# Lacustrine Cyanobacteria, Algal Blooms and Cyanotoxins in East Africa: Implications for Human and Ecological Health Protection

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**Abstract:** Advected cyanobacteria, algal blooms and cyanotoxins have been increasingly detected in freshwater ecosystems. This review gives an insight into the present state of knowledge on the taxonomy, dynamics, toxic effects, human and ecological health implications of cyanobacteria, algal blooms and cyanotoxins in the East African Community lakes. The major toxigenic microalgae in East African lakes include *Microcystis*, *Arthrospira*, *Dolichospermum*, *Planktolyngbya* and *Anabaenopsis* species. Anatoxin-a, homoanatoxin-a, microcystins (MCs), cylindrospermopsin and nodularin have been quantified in water from below method detection limits to 81 µg L$^{-1}$, with peak concentrations characteristically reported for the wet season. In whole fish, gut, liver and muscles, MCs have been found at concentrations of 2.4 to 1479.24 µg kg$^{-1}$, which can pose human health risks to a daily consumer. While there have been no reported cases of cyanotoxin-related poisoning in humans, MCs and anatoxin-a (up to 0.0514 µg kg$^{-1}$) have been identified as the proximal cause of indiscriminate fish kills and epornitic mortality of algivorous *Phoeniconaias minor* (lesser flamingos). With the unequivocal increase in climate change and variability, algal blooms and cyanotoxins will increase in frequency and severity, and this will necessitate swift action towards the mitigation of nutrient-rich pollutants loading into lakes in the region.

**Keywords:** *Arthrospira fusiformis*; cylindrospermopsin; hepatotoxicity; lesser flamingos; Lake Victoria; microcystins; *Microcystis*; nodularins

## 1. Introduction

Industrialization has been the key driver of economic growth and inclusive prosperity because it does not only foster economic and infrastructural development, but also enhances the realization of some vital targets enshrined in the 2015–2030 Sustainable Development Goals [1,2]. This is evident from the employment opportunities it creates, improved working conditions, optimal resource use [3] and the innovations that have led to nascent and environmentally benign (greener) production technologies [4,5]. Despite this, there are various environmental challenges that have been associated with industrialization. One of

the most pronounced concerns has been the occurrence of cyanobacteria (CYB), harmful algal blooms (CYBHAB) and cyanotoxins (phycotoxins) in aquatic ecosystems, attributed to anthropogenic pollution and accelerated climate change [6].

Algal blooms were initially not considered to be harmful because they largely occurred in summer or typically dry months [7]. Lately, rising temperatures have doubled or tripled algal bloom incidences in coastal countries [7]. At present, CYBHAB are at the forefront of toxicological research because of the negative effects that they can exert on both ecosystems and humans. Cyanobacterial phytoplankton blooms are contextualized "*as noticeable, CYB-HAB with appreciable effects, including scum formation, marked discoloration of surface waters as well as fish, human, or other invertebrate mortalities*" [8]. In other words, CYBHAB occur when algal densities surpass baseline population levels. More than 5000 species of microalgae are classified, but only 300 species (or less) may induce algal blooms that are toxic [9]. Despite the spontaneous occurrence of various microalgae in bloom conditions, CYB or blue-green algae are of primary concern because they can produce toxic metabolites (cyanotoxins). Cyanotoxins are mostly produced by CYB, dinoflagellates and benthic diatoms from genera *Dolichospermum, Microcystis, Arthrospira, Anabaenopsis, Alexandrium, Protogonyaulax, Gymnodinium, Dinophysis, Gonyaulax, Prorocentrum, Pseudonitzschia* and *Pyrodinium* [10].

CYBHAB is a globally recognized phenomenon, and several incidences have been reported in more than 25 countries, including India, Italy, Germany, Netherlands, Sweden, Greece, USA, China, Madagascar, Algeria, Ghana, Ethiopia, Zimbabwe, Botswana, Egypt, Cameroon, Mozambique, Uganda, Sudan, Kenya, Senegal, Burkina Faso, Lesotho, Morocco, Nigeria, South Africa, Tanzania and Tunisia [7]. It is believed that the incidences of CYBHAB and algal toxins production will continue to increase dramatically, plausibly due to anthropogenic nutrient loading and global warming with its impact on the vertical stratification of lakes [11,12]. Despite the central body of knowledge that CYBHAB tend to be recurrent in high nutrient-load water resources, there is accumulating evidence that blooms also occur in oligotrophic ecosystems [11]. Moreover, strong re-oligotrophication (that increases light in the metalimnion) may favor CYBHAB where metalimnetic bloom-forming CYB are present [11]. The high-nutrient paradigm as the major driver of CYBHAB is also challenged [12], because CYB have undergone adaptations so that they can thrive even under the harshest environmental conditions.

The East African Community (hereafter EAC), comprising seven sovereign states (Democratic Republic of Congo, Burundi, South Sudan, Rwanda, Tanzania, Uganda and Kenya), is bountifully blessed with water resources (Figure 1). The region's water demands are, to a greater extent, fulfilled by eutrophic water bodies, which, regrettably, have been under intense land use charges and pollution pressure, and this could lead to increased incidences of CYB and CYBHAB [13–15]. The close proximity between human settlements, industries, cities, ports and most water bodies [16] lead to the recognition that CYBHAB may be a common occurrence. To this end, various event-driven studies in the region have been undertaken on the phytoplankton composition, occurrence of CYB and cyanotoxins in lacustrine ecosystems. Three reviews in regional and continental contexts have been published on CYB and cyanotoxins, with the EAC in focus. The first of its kind was by Ndlela et al. [7], who gave an overview of CYBHAB incidences and the research strides in Africa. Later, Kimambo et al. [17] synthesized data pertaining to the presence of CYBHAB in inland aquatic ecosystems of the United Republic of Tanzania, and the linkages with the country's climatic conditions. The latest collation by Olokotum et al. [14] examined the socioecological causes and consequences of CYBHAB in Lake Victoria (L. Victoria), the largest lentic water resource in the EAC. With the inclusion of the Democratic Republic of Congo (DRC) into the EAC in 2022, more knowledge on CYB, CYBHAB and cyanotoxins could be revealed as it shares some lakes with Rwanda (Lake Kivu), Uganda (Lake Albert and Lake Edward) and Tanzania (Lake Tanganyika). We built on the foregoing reviews to examine the current understanding of the taxonomy, algal bloom dynamics, toxicity, human and ecological health implications of CYB, CYBHAB and algal toxins in the EAC.

