess the immediate and cumulative impacts of human activities and helps us understand the pollution levels and the lake's health. Pollutants jeopardize the delicate balance of ecosystems, necessitating an understanding of the pollutant levels for adequate preservation. Additionally, Lake Victoria is a crucial water source, influencing River Nile's flow and impacting hydropower generation, irrigation, and water supply (Sene et al., 2021; Vanderkelen et al., 2018).

Heavy metal contamination from lead, mercury, and cadmium is a significant concern in the agricultural hinterland around Lake Victoria in East Africa. Industrial discharges and agrarian runoff introduce these heavy metals into the lake environment (Marriott et al., 2023; Sabo et al., 2021; Ssanyu et al., 2023). Pesticide application in agricultural areas also poses challenges, as it can lead to human pesticide poisoning and environmental pollution through pesticide residues (Onyando et al., 2023). Additionally, microplastics are another pollutants of concern in the region. These microplastics are introduced into the surface waters of Lake Victoria in East Africa through various sources such as urban waste, consumer use, fishing and tourism activities, and plastic debris from shoreline and sediment (Biginagwa et al., 2016; Egessa et al., 2020). These pollutants present distinct challenges to water quality monitoring and management, therefore, investigating their presence and distribution in the lake is vital for comprehending the extent of their risk and potential ecological consequences.

Lake Victoria faces contamination from various organic pollutants, including pesticides, persistent organic pollutants, and emerging contaminants such as pharmaceutically active substances, Per- and polyfluoroalkyl Substances (PFAS), and personal care products. The presence of these pollutants in the lake is a result of various factors such as wastewater treatment, agricultural activities, soil surface runoffs, bathing practices, rubbish dumping, and industrial wastewater (Lujjimbirwa and Odoki, 2023; Makaka et al., 2022; Olokotum et al., 2022). Lake Victoria's water and sediment contamination has been found to pose potential health risks to shoreline populations, including pathogenic bacteria and cyanotoxins from cyanobacteria (Ribbe et al., 2021).

The emergence of endocrine-disrupting compounds and personal care products in Lake Victoria has raised concerns about their impact on the aquatic ecosystems and human health in the region (Dalahmeh et al., 2020; Nantaba et al., 2021; Okoye et al., 2022). These contaminants are ubiquitous in the lake and its surroundings, posing a threat to the reproductive system, immunity, and child development (Chakraborty et al., 2023; Diamanti-Kandarakis et al., 2009). Additionally, the lake faces contamination from potentially harmful elements due to population expansion and economic growth, which can harm the aquatic ecosystems and the local communities relying on the lake for drinking water and fish (Marriott et al., 2023). The occurrence of organic micropollutants in the lake, including phthalates, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and organochlorine pesticides (OCPs), further highlights the need for monitoring and pollution control measures which are a potential ecotoxic risk to aquatic organisms (Nyamweya et al., 2023; Zhao et al., 2022). Comprehensive strategies are required to address these issues and mitigate the adverse effects of pollutants on the environment and the well-being of the communities relying on Lake Victoria (Njagi et al., 2022).

Therefore, a comprehensive review of contaminant levels, considering papers published between January 2000 and December 2022, focusing on organic pollutants, emerging contaminants, water quality parameters, microplastics, and heavy metal contamination within both the lake and its basin is vital for ensuring the sustainable use of this resource, safeguarding water security for the growing populations in the basin. This review paper, focusing on available information, aims to unveil the complexities of pollutants in Lake Victoria and identify knowledge gaps. By scrutinizing existing research, it seeks to pinpoint areas where further investigation is needed, paving the way for future directions in the research community exploring temporal trends in water quality, heavy metals, microplastics, and emerging organic pollutants.

## 2. Methodology

This systematic review followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) methodology (Aguilar-Aguilar et al., 2023; Page et al., 2021).

### 2.1. Identification

Two databases, SCOPUS and Web of Science, served as the primary sources for scholarly articles in this study. Additional articles were obtained through Google Scholar. The literature search spanned 22 years, from January 2000 to December 2022. All articles covering water quality, organic pollutants, heavy metals, and emerging contaminants within Lake Victoria, its basin, water, and sediments were included.

The search terms used were"Lake Victoria," "heavy metals," "water quality," "pollutants," "organic*," " "Africa*," "microplastics," "contaminants of emerging concern," "Pharmaceutical and Personal care products," and "pesticides." Across all databases, 101 research papers were found for heavy metals, 425 for organic pollutants, 279 for water quality, and 4 for microplastics during the study period. The PRISMA methodology flow diagrams (Figures S1, S2, and S3) illustrate the screening and selection process, resulting in 35 research articles for heavy metals, 18 for organic pollutants, 23 for water quality, and only 2 for microplastics in water and sediments.

### 2.2. Screening

All research articles underwent rigorous screening to remove duplicates, as indicated in the PRISMA flow diagrams (Figures S1, S2, and S3).

### 2.3. Eligibility

The eligibility criteria for research papers included: i) journal articles, dissertations and theses (with more than five citations) mentioning water quality, heavy metals, organic pollutants, persistent organic pollutants, pesticides, microplastics, and contaminants of emerging concern within Lake Victoria and its basin (considering basin areas closest to the lake). ii) The study was conducted within Lake Victoria and its basin, covering water and sediments of Lake Victoria, streams, rivers, and lakes, including satellite lakes that feed into Lake Victoria. These studies involved only water samples and sediments, excluding soil, plants, or fish.

### 2.4. Inclusion

A total of 78 research papers meeting the eligibility criteria were included in the review.

### 2.5. Exclusion

Research papers on water quality using remote sensing were not considered. Papers only mentioning pollutants in fish without addressing their presence in water were excluded. Some research articles mentioning contaminants in soil and plants within Lake Victoria and its basin were also excluded. Studies on the same contaminants in the basin, even if within the basin but not proximate to or located far away from the lake, were not considered in this study.

## 3. Current research

### 3.1. Study area

Lake Victoria is a critical freshwater source for industries and farms within its catchment area. Additionally, it plays a vital role as a domestic water source for surrounding communities. Despite its significance, the water quality of Lake Victoria has been consistently declining. This decline has prompted numerous studies to investigate its quality levels, assess detrimental effects on aquatic life and human users, and propose remedies crucial for the economic well-being of the involved countries. This study concentrated on sediment and water samples from Lake Victoria and its immediate basin. While the basin is expansive, our review specifically targeted regions proximate to the lake, as illustrated in Fig. 1. Maroon highlights in the basin showcase areas with at least one published paper, indicating considerable attention on Kenya, Uganda, and Tanzania. However, there's a need for more comprehensive research, particularly in the northwestern, western, and southwestern parts of the basin highlighted in green in Fig. 1, where Masaka City, Bukoba town, and Emin Pasha Gulf are located. Given their growing populations and potential influence on lake water quality, these areas require further exploration.

Utilizing the Basic Demographic Characteristics dataset through Google Earth Engine, the population map in Fig. 2(a) emphasizes the need for research in these underexplored regions. Additionally, our review revealed a significant gap in studies concerning the islands within Lake Victoria across all countries. Despite lower population density, commercial agriculture, and fishing activities in these islands pose risks to water quality, especially considering the identified presence of microplastics in the lake's surface waters and fish around the islands (Biginagwa et al., 2016; Egessa et al., 2020; Nicholson, 2021; Pan et al., 2023). Frequent monitoring is imperative, particularly in Winam Gulf, Mwanza Gulf, Napoleon, Murchison, Thurston, and Waiya Bays, where distinct watercolors in Fig. 2(b) indicate pollution. Notably, Winam Gulf in Kenya exhibits significant pollution. To substantiate these observations, a true color image of Lake Victoria and its surrounding areas was generated using Google Earth Engine APIs and Sentinel-2 2023 satellite imagery. Derived from bands 2, 3, and 4 of the electromagnetic spectra, this image underscores the importance of vigilant surveillance to safeguard the ecological balance of Lake Victoria and its basin. Continuous monitoring is essential to curb pollutants, especially in densely populated gulfs and bays, as highlighted in Fig. 2 (a).

### 3.2. Trends in research publications between 2000 and 2022

#### 3.2.1. Water quality

In our extensive analysis of water quality research publications from 2000 to 2022 across Kenya, Tanzania, and Uganda (Fig. 3), discernible patterns emergeshowing the evolving landscape of water quality studies around Lake Victoria. It is essential to note that water quality papers from remote sensing publications are not included in this review, highlighting a potential avenue for supplementary exploration in the literature. Kenya's engagement in water quality research displays varying activity levels, with a noticeable upward trend observed from 2003 onwards. Despite fluctuations, Kenya has consistently demonstrated a keen interest in water quality research, particularly in the last decade. Tanzania's involvement appears sporadic, with minimal activity observed between 2011 and 2016, reinforcing the need for renewed attention to water quality issues in Tanzanian waters.

In contrast, Uganda exhibits a more consistent and gradually increasing pattern in water quality research. The overall trend across the region indicates a collective upswing in water quality research, particularly in the last decade. Kenya stands out with intermittent yet sustained interest, while Tanzania has faced a notable research gap since 2011. Uganda, maintaining a more consistent pattern, signifies a dedicated effort to understanding and addressing water quality concerns. Collaborative efforts among these countries are imperative to address Lake Victoria's broader challenges regarding water quality. As the importance of water quality research grows, bridging gaps and fostering collaboration will be essential for developing effective strategies to safeguard the lake's water quality and, consequently, the overall environmental health of the region.

#### 3.2.2. Heavy metals

The number of publications on heavy metals in Lake Victoria and its basin varies across Kenya, Tanzania, and Uganda (Fig. 3). In Kenya, studies have been consistent up to 2019, with intermittent research, peaks in 2005–2010, and a resurgence between 2013 and 2019. In contrast, Tanzania and Uganda show several studies from 2000 to 2010, followed by a decade of no study between 2010 and 2020. These variations may be attributed to distinct research timelines, regional priorities, and shifts in research focus.

#### 3.2.3. Organic pollutants

The study of organic contaminants in Lake Victoria has seen limited exploration, but a noticeable surge in activity has been observed in Kenya and Uganda over the last decade (Fig. 3). Uganda, in particular, has emerged as a leader in recently published papers, signaling a promising trend. Our thorough analysis of research publications from 2000 to 2022 across Kenya, Tanzania, and Uganda reveals intermittent publications in Kenya, with only seven papers between 2005 and 2020. Tanzania has two publications recorded between 2004 and 2005, with no study on organic pollutants in almost two decades. In contrast, Uganda has maintained a consistent yet modest pattern with 11 publications indicating intensified research during specific periods. Despite research gaps within the last decade, the heightened focus on the area is apparent. Notably, before 2011, minimal studies on organic pollutants in the lake were conducted, indicating a recent surge in interest and the importance of current investigations. Collaborative efforts among these countries are pivotal for a holistic understanding of the environmental dynamics and challenges faced by the lake. As the organic contaminant research landscape evolves, addressing these gaps and fostering interdisciplinary approaches will be instrumental in enhancing our knowledge and refining management strategies for Lake Victoria and its surrounding basin.

#### 3.2.4. Microplastics

The study on microplastics in the Lake Victoria region shows that only four papers have been published, with only two focusing on surface waters in Uganda (Fig. 3), while the others concentrate on fish. Notably, there is no paper published on microplastics in surface waters on the Kenyan and Tanzanian sides. This shows the urgent need to initiate research in these areas to understand the extent and impact of microplastic pollution comprehensively. As microplastics gain recognition as a significant environmental concern, addressing this research gap becomes crucial for devising effective strategies to mitigate microplastics' presence and potential harm in Lake Victoria and its surrounding basin.

