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REVIEW

Cyanotoxins in African waterbodies: occurrence, adverse effects, and potential risk to animal and human health

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Abstract Public concerns about cyanotoxins production in water and its detrimental impacts on human and animal health are growing primarily due to the widespread eutrophication observed in aquatic ecosystems. A review of relevant literature was done to determine the degree of cyanotoxin occurrence and its harmful effects in African waterbodies. Data were extracted from 64 published studies from 1990 to 2022 that quantified the concentration of cyanotoxins in African aquatic ecosystems. Cyanotoxins have been reported in 95 waterbodies (29 lakes, 41 reservoirs, 10 ponds, 9 rivers, 5 coastal waters, and 1 irrigation canal) from 15 African countries. Cyanotoxins were documented in all the regions of Africa except the central region. Microcystins have been reported in nearly all waterbodies (98.9%), but anatoxin-a (5.3%), cylindrospermopsin (2.1%), nodularins (2.1%), homoanatoxin-a (1.1%), and β-*N*-methylamino-L-alanine (1.1%) were encountered in a small number of water ecosystems, homoanatoxin-a and β-*N*-methylamino-L-alanine each occurred in one waterbody. The largest concentrations of microcystins and nodularins were reported in South African Lakes Nhlanganzwani (49,410 μg L^{-1}) and Zeekoevlei (347,000 μg g^{-1}). Microcystin concentrations exceeding the WHO guideline for lifetime drinking water (1 μg L^{-1}) were reported in 63% of the aquatic ecosystems surveyed. The most frequently reported toxin-producing cyanobacteria genus is *Microcystis* spp. (73.7%), followed by *Oscillatoria* spp. (35.8%) and *Dolichospermum* spp. (33.7%). Cyanotoxin-related animal mortality and human illness were reported in the continent. Consequently, it is necessary to regularly monitor the level of nutrients, cyanobacteria, and cyanotoxins in African waterbodies in an integrated manner to devise a sustainable water resources management.

Keywords Adverse effects · African water bodies · Cyanobacteria · Cyanotoxins · Microcystins · *Microcystis*

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Introduction

The formation of cyanobacterial blooms, which are usually linked to the development of cyanotoxins, is favored by excessive nutrient enrichment, water stillness, and favorable light and temperature conditions (Merel et al., 2013; Paerl, 2014). Cyanotoxins are commonly alkaloids of low molecular weight or cyclic peptides that cause harm to organisms, including humans (Carmichael et al., 2001; Metcalf & Codd, 2012). They are secondary metabolites, the organism does not utilize them for its primary metabolism and either retains them in producer cells or releases them into the water (Metcalf & Codd, 2012). Cyanotoxins comprise over a hundred different chemicals, each with a unique chemical structure and toxicity (Manning & Nobles, 2017).

Many authors have linked the poisoning and death of animals to cyanotoxins (Carmichael et al., 2001; Chellappa et al., 2008; Harding & Paxton, 2001; Masango et al., 2010; Scott et al., 1981; Shaw et al., 2002; Soll & Williams, 1985; Steyn, 1943; Van Halderen et al., 1995). Microcystins (MCs) are the most commonly reported cyanotoxins (Dawson, 1998; Gupta et al., 2003), and are known to cause cell necrosis, massive hemorrhage, and death (Hooser, 2000; Kuiper-Goodman et al., 1999). Carmichael et al. (2001), Funari and Testai (2008), and Buratti et al. (2017) documented several cases of human intoxication associated with cyanotoxins. Exposure to cyanotoxin-contaminated waters is known to cause skin irritations, conjunctivitis, earaches, gastroenteritis, respiratory diseases, allergic responses, and liver damage (Dietrich & Hoeger, 2005; Vidal et al., 2017).

Nearly every nation in the world has reported the occurrence of cyanobacteria and cyanotoxins (Fristachi et al., 2008), *Microcystis* and MCs being predominant in many countries (Harke et al., 2016; Ndlela et al., 2016). MCs are the most often reported cyanotoxins worldwide, followed by cylindrospermopsin (CYN), anatoxin-a (ATX-a), saxitoxins (STX), and nodularins (NOD) (Pelaez et al., 2010; Svirčev et al., 2019). In several cases, the levels of MCs, CYN, and STX have exceeded the provisional standards for drinking and recreational water around the world (Loftin et al., 2016; Roegner et al., 2020; Szlag et al., 2015). The most commonly reported cyanobacterial genera found worldwide with cyanotoxins in environmental samples are *Microcystis* spp., *Dolichospermum* (Formerly: Anabaena) spp., *Aphanizomenon* spp., *Planktothrix* spp., and *Oscillatoria* spp. (Ibelings et al., 2021; Svirčev et al., 2019).

There are numerous reports of cyanotoxin production in the waterbodies of Africa and its adverse effects. Animal illness and mass deaths have been documented for decades in the aquatic ecosystems of South Africa, Morocco, and Kenya (Krienitz et al., 2005; Oberholster et al., 2009; Oudra et al., 2001, 2002; Scott, 1991; Steyn, 1945). Many Africans have been experiencing broad toxicities resulting in itching, sore eyes, gastroenteritis, and skin rashes (Zilberg, 1966). The problem of eutrophication and algal blooming in Africa is exacerbated due to rapid population growth, urbanization, intensive agriculture, and industrialization (Giri, 2021; Juma et al., 2014).