Cyanotoxins are still considered to be contaminants of emerging concern, because their toxicity mechanisms and effects on humans and ecosystems are not fully understood [10].
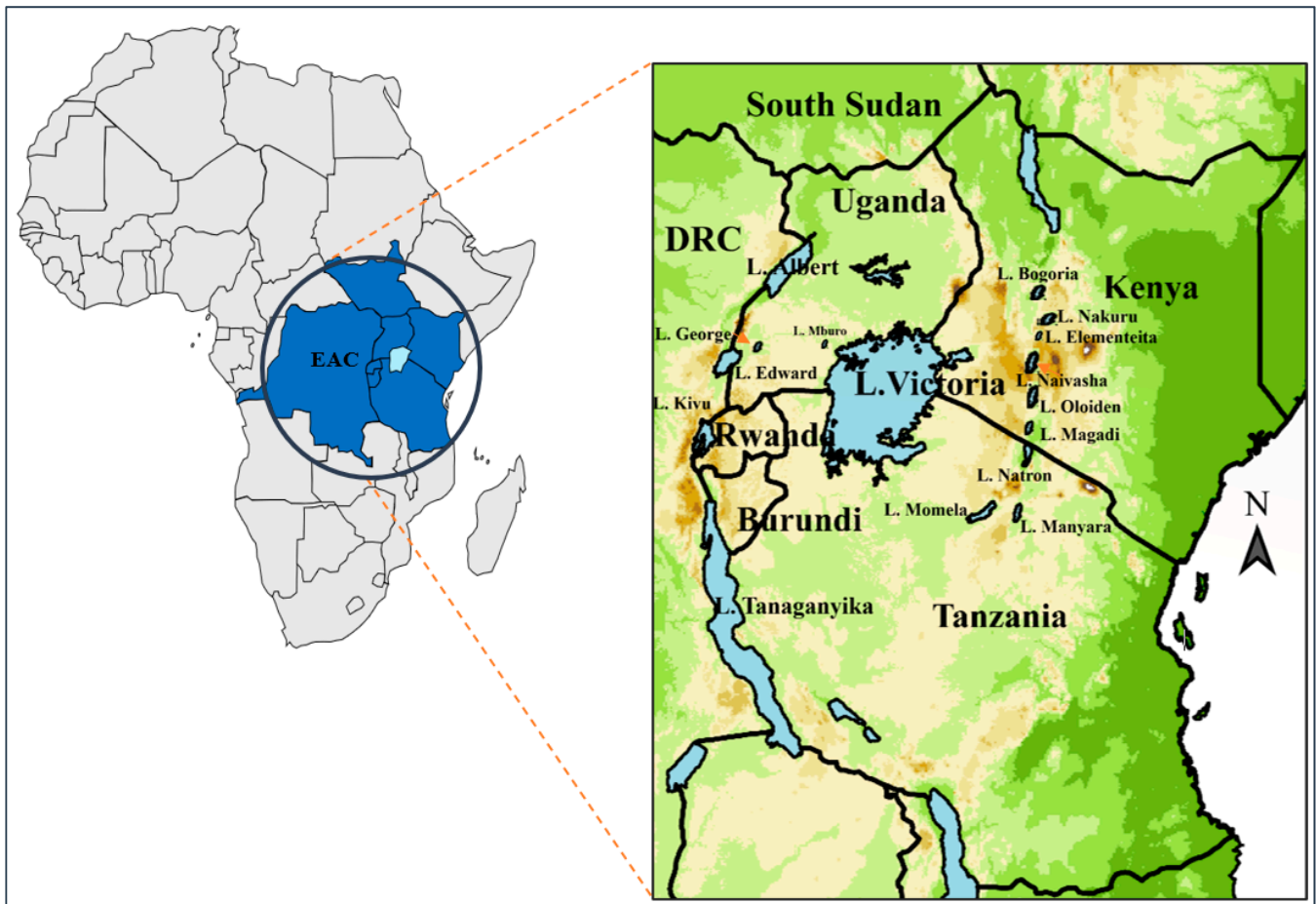


**Figure 1.** Map of East African Community (EAC) showing the partner states and location of lakes with reports of cyanobacteria, algal blooms, cyanotoxins, indiscriminate fish deaths and mass mortalities of lesser flamingos. Adapted from Ayugi et al. [18].

## 2. Materials and Methods

Electronic search on the occurrence of CYB, algal blooms and cyanotoxins in EAC lakes were performed in Web of Science Core Collection®, Scopus®, Science Direct, Google Scholar®, Springer Link, Taylor and Francis Online, Scientific Electronic Library Online, PubMed, Google search engine and EAC university repositories from August 2022 to December 2022. The specific search terms used were cyanobacteria, blue-green algae, algal bloom, cyanobacterial bloom, harmful algal bloom, CyanoHABs, HABs, microcystins, saxitoxin, anatoxin, cylindrospermopsin, nodularin, brackish water and the specific names of the EAC partner states or major lakes such as Lake Victoria, Lake Tanganyika, Lake Kivu, Lake Naivasha and Lake Nakuru. Reports from websites of all Nile basin organizations were searched. The review considered articles dated until December 2022.

### 3. Occurrence of Cyanobacteria, Algal Blooms and Phycotoxins in EAC Lakes

Toxic and non-toxic CYB are photosynthetic prokaryotes that occur naturally in terrestrial as well as aquatic ecosystems [10]. They are typically larger than normal bacterial cells, and their inherent mass production of phycobilin pigment confers upon them a bluish tint at high concentrations, hence their naming as blue-green algae [7]. They are Gram-negative bacteria that may be filamentous, unicellular or multicellular (occuring as colonies), contingent on the prevailing conditions. Under suitable environmental conditions that afford competitive advantages (e.g., alkaline pH, buoyancy, high sunlight-for conversion of ferric ion to ferrous ion, moderate temperature, i.e., 20 °C to 30 °C (10 °C in winter for *Planktothrix rubescens*), nutrients phosphorous and nitrogen, and water column stability), CYB are capable of proliferating and forming CYBHAB or scums in the upper sunlit layers. Such unsightly scums and blooms contain malodorous compounds such as geosmin and methylisoborneol, which are responsible for the aesthetically unpleasant taste of CYB-contaminated water. While the biology and ecology of CYB has been a subject of intensive research globally, there is a paucity of clearly articulated information regarding factors and processes that regulate toxin production in most cyanobacterial species [12]. In lentic freshwater resources (such as L. Victoria, Lake Tanganyika and Lake Kivu in the EAC), the occurrence of CYB is favored by climate variability, anthropogenic activities, hydrological shifts and high nutrient loads [19]. In part (for Ugandan lakes such as Mburo and Kachera), loading is from influx of nutrient-rich hippopotamus and cattle dung wastes [20].

Cyanobacteria are usually associated with the production of nocive cyanotoxins. The great diversity and high metabolic potential of CYB implies that there are other unknown or at least little studied cyanotoxins. According to CyanoMetDB (a comprehensive database of cyano-metabolites), at least 2000 molecules, including more than 300 microcystin congeners, are already known [21]. Cyanotoxins are contaminants of emerging concern that are potentially (eco)toxic. They can adversely impact ecosystem services provided by water resources by depleting oxygen, altering food webs, species assemblages and poisoning animals and humans [22]. Examples of cyanotoxins include cyclic hepatotoxic peptides (microcystins, nodularins), dermatoxic, cytotoxic, genotoxic or neurotoxic alkaloids, polyketides and amino acids (lyngbyatoxin-a, cylindrospermopsins, anatoxins, saxitoxins, aetokthonotoxin, lipopolysaccharides (endotoxins), guanitoxin, beta-*N*-methylamino-L-alanine and aplysiatoxins) [22].