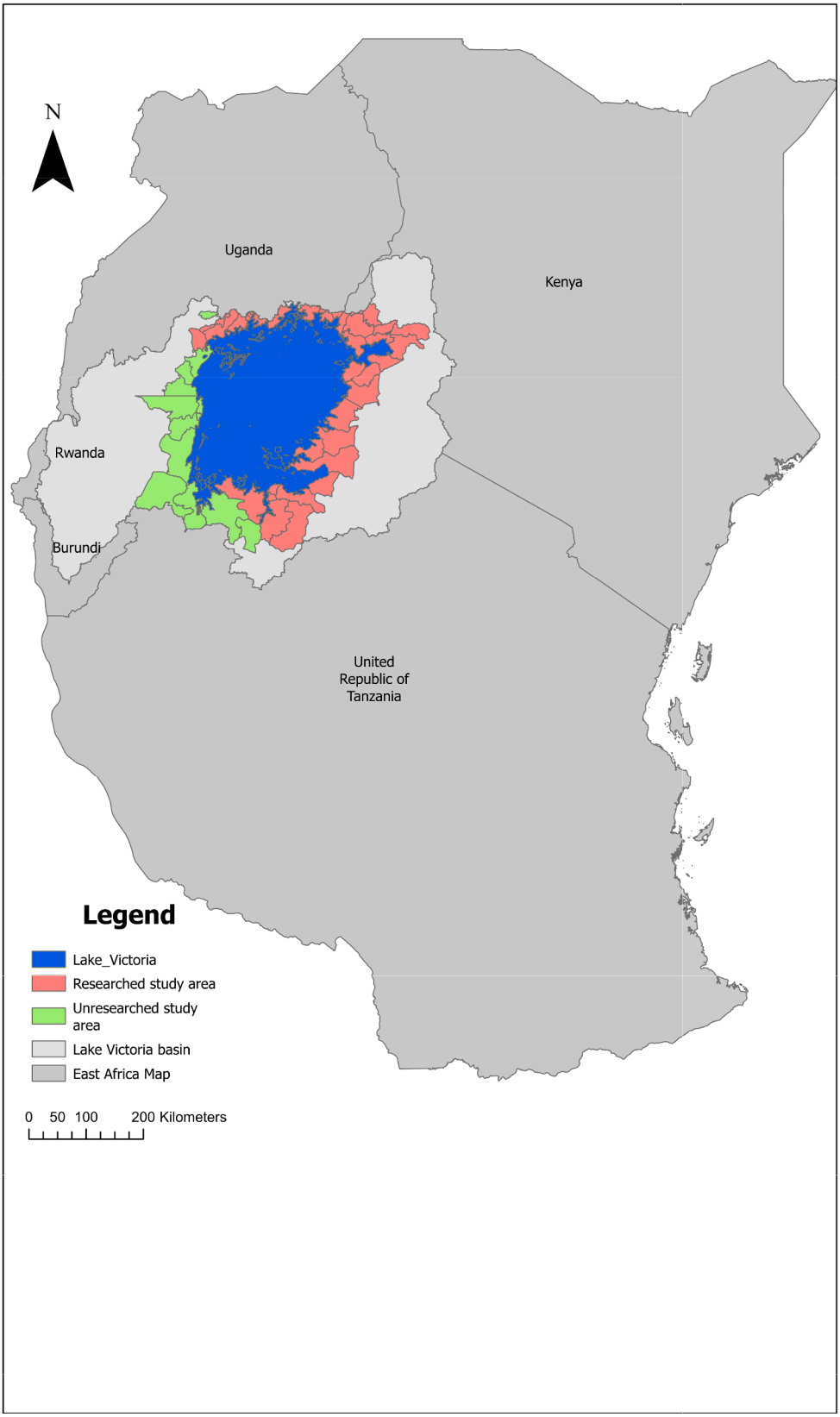


**Fig. 1.** Map of East Africa showing Lake Victoria study area and its surrounding basin. The maroon-colored basin highlights locations studied, while the green area signifies regions with very limited to no research for over two decades. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

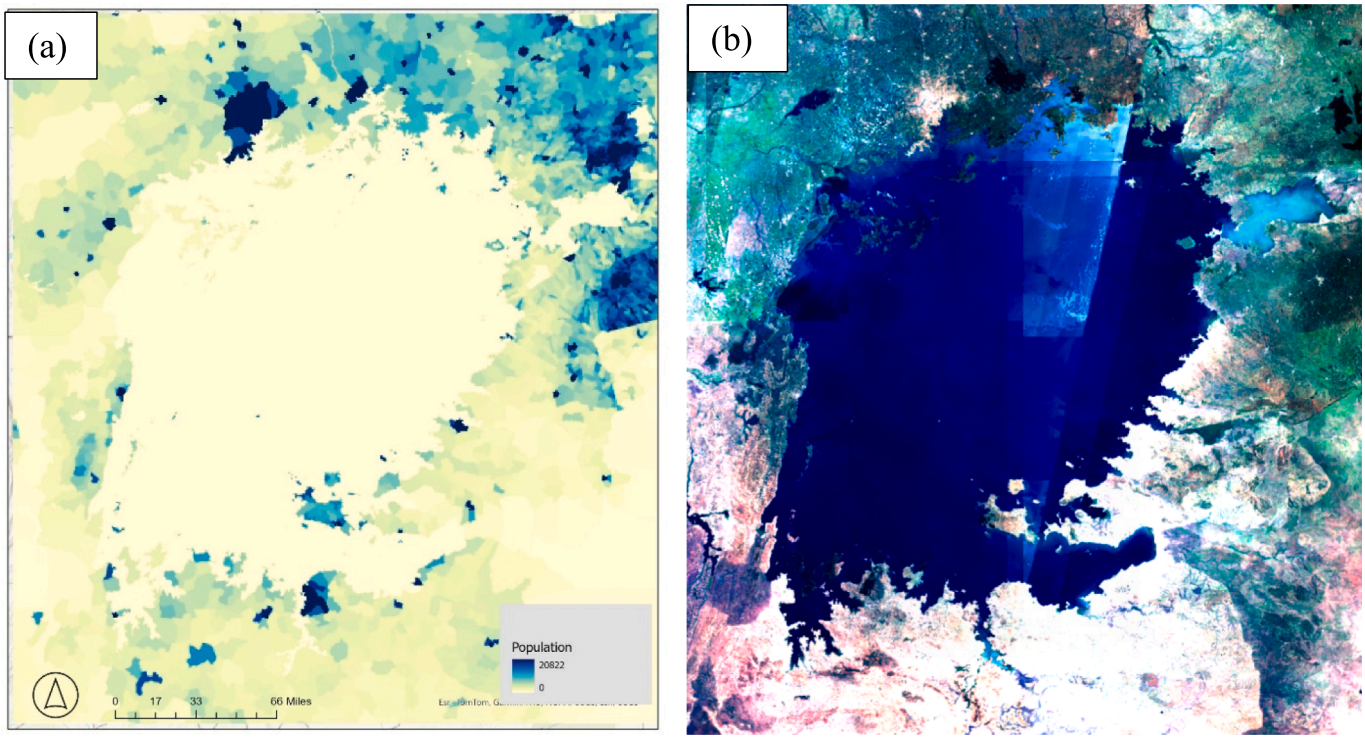


**Fig. 2.** (a) The population distribution around Lake Victoria in 2020 (b) The true color image of the lake and its surroundings in 2023.

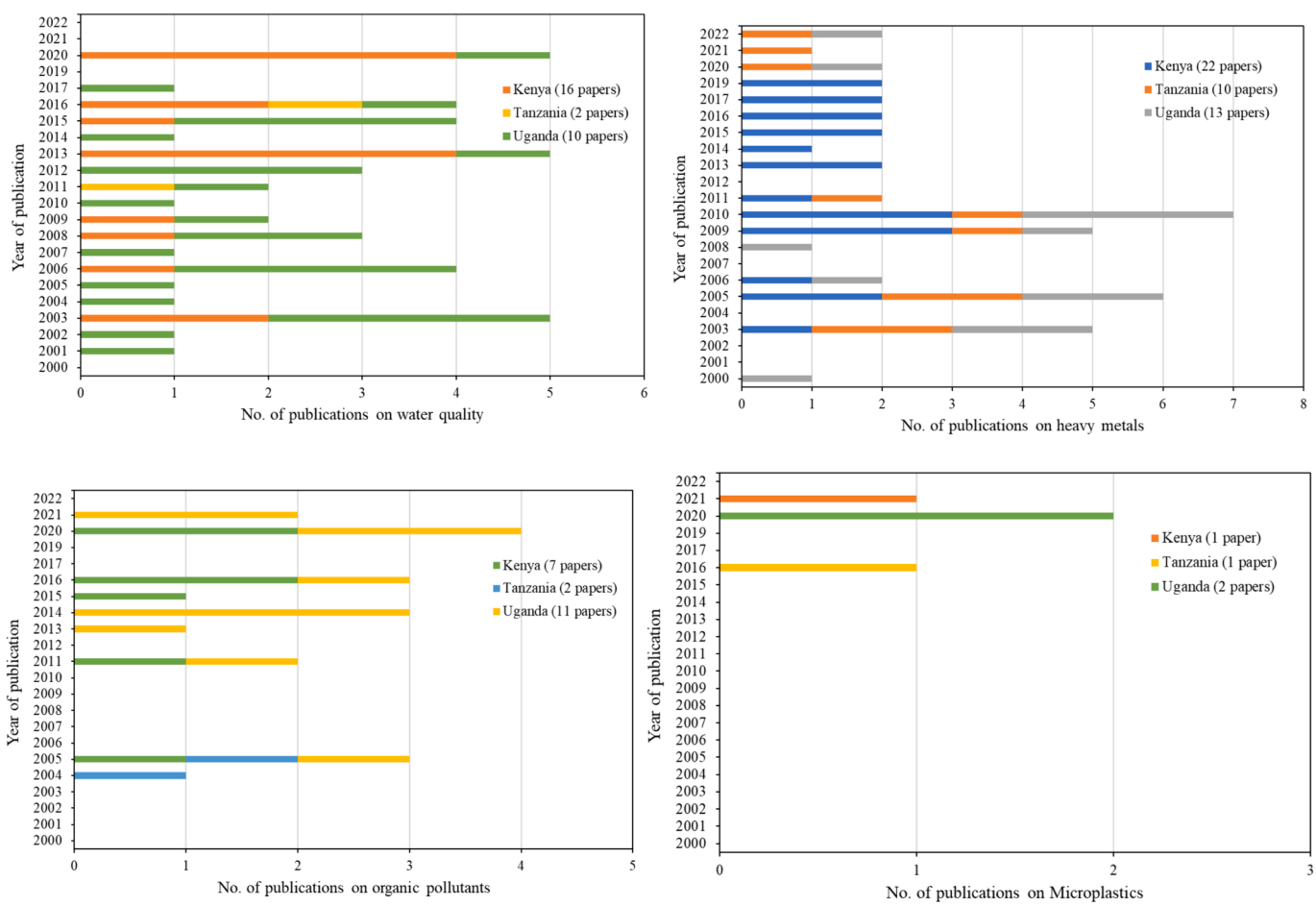


**Fig. 3.** Trends in Research Publications on water quality, heavy metals, organic pollutants and microplastic in Lake Victoria and its Basin from January 2000 to December 2022.

## 4. Environmental contaminants in Lake Victoria

### 4.1. Water quality parameters

Various studies have identified fluctuations in water quality parameters at different points within Lake Victoria and its basin. Despite these individual insights, there is a notable gap in the literature—a comprehensive analysis of these parameters across the entire basin is lacking. This article endeavors to fill this void by conducting an in-depth review of water quality parameters for the whole of the Lake Victoria area.

#### 4.1.1. Water quality within the lake

The water quality of Lake Victoria undergoes temporal fluctuations, evidenced by extensive studies conducted over the years (Tables 1, S1, S2). These variations result from natural processes and anthropogenic activities, including industrial and domestic discharges linked to increased industrialization and population growth, runoff from urban areas, and agricultural inputs such as pesticides, and fertilizers.

Examining parameters such as turbidity, temperature, total solids (T.S.), total suspended solids (TSS), total dissolved solids (TDS), electrical conductivity (E.C.), pH, alkalinity, hardness, nitrate ($NO_3$), nitrite ($NO_2$), total nitrogen (T.N.), total phosphates (T.P.), soluble reactive phosphorus (SRP), ammonia ($NH_3$), dissolved oxygen (D.O.), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC), chlorophyll, and nitrogen isotopes (NITZ) (Table 1) across different sampling sites provides insights into the lake's water quality trends.

Turbidity levels exhibit a wide range, from the lowest recorded at 35.1 NTU in 2006 to the highest at 561 NTU in 2013. These variations

**Table 1**
Water Quality Parameters within Lake Victoria.

| Location | Year | $NO_3$ (mg/L) | TN (ug/L) | Total P (mg/L) | $NH_4^+$ (mg/L) | DO (mg/L) | BOD (mg/L) | Chlorophyll (μg/L) | Reference |
|---|---|---|---|---|---|---|---|---|---|
| **Uganda** | | | | | | | | | |
| Kitubulu | 2015 | 39 | | | | | | | Jovanelly et al., (2015) |
| Lake Victoria | 2020 | 2 | | | | 20 | 14 | | Dalahmeh et al.,(2020) |
| Murchison Bay | 2015 | 0.084 | | | | | | 23 | Kabenge et al., (2015) |
| Murchison Bay | 2015 | 0.065 | | | | | | 78.5 | Kabenge et al., (2015) |
| Murchison Bay | 2015 | 9.3 | | | | | 23.1 | | Kabenge et al., (2015) |
| Murchison Bay | 2015 | 31.2 | | | | | 25.76 | | Kabenge et al., (2015) |
| Murchison Bay | 2015 | 0.412 | | | | | | 38.23 | Kabenge et al., (2015) |
| Jinja Bay | 2003 | | | | | 7.1 | | | Linda et al., (2003) |
| Inner Murchison Bay | 2012 | | 2,108 | 0.1 | | | | 96.5 | Amanda et al., (2012) |
| Napoleon Gulf | 2012 | | 1,644 | 0.06 | | | | 24.7 | Amanda et al., (2012) |
| NG, Napoleon Gulf | 2012 | 28.6 | | | | 8.43 | | 25.7 | Kiggundu et al.,(2012) |
| SN, Source of the Nile; | 2012 | 32.7 | | | | 6.53 | | 17.3 | Kiggundu et al., (2012) |
| SL, Sewage Lagoons; | 2012 | 2,122 | | | | 14.3 | | 1,148 | Kiggundu et al., (2012) |
| Murchison Bay | 2001 | | | 0.2 | 0.1 | 5 | 0.9 | | Akurut et al., (2017) |
| Murchison Bay | 2002 | | | 0.1 | 0.1 | 4.7 | 0.9 | | Akurut et al., (2017) |
| Murchison Bay | 2003 | | | 0.1 | 0.2 | 4.7 | 3.1 | | Akurut et al., (2017) |
| Murchison Bay | 2004 | | | 0.2 | 0.2 | 4.5 | 5.2 | | Akurut et al., (2017) |
| Murchison Bay | 2005 | | | 0.2 | 0.1 | 5.7 | 3.8 | | Akurut et al., (2017) |
| Murchison bay | 2006 | | | 0.2 | 0.1 | 5.9 | 3.9 | | Akurut et al., (2017) |
| Murchison Bay | 2007 | | | 0.2 | 0.2 | 6.1 | 3.9 | | Akurut et al., (2017) |
| Murchison Bay | 2008 | | | 0.2 | 0.2 | 5.7 | 2 | | Akurut et al., (2017) |
| Murchison Bay | 2009 | | | 0.2 | 0.1 | 5.7 | 1.7 | | Akurut et al., (2017) |
| Murchison Bay | 2010 | | | 0.2 | 0.1 | 5.7 | 1.4 | | Akurut et al., (2017) |
| Murchison Bay | 2011 | | | 0.2 | 0.1 | 5.4 | 0.9 | | Akurut et al., (2017) |
| Murchison Bay | 2012 | | | 0.2 | 0 | 4.7 | 4.2 | | Akurut et al., (2017) |
| Murchison Bay | 2013 | | | 0.3 | 0.3 | 4.7 | 7.1 | | Akurut et al., (2017) |
| Murchison Bay | 2014 | | | 0.5 | 0.3 | 4.7 | 5.9 | | Akurut et al., (2017) |
| Jinja | 2003 | | | | | 3.3 | | 5.7 | Campbell et al.,(2003) |
| **Kenya** | | | | | | | | | |
| Gingra | 2003 | | | | | 6 | | 16 | Campbell et al.,(2003) |
| Lake Victoria | 2017 | | 1,987 | 209.7 | | 7.6 | | 66.7 | Kundu et al., (2017) |
| Lake Victoria | 2017 | | 1,513 | 153 | | 7.2 | | 20.9 | Kundu et al., (2017) |
| Lake Victoria | 2017 | | 1,392 | 123.69 | | 7.3 | | | Kundu et al., (2017) |
| Lake Victoria | 2013 | | | | | 8.8 | | | Mwamburi (2013) |
| Nyanza Gulf | 2016 | | | | | 11.12 | | | Mwamburi, (2016) |
| Lake water | 2016 | | | | | 10.13 | | | Mwamburi, (2016) |
| Winam Gulf | 2006 | | | | | 7.2 | | | Ochieng et al., (2006) |
| Kisumu | 2003 | | | | | 7.31 | | | Campbell et al., (2003) |
| Gingra Rock | 2003 | | | | | 8.18 | | | Campbell et al., (2003) |
| Nyanza Gulf | 2013 | 272 | 1,644 | 110 | 0.062 | | | 6 | Lewis et al., (2013) |
| Nyanza Gulf | 2013 | 182 | 1,625 | 129 | 0.02 | | | 7 | Lewis et al., (2013) |
| Nyanza Gulf | 2020 | 0.093 | | | 0.015 | 8.15 | | 22.29 | Mwamburi et al., (2013) |
| Nyanza Gulf | 2020 | 0.0322 | | | 0.026 | 7.42 | | 10.74 | Mwamburi et al., (2013) |
| Nyanza Gulf | 2013 | | | | | 10.6 | | | Mwamburi et al., (2013) |
| Open lake | 2013 | | | | | 8.8 | | | Mwamburi et al., (2013) |
| **Tanzania** | | | | | | | | | |
| Mwanza North Bay | 2016 | | | | | 6.65 | | 12.04 | Salom S. & Samuel M. (2018) |
| Magu Bay | 2016 | | | | | 7.36 | | 15.13 | Salom S. & Samuel M. (2018) |
| Kayenze Bay | 2016 | | | | | 6.68 | | 16.75 | Salom S. & Samuel M. (2018) |

emphasize the influence of diverse human activities on the lake's cloudiness over the years. Temperature fluctuations, ranging from 24 to 30 °C across the lake sites over decades, show no statistically significant variation with seasons, emphasizing the need for continuous monitoring (Dalahmeh et al., 2020).

Total solids (T.S.) measurement, reported in one study at 130 mg/L (Dalahmeh et al., 2020), highlights the need for more comprehensive assessments. TSS at Mwanza Gulf (Tanzania) ranged from 4.73 mg/L in 2011 to 54.47 mg/L in 2016 (Shayo et al., 2011; Shayo & Limbu, 2018), while Murchison Bay (Uganda) reported values between 9 mg/L in 2010 and 56 mg/L in 2014 (Akurut et al., 2017). Despite these fluctuations, statistically, there is no significant change in TSS over time.

The pH of Lake Victoria's water varies from 5.3 to 9, indicating its slightly alkaline nature, consistent with its basin. Alkalinity and hardness measurements fall within the ranges of 66–87.8 mg $CaCO_3$/L and 7.13–54 mg $CaCO_3$/L, respectively (Mwamburi, 2009; Mwamburi et al., 2020), suggesting the water is adequately soft for regular use.

Total nitrogen (T.N.) assessment in Kenya reveals values between 1,392 to 2,108 μg/L (Miruka et al., 2021), emphasizing the need for more comprehensive studies. Nitrate levels range from 0.065 mg/L in Murchison Bay (1992–1996) (Kabenge et al., 2016) to 2,122 mg/L in sewage lagoons at Napoleon Gulf (2012) (Vincent et al., 2012). Eutrophication, indicated by T.P. levels exceeding 0.05 mg/L, was observed at all sampled sites from 2001 to 2015.

Dissolved oxygen (D.O.) measurements across the lake suggest suitable conditions for aquatic life, with organic matter concentrations in Murchison Bay ranging from 0.9-7.1 mg/L (Akurut et al., 2017; Akurut et al., 2014). Chlorophyll values, ranging from 6 to 40 μg/L, highlight the eutrophic nature of Lake Victoria, particularly along its shores.

While significant strides have been made in understanding specific parameters, it is evident that critical knowledge gaps persist. The call for a comprehensive basin-wide analysis, exploration of total solids concentrations, and in-depth investigations into nitrogen components and phosphates concentrations signify the need for a more holistic understanding of LakeVictoria's water quality dynamics.

#### 4.1.2. Water quality parameters in Lake Victoria basin

The data for parameters such as turbidity, temperature, T.S., TSS, TDS, E.C., and pH are given in Table S1, while data for alkalinity, hardness, $NO_3$, $NO_2$, TN, T.P., soluble reactive phosphorus (SRP), $NH_3$, D.O., BOD, COD, TOC, chlorophyll, and nitrogen isotopes (NITZ) are given in Table S2.

*Total Solids:* Total suspended solids (TSS) and total dissolved solids (TDS) are included in the measurement of T.S., which is frequently used in the water treatment sector worldwide. TDS values provide an overall measure of the total amount of dissolved substances in the water. Additionally, most of the TSS are made up of inorganic substances. Many studies have reported TSS; however, only one study reported a concentration of T.S. in the basin. This was done in Uganda, Kampala, and T. S. and ranged between 1,190 and 570 mg/L (Dalahmeh et al., 2020). Studies have shown variations in TSS and TDS in the Lake Victoria basin over the decades. A study conducted at the Nakivubo channel and wetland reported TSS results of 480 mg/L for the Nakivubo channel and 250 mg/L for the wetland (Dalahmeh et al., 2020). TSS values for the Winam Gulf basin were 63.74–112 mg/L (Miruka et al., 2021). In the rural Dunga, Luanda Usoma, and Marengo rural catchments, TSS results ranged from 199 to 397 mg/L (Tazaki and Asada, 2007). All TDS measurements for the basins of Lake Victoria have been done in Kenya. The figure ranged from the smallest of 0.04 mg/L to the highest of 382 mg/L (Bavor and Waters, 2008; Miruka et al., 2021; Tazaki and Asada, 2007). These variations are a result of several factors and activities that have happened over the years, such as industrial waste discharges, plants and animals, surface runoff from cities along the lake and wetlands.

*Electrical Conductivity:* The total concentration, mobility, valence, relative concentration of ions, and water temperature all affect the E.C. Conductivity values provide insights into water's overall salinity and mineral content. In Lake Victoria basin, studies reported E.C. in range of 102–5,850,000 μS/cm (Jovanelly et al., 2015; Miruka et al., 2021; Mwamburi, 2009; Mwamburi et al., 2020; Nyairo et al., 2015; Nyilitya et al., 2020; Oguttu et al., 2008; Ondhoro et al., 2016; Ramlal et al., 2003; Shayo et al., 2011; Sitoki et al., 2013; Tazaki and Asada, 2007; Vincent et al., 2012). The highest values were recorded at Murchison Bay wetland in Uganda to industrial discharges (Nabulo et al., 2008). Almost all values were below the World Health Organization (WHO) standards for drinking water expect two sites, i.e., Murchison Bay and Lake Simbi, suggesting moderate conductivity levels (WHO, 2018).

*pH:* The pH scale measures the acidity or basicity of water or the molar concentration of hydrogen ions in the solution. The pH scale measures the acidity or basicity of water or the molar concentration of hydrogen ions in the solution. Studies have revealed that the pH within Lake Victoria basin ranges from 5 to 10 (Campbell et al., 2003; Gikuma-Njuru et al., 2013; Lindenschmidt et al., 1998; Mwamburi et al., 2020; Nyairo et al., 2015; Nyilitya et al., 2021; Nyilitya et al., 2020; Oguttu et al., 2008; Shayo et al., 2011; Tazaki and Asada, 2007). In most studies, the pH was within the acceptable limit of 6.5 to 8.5 for drinking water (WHO, 2018). The water from the basin to Lake Victoria is slightly alkaline. This information is essential for understanding water chemistry and its potential impact on aquatic life.

*Alkalinity:* There has been a significant increase in the alkalinity of the Lake Victoria water basin over the years. Two studies reported about the alkalinity of water within the basin. Both studies were done on the Kenyan side. The lowest values were reported in 1998 and ranged from 14-64 mg/L (Lindenschmidt et al., 1998), and the highest was in 2009, ranging between 60–43,160 mg/L (Mwamburi, 2009). The alkalinity concentration at Nyanza Gulf, part of Lake Victoria, was similar to its tributaries: Sare, Kanyaboli, and Namboyo (Mwamburi, 2009). The results revealed that the alkalinity is within acceptable requirements for drinking water.

*Total Nitrogen:* $NO_3$, $NO_2$, organic nitrogen, and $NH_3$ are all considered part of T.N. Generally, studies in the Lake Victoria basin have exhibited significant increases in the nitrogen components. T.N. measurements were conducted in one study, and values were between 615 to 1,243 μg /L for sampled sites in Winam Gulf Basin, Kenya (Miruka et al., 2021). The nitrate levels in Nakivubo wetland and channel, Uganda, were 80 and 18 mg/L, respectively (Dalahmeh et al., 2020). In contrast, the levels of Winam Gulf basin were between 30–167 mg/L (Miruka et al., 2021). $NO_2$ was reported in the range of 25–70 mg/L for Winam Gulf only (Miruka et al., 2021). The most significant contributors to changes in total nitrogen are wastewater treatment plants, industrial discharges, surface runoff coupled with fertilized agricultural lands, and animal manure.

*Total Phosphorus:* Similarly, total phosphorus (T.P.) is an assessment of all phosphorus, whether dissolved or particulate, in water specimens. T.P. in the basin at sampled sites was 8.32 to 10.5 mg/L on the Ugandan side (Nakivubo Channel and Wetland) (Dalahmeh et al., 2020)and 132–264 mg/L on the Kenyan side, Winam Gulf (Miruka et al., 2021). River Amala and Nyangores had T.P. in the range of 52–500 mg/L (Nyairo et al., 2015). Phosphate values between 0–49,000 μg/L were reported in Uganda's Zika, Kitubulu, Mabira, and Mpanga forest reserves (Jovanelly et al., 2015). Soluble reactive phosphorus (SRP) was reported in two studies, one in Uganda and another in Kenya (Campbell et al., 2003). All studies revealed SRP results for the sites within tolerable limits apart from Bungungu sites in Uganda and Confluence in Kenya. These phosphate concentrations in natural waters are indicators of phosphate pollution caused by humans.

*Dissolved Oxygen:* The amount of oxygen dissolved in the water, or the amount available to living aquatic organisms, is measured by the dissolved oxygen (D.O.). In 2016, a study by Ondhoro et al. (2016) revealed that River Nile, Victoria, and Kazinga channels had D.O. in the range of 3–5 mg/L. D.O. of the four forest reserves of Zika, Kitubulu, Mabira, and Mpanga was in the range of 1–8 mg/L (Jovanelly et al., 2015). It was reported that industrial discharges into Lake Victoria from

different factories in Jinja had a D.O. between 1 and 5 mg/L (Oguttu et al., 2008). Tazaki and Asada (2007) results for D.O. were spread out in the 1–13 mg/L range for the sampling stations/points of Mugusu, Samena, Nyankumbu, Magema, Rwamagaza, and Muhama. In a study by Campbell et al. (2003), D.O. ranged between 6–8, and 2–8mg/L for Winam Gulf and Napoleon Gulf respectively. It should be noted that the majority of species will struggle to survive if D.O. levels fall below 3.0 mg/L. Therefore, D.O. levels below 1–2 mg/L are considered hypoxic, and the water will likely be completely lifeless. Healthy water should have dissolved oxygen concentrations between 6.5 and 8.0 mg/L. However, with industrial development, population growth, and wastewater treatment plants, BOD values have significantly increased; for example, the Bugolobi treatment plant was able to remove only 30 % from the influent (Dalahmeh et al., 2020). The data indicates varying levels of D.O. across different locations. The range of D.O. in Lake Victoria is 2–13 mg/L, which suggests that the lake experiences fluctuations in oxygen availability.