The frequently encountered cyanotoxins are anatoxins, cylindrospermopsin (CYN), nodularins (NODs), saxitoxin, and microcystins (MCs), but the most-studied members are MCs (the -LR variant). Thus, in addition to anatoxin-a (ATX), they are the main cyanotoxins that garnered early scientific interest in Eastern Africa (Figure 2). In the EAC, toxigenic freshwater CYB and CYBHAB have been implicated in the reoccurrence of eutrophic and hypoxic conditions in L. Victoria [14,23–27]. Table S1 shows a summary of reports on the occurrence and abundance of CYB and other phytoplankton, their dominant species and MCs in EAC lakes. These are discussed per country in the following.
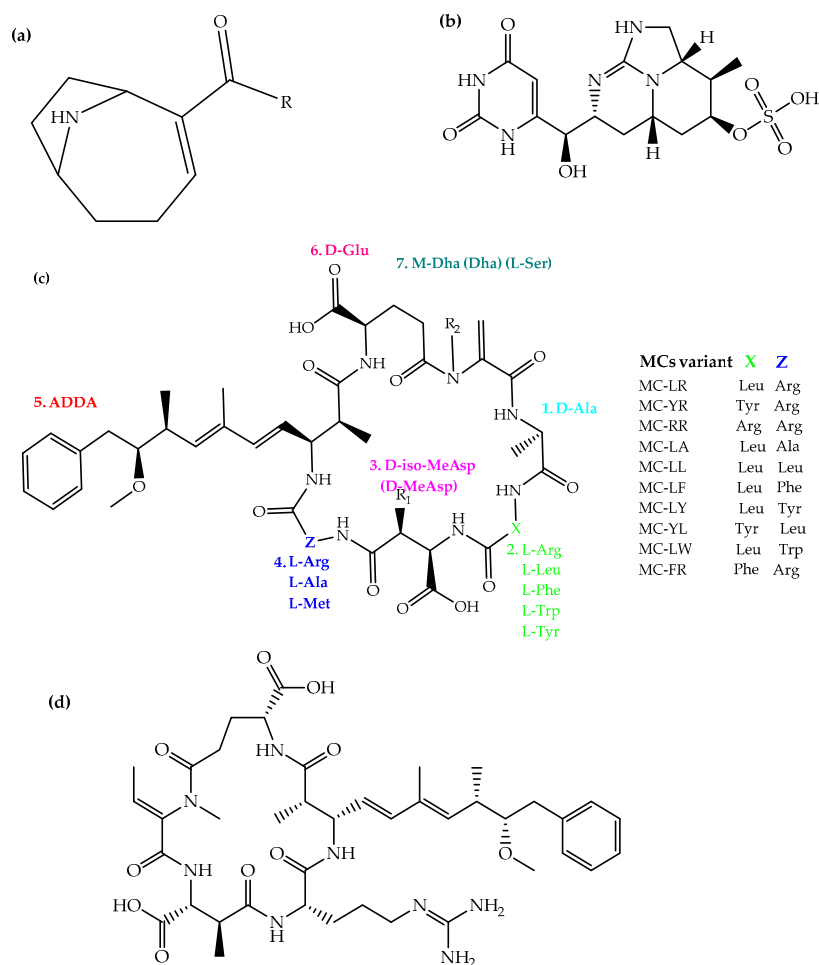
**Figure 2.** Chemical structure of some of the phycotoxins reported in East African Community lakes: (**a**) ATX and HATX (R = $CH_3$ and $C_2H_5$, respectively); (**b**) cylindrospermopsin; (**c**) microcystins: 1 to 7 are amino acid residues; congeners (variants) with different combinations of amino acids are shown; (**d**) nodularins.

### 3.1. DRC

In the Congolese part of the oligotrophic Lake Tanganyika, the occurrence of CYB (*Dolichospermum flosaquae*, *Anabaenopsis* species and *Limnococcus limneticus*), along with *Nitzschia asterionelloides* (Bacillariophyta), has been reported [28,29]. These diazotrophic CYB were implicated in the CYBHAB witnessed in 1955 and 2018, but cyanotoxin concentrations of water sampled from the lake have not been established.

Another unique lake in DRC is Lake Kivu, a deep oligotrophic and meromictic water resource. Though it contains copious volumes of exploitable methane, CYB (*Synechococcus* species and *Planktolyngbya limnetica*) dominate the phytoplankton biomass in this lake, followed by pennate diatoms (*Nitzschia bacata* and *Fragilaria danica*) [30,31]. These reports resonate well with that of Hecky and Kling [32], who showed that CYB and chlorophytes (with biomass contents that are higher than in the neighboring Lake Tanganyika) dominated in Lake Kivu. Their report, however, pointed to the presence of additional CYB *Lyngbya circumcreta* West, *Anabaenopsis*, *Cylindrospermopsis* and *Raphidiopsis* species. Sarmento et al. [33] found a strikingly contradicting result, with pennate diatoms being more abundant than CYB in Lake Kivu. Nevertheless, picocyanobacterial *Synechococcus* species was found to still form a significant proportion of the annual autotrophic plankton of the lake [34]. Further, *Urosolenia* and *Microcystis* genera are dominant holopelagic species under certain stratification scenarios [33]. The dominance of diatoms in Lake Kivu thus seems to occur solely during dryer periods, when deep mixing occurs [35].

### 3.2. Kenya

With regard to cyanotoxins, one of the groundbreaking reports was by Ballot et al. [36] who found intracellular ATX (0.3 to 9 and 5 to 223 µg g$^{-1}$ dry weight (DW)) and MCs (16 to 155, and 130 to 4593 µg MC-LR eq. g$^{-1}$) in seston samples from Lake Bogoria and Lake Nakuru. Interestingly, phycotoxins were not detected (UDT) in Lake Elmenteita cyanobacterial samples. Later, MCs (2.2 µg MC-YR g$^{-1}$ DW) and ATX (0.3 µg g$^{-1}$ DW) were traced in axenic *Arthrospira fusiformis* (*A. fusiformis*) from Lake Sonachi, though the same species along with *Anabaenopsis* species from Lake Simbi had no detectable phycotoxins [37]. The authors similarly found cyanotoxins at concentrations of 1.6 to 12.0 µg MC-YR g$^{-1}$ DW (in Lake Sonachi) and 19.7 to 39.0 µg MC-YR g$^{-1}$ DW (in Lake Simbi) for MCs, and 0.5 to 2.0 and UDT to 1.4 µg g$^{-1}$ DW for ATX, respectively. Kotut et al. [38] similarly reported MCs (2.2 and 15.02 µg g$^{-1}$ DW) in *A. fusiformis* (synonym: *Spirulina fusiformis*) growing in Lakes: Sonachi and Bogoria. ATX occurred at levels of 0.3 to 10.38 µg g$^{-1}$ DW in *A. fusiformis* sampled from lakes Sonachi, Bogoria and Nakuru, despite them being UDT in cultures from L. Simbi and L. Elmenteita. All these reports corroborate previous observations that strongly suggested the dominance of *A. fusiformis* in the volcanic crater and meromictic soda lakes of Kenya [39–41]. In later investigations, Kenyan lakes Bogoria, Nakuru, Oloidien and Elmenteita had more than 97% scum of *A. fusiformis*. As expected, MCs occurred at 16 to 155 µg MC-LR eq L$^{-1}$ in Lake Bogoria and 130 to 4593 µg MC-LR eq L$^{-1}$ in Lake Nakuru [36,42–44]. These reports were divergent from earlier findings of Vareschi [45], where CYB in Lake Nakuru were reported to be dominated by *Spirulina platensis*.