*Turbidity:* Turbidity is a critical parameter that can provide insights into the lake's water quality and ecological health. Based on the reviewed studies, the turbidity levels in the basin varied between 20.8 and 718.9 NTU. The lowest value was recorded for Lake Sare in Kenya (Mwamburi, 2009), and the highest measurement was at Busia, Uganda (Muwanga and Barifaijo, 2006).

*Temperature:* Temperature variations can affect the lake ecosystem's biological and chemical processes. In the reviewed studies, the water temperature within the basins that make up Lake Victoria ranged between 17–34 °C. Temperature variations can affect various biological and chemical processes in the lake ecosystem. The water color of the rural catchment was between 11–14 Hazen Units (H.U.) in the only four sites tested for color in the basin (Ouma et al., 2016).

However, a critical knowledge gap exists in a lack of a comprehensive basin-wide analysis covering the entire Lake Victoria catchment. Moreover, the identified knowledge gaps related to T.S. concentration, alkalinity, total nitrogen dynamics, phosphates concentrations, D.O. variability, turbidity dynamics, and temperature impacts highlight areas where further investigation is essential for a more comprehensive understanding.

### 4.2. Heavy metals in water and sediments of Lake Victoria and its surrounding basin

The evaluation of heavy metal concentrations in Lake Victoria and its basin is vital in understanding environmental risks and ensuring the enduring sustainability of this freshwater ecosystem. This section comprehensively analyzes heavy metal concentrations in sediment and water samples (Tables 2 and 3), offering insights into Lake Victoria's environmental dynamics and potential implications for the health of humans and aquatic ecosystems.

*Lead:* The concentration of lead (Pb) in water samples within Lake Victoria consistently surpasses sediment levels across studied regions in Kenya and Uganda. Unfortunately, the Tanzanian side of Lake Victoria has only been subject to sediment studies, lacking water sample investigations. Pb concentrations in lake water studies conducted before 2017 often exceeded 800 μg/L, particularly in Kenya and Uganda (Fuhrimann et al., 2015; Mbabazi et al., 2010a; Mbabazi et al., 2010b; Ogoyi et al., 2011; Ouma et al., 2016). However, a sharp decline in Pb concentrations after 2017 suggests a potential correlation with the 2017 EPA regulations, leading to stricter effluent rules. It is crucial to highlight that the Nakivubo Channel in Uganda contained exceptionally high Pb concentrations in sediment samples in 2015 (25,600 μg/kg d.w.), hence the need for continuous monitoring due to its significant contribution to pollution. Elevated Pb concentrations were also observed in

**Table 2**
Concentration of heavy metals in sediments (mg/kg d.w.) and in lake water (μg/L) of Lake Victoria. Also given are the proposed critical limits of WHO and EPA for drinking water (WHO, 2017; USEPA, 2018).

| Location | Year | Pb | Cd | Zn | Cr | Hg | Cu | Fe | Mn | Ni | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sediments samples** | | | | | | | | | | | |
| **Kenya** | | | | | | | | | | | |
| Winam gulf | 2019 | 195 | 0.556 | 295 | 56.9 | | 60.1 | | | 29 | (Outa et al., 2020) |
| Winam gulf | 2017 | 0.15 | | | | 0.41 | | | | | (Kundu et al., 2017) |
| Winam gulf | 2017 | 181 | 1.2 | 187 | 36 | | 122.9 | 1,469 | 1631 | | (Kiema et al., 2017) |
| Nyanza gulf | 2016 | | | | 103 | | | | | | (Mwamburi, 2016) |
| Winam gulf | 2013 | 56.3 | | 51 | | 1.1 | 60.7 | 37540 | 1,315 | 25.7 | (Mwamburi, 2013) |
| Winam gulf | 2013 | 85 | 3.3 | 277 | 21 | | | | | | (Ribbe et al., 2021) |
| Winam gulf | 2011 | 0.28 | | 1.019 | 0.24 | 0.004 | | | | | (Ogoyi et al., 2011) |
| Within lake | 2010 | 3.64 | 0.12 | 3.44 | 1.12 | | | | | | (Oyoo-Okoth et al., 2010) |
| Port Victoria | 2009 | 9.5 | 0.758 | 45.1 | | | 21.3 | 3,540 | | | (Ongeri et al., 2009) |
| Winam gulf | 2006 | 90.03 | 0.79 | 232.1 | 4.71 | | 38.77 | | 1,754 | 27 | (Ochieng et al., 2006) |
| **Tanzania** | | | | | | | | | | | |
| Mwanza gulf | 2022 | 72.14 | 0.32 | 2691 | 444 | 0.63 | 35.51 | | | 31 | (Shen et al., 2022) |
| Mwanza gulf | 2011 | 0.33 | 0.021 | 0.889 | 0.18 | 0.007 | | | | | (Ogoyi et al., 2011) |
| Speke gulf | 2010 | 71.4 | 1.75 | 294 | 54.6 | | 89.7 | | | | (Kishe and Machiwa, 2003) |
| Mwanza gulf | 2003 | 29.6 | 2.5 | 36.4 | 11 | 0.1 | 21.6 | | | | (Shen et al., 2022) |
| **Uganda** | | | | | | | | | | | |
| Portbell | 2022 | 42.18 | 3.283 | | 0.46 | | 6.47 | | | | (Baguma et al., 2022) |
| Within lake | 2021 | 25 | 0.26 | 103 | 100 | | 121 | | | 56 | (Ribbe et al., 2021) |
| **Water samples** | | | | | | | | | | | |
| **Kenya** | | | | | | | | | | | |
| donga | 2016 | 895 | | 71 | | | | 318 | | | (Ouma et al., 2016) |
| Winam gulf | 2011 | 823 | | 50 | 178 | | | | | | (Ogoyi et al., 2011) |
| Kisumu bay | 2010 | 114.1 | 151.1 | | 87.9 | | 94.2 | | | | (Oyoo-Okoth et al., 2010) |
| Inside lake | 2010 | 990 | 60 | 940 | 790 | | | | | | (Oyoo-Okoth et al., 2010) |
| Inside the lake | 2010 | 114.1 | 151.1 | | 87.9 | | 94.2 | | | | (Oyoo-Okoth et al., 2010) |
| Winam gulf | 2006 | 24.42 | 2.69 | 62.83 | 11.15 | | 11.11 | | 97.28 | 8.85 | (Ochieng et al., 2006) |
| **Uganda** | | | | | | | | | | | |
| Murchson bay | 2020 | 6.07 | 0.33 | 10 | 0.5 | | | 25.67 | 1.4 | | (Bhaskar and Gidudu, 2020) |
| Murchson bay | 2015 | 1,250 | 100 | 300 | 14 | | 1,400 | 17700 | | | (Fuhrimann et al., 2015) |
| Napoleon gulf | 2010 | 942 | 79 | 1,216 | | | 978 | | | | (Mbabazi et al., 2010b) |
| Inside the lake | 2010 | 1,054 | 93 | 1,478 | | | 1,123 | | | | (Mbabazi and Wasswa, 2010) |
| WHO | | 10 | 3 | – | 50 | | | – | 400 | | |
| EPA | | 10 | 5 | 5,000 | 100 | | | 300 | 50 | | |

**Table 3**
Concentration of heavy metals in sediments (**mg/kg d.w.**) and in lake and river water (**μg/L**) within Lake Victoria basin.

| Location | Year | Pb | Cd | Zn | Cr | Cu | Fe | Mn | Reference |
|---|---|---|---|---|---|---|---|---|---|
| **Sediment samples** | | | | | | | | | |
| **Kenya** | | | | | | | | | |
| R. Isiukhu | 2019 | 41.6 | 0.49 | 140 | 133 | 43.2 | | | (Oremo et al., 2019) |
| Kisumu | 2015 | 64.7 | 1.78 | 117 | 47.4 | 39.3 | 63800 | 5,440 | (Ongeri et al., 2014) |
| lake Sare water | 2009 | 40 | | 45 | 15 | | 81700 | 1,120 | (Mwamburi, 2009) |
| Nyando | 2009 | 62 | 0.28 | 14.6 | | 6.23 | | 394 | (Henry and Omutange, 2009) |
| Nyando | 2005 | 0.0016 | 0.0001 | 0.0678 | | 0.00113 | | 0.00985 | (Nyangababo et al., 2005a) |
| **Tanzania** | | | | | | | | | |
| R. Mara | 2020 | 2.7 | 1.28 | | 1.2 | | | | (Nkinda et al., 2020) |
| Simiyu | 2009 | 94 | 3.81 | 70 | | 53 | | 647 | (Henry and Omutange, 2009) |
| Simiyu | 2005 | 0.00148 | 0.00317 | 0.1077 | | 0.00705 | | 0.09113 | (Nyangababo et al., 2005a) |
| Mwanza | 2000 | 1,553 | | 533 | | | 38707 | 848 | (Makundi, 2001) |
| **Uganda** | | | | | | | | | |
| Nakivubo channel | 2015 | 25,600 | 2,100 | 134,900 | 49,800 | 35,800 | 25,000,000 | | (Fuhrimann et al., 2015) |
| Katonga | 2009 | 63 | 1.26 | 121 | | 44 | | 116 | (Henry & Omutange, 2009) |
| Nakivubo channel | 2006 | 157.2 | | 1,641 | 156.9 | 24.9 | | 250.3 | (Muwanga and Barifaijo, 2006) |
| Katonga | 2005 | 0.0017 | 0.003 | 0.09938 | | 0.029 | | 0.0375 | (Nyangababo et al., 2005a) |
| **Water samples** | | | | | | | | | |
| **Kenya** | | | | | | | | | |
| R.Nyangores | 2015 | 5.27 | 2.28 | 111.49 | 0.56 | 13.39 | | 3.85 | (Nyairo et al., 2015) |
| R. Mara | 2015 | 3.78 | 3.86 | 60.03 | 1.37 | 17.46 | | 3.43 | (Nyairo et al., 2015) |
| Migori gold mine | 2014 | 13.1 | 10.5 | | | | | | (Ngure et al., 2014) |
| Nyando | 2005 | 19,000 | 13,000 | 16,000 | | 1,800 | | 156,000 | (Nyangababo et al., 2005c) |
| **Tanzania** | | | | | | | | | |
| Simiyu | 2005 | 29,000 | 67,000 | 78,000 | | 60,000 | | 257,000 | (Nyangababo et al., 2005c) |
| **Uganda** | | | | | | | | | |
| Nakivubo channel | 2015 | 1,600 | 140 | 1,400 | 60 | 3,300 | 21,500 | | (Fuhrimann et al., 2015) |
| Nakivubo wetland | 2015 | 1,020 | 130 | 300 | 10 | 2,300 | 18,600 | | (Fuhrimann et al., 2015) |
| Nakivubo channel | 2010 | 1,864 | 166 | 1,956 | | 1,189 | | | (Mbabazi et al., 2010a) |
| Murchison bay wetland | 2008 | 50 | | 50 | | | | | (Nabulo et al., 2008) |
| Nakivubo channel | 2006 | 260 | 14 | 120 | | 20 | | 820 | (Muwanga and Barifaijo, 2006) |
| Katonga | 2005 | 9,680 | 600 | 45,600 | | 2,900 | | 54,300 | (Nyangababo et al., 2005a) |

basin water samples in Nyando, Simiyu, and Katonga in 2005 (Nyangababo et al., 2005a; Nyangababo et al., 2005c), underscoring the necessity for persistent efforts to address ongoing pollution. The levels of Pb in Murchison Bay in 2022 exceeded EPA and WHO standards (Tables 2 and 3) for drinking water, emphasizing the urgency of reassessing Pb contamination in Kenyan and Ugandan lake water (Ouma et al., 2016). Recognizing the potential impacts of heavy metals on human and environmental health, particularly neurotoxicity of lead, reinforces the importance of continuous monitoring to safeguard human health and maintain ecosystem health.

*Cadmium:* Cadmium (Cd) concentrations in water consistently exceeded sediment levels across regions, with no studies on water samples within the Tanzanian side of Lake Victoria from 2000 to 2022. Before 2017, reported Cd values were higher than EPA and WHO (Tables 2 and 3) recommended values, but post-2017 values were within acceptable limits. Recent Cd concentrations in lake sediment samples indicate lower levels after 2017, with Winam Gulf in 2019 (0.556 mg/kg d.w.), Mwanza Gulf in 2022 (0.32 mg/kg d.w.), and Portbell in 2022 (3.283 mg/kg d.w.) (Baguma et al., 2022; Outa et al., 2020; Shen et al., 2022). Although Cd levels in the basin water and sediments post-2017 were low, monitoring is crucial to ensure the safety of drinking water and prevent bioaccumulation in aquatic organisms.

*Zinc:* Zinc (Zn) concentrations in Lake Victoria's water and sediment samples exhibit intricate patterns, with Mwanza Gulf in 2022 reporting remarkably high sediment concentration (2,691 μg/L or 2.691 mg/kg d.w.). Post-2017, most studies showed low Zn concentrations in water and sediment samples within the lake. However, basin sites in Uganda, Tanzania, and Kenya displayed lower zinc concentrations post-2017, with River Isiukhu sediment samples reaching 140 mg/kg d.w. in 2019 (Oremo et al., 2019). The concentrations of zinc in Murchison Bay in 2022 were within EPA standards, but ongoing analysis is essential for mitigating potential environmental risks. Monitoring zinc levels is crucial, as excessive concentrations can harm aquatic life (Oremo et al., 2019).