Other reports on CYB in Kenya are from its L. Victoria part (bays, gulfs and satellite lakes), where CYB (>35%) and diatoms (>30%) of *Microcystis*, *Merismopedia* and *Dolichospermum* species are the primary phytoplankton (Table S1). As far as cyanotoxins are concerned, Sitoki and others [46] detailed the incidence of MCs in L. Victoria water. They concluded that the levels varied greatly between seasons. This comes in concordance with later inferences of other researchers [47,48] who investigated MCs contamination of water and fish consumed by fisher communities of Winam Gulf, Homa Bay, Kisumu, Siaya and Busia counties of L. Victoria (Kenya). Regrettably, up to 30% of water from these points exceeded the regulatory set value (1.0 µg L$^{-1}$) of the WHO [48]. The study suggested that CYBHAB pose potential year-round health risks to riparian communities [48].

Recently, a team of researchers collated the insights and awareness of L. Victoria shore community on MCs toxicity [47]. The authors appreciated that more than 70% of the fisherfolk are conversant with the toxic effects of MCs, and showed the urgency required to mitigate them. An earlier investigation [49] echoed that higher average values of MCs (5 to 109 µg kg$^{-1}$) occurred in fish from Nyanza Gulf (Kisumu Bay) compared with those from Rusinga channel water (14 µg kg$^{-1}$). These reports reaffirmed that CYBHAB are recurrent in L. Victoria.

### 3.3. Tanzania

Previous studies conducted about lakes Big Momela, Embagai and Manyara indicated that CYB (>50%), mostly *Anabaenopsis elenkenii*, *A. fusiformis* (Lake Big Momela), *A. fusiformis*, *Oscillatoria*, *Hantzschia* (Lake Embagai), *Oscillatoria jenensis* and *Pseudoanabaena terebriformis* (Lake Manyara), were dominant in the phytoplankton [50,51]. Similarly, CYB (specifically *A. fusiformis*) have been prevalent in Momela Lakes and Lake Natron with MCs detected in water at concentrations of 0.1–4.5 µg mL$^{-1}$ of scum in the latter [52].

For L. Victoria, the occurrence of CYB (upto 82%) was quantified in several parts of the southern part. Miles et al. [53] found putative MCs analogues in extracts of a cyanobacterial bloom from Mwanza Gulf but did not quantify them. On 27 islands of Ukerewe district, MCs (0.0028 to 0.0102 µg L$^{-1}$) were reported [54]. Other studies in L. Victoria (several bays, open water and Gulfs) have found MCs (up to 13 µg MC-LR eq L$^{-1}$; Table S1). An incidence of multiple cyanotoxins: CYN (0.004 to 0.01 µg L$^{-1}$), NODs (0.010 µg L$^{-1}$) and MCs (0.0028 to 0.0118 µg L$^{-1}$) in water from L. Victoria has been communicated [54]. The

report emphasized that multiple and repeated exposure to phycotoxins could amplify their toxicity and/or adverse effects.

### 3.4. Uganda

From the available literature, Uganda has the highest number of reports about CYB in several lakes. Of these, Western Uganda crater lakes (Kyaninga, Saaka, Nyabikere, Nyinambuga, Munyayange, Kikorongo, Maseche, Murumuli, Bunyampaka, Katwe, Bagusa, Nyamunuka, Mwamba, Katanda, Karolero, Kerere, Kacuba, Mwengenyi, Kyerbwato, Katanda, Kanyamukali, Nkugute, Kyanga, Mirambi, Nyanswiga, Kitere, Chibwera, Lugembe, Nyanswiga, Kamweru (Figure 3), Nyahirya, Nyabikere, Kyasanduka, Kifuruka, Wandakara, Nyamusingire, Nyungu and Katinda) were found to contain CYB (35% to 100%), primarily of the genera *Planktolyngbya*, *Microcystis*, *Anabaena* and *Cylindrospermopsis*. No determination of cyanotoxins was performed [55,56].



**Figure 3.** Brackish water in Lake Kamweru, a cyanobacteria-rich twin crater lake in Rubirizi district, Western Uganda. The lake and its twin (Lake Kyema) are the only co-joined lakes in Africa, which are filled by water from a heritage cave (photo credit: Ivan Kahwa, December 2022).

Other interesting studies are available on the Albertine lakes (Edward and George) [57]. Species from *Raphidiopsis* and *Anabaenopsis* genera are the primary community in Lake Edward, though *Aphanocapsa*, *Merismopedia*, *Microcystis*, *Aphanothece* and *Anathece* genera are also present. According to several authors, shallow Ugandan lakes near Mount Rwenzori (Lake George, Lake Edward and Lake Mburo) are eutrophic, with *Microcystis* species being the most abundant CYB [57–61]. Lake Mburo was earlier reported to have more than 90% of its phytoplanktonic community as CYB [62,63]. Later, Okello et al. [59] found that MCs (majorly MC-LR) occurred from UDT to 3.5 µg L$^{-1}$ in the foregoing shallow lakes, which were lower than 0.5 to 10.2 µg L$^{-1}$ analogously investigated for Lake Shaka. Another report by Poste [64] highlighted that several fish species from Ugandan lakes contained MCs at 0.0005 to 0.198 µg kg$^{-1}$ in filleted muscle tissues, 0.0034 to 1.189 µg kg$^{-1}$ in gutted and beheaded fish, and 0.0028 to 0.8987 µg kg$^{-1}$ in whole fish samples (Table 1).

**Table 1.** Occurrence and levels of microcystins in fish from some East African lakes.

| Lake | Fish Species | MCs Content (Average/Range, µg kg$^{-1}$) [1] | References |
|---|---|---|---|
| L. Victoria (Murchison Bay) | *Clarias gariepinus* | 23.9 | [64] |
| | *Haplochromis* spc (filleted and whole) | 35.6 and 19.9 | |
| | *Lates niloticus* | 13.5 | |
| | *Oreochromis leucostictus* | 30.3 | |
| | *Oreochromis niloticus* | 13.7 | |
| | *Protopterus aethiopicus* | 4.1 | |
| | *Rastrineobola argentea* (whole/dry from market) | 36.2–41.2 | |
| | *Synodontis afrofischeri* | 28.8 | |
| | *Synodontis victoriae* | 16.7 | |
| | *Tilapia zilli* | 15.5 | |
| | *Oreochromis niloticus* (gut, liver and muscle) | 1479.24, 48.07 and 9.65 | [65] |
| | *Lates niloticus* (gut, liver and muscle) | 27.78, 3.74 and 1.86 | |
| L. Victoria (Napoleon Gulf) | *Astatoreochromis alluaudi* | 6.2 | [64] |
| | *Bagrus docmac* | 15.1 | |
| | *Brycinus sadleri* | 24.6 | |
| | *Haplochromis* spc (filleted and whole) | 13.0–17.1 and 15.3 | |
| | *Lates niloticus* (filleted and gutted/beheaded) | 7.3 and 12.9 | |
| | *Mormyrus kannume* | 21.1 | |
| | *Oreochromis leucostictus* | 3.2–4.3 | |
| | *Oreochromis niloticus* (filleted and gutted/beheaded) | 9.8 and 6.1 | |
| | *Oreochromis variabilis* | 30.1 | |
| | *Protopterus aethiopicus* | 2.8 | |
| | *Rastrineobola argentea* (whole/dry from market) | 83.7 | |
| | *Synodontis afrofischeri* | 31.0 | |
| | *Synodontis victoriae* | 16.7 | |
| | *Tilapia zilli* (filleted and gutted) | 8.4 and 3.4 | |
| L. Victoria (open lake at Rusinga channel and Nyanza Gulf) | *Rastrineobola argentea* | 14 and 25–109 | [49] |
| Lake Mburo | *Bagrus docmac* | 13.4 | [64] |
| | *Clarias gariepinus* | 20.6 | |
| | *Haplochromis* spc (filleted) | 2.5–5.6 | |
| | *Haplochromis* spc (gutted/beheaded) | 5.4–11.8 | |
| | *Haplochromis* spc (whole) | 12.1 | |
| | *Oreochromis esculentus* | 17.9 | |
| | *Oreochromis leucostictus* | 8.4 | |
| | *Oreochromis leucostictus* (gutted/head removed) | 7.4 | |
| | *Protopterus aethiopicus* | 2.5 | |
| | *Oreochromis niloticus* (gut, liver and muscle) | 1312.08, 73.10 and 208.65 | [65] |
| Lake Nkuruba | *Poecelia reticulata* | 4.5 to 73.3 | |
| | *Tilapia zilli* (filleted and whole) | 11.7 and 42.5 | |
| | *Oreochromis leucostictus* (filleted and gutted/beheaded) | 8.3 and 17.2 | |
| Lake George | *Bagrus docmac* | 9.1 | [64] |
| | *Clarias gariepinus* | 6.1 | |
| | *Oreochromis leucostictus* | 21.2 | |
| | *Oreochromis niloticus* | 10.2 | |
| | *Protopterus aethiopicus* | 2.4 | |
| | *Oreochromis esculentus* | 6.3 | |
| | *Haplochromis squamipinnis* (filleted and gutted) | 6.7 and 11.8 | |

**Table 1.** *Cont.*

| Lake | Fish Species | MCs Content (Average/Range, μg kg$^{-1}$) [1] | References |
|------|-------------|:---:|:---:|
| Lake Saka | *Astatoreochromis alluaudi* (filleted and gutted/beheaded) | 71.3 and 10.5 | [64] |
| | *Astatoreochromis alluaudi* (whole) | 32.5 | |
| | *Barbus neumayerii* (gutted/beheaded) | 9.5 | |
| | *Haplochromis* spc (filleted) | 52.1 | |
| | *Haplochromis* spc (gutted/beheaded and whole) | 23.2–1189.3 and 21.3–215.2 | |
| | *Lates niloticus* | 16.4 | |
| | *Oreochromis niloticus* | 17.0 | |
| | *Tilapia zilli* (filleted and whole) | 4.9 and 898.7 | |
| Lake Edward | *Bagrus docmac* | 6.2 | |
| | *Barbus bynni* | 5.3 | |
| | *Clarias gariepinus* | 8.6 | |
| | *Haplochromis* spc | 10.0 | |
| | *Haplochromis squamipinnis* | 8.6 | |
| | *Oreochromis leucostictus* | 21.9 | |
| | *Oreochromis niloticus* | 8.0 | |
| | *Protopterus aethiopicus* | 5.3 | |
| Lake Albert | *Lates niloticus* | 3.9–11.6 | |
| | *Tilapia zilli* | 2.7–6.2 | |

[1] All mean values exceed the permissible MCs limit of 0.04 μg kg$^{-1}$ in fish [65]; spc = species.

In the Ugandan part of L. Victoria, *Microcystis*, *Dolichospermum* and *Cylindrospermopsis* species are the prevalent CYB (>80%) (Table S1). Cyanotoxin analyses have reported concentrations of UDT to 93 μg L$^{-1}$ of MCs in water from Murchison Bay, Napoleon gulf and open lake water. Worth citing are pioneering studies in Murchison Bay where MCs were quantified in *Oreochromis niloticus* (Nile tilapia fish), unveiling that the concentrations in biota and aqueous phase were correlated. The study highlighted that there has been an increase in MCs-producing CYB in the lake which are plausibly ingested by fish, agreeing with previous research findings [61,65,66]. The maximum concentration of total MCs reported for guts, liver and muscles of phytoplanktivorous *Oreochromis niloticus* (Nile tilapia) and *Lates niloticus* (Nile perch) from Murchison Bay of L. Victoria (1.86 to 1479.24 μg kg$^{-1}$) is slightly higher than those from other Ugandan lakes such as Lake Mburo (73.10 to 1312 μg kg$^{-1}$) [65]. A study published in 2022 unveiled for the first time the occurrence of homoanatoxin-a (HTX; <0.04 HTX L$^{-1}$ in water from an inshore station of Murchison Bay [67], along with MCs (0.15–11.7 μg MC-LR eq L$^{-1}$). At recreation sites, MCs (0.180 to 14.800 μg MC-LR eq L$^{-1}$) equally occurred. The study demonstrated that whereas CYB were eliminated by water treatment, MCs remained detectable in water during and post-treatment (0.14 μg L$^{-1}$) [67]. This shows that remediation of cyanotoxins in water from L. Victoria will require more efficient technologies to avoid exposing the local population to potential effects of MCs.

At this point, it can be suggested that shallow lakes in Uganda exhibit less seasonality in their CYB composition when compared with satellite lakes and others in the main L. Victoria basin. Unlike in oligotrophic lakes in the region, the CYB dynamics (spatial and temporal variations in prevalent cyanobacterial genera) in L. Victoria are, however, inconsistent in its different parts. This may be related to external anthropogenic influences, especially nutrient loading, because the lake receives a cocktail of pollutants from different countries.

### 3.5. Rwanda

The only report on CYB in a Rwandese Lake (Lake Muhazi) showed that it contains mainly *Microcystis aeruginosa*, followed by the dinoflagellate *Cerutium hirundinellu* [68].

These are ingested by Nile tilapia present in the lake [69], suggesting the need to establish the concentrations of cyanotoxins in water and fish from this lake.

Overall, volcanic and tectonic lakes in the East African Great Rift Valley possess distinguished extents of hydrological connections. Volcanicity in the region resulted in endorheic basins whose bedrock, groundwater connection and climate have favored schizohaline water formation [70]. These, in turn, have contributed to the dominance of CYB, and occurrence of CYBHAB and cyanotoxins. The literature reveals that toxigenic microalgae recorded from EAC lakes are *Dolichospermum*, *Microcystis, Arthrospira*, *Planktolyngbya* and *Anabaenopsis* species. The prevalence of CYBHAB and cyanotoxins in EAC lakes is of concern due to potential bioaccumulation and trophic transfer in zooplanktivorous and carnivorous fish species [61,66]. Moreover, the observed levels of MCs in whole fish, gut, liver and muscles (2.4 to 1479.24 $\mu$g kg$^{-1}$) could pose human health risks to a daily consumer, as the WHO daily intake limit of MCs in fish is 0.04 $\mu$g kg$^{-1}$ [65].