*Chromium:* Chromium concentrations in Lake Victoria sediments indicated noteworthy levels, including 444 mg/kg d.w. in Mwanza Gulf in 2022 and 56.9mg/kg d.w. in Winam Gulf in 2019 (Outa et al., 2020; Shen et al., 2022), exceeding 2017 EPA guidelines. High Cr concentrations were found in basin water samples of all three countries, emphasizing the need for continuous monitoring to prevent ecological disruptions. However, data gaps exist for chromium in specific years and locations, underscoring the importance of addressing these gaps for a comprehensive understanding.

*Mercury:* Mercury (Hg) concentrations in sediment samples in Lake Victoria were 0.63 mg/kg d.w. in Mwanza Gulf in 2022 and 0.41 mg/kg d.w. in Winam Gulf in 2017 (Shen et al., 2022). Notably, no studies were conducted for mercury in water samples within the lake, raising concerns about understanding mercury pollution in these regions. Furthermore, no studies were conducted for mercury in the basin's sediment and water samples, underscoring the need for comprehensive monitoring. Mercury is a potent neurotoxin with several adverse effects on human and environmental health.

*Copper:* Copper (Cu) in sediment samples in Lake Victoria highlighted specific concentrations, including 35.51 mg/kg d.w. in Mwanza Gulf in 2022 and 122.9 mg/kg d.w. and 60.1 mg/kg d.w. in Winam Gulf in 2017 and 2019 respectively (Shen et al., 2022). There was no data on the levels of Cu in water samples for specific years and locations, indicating data collection or analysis gaps. Copper concentrations in sediment samples from various Kenya, Tanzania, and Uganda basin sites varied significantly. Nakivubo Channel exhibited a concentration of 35,800 mg/kg d.w. in 2015 (Mbabazi et al., 2010b), indicating considerable variability. However, there is no copper concentration data in Lake Victoria for Tanzania after 2016, and similar data gaps exist in Kenya's lake waters after 2010 and for Uganda after 2016. Monitoring copper levels in sediments and water is necessary to prevent adverse effects on aquatic organisms.

*Iron:* Iron (Fe) levels in sediment samples in Lake Victoria were very high before 2017, but studies after 2017 in Murchison Bay reported

water concentrations below 25.67 mg/kg d.w.) (Shen et al., 2022). In 2017, lake sediments in Winam Gulf contained 1,468 mg/kg d.w. of Fe. There were no reports on Fe concentrations for specific years and locations, indicating a data collection or analysis inconsistencies. Varying Fe concentrations in sediment samples from different basin sites were observed, with no Fe concentration data in Lake Victoria sediment samples within Uganda's and Tanzania's waters.

*Manganese:* Manganese (Mn) notable concentrations in sediment samples within Lake Victoria include 1,631 mg/kg d.w. in Winam Gulf in 2017 and 1.4 mg/kg d.w. in Murchison Bay lake water in 2020, within EPA standards (Shen et al., 2022). However, data gaps exist in Kenyan Lake Victoria waters after 2017 and for Ugandan and Tanzanian waters between 2000 and 2022, emphasizing the need for continuous monitoring to address data gaps.

*Nickel:* The levels of nickel (Ni) in sediment samples within Lake Victoria display notable concentrations, such as 31 mg/kg d.w. in Mwanza Gulf in 2022 and 29 mg/kg d.w. in Winam Gulf in 2019 (Shen et al., 2022). The absence of nickel concentration data in water samples within the lake and in basin sediments and water samples for all three countries underscores the need for comprehensive studies.

Determining the concentrations of these heavy metals in both lake water and the basin is critical for safeguarding human health, protecting aquatic ecosystems, and ensuring the overall environmental sustainability of Lake Victoria and its surrounding regions. The potential sources of these pollutants, ranging from industrial discharges to urban runoff and agricultural activities, underscore the importance of ongoing monitoring efforts to identify and mitigate pollution sources. Continuous research and data collection are essential for addressing knowledge gaps and developing effective strategies for the sustainable management of this vital freshwater ecosystem.

### 4.3. Organic pollutants in Lake Victoria

Organic pollutants, including antibiotics, pesticides, pharmaceuticals, personal care products, and PFAS, have been detected in Lake Victoria and its surrounding basin. Understanding the concentrations and distribution of these pollutants is essential for several reasons. Firstly, it sheds light on the potential ecological risks these contaminants pose. Secondly, studying organic pollutants is crucial for assessing the risks to human health. As the lake serves as a vital source of drinking water for the local population, identifying and continuously monitoring these contaminants becomes significant. These substances may pose long-term health risks through direct ingestion and bioaccumulation in aquatic organisms. This section gives a comprehensive overview of the status of organic pollutants in Lake Victoria and its basin.

#### 4.3.1. The prevalent organic contaminants identified in sediments and water samples

On comprehensive examination of organic pollutants in both water and sediment samples from the papers reviewed from Lake Victoria and its surrounding basin, more than 170 distinct organic pollutants (Tables 4, S3 and S4) were discovered. Of the over 170 organic pollutants, 162 are from Kenya, 9 are from Tanzania, and 83 are from Uganda. Furthermore, the six common pollutants among the three countries are DDT and its derivatives, Dieldrin, Endosulfan (alpha, beta, gamma), Heptachlor, Lindane, and Parathion methyl (Tables 4, S3 and S4), all pesticides, showing the effect of agricultural runoff into the lake. Kenya has only two studies on organic pollutants in sediments of Lake Victoria water and no study at all on organic pollutants in Lake Victoria water. In contrast, Uganda has conducted sediment and water sample studies (Tables 4 and S3) within Lake Victoria. There are no studies on the lake water or sediments in Tanzania. Most compounds detected in the three countries are found in water and sediment samples within the lake basin (Tables 4, S3 and S4). The prevalence of these pollutants, as obtained from the reviewed papers, is represented in Fig. 4, where DDT and its derivatives emerged as the most dominant, with a frequency of detection

**Table 4**
Organic pollutants concentration in sediment (in μg/ kg d.w) samples within Lake Victoria

| Location | Organic Pollutant | Publication Year | Concentration | Reference |
|---|---|---|---|---|
| **Sediments Uganda** | | | | |
| In lake water | PCBs | 2016 | 20 | (Arinaitwe et al., 2016b) |
| | DDTs | 2016 | 16.97 | (Arinaitwe et al., 2016b) |
| | Endosulfan | 2016 | 0.24 | (Arinaitwe et al., 2016b) |
| | HCHs | 2016 | 11.29 | (Arinaitwe et al., 2016b) |
| | HCB | 2016 | 0.55 | (Arinaitwe et al., 2016b) |
| | Heptachlor | 2016 | 1.24 | (Arinaitwe et al., 2016b) |
| | Chlordanes | 2016 | 6.08 | (Arinaitwe et al., 2016b) |
| Napoleon gulf | PCB | 2014 | 2.52 | (Ssebugere et al., 2014a) |
| | PCDDs | 2013 | 0.11 | (Ssebugere et al., 2013) |
| | PCDFs | 2013 | 0.026 | (Ssebugere et al., 2013) |
| Murchison Bay | PCDFs | 2014 | 0.76 | (Ssebugere et al., 2014b) |
| | PCDDs | 2014 | 0.45 | (Ssebugere et al., 2014b) |
| | PBDEs | 2014 | 0.66 | (Ssebugere et al., 2014b) |
| | PCB | 2014 | 12.3 | (Ssebugere et al., 2014c) |
| Thurston bay | PCDDs | 2013 | 0.04 | (Ssebugere et al., 2013) |
| | PCDFs | 2013 | 0.04 | (Ssebugere et al., 2013) |
| Waiya Murchison bay and Napoleon gulf | Endosulphan sulphate | 2011 | 5.62 | (Wasswa et al., 2011) |
| | beta Endosulphan | 2011 | 0.22 | (Wasswa et al., 2011) |
| | alpha Endosulphan | 2011 | 9.67 | (Wasswa et al., 2011) |
| | Aldrin | 2011 | 15.96 | (Wasswa et al., 2011) |
| | Dieldrin | 2011 | 7.18 | (Wasswa et al., 2011) |
| | p,p' −DDE | 2011 | 3.59 | (Wasswa et al., 2011) |
| | p,p' −DDD | 2011 | 4.02 | (Wasswa et al., 2011) |
| | p,p' −DDT | 2011 | 1.46 | (Wasswa et al., 2011) |
| | o,p' −DDE | 2011 | 2.72 | (Wasswa et al., 2011) |
| | o,p' −DDT. | 2011 | 1.63 | (Wasswa et al., 2011) |
| | eta HCH | 2011 | 0.66 | (Wasswa et al., 2011) |
| | lpha HCH | 2011 | 1.27 | (Wasswa et al., 2011) |
| | gamma HCH | 2011 | 5.48 | (Wasswa et al., 2011) |

(continued on next page)

**Table 4** (*continued*)

| Location | Organic Pollutant | Publication Year | Concentration | Reference |
|---|---|---|---|---|
| | Heptachlor | 2011 | 0.81 | (Wasswa et al., 2011) |
| | Heptachlor epoxide | 2011 | 3.19 | (Wasswa et al., 2011) |
| | Chlordane | 2011 | 0.76 | (Wasswa et al., 2011) |
| **Kenya** | | | | |
| Winam Gulf | PCBs | 2015 | 5.46 | (Omwoma et al., 2015) |
| | PCDDs | 2015 | 1.01 | (Omwoma et al., 2015) |
| | PCDFs | 2015 | 0.07 | (Omwoma et al., 2015) |
| Nyanza Gulf | PCB | 2016 | 183 | (Oluoch-Otiego et al., 2016) |

of 38, signifying their pervasive presence in the aquatic environment. Subsequent significant identifications included Alpha-endosulfan and heptachlor, each occurring with a frequency of 10 times (Fig. 4), highlighting potential environmental implications (Arinaitwe et al., 2016; Musa et al., 2011; Nyangababo et al., 2005b; Wasswa et al., 2011). The existence of various other pollutants emphasizes the intricate and diverse nature of organic pollutants in the lake and its basin. These findings demonstrate the critical need for continuous monitoring and effective environmental management to mitigate these contaminants' potential ecological and human health risks.

#### 4.3.2. Organic pollutants within Lake Victoria

In Uganda, analysis of sediment samples from wake water (Tables 4 and S3) in 2016 revealed notable concentrations of diverse organic pollutants, including PCBs, DDTs, endosulfan, HCHs, HCB, heptachlor, and chlordane. Exceptionally high concentrations of PCBs were observed in Napoleon Gulf in 2014, and PCDDs and PCDFs in 2013, indicating significant contamination (Ssebugere et al., 2013a; Ssebugere et al., 2013b; Ssebugere et al., 2014a). Studies conducted in Murchison Bay in 2014 revealed significant concentrations of PCDFs, PCDDs, PBDEs, and PCBs, highlighting the persistent nature of these pollutants in the environment (Ssebugere et al., 2014b). Thurston Bay in 2013 had lower concentrations of PCDDs and PCDFs. Waiya, Murchison Bay and Napoleon Gulf 2011 presented concentrations of various pollutants, reflecting the historical usage of these substances in the region (Ssebugere et al., 2013b; Wasswa et al., 2011). In Kenya, Winam Gulf in 2015 displayed significant levels of PCBs, PCDDs, and PCDFs, indicating the presence of these pollutants in the sediment (Oluoch-Otiego et al., 2016; Omwoma et al., 2015). Nyanza Gulf in 2016 contained a significant concentration of PCBs, suggesting potential ongoing contamination. Ugandan lake water samples in 2021 revealed concentrations of various organic pollutants, including pharmaceutical and personal care products, indicating the presence of a wide range of industrial and personal care products, plasticizers, and emerging pollutants (Nantaba et al., 2021). In the open lake, Nantaba et al. (2020) reported the presence of perfluoroalkyl substances, suggesting the presence of these emerging contaminants. These findings underscore the complex interplay of historical and contemporary sources of organic pollutants within Lake Victoria, emphasizing the need for ongoing monitoring and regulatory measures to mitigate environmental risks. The presence of contaminants, including PCBs, DDTs, endosulfan, and emerging substances, poses risks to drinking water quality. The potential for direct ingestion and bioaccumulation in aquatic organisms raises concerns about long-term health effects and underscores the importance of ongoing monitoring and comprehensive research. The observed trends highlight the necessity for collaborative efforts among East African countries to address gaps in knowledge, implement effective management strategies, and ensure the safety of drinking water from Lake Victoria.

#### 4.3.3. Organic pollutants in the Lake Victoria basin

Examining the Lake Victoria basin reveals significant concentrations of specific pollutants detected in various regions, emphasizing the prevalence of organic contaminants in both sediment and water samples. In the Kisumu, Homabay, and Eldoret Basin of Kenya in 2016 (Table S4), notable levels of ciprofloxacin, ampicillin, sulfamethoxazole, and chloramphenicol were identified (Kimosop et al., 2016). Additionally, the Western Kenya South Basin (Kissi) displayed a spectrum of organic pollutants in 2020, with concentrations ranging from 0.5 to 152.76 ng/g, including substances like 2-isopropylthioxanthone, 2-morpholinothiobenzothiazole, and DEET (Kandie et al., 2020a). In a

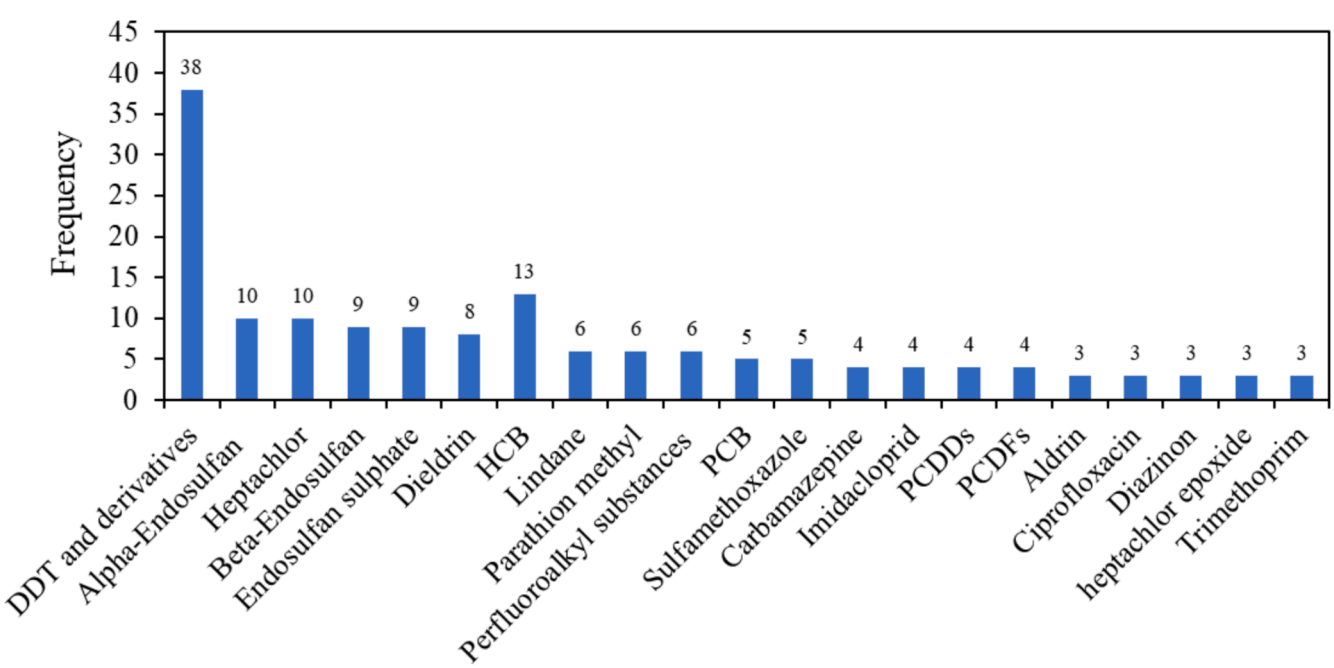


**Fig. 4.** The prevalent organic contaminants identified in sediments and water samples within the lake and in the lake basin of Lake Victoria.

related study, the Nyando-Sondu-Miriu Basin in 2011 revealed the presence of various pollutants such as diazinon, dimethoate, and DDT, with concentrations spanning from 0.03 to 69.55 ng/g. Similarly, the Nyando Basin 2005 exhibited concentrations of endosulfan alpha, endosulfan beta, and DDT-related compounds ranging from 0.15 to 0.715 ng/g (Musa et al., 2011). The Simiyu Basin in 2005 showed diverse organic pollutants, with concentrations ranging from 0.5 to 2.61 ng/g (Nyangababo et al., 2005b) (Table S5), including endosulfan alpha, endosulfan beta, and DDT-related compounds. These findings underscore the prevalence of organic pollutants in sediment samples within the Lake Victoria basin, raising concerns about potential ecological and health risks.

Parallel analysis of organic pollutant concentrations in water samples from Lake Victoria basins (Table S5) demonstrates a diverse range of substances across different locations and years. In Kenya, the South Basin in 2020 had elevated concentrations of various pollutants, such as 10,11-dihydro-10,11-dihydroxycarbamazepine, 10,11-dihydro-10-hydroxycarbamazepine, and 2,4-dichlorophenoxyacetic acid. Notably, this basin demonstrated high concentrations of acetaminophen, acetamiprid, and carbamazepine, emphasizing the presence of pharmaceuticals and pesticides (Kandie et al., 2020b). Similarly, in the Kisumu, Homabay, and Eldoret basin of Kenya in 2016, the concentrations of ciprofloxacin, ampicillin, amoxicillin, and chloramphenicol were indicative of their presence in the water samples (Kimosop et al., 2016). In the Nyando-Sondu-Miriu Basin in 2011 (Musa et al., 2011), persistent organic pollutants, including α-HCH, β-HCH, p,p'-DDT, and endosulfan, were reported.

In Tanzania, the Mwanza Basin in 2004 revealed significant concentrations of DDT and HCH, suggesting historical pesticide use (Kishimba et al., 2004). Notably, there have been no recent studies on organic pollutants in water samples in Tanzania, indicating a gap in current knowledge. The Simiyu Basin in 2005, also in Tanzania, displayed concentrations of endosulfan alpha, endosulfan beta, and DDT-related compounds (Nyangababo et al., 2005b). In Uganda, the Bugolobi-Nakivubo basin in 2020 contained notable concentrations of pharmaceuticals such as atenolol, carbamazepine, and sulfamethoxazole, indicating potential contamination from human activities (Dalahmeh et al., 2020). The concentrations of perfluoroalkyl substances in the same basin in 2021 further underline the need for ongoing monitoring of emerging pollutants (Arinaitwe et al., 2021). The River Sio and River Kagera basins in 2021 demonstrated concentrations of perfluoroalkyl substances, suggesting the presence of emerging contaminants in these water bodies. These findings emphasize the need for continued monitoring and assessment of organic pollutant concentrations in Lake Victoria basins to understand better the evolving environmental landscape and potential risks to ecosystems and human health. The identified substances, spanning antibiotics, pesticides, and pharmaceuticals, highlight the need for sustained monitoring, further research efforts, and the implementation of regulatory measures to mitigate potential contamination. The absence of recent studies in Uganda and Tanzania accentuates the significance of renewed research endeavors to assess the current status of organic pollutants in sediments and water in these regions.

The collaborative efforts of East African countries are crucial for monitoring and understanding the environmental implications of the deteriorating water quality of Lake Victoria, the largest freshwater lake in East Africa. This involves implementing effective management strategies to safeguard its ecological integrity. The presence of organic pollutants in both sediments and water poses a significant threat, impacting the quality of the lake's water, a crucial source for millions of people. Contaminants like PCBs, DDTs, and endosulfan can disrupt the delicate ecosystem. Emerging substances, such as pharmaceuticals, add uncertainties to long-term effects on human health. Collaborative efforts, including rigorous monitoring, research, and management, are essential due to the shared nature of Lake Victoria. Despite regular monitoring, gaps in knowledge about specific pollutants raise concerns, emphasizing the need for sustained research efforts. With support from international organizations, East African countriess can address these gaps through standardized monitoring, increased research funding, and knowledge-sharing platforms. Protecting Lake Victoria is vital amid challenges like population growth and industrialization, requiring a collective commitment to environmental stewardship for sustainable management.

### 4.4. Microplastics in Lake Victoria

Microplastics are synthetic polymer particles $\leq$ 5 mm in size, originating from various human activities and consumer products. Primary microplastics are manufactured for commercial or industrial use, such as polyethylene microbeads in cosmetics, whereas secondary microplastics result from the degradation of larger plastic debris into smaller particles. The degradation of plastic debris is caused by excessive use, mechanical abrasion, photodegradation, and oxidation of fibers from textiles, rubber fragments from tires, and paint flakes. Microplastics enter the environment through effluents, littering, landfills, and runoff, and can be found in waterbodies and sludge and even transported by winds to remote locations (D'Avignon et al., 2022). The amount of microplastics in highly polluted water bodies often exceeds the number and mass of living organisms such as zooplankton and fish larvae. The levels of microplastics are usually higher in sediments of fresh water bodies, comparable to those in heavily contaminated marine environments. No study searching for microplastics has failed to detect them, highlighting the need for standardized protocols to monitor and manage their impact (D'Avignon et al., 2022).

Microplastics in aquatic environments are of scientific concern because they are ubiquitous, environmentally persistent, and interact with critical ecological processes. Worldwide, microplastics have been identified in marine and freshwater bodies (Pan et al., 2023). A study conducted in Tanzania on the presence of microplastics in the gut of the two most important fish species in Lake Victoria revealed the presence of fragments of polyethylene, polyurethane, polyester, polyethylene/polypropylene copolymer, and silicone rubber. These are common polymer materials used in packaging, drink containers, clothing, food, insulation, and various other industrial applications (Biginagwa et al., 2016). In a related study, Egessa et al. (2020) investigated microplastics' prevalence in Lake Victoria's surface water. It was found that a large proportion of secondary microplastics of size $<$ 1 mm, mainly polythene and polypropylene, were the most dominant in the water. This category of low-density polymer fragments is easily ingested by fish and other aquatic biota, posing a significant threat to the aquatic ecosystem.

The study of microplastics in Lake Victoria is relatively new. Some of the knowledge gaps in microplastics studies include: (i) Current studies highlight the presence of various microplastics, including polyethylene, polyurethane, polyester, and polyethylene/polypropylene copolymer. However, other types and sizes may remain undetected, emphasizing the need for more extensive analyses to capture the full spectrum of microplastics present in the lake. (ii) Existing research provides snapshots of microplastic prevalence in Lake Victoria at specific points in time. Long-term studies tracking the temporal dynamics of microplastic pollution are crucial to discern patterns, changes, and potential trends over different seasons and years. (iii) While general categories of sources, such as effluents, littering, landfills, and runoff, are acknowledged, a more detailed understanding of specific sources and entry pathways is necessary. Identifying the primary contributors will facilitate targeted interventions to curb microplastic input into the lake. (iv) Although the studies recognize the threat of microplastics to aquatic biota, there is a gap in understanding the broader ecological impacts on Lake Victoria's ecosystem. Investigating how microplastics interact with different trophic levels, from zooplankton to fish, is essential for evaluating potential cascading effects on the entire food web. (v) The potential implications of microplastics on human health, mainly through consuming contaminated fish or water, remain understudied. Research focusing on the

transfer of microplastics through the food chain and assessing associated health risks is crucial for safeguarding the well-being of communities dependent on Lake Victoria. (vi) While studies mention the prevalence of microplastics in freshwater sediments, a more comprehensive analysis of sedimentary microplastics, including their distribution, composition, and potential impact on benthic environments, is needed for a holistic understanding. (vii) The call for standardized protocols in existing studies stresses the lack of consistent microplastic detection and quantification methodologies. Developing and adopting standardized monitoring protocols will enhance comparability across studies and facilitate a more cohesive assessment of microplastic pollution in Lake Victoria. (viii) Most current studies are limited to specific regions or countries within the Lake Victoria basin. Collaborative, region-wide studies involving multiple East African countries would provide a more comprehensive perspective on the spatial distribution and magnitude of microplastic pollution.