In L. Victoria, cyanobacterial biomasses and MCs levels in water from gulfs and bays comparatively surpasses their levels in the open lake water, with *Microcystis* and *Dolichospermum* species being the most prevalent CYB genera. Further, CYBHAB in the lake has increased costs associated with water treatment, e.g., National Water and Sewerage Cooperation Uganda reported increased chlorine demand for water treatment, unpleasant odors and tastes in untreated water supplies, and clogging of pumps and filters. Fishermen have reported that CYB has hampered fishing operations on the lake [71]. Anecdotal reports point that portions of the lake covered by CYB were observed to have small dead fish, whereas larger fish from such brackish waters are often weak and stressed. Earlier (in 1984), indiscriminate fish die-offs were witnessed in L. Victoria (Kenya), and this was plausibly connected with CYBHAB [72]. Similar mass mortalities were observed in 1991 for fish in Lake Magadi, Kenya [73], and this event was anticipated to have been caused by reduction in the algae *Spirulina platensis*. These effects, according to a recent report [67], may increase in severity in the coming decades. For example, MCs detected from Murchison Bay of L. Victoria now range from 0.20 to 15.00 $\mu$g MC-LR eq L$^{-1}$, which is higher than those reported previously (0.20 to 0.70 and UDT to 1.6 $\mu$g MC-LR eq L$^{-1}$ between 2004 and 2005, and then 2007 to 2008) [66,74], possibly due to the doubling of the mean *Microcystis* biovolume [67]. The EAC recreational waters are not often screened for pelagic cyanobacterial species, implying that the sanitary activities in contaminated lakes may expose both humans and animals to the potential negative effects of CYBHAB and cyanotoxins.

## 4. Toxicity, Human and Ecological Health Implications of Cyanotoxins in EAC Lakes
### 4.1. MCs

MCs are hepatotoxins, majorly produced as secondary metabolites of planktonic cyanobacterial species from genera such as *Microcystis, Cylindrospermopsis, Anabaena, Oscillatoria (Planktothrix), Anabaenopsis, Nostoc, Arthrospira, Hapalosiphon, Limnothrix, Lyngbya, Phormidium, Rivularia, Synechocystis* and *Synechococcus* [75]. Acute effects such as nausea, diarrhea, dermal, eye and throat irritations have been associated with their ingestion. Chronic exposure to MCs culminates in hepatic necrosis, retarded growth, reduced reproduction potential and, ultimately, death in fish and humans. The neurotoxicity of MCs is also known, but this applies specifically to invertebrates without livers [76]. In addition, exposure to MCs is associated with colorectal and primary liver cancer, with MC-LR receiving classification as a possible human carcinogen (group 2B) [77]. For humans, exposure to MCs occurs principally through the ingestion of contaminated aquatic organisms (e.g., fish) or water, as well as through the recreational use of water. Upon ingestion and absorption into the liver by organic anion transport proteins, MCs inhibit protein phosphatases, thereby selectively distorting cytoskeleton formation, degrading hepatic ultrastructure in eukaryotic cells, resulting in hepatic failure, intrahepatic hemorrhage and shock [78,79].

In EAC, MCs and ATX were implicated in the death of *Phoeniconaias minor* Geoffroy Saint-Hilaire 1798 (lesser flamingos) [80]. The pink birds (Figure 4a) feed on *A. fusiformis* [81], which confers upon them the pink plumage following the accumula-

tion of ingested cyanobacterial pigments [82]. While this phenomenon is not new (e.g., in the Greater flamingos and Western Tanager [83,84]), it should be anticipated that other nutrition-based compounds may become bioaccumulated in lesser flamingos, e.g., potentially toxic metals. Event-driven reports of lesser flamingo die-offs are available for soda lakes such as Bogoria and Nakuru of Kenya [85,86], Momela, Natron, Rishateni, Manyara and Empakai Crater of Tanzania [13,51,87,88] (Table 2). Some of these reports substantiated the anecdotal claims by quantifying MCs and ATX levels in carcasses of the birds. Krienitz et al. extended the hypothesis further and examined the concentration of MCs and ATX in Lake Bogoria, in the surrounding hot springs and in flamingo birds [89]. They concluded that the cyanotoxins from the hot-spring mats could be responsible for the mass mortalities of the birds because: (i), there were evident cyanobacterial cells, fragments in hot spring mats, and elevated levels of ATX and MCs (0.00434 and 0.000196 $\mu$g kg$^{-1}$); and (ii) there were clinically indisputable signs of flamingo intoxications. Such intoxication with the biotoxins could plausibly have been caused by direct or indirect intake of CYB or their cells [89]. Wings, breasts and head feathers of the flamingos reportedly had ATX and MCs concentrations ranging from UDT to 0.03 MC-LR eq $\mu$g kg$^{-1}$ [90]. Moreover, amino acid neurotoxins $\beta$-*N*-methylamino-L-alanine (0.0035 $\mu$g kg$^{-1}$ DW) and 2,4-diaminobutyric acid (0.0085 $\mu$g kg$^{-1}$ DW) were recently quantified in lesser flamingo feathers from Lake Nakuru [91].



**(a)** **(b)**

**Figure 4.** Lesser flamingos at the Kenyan Lake Bogoria (**a**) a flock wading ashore (photo by Steve Garvie. Source: Riley [92]), and (**b**) massive die-off in July 2008 [93].

**Table 2.** Microcystin and anatoxin-a-related massive mortalities of lesser pink flamingos in alkaline-saline (soda-rich and schizohaline) lakes of East African Community in comparison with cyanotoxin-related bird mortality reports from other countries.

| Waterbody (Country) | Report (s) | Year | Reference(s) |
|---|---|---|---|
| **East Africa** | | | |
| Lake Nakuru (Kenya) | 0.00003 to 0.0004 $\mu$g MC-LR eq kg$^{-1}$ and 0.00004–0.0058 $\mu$g kg$^{-1}$ in liver, stomach/intestine | 2001–2003 | [94] |
| | 35,000 birds died | 2006 | [44] |
| Lake Bogoria and Lake Nakuru (Kenya) | 40,000 birds died | 1991 | [93] |
| | More than 30,000 birds died; 0.00021 and 0.00093 $\mu$g MC-LR eq kg$^{-1}$ fresh weight, ATX ranged between 0.00106 and 0.00582 $\mu$g kg$^{-1}$ fresh weight | 1993 | [85,86,95,96] [1] |
| | 50,000 birds died | 1995/1996 | [94] |