## 5. Future directions

1. Making data available to the public and research community: Lake Victoria monitoring agencies should enhance data transparency by making their information accessible to the public. This shared data is invaluable for improving predictive modeling of pollutants in the lake, especially in the context of the growing significance of Machine Learning and Deep Learning, which rely on substantial datasets for accurate modeling and prediction. Open access to such information fosters collaboration within the research community and empowers collective efforts in effectively managing and preserving the ecological health of Lake Victoria.
2. Extensive research in neglected basin areas: In-depth studies should be directed to the northwestern, western, and southwestern parts of Lake Victoria's basin, including Masaka and Bukoba Cities. With growing populations, these regions demand focused research to assess water quality, pollutant levels, and potential impacts on aquatic ecosystems and human health.
3. In-depth island studies: Advocating for dedicated studies on the islands within Lake Victoria which have been neglected for far too long tounderstand the impact of commercial agriculture, agricultural use, and fishing activities on water quality.
4. Continuous monitoring of polluted areas: Stressing the importance of frequent monitoring in polluted areas, such as Winam Gulf, Mwanza Gulf, Napoleon, Murchison, and Waiya Bays, is vital for understanding the ongoing dynamics of pollution and its effects over time. Implementing both water quality assessments and ecological monitoring in these critical areas ensures a comprehensive understanding of pollution trends, allowing for the development of targeted interventions to mitigate environmental degradation.
5. Integration of remote sensing technologies: Promoting the incorporation of advanced remote sensing technologies for continuous monitoring offers real-time and accurate data on the lake and its surroundings.
6. Collaborative regional research initiatives: Advocating for collaborative research initiatives among the three countries sharing Lake Victoria is essential for a unified approach to understanding and addressing pollution. A collaborative effort facilitates sharing of resources, knowledge, and data, leading to more effective and comprehensive solutions. Researchers can collectively contribute to conserving Lake Victoria's environmental health by fostering regional collaboration.
7. Long-term temporal trends: Extending the temporal analysis to encompass a more extended timeframe allows for a deeper understanding of long-term trends in water quality, heavy metals, microplastics, and emerging organic pollutants. This longitudinal approach enhances the ability to effectively predict and respond to environmental changes. By analyzing trends over an extended period, researchers can gain significant understanding of pollutants in Lake Victoria and its basin.
8. International cooperation: Encouraging international collaboration and knowledge exchange on freshwater management is crucial for addressing the global dimensions of environmental challenges. Partnering with neighboring countries, global ecological organizations, and research institutions facilitates the sharing of expertise, data, and resources. This collaborative, cross-border approach ensures a more holistic and globally informed strategy for Lake Victoria's environmental conservation.
9. Integration of remote sensing data: Recognizing the exclusion of water quality papers from remote sensing publications and considering it for future research is a strategic moveto better understand changes in water quality, enhancing the comprehensiveness of the analysis.
10. Targeted research in Tanzanian waters: Prioritizing pollutant research addresses a research gap and contributes to a more comprehensive understanding of environmental dynamics. Focused research initiatives and increased monitoring efforts in Tanzanian waters ensure that this region's unique characteristics and challenges are considered in future studies. This will contribute to filling identified research gaps and enhancing the overall understanding of water quality dynamics in Lake Victoria.
11. Initiation of microplastics research in untapped areas: With the current lack of research on microplastics in surface waters on the Kenyan and Tanzanian sides and few studies from the Ugandan side, future investigations should prioritize these areas. Initiating microplastics research will provide a comprehensive understanding of the distribution and impact of this emerging pollutant in diverse regions of Lake Victoria. Microplastics research in untapped areas fills knowledge gaps and enhances the understanding of the ecological impact of microplastics in the lake.
12. In-depth study of pollution hotspots: Identified pollution hotspots, like the Nakivubo Channel in Uganda, should be subject to in-depth analyses to identify the sources of exceptionally high concentrations for targeted interventions and pollution control measures.
13. Bioaccumulation studies: Investigate potential bioaccumulation of heavy metals in aquatic organisms. Understanding the transfer of heavy metals through the food chain is vital for assessing the broader ecological implications and potential risks to human health through consuming contaminated aquatic resources.
14. Comprehensive spatial surveys: Conduct extensive and systematic spatial surveys covering diverse regions within Lake Victoria. This will provide a better understanding of the spatial distribution of microplastics and other pollutants, allowing for the identification of hotspots and variations across different areas.
15. Climate change impacts**:** Future studies should explore the effects of climate change on water pollutants. Understanding how climate variations influence the lake's ecological dynamics will contribute to adaptive management strategies amid changing environmental conditions.
16. Interdisciplinary approaches: Encourage multidisciplinary collaborations tointegrate diverse expertise to understand Lake Victoria's pollutants and contaminants' interactions.

## 6. Conclusion

The study on Lake Victoria's environmental dynamics provides a comprehensive understanding of the interplay of various pollutants, including water quality parameters, heavy metals, organic pollutants, and microplastics. The findings reveal both existing knowledge and critical gaps in research across the three countries, Kenya, Tanzania, and Uganda, highlighting the need for a collaborative and proactive

approach to address environmental challenges in the region.

The temporal trends in water quality, heavy metals, and organic pollutants show the dynamic nature of Lake Victoria's ecosystem. Examining research publications from 2000 to 2022 revealed disparities in research efforts among the countries, emphasizing the urgency for renewed attention and comprehensive studies, particularly in underexplored areas and islands. The analysis of heavy metals points to spatial disparities, regulatory impacts, challenges with certain metals, and the need for continuous monitoring to ensure sustainable improvements.

The review of organic pollutants emphasizes the diverse nature of contamination, regional disparities in research efforts, and the urgent need for studies in Tanzanian waters. The identified pollutants pose risks to ecological balance and human health, necessitating ongoing monitoring. The microplastics analysis reveals widespread presence, ecological threats, and potential bioaccumulation, calling for standardized monitoring protocols, collaborative efforts, and public awareness to address these challenges.

Therefore, the study provides a foundation for future research, policy formulation, and sustainable management practices to safeguard Lake Victoria's ecological balance, water quality, and the well-being of the communities dependent on this vital freshwater resource. The interconnectedness of environmental, societal, and regulatory factors highlights the need for a holistic and adaptive approach to address Lake Victoria's evolving pollution dynamics.

We earnestly call upon the monitoring agencies overseeing Lake Victoria and its basin in Uganda, Kenya, and Tanzania to take a transformative step to work towards making their invaluable data openly accessible to the public. The significance of this initiative cannot be overstated, as shared data becomes a linchpin for advancing predictive modeling of pollutants crucial for the lake's ecological health. By embracing data transparency, these agencies will catalyze collaborative efforts within the research community and contribute significantly to Lake Victoria's sustainable management and preservation. It is a collective responsibility to ensure the longevity and well-being of this vital ecosystem for the benefit of present and future generations.

## Funding

Ivan Oyege is grateful for the funding received from the Fulbright Foreign students program Uganda.

## CRediT authorship contribution statement

**Ivan Oyege:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Richard Katwesigye:** Methodology, Investigation, Formal analysis, Data curation. **Moses Kiwanuka:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Data curation. **Hosea Eridadi Mutanda:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation. **John Bosco Niyomukiza:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation. **Dafrosa John Kataraihya:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation. **Solomon Kica:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation. **Moses Egor:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Data curation.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

## Acknowledgement

Not Applicable.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enmm.2024.100962.

## References

Aguilar-Aguilar, A., de León-Martínez, L.D., Forgionny, A., Soto, N.Y.A., Mendoza, S.R., Zárate-Guzmán, A.I., 2023. A systematic review on the current situation of emerging pollutants in Mexico: A perspective on policies, regulation, detection, and elimination in water and wastewater. Sci. Total Environ. 167426.

Akurut, M., Willems, P., Niwagaba, C.B., 2014. Assessing the influence of Lake Victoria flux on the Inner Murchison Bay water quality. Water Pollution XII 51–62.

Akurut, M., Niwagaba, C.B., Willems, P., 2017. Long-term variations of water quality in the Inner Murchison Bay, Lake Victoria. Environ. Monit. Assess. 189, 22.

Andama, M., 2012. Holocene Climate and Environmental History of Lake Victoria basin: Evidence from Geochemical Proxies. Quat. Int. 279–280, 18.

Arinaitwe, K., Kiremire, B.T., Muir, D.C.G., Fellin, P., Li, H., Teixeira, C., et al., 2016. Legacy and currently used pesticides in the atmospheric environment of Lake Victoria, East Africa. Sci. Total Environ. 543, 9–18.

Arinaitwe, K., Keltsch, N., Taabu-Munyaho, A., Reemtsma, T., Berger, U., 2021. Perfluoroalkyl substances (PFASs) in the Ugandan waters of Lake Victoria: Spatial distribution, catchment release and public exposure risk via municipal water consumption. Sci. Total Environ. 783, 146970.

Baguma, G., Musasizi, A., Twinomuhwezi, H., Gonzaga, A., Nakiguli, C.K., Onen, P., et al., 2022. Heavy Metal Contamination of Sediments from an Exoreic African Great Lakes' Shores (Port Bell, Lake Victoria), Uganda. Pollutants 2, 407–421.

Bavor HJ, Waters MT. Pollutant transformation performance and model development in African wetland systems: large catchment extrapolation. Wastewater Treatment, Plant Dynamics and Management in Constructed and Natural Wetlands 2008: 319-327.

Biginagwa, F.J., Mayoma, B.S., Shashoua, Y., Syberg, K., Khan, F.R., 2016. First evidence of microplastics in the African Great Lakes: Recovery from Lake Victoria Nile perch and Nile tilapia. J. Great Lakes Res. 42, 146–149.

Britannica, 2023. The Editors of Encyclopaedia. "Lake Victoria". Encyclopedia Britannica.

Campbell, L., Dixon, D.G., Hecky, R.E., 2003. A review of mercury in Lake Victoria, East Africa: implications for human and ecosystem health. J. Toxicol. Environ. Health B Crit. Rev. 6, 325–356.

Chakraborty, A., Adhikary, S., Bhattacharya, S., Dutta, S., Chatterjee, S., Banerjee, D., et al., 2023. Pharmaceuticals and Personal Care Products as Emerging Environmental Contaminants: Prevalence, Toxicity, and Remedial Approaches. ACS Chemical Health & Safety 30, 362–388.

D'Avignon, G., Gregory-Eaves, I., Ricciardi, A., 2022. Microplastics in lakes and rivers: an issue of emerging significance to limnology. Environ. Rev. 30, 228–244.

Dalahmeh, S., Bjornberg, E., Elenstrom, A.K., Niwagaba, C.B., Komakech, A.J., 2020. Pharmaceutical pollution of water resources in Nakivubo wetlands and Lake Victoria, Kampala. Uganda. Sci Total Environ 710, 136347.

Diamanti-Kandarakis, E., Bourguignon, J.P., Giudice, L.C., Hauser, R., Prins, G.S., Soto, A.M., et al., 2009. Endocrine-disrupting chemicals: an Endocrine Society scientific statement. Endocr. Rev. 30, 293–342.

Egessa, R., Nankabirwa, A., Ocaya, H., Pabire, W.G., 2020. Microplastic pollution in surface water of Lake Victoria. Sci. Total Environ. 741, 140201.

Fuhrimann, S., Stalder, M., Winkler, M.S., Niwagaba, C.B., Babu, M., Masaba, G., et al., 2015. Microbial and chemical contamination of water, sediment and soil in the Nakivubo wetland area in Kampala. Uganda. Environmental Monitoring and Assessment 187, 1–15.

Gikuma-Njuru, P., Guildford, S.J., Hecky, R.E., Kling, H.J., 2013. Strong spatial differentiation of N and P deficiency, primary productivity and community composition between Nyanza Gulf and Lake Victoria (Kenya, East Africa) and the implications for nutrient management. Freshw. Biol. n/a-n/a.

Jovanelly, T.J., Johnson-Pynn, J., Okot-Okumu, J., Nyenje, R., Namaganda, E., 2015. Pioneering water quality data on the Lake Victoria watershed: effects on human health. J. Water Health 13, 920–930.

Juma, D.W., Wang, H., Li, F., 2014. Impacts of population growth and economic development on water quality of a lake: Case study of Lake Victoria Kenya water. Environ. Sci. Pollut. Res. 21, 5737–5746.

Kabenge, M., Wang, H., Li, F., 2016. Urban eutrophication and its spurring conditions in the Murchison Bay of Lake Victoria. Environ. Sci. Pollut. Res. 23, 234–241.

Kandie, F.J., Krauss, M., Beckers, L.M., Massei, R., Fillinger, U., Becker, J., et al., 2020a. Occurrence and risk assessment of organic micropollutants in freshwater systems within the Lake Victoria South Basin. Kenya. Sci Total Environ 714, 136748.

Kandie, F.J., Krauss, M., Massei, R., Ganatra, A., Fillinger, U., Becker, J., et al., 2020b. Multi-compartment chemical characterization and risk assessment of chemicals of

emerging concern in freshwater systems of western Kenya. Environ. Sci. Eur. 32, 1–12.
Kang, T.W., Yang, H.J., Han, J.H., Han, Y.U., Kim, M.S., Kim, J., et al., 2022. Identifying pollution sources of sediment in Lake Jangseong, Republic of Korea, through an extensive survey: Internal disturbances of past aquaculture sedimentation. Environ. Pollut. 306, 119403.
Kimosop, S.J., Getenga, Z.M., Orata, F., Okello, V.A., Cheruiyot, J.K., 2016. Residue levels and discharge loads of antibiotics in wastewater treatment plants (WWTPs), hospital lagoons, and rivers within Lake Victoria Basin, Kenya. Environ. Monit. Assess. 188, 532.
Kishimba, M.A., Henry, L., Mwevura, H., Mmochi, A.J., Mihale, M., Hellar, H., 2004. The status of pesticide pollution in Tanzania. Talanta 64, 48–53.
Lindenschmidt, K.-E., Suhr, M., Magumba, M., Hecky, R., Bugenyi, F., 1998. Loading of solute and suspended solids from rural catchment areas flowing into Lake Victoria in Uganda. Water Res. 32, 2776–2786.
Lujjimbirwa, F., Odoki, M., 2023. Pathogenic bacteria in lake Victoria shore water at Kasenyi landing site in Entebbe municipality, Uganda: a cross-sectional pilot survey on occurrence profiles and associated factors. Student's Journal of Health Research Africa 4, 10.
Makaka, R., Misi, S.N., Masocha, M., Kimwaga, R.J., 2022. Spatial and Temporal Variation of Selected Water Quality Parameters in the Tanzanian Side of Lake Victoria. Tanzania Journal of. Eng. Technol. 40.
Marriott, A.L., Osano, O.F., Coffey, T.J., Humphrey, O.S., Ongore, C.O., Watts, M.J., et al., 2023. Considerations for environmental biogeochemistry and food security for aquaculture around Lake Victoria, Kenya. Environmental Geochemistry and Health 45, 6137–6162.
Mbabazi, J., Kwetegyeka, J., Ntale, M., Wasswa, J., 2010a. Ineffectiveness of Nakivubo wetland in filtering out heavy metals from untreated Kampala urban effluent prior to discharge into Lake Victoria. Uganda. African Journal of Agricultural Research 5, 3431–3439.
Mbabazi, J., Twinomuhwezi, H., Wasswa, J., Ntale, M., Mulongo, G., Kwetegyeka, J., et al., 2010b. Speciation of heavy metals in water from the Uganda side of Lake Victoria. Int. J. Environ. Stud. 67, 9–15.
Miruka, J.B., Getabu, A., Sitoki, L., James, O., Mwamburi, J., George, O., et al., 2021. Water quality, phytoplankton composition and microcystin concentrations in Kisumu Bay (Kenya) of Lake Victoria after a prolonged water hyacinth infestation period. Lakes Reserv. Res. Manag. 26, e12380.
Musa, S., Gichuki, J.W., Raburu, P.O., Aura, C.M., 2011. Risk assessment for organochlorines and organophosphates pesticide residues in water and Sediments from lower Nyando/Sondu-Miriu river within Lake Victoria Basin, Kenya. Lakes Reserv. Res. Manag. 16, 273–280.
Muwanga, A., Barifaijo, E., 2006. Impact of industrial activities on heavy metal loading and their physico-chemical effects on wetlands of Lake Victoria basin (Uganda). Afr. J. Sci. Technol. 7.
Mwamburi, J., 2009. Trace metal concentration in water and sediments of satellite lakes within Lake Victoria (Kenya) basin. Lakes Reserv. Res. Manag. 14, 203–220.
Mwamburi, J., Basweti, G., Owili, M., Babu, J., Wawiye, P., 2020. Spatio-temporal trends of nutrients and physico-chemical parameters on lake ecosystem and fisheries prior to onset of cage farming and re-opening of the Mbita passage in the Nyanza Gulf of Lake Victoria. Lakes Reserv. Res. Manag. 25, 292–313.
Nantaba, F., Wasswa, J., Kylin, H., Palm, W.U., Bouwman, H., Kummerer, K., 2020. Occurrence, distribution, and ecotoxicological risk assessment of selected pharmaceutical compounds in water from Lake Victoria. Uganda. Chemosphere 239, 124642.
Nantaba, F., Palm, W.U., Wasswa, J., Bouwman, H., Kylin, H., Kummerer, K., 2021. Temporal dynamics and ecotoxicological risk assessment of personal care products, phthalate ester plasticizers, and organophosphorus flame retardants in water from Lake Victoria. Uganda. Chemosphere 262, 127716.
Newton, A., Icely, J., Cristina, S., Perillo, G.M.E., Turner, R.E., Ashan, D., et al., 2020. Anthropogenic, Direct Pressures on Coastal Wetlands. Front. Ecol. Evol. 8.
Nicholson, H., 2021. Investigation of microplastics in the tilapia found in Lake Victoria. University of Nottingham, Kenya.
Njagi, D.M., Routh, J., Odhiambo, M., Luo, C., Basapuram, L.G., Olago, D., et al., 2022. A century of human-induced environmental changes and the combined roles of nutrients and land use in Lake Victoria catchment on eutrophication. Sci. Total Environ. 835, 155425.
Nyairo, W.N., Owuor, P.O., Kengara, F.O., 2015. Effect of anthropogenic activities on the water quality of Amala and Nyangores tributaries of River Mara in Kenya. Environ. Monit. Assess. 187, 691.
Nyamweya, C., Lawrence, T.J., Ajode, M.Z., Smith, S., Achieng, A.O., Barasa, J.E., et al., 2023. Lake Victoria: Overview of research needs and the way forward. J. Great Lakes Res. 49, 102211.
Nyangababo, J., Henry, L., Omutange, E., 2005a. Heavy metal contamination in plants, sediments, and air precipitation of katonga, simiyu, and nyando wetlands of Lake Victoria basin, East Africa. Bull. Environ. Contam. Toxicol. 75, 189–196.
Nyangababo, J., Henry, L., Omutange, E., 2005b. Organochlorine pesticide contamination in surface water, sediment, and air precipitation of Lake Victoria Basin, East Africa. Bull. Environ. Contam. Toxicol. 75, 960–967.
Nyangababo, J.T., Henry, L., Omutange, E., 2005c. Lead, Cadmium, Copper, Manganese, and Zinc in Wetland Waters of Victoria Lake Basin, East Africa. Bull. Environ. Contam. Toxicol. 74, 1003–1010.
Nyilitya, B., Mureithi, S., Boeckx, P., 2020. Land use controls Kenyan riverine nitrate discharge into Lake Victoria–evidence from Nyando, Nzoia and Sondu Miriu river catchments. Isot. Environ. Health Stud. 56, 170–192.
Nyilitya, B., Mureithi, S., Bauters, M., Boeckx, P., 2021. Nitrate source apportionment in the complex Nyando tropical river basin in Kenya. J. Hydrol. 594.
Ogoyi, D.O., Mwita, C., Nguu, E.K., Shiundu, P.M., 2011. Determination of heavy metal content in water, sediment and microalgae from Lake Victoria, East. Africa.
Oguttu, H., Bugenyi, F.W., Leuenberger, H., Wolf, M., Bachofen, R., 2008. Pollution menacing Lake Victoria: quantification of point sources around Jinja Town. Uganda. Water Sa 34, 89–98.
Okello, C., Tomasello, B., Greggio, N., Wambiji, N., Antonellini, M., 2015. Impact of Population Growth and Climate Change on the Freshwater Resources of Lamu Island. Kenya. Water 7, 1264–1290.
Okoye, C.O., Okeke, E.S., Okoye, K.C., Echude, D., Andong, F.A., Chukwudozie, K.I., et al., 2022. Occurrence and fate of pharmaceuticals, personal care products (PPCPs) and pesticides in African water systems: A need for timely intervention. Heliyon 8, e09143.
Olokotum, M., Humbert, J.-F., Quiblier, C., Okello, W., Semyalo, R., Troussellier, M., et al., 2022. Characterization of Potential Threats from Cyanobacterial Toxins in Lake Victoria Embayments and during Water Treatment. Toxins 14, 664.
Oluoch-Otiego, J., Oyoo-Okoth, E., Kiptoo, K.K.G., Chemoiwa, E.J., Ngugi, C.C., Simiyu, G., et al., 2016. PCBs in fish and their cestode parasites in Lake Victoria. Environ. Monit. Assess. 188, 1–11.
Omwoma, S., Lalah, J.O., Virani, M., Schramm, K.W., Henkelmann, B., 2015. Dioxin-like PCBs and PCDD/Fs in surface sediments near the shore of Winam Gulf. Lake Victoria. Chemosphere 118, 143–147.
Ondhoro, C.C., Masembe, C., Maes, G.E., Nkalubo, N.W., Walakira, J.K., Naluwairo, J., et al., 2016. Condition factor, Length – Weight relationship, and the fishery of Barbus altianalis (Boulenger 1900) in Lakes Victoria and Edward basins of Uganda. Environ. Biol. Fishes 100, 99–110.
Onyando, Z.O., Omukunda, E., Okoth, P., Khatiebi, S., Omwoma, S., Otieno, P., et al., 2023. Screening and Prioritization of Pesticide Application for Potential Human Health and Environmental Risks in Largescale Farms in Western Kenya. Agriculture 13, 1178.
Oremo, J., Orata, F., Owino, J., Shivoga, W., 2019. Assessment of heavy metals in benthic macroinvertebrates, water and sediments in River Isiukhu, Kenya. Environ. Monit. Assess. 191, 646.
Oryiema, R., 2022. Arima Model for Forecasting of Monthly Rainfall and Temperature in the Lake Victoria Basin. Asian Journal of Probability and Statistics 17, 12–22.
Ouma, S., Ngeranwa, J., Juma, K., Mburu, D., 2016. Seasonal variation of the physicochemical and bacteriological quality of water from five rural catchment areas of lake victoria basin in Kenya. Journal of Environmental Analytical Chemistry 3, 2.
Outa, J.O., Kowenje, C.O., Plessl, C., Jirsa, F., 2020. Distribution of arsenic, silver, cadmium, lead and other trace elements in water, sediment and macrophytes in the Kenyan part of Lake Victoria: spatial, temporal and bioindicative aspects. Environ. Sci. Pollut. Res. 27, 1485–1498.
Owens, P.N., 2020. Soil erosion and sediment dynamics in the Anthropocene: a review of human impacts during a period of rapid global environmental change. J. Soil. Sediment. 20, 4115–4143.
Page, M.J., McKenzie, J.E., Bossuyt, P.M., Boutron, I., Hoffmann, T.C., Mulrow, C.D., et al., 2021. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. Int. J. Surg. 88, 105906.
Pan, T., Liao, H., Yang, F., Sun, F., Guo, Y., Yang, H., et al., 2023. Review of microplastics in lakes: sources, distribution characteristics, and environmental effects. Carbon Research 2.
Pavur, G., Lakshmi, V., 2023. Observing the recent floods and drought in the Lake Victoria Basin using Earth observations and hydrological anomalies. J. Hydrol.: Reg. Stud. 46, 101347.
Ramlal, P.S., Bugenyi, F.W., Kling, G.W., Nriagu, J.O., Rudd, J.W., Campbell, L.M., 2003. Mercury concentrations in water, sediment, and biota from Lake Victoria, East Africa. J. Great Lakes Res. 29, 283–291.
Ribbe, N., Arinaitwe, K., Dadi, T., Friese, K., von Tümpling, W., 2021. Trace-element behaviour in sediments of Ugandan part of Lake Victoria: results from sequential extraction and chemometrical evaluation. Environ. Earth Sci. 80, 323.
Sabo, S., Vukmirović, S., Sudi, J., Juriš, P., Tomić, Z., Bjelović, S., et al., 2021. Pesticide and Toxic Metal Pollution in Waters, Fish and Wild Animals in Vojvodina. Serbia. Sustainability 13, 9809.
Sene, K., Houghton Carr, H., Tych, W., 2021. Reflections on almost a century of hydrological studies on Africa's largest lake. Proc. IAHS 384, 141–147.
Shayo, S.D., Lugomela, C., Machiwa, J.F., 2011. Influence of land use patterns on some limnological characteristics in the south-eastern part of Lake Victoria, Tanzania. Aquatic Ecosystem Health & Management 14, 246–251.
Shen, Q., Friese, K., Gao, Q., Kimirei, I.A., Kishe, M.A., Chen, C., et al., 2022. Accumulation characteristics and ecological implications of heavy metals in surface sediments of the Mwanza Gulf, Lake Victoria. Environmental Monitoring and Assessment 194, 756.
Sitoki, L., Kofler, W., Rott, E., 2013. Planktonic needle-shapedNitzschiaspecies from Lake Victoria, Africa, revisited. Diatom Res. 28, 165–174.
Ssanyu GA, Kiwanuka M, Lunkuse I, Mutekanga NM. Community perception of heavy metal pollution and related risks in Lake Victoria Wetlands, Uganda. 2023.
Ssebugere, P., Kiremire, B.T., Henkelmann, B., Bernhoft, S., Kasozi, G.N., Wasswa, J., et al., 2013a. PCDD/Fs and dioxin-like PCBs in fish species from Lake Victoria, East Africa. Chemosphere 92, 317–321.
Ssebugere, P., Kiremire, B.T., Henkelmann, B., Bernhoft, S., Wasswa, J., Kasozi, G.N., et al., 2013b. PCDD/Fs and dioxin-like PCBs in surface sediments from Lake Victoria, East Africa. Sci. Total Environ. 454–455, 528–533.
Ssebugere, P., Sillanpaa, M., Kiremire, B.T., Kasozi, G.N., Wang, P., Sojinu, S.O., et al., 2014a. Polychlorinated biphenyls and hexachlorocyclohexanes in sediments and fish species from the Napoleon Gulf of Lake Victoria, Uganda. Sci. Total Environ. 481, 55–60.

Ssebugere, P., Sillanpaa, M., Wang, P., Li, Y., Kiremire, B.T., Kasozi, G.N., et al., 2014b. Polychlorinated biphenyls in sediments and fish species from the Murchison Bay of Lake Victoria, Uganda. Sci. Total Environ. 482–483, 349–357.
Tazaki, K., Asada, R., 2007. Transmission electron microscopic observation of mercury-bearing bacterial clay minerals in a small-scale gold mine in Tanzania. Geomicrobiol J. 24, 477–489.
Vanderkelen, I., van Lipzig, N.P.M., Thiery, W., 2018. Modelling the water balance of Lake Victoria (East Africa) – Part 2: Future projections. Hydrol. Earth Syst. Sci. 22, 5527–5549.
Vincent, K., Mwebaza-Ndawula, L., Makanga, B., Nachuha, S., 2012. Variations in zooplankton community structure and water quality conditions in three habitat types in northern Lake Victoria. Lakes Reserv. Res. Manag. 17, 83–95.
Virts, K.S., Goodman, S.J., 2020. Prolific Lightning and Thunderstorm Initiation over the Lake Victoria Basin in East Africa. Mon. Weather Rev. 148, 1971–1985.
Wang, H., Wang, T., Toure, B., Li, F., 2012. Protect Lake Victoria through green economy, public participation and good governance. Environ. Sci. Tech. 46, 10483–10484.
Wasswa, J., Kiremire, B.T., Nkedi-Kizza, P., Mbabazi, J., Ssebugere, P., 2011. Organochlorine pesticide residues in sediments from the Uganda side of Lake Victoria. Chemosphere 82, 130–136.
WHO. Guidelines on sanitation and health. In World Health Organization. 2018.
Zhao, Z., Yao, X., Ding, Q., Gong, X., Wang, J., Tahir, S., et al., 2022. A comprehensive evaluation of organic micropollutants (OMPs) pollution and prioritization in equatorial lakes from mainland Tanzania, East Africa. Water Res. 217, 118400.