**Table 2.** *Cont.*

| Waterbody (Country) | Report (s) | Year | Reference(s) |
|---|---|---|---|
| Lake Bogoria | 30,000 birds died | 1999/2000 | [89,93] |
| | 0.00003–0.0009 µg MC-LR eq kg$^{-1}$ and 0.00004–0.0002 µg kg$^{-1}$ in liver, stomach/intestine | 2001–2003 | [94] |
| | 30,000 birds died | 2008 | [44,93] |
| | 2000 birds died | 2009 | [93] |
| Lake Natron and Empakai crater (Tanzania) | 43,800 birds died. Total MCs (MC-RR, -YR, -LR and -RY) were 0.1–4.5 µg mL$^{-1}$ | July–August 2004 | [51,85,88] [2] |
| Lake Big Momela (Tanzania) | 15 and 50 individuals per day for 2004 case; elevated levels (up to 150 million filaments L$^{-1}$ of *A. fusiformis* were quantified in sampled scum; no MCs detected | | |
| Lake Manyara (Tanzania) | 521 deaths per month; bird livers contained 0.0003–0.0541 µg kg$^{-1}$ wet weight of MCs. *Corynebacteria* species, *Pasteurella multocida* and *Proteus* species were found in visceral organs of all carcasses tested | 2004, August–October 2008 | [87,88,97] [3*] |
| **Other regions** | | | |
| The Salton Sea (USA) | Over 20,000 deaths of Eared grebe (*Podiceps nigricollis*). Water contained up to 0.001 µg kg$^{-1}$ DW and UDT to 0.00011 µg kg$^{-1}$ DW in grebe liver tissues | 1990–2006 | [98,99] |
| Doñana National Park (Spain) | 579 Greater flamingos (*Phoenicopterus roseus*) died; MCs at concentrations of 0.44 µg kg$^{-1}$ of liver wet weight and 0.625 µg kg$^{-1}$ in crop contents | 2001 | [100] |
| Pond in Nishinomiya (Japan) | 20 spot-billed ducks died; MCs were detected in water (0.512 µg kg$^{-1}$ cyanobacterial cell powder) | 1995 | [101] |
| Lake Knudsø (Denmark) | 3 ducks, 16 ducklings, 1 coot, coot chicks | 23rd and 26th June 1981 | [102] ** |
| | 2 ducks and crows (unknown number) | 12th and 17th June 1988 | |
| | 2 grebes; 14–19 birds (black-necked and crested grebes, seagulls and a duck) and 2 grebes, respectively. ATX was recorded at 2.30 µg kg$^{-1}$ | 10th June, 1st and 4th July 1993 | |
| | Birds (unreported number), and 1 coot, 1 duck. ATX was recorded at 3.30 µg kg$^{-1}$ while MCs occurred at 0.0001 to 0.0009 µg kg$^{-1}$ | 28th June and 6th July 1994 | |
| | 1 duck | 9th July 1995 | |

[1,2,3] In part, *Pseudomonas aeruginosa*, *Mycobacterium avium*, *Escherichia coli* and heavy metals were claimed to be contributors to these flamingo die-offs [96,103,104]. * In 2004, over 43,800 flamingo die-off was experienced in this lake [105]. ** Several other animals (6 dogs, cows, crows and some fish) succumbed to cyanotoxins after swimming in this lake or drinking its water, which was rich in *Anabaena* species.

While it is still debated that MCs may be a potential initiator of avian botulism, other probable causes of the unnatural mass death of wild birds include avian tuberculosis [96], cholera, botulism, heavy metals [95,106], pesticide residues, or combinations of these [85,98,103,107,108]. Indeed, mycobacteriosis was reported in lesser flamingos from Lake Nakuru, Kenya [109]. Nevertheless, anatoxins and MCs (at concentrations higher than reported in EAC flamingos) have been associated with avian mortalities [98,101,102,110,111]. From an ecological perspective, lesser flamingos are "Near Threatened" supported by the limited and ungazetted nesting areas, as well as the reduced bird populations [112–114]. At present, they reportedly breed in only five sites: one in EAC (Lake Natron, with at least 75% of the breeding birds), Etosha and Makgadikgadi Pans in Namibia and Botswana, and Purabcheria Salt and Zinzuwadia Pans of India [115]. An attempt has been made to hand-rear lesser flamingos so as to restore and conserve this rare species of birds [116], but there is no available literature with any registered success.

### 4.2. Anatoxin-a

ATX is toxicologically known as Very Fast Death Factor for its fast lethal effect in animals, which could be related to its high rate of absorption into the gastrointestinal tract [117]. ATX is a secondary bicyclic amine alkaloid with peracute neurotoxic effects. Its discovery and identification in the 1960s and 1972 from CYB (*Anabaena flos-aquae*) followed the mortality of cattle herds that ingested contaminated water from Saskatchewan Lake in Ontario [117]. It is known to be biosynthesized by CYB from *Arthrospira, Anabaena, Microcystis, Planktothrix, Oscillatoria, Aphanizomenon* and *Cylindrospermum* genus [117].

Exposure to ATX (through ingestion of contaminated water or dried algal crusts, accidental swallowing/inhalation) has been associated with burning, tingling, respiratory paralysis and dysrhythmias, which are fatal. ATX antagonizes the activity of neuronal $\alpha 4\beta 2$ and $\alpha 4$ nicotinic acetylcholine receptors (nAchRs) of the central nervous system and $(\alpha 1)2\beta\gamma\delta$ muscle-type nAchRs of the neuromuscular junction [118]. With an affinity >20 times that of acetylcholine, ATX has the same effect as the former when it binds with nAchRs, i.e., it induces a conformational effect on the receptor, opening the channel pore to permit the passage of ions ($Ca^{2+}$ and $Na^+$) into the neuron. This culminates into cell depolarization, the generation of action potentials and thus muscle contraction. During ATX-mediated toxicity, the acetylcholine neurotransmitter does not dissociate from the nAchRs, resulting into irreversible inhibition and blockage of neuromuscular transmission [119]. This inhibitory effect generally accumulates the neurotransmitter within the synaptic cleft, eventually causing paralysis, asphyxiation and death, specifically if respiratory muscles are affected. In the epornitic mortalities of algivorous EAC lesser flamingos (such as in Lake Bogoria; Figure 4b), clinical symptoms have included opisthotonus, supporting that such die-offs are (at least in part) due to ATX intoxication. Other than the foregoing, ATX possess modulatory effects on nAChRs, which can result in the release of dopamine and noradrenaline [120].

### 4.3. Homoanatoxin-a

HATX being structurally a higher homologue of ATX has the same toxic effects as ATX. In addition to its nicotinic agonistic effects, HATX also upregulates acetylcholine release from cholinergic nerves [121]. This may explain why the potency of HATX is greater than that of ATX. Mortalities from CYBHAB with HATX are rare, but a report of dog neurotoxicosis from New Zealand (where the animals ingested CYB from Hutt River, lower North Island with 4400 µg kg$^{-1}$ wet weight of HATX) has been published [122].

### 4.4. Cylindrospermopsin

CYN is a hydrophilic potentially hepatotoxic and immunotoxic cyclic guanidinium alkaloid, with characteristic tricyclic hydroxymethyl uracil [76]. It has some analogues such as deoxy-CYN (lacking an oxygen atom), demethoxy-CYN and 7-epiCYN (difference in the orientation of hydroxyl group) isolated in CYB *Cylindrospermopsis raciborskii*. The discovery of CYN toxicity happened when more than 100 children from Palm Island in Queensland, Australia suffered from unprecedented gastroenteritis and hepatomegaly. The ordeal was finally found to be due to the ingestion of CYN in contaminated water with CYBHAB of *C. raciborskii* [123]. However, CYN is also produced by other CYB, including *Aphanizomenon flos-aquae, Anabaena* species (*bergii,* and *lapponica*), *Aphanizomenon ovalisporum, Lyngbya wollei, Raphidiopsis curvata Oscillatoria (Planktothrix)* species and *Umezakia natans* [75]. With guideline values of 0.5 to 3 µg L$^{-1}$ in drinking water across continents, CYN is the second-most-studied cyanotoxin known to target the liver, kidneys, heart, spleen, ovary, eye, lung, T lymphocytes, neutrophils and vascular endothelium [124]. CYN elicit toxicity through inhibition of protein synthesis, which can also occur at subtoxic concentrations [125]. Other toxicologists stated that CYN (with its inherent reactive guanidine) could be largely toxic through the induction of DNA wreckage and disruption of the kinetochore spindle. This could possibly result in chromosome loss, aneugenic and clastogenic effects [126]. Chichova et al. [124] found that CYN elicited

moderate toxicity in human intestinal epithelial cells with suppression of cellular regeneration of the epithelial layer. CYN shows hepatotoxic, nephrotoxic, and cytotoxic effects, suggesting potential carcinogenicity. The neurotoxic potential of CYN has also been cited, though this could be a direct consequence of its cytotoxicity. To this end, the full underlying mechanisms of CYN toxicity needs to be elucidated [76].

In the EAC, there are no toxicity reports on CYN, which may be due to the absence of robust data on this cyanotoxin. There are, however, episodes of human and animal CYN-related poisoning from other countries. The most notable human poisoning is the 1979 Solomon dam gastroenteritis and hepatomegaly incidence in children from Palm Island [123]. The mortality of a cow and three calves after drinking water from McKinley Shire dam, Northern Queensland (Australia) was also reported. The animals had severe abdominal and thoracic haemorrhagic effusion, hyperaemic mesentery, pale and swollen liver, extremely distended gall bladder with dark yellow bile and epicardial haemorrhages [127]. In the subsequent 21 days, another eight animals (two cows and six calves) died, and analyses implicated CYN in *C. raciborskii* as the cause [127]. In Lake Aleksandrovac (Serbia), indiscriminate fish deaths due to the ingestion of CYN (range: 1.91 and 24.28 $\mu$g L$^{-1}$) were reported [128]. This report may point to the need to establish CYN levels in EAC lakes where indiscriminate fish deaths have been reported, as CYN may be a contributing factor in addition to MCs.

*4.5. Nodularins*

Nodularins, a class of hepatotoxic non-ribosomal cyclic pentapeptides, possess toxicity mechanisms similar to those of MCs [129]. They are structurally analogous to MCs, but differentiable from MCs in their amino acid components (Figure 2). To date, ten naturally occurring variants (isoforms) of NODs have been discovered, but nodularin-R (with Z amino acid = arginine) is the most common, most commercially available and most studied variant. The toxicity of NODs mainly targets the liver, but they also accumulate in the intestines, blood and kidneys [130]. Upon ingestion, NODs diffuse from the proximal and distal ileum into the liver [131], where they inhibit active sites of serine/threonine protein phosphatases (PP) namely: 1 (PP-1), 2A (PP-2A) and 3 (PP-3). A non-covalent interaction occurs at first with the side chain (ADDA part) and a free D-glutamyl carboxyl group in the cyclic structure of the PP, followed by the inhibition of the phosphatase activities. NODs–phosphatase complexes (NODs-PP-1 and NODs-PP-2A) are formed with exceptionally stable bonds. Thus, the key difference between NODs and MCs in their toxicity via protein phosphatases inhibition is that the former binds non-covalently to phosphatases, while the latter forms a covalent bond [130].

Furthermore, NODs also elicit toxicity through formation of superoxide and hydroxyl radicals (reactive oxygen species) according to a yet incompletely elucidated pathway [130]. Their tumor-promoting activity is, on the other hand, mediated through the induced gene expression of TNF-alpha and proto-oncogenes, the exact mechanism of which is yet to be unraveled. In addition, the deactivation of the resultant tumor suppressor gene products (retinoblastoma and p53) progresses via phosphorylation, and this inevitably promotes tumorigenesis [132]. Overall, the cascade of reactions following NOD ingestion causes cellular disorganizations and damages, apoptosis, necrosis, loss of cell integrity, DNA fragmentation and strand breaks, intrahepatic bleeding and rapid blistering of hepatocytes which results in blood pooling and doubling of the liver weight [133]. Thus, mortalities associated with NOD poisoning is mediated through hemorrhagic shocks, which occurs in a few hours when ingested at high concentrations [134].

There are no toxicity events involving NODs in the EAC. Nevertheless, animal (cattle, dog, sheep, horse, pig and guinea pig) NOD-poisoning-related mortalities have been reported in other parts of the world. For example, hepatotoxicosis of a South African dog following the ingestion of NODs (0.00000347 $\mu$g kg$^{-1}$ DW) was reported [135]. Main et al. [136] recorded 52 sheep deaths in South Western Australia from drinking water

contaminated with NODs from *Nodularia spurnigena*. These reports emphasize that more studies on this cyanotoxin are warranted in EAC lakes.

## 5. Conclusions and Recommendations

CYB, CYBHAB and cyanotoxins have increased in EAC lacustrine ecosystems. *Dolichospermum*, *Microcystis, Arthrospira*, *Planktolyngbya* and *Anabaenopsis* species are the major groups of toxigenic CYB prevalent in EAC lakes producing ATX, HATX, MCs, CYN and NODs. Shallow EAC lakes exhibit less seasonality in their CYB composition, with *Microcystis* being the CYB producing MCs under shallow and eutrophic lacustrine conditions. The only direct ecological effects of cyanotoxins in EAC lakes is indiscriminate fish deaths and mass die-offs of lesser flamingos. With the unequivocal increase in climate change and variability, it is inferred that CYBHAB and cyanotoxins will increase in frequency and severity. This calls for urgent action to mitigate nutrient-rich pollutants loading into water resources and the expansion of CYBHAB from eutrophic lakes to the surrounding marine environments. The (eco)toxicological relevance of co-production of phycotoxins should be assessed in the EAC because such exposure may amplify the toxicological outcomes in aquatic biota and humans. As some CYB encountered in EAC lakes produce other cyanotoxins (such as β-*N*-methylamino-L-alanine and saxitoxins), studies targeting these cyanobacterial metabolites should be initiated. While there are no reports of cyanotoxin poisoning of humans in the EAC, future studies should examine the risk of hepatocellular cancer, the ingestion of CYB and mycotoxin-contaminated water and foods, and hepatitis virus, which were earlier linked to increased primary liver cancer cases in Asia. Another potential relationship with microplastics should be assessed because they are known to accumulate toxins and amplify their toxicity.

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