There is paucity of compiled information on the presence and quantification of cyanotoxins and cyanobacteria in African waterbodies. This could probably be due to lack of resource, skilled technicians and analytical instruments to detect and quantify cyanotoxins. Therefore, this review aims to thoroughly examine the research articles about the prevalence of cyanotoxins and their adverse effects in African waters. This review on several cyanotoxins research aspects will serve as a foundation for ongoing research, monitoring, and management of cyanobacterial blooms in various water resources of Africa.

Research approach: inclusion and exclusion of literature

Articles, books, book chapters, and brief communications that addressed the occurrence, toxic effects, and health risk of cyanotoxins to humans and animals in African aquatic ecosystems was gathered from the Scopus, Web of Science, PubMed, and Science Direct databases. Articles that were published from 1990 to 2022 was searched using a combination of relevant key words/phrases that include "cyanotoxins," "microcystin," "cyanobacteria," "mortality," "adverse effects" "African waterbodies," "Eutrophication," "Southern African waterbodies," "Eastern African aquatic ecosystems," "North African waters," "West African water resources," and "Central Africa water systems." Key words/phrases were combined using conjunctions like AND, AND NOT, NOT, and OR.

Inclusion and exclusion of literature was conducted based on the preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines checklist (Salameh et al., 2020) that include journal ranking, impact factor, the relevance of the article to the research theme, reproducibility, and novelty. Abstracts and full-text contents were thoroughly assessed to check the quality and relevance of literature to study objectives. Consequently, 32 publications out of a total of 172 assessed literature found were rejected for not meeting the minimum set requirements (Fig. 1). Numerical data of cyanotoxin

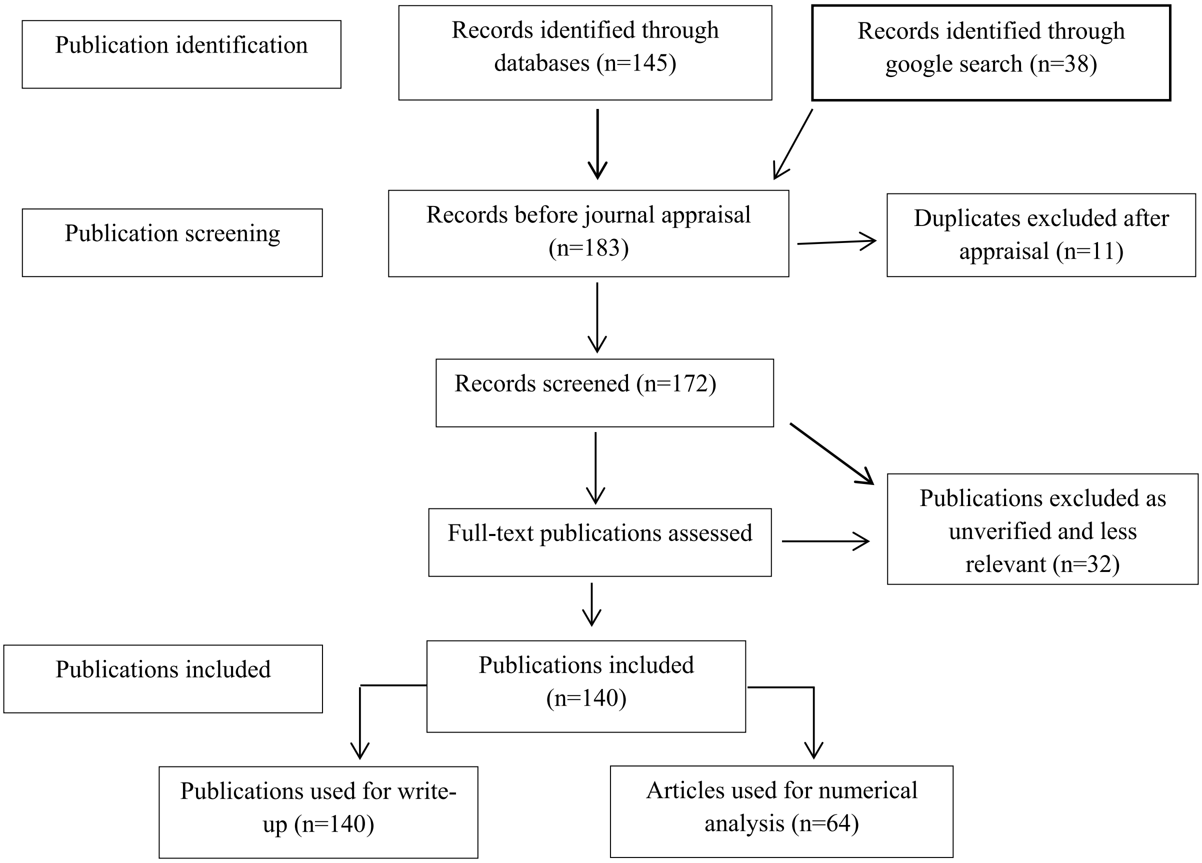

Fig. 1 Identification, screening, inclusion, and exclusion of literature used for numerical analysis

concentrations were extracted from only 64 articles studied in various African aquatic ecosystems.

Lake Victoria was classified as a three-ecosystem since it was regarded as a water resource for Kenya, Tanzania, and Uganda. The cyanotoxin concentrations are presented as maximum content in two different units (μg L^{-1} and μg g^{-1}). Toxin concentrations that were reported in μg L^{-1} only were compared with the WHO recommended values of drinking and recreational water. The analysis did not include studies conducted on tap water and experimental research involving cyanotoxins.

The role of eutrophication in the occurrence of cyanotoxins in African water bodies

In many African countries, industrialization and urbanization coupled with intensive agricultural practices driven by rapid population growth led to land degradation with knock-on effect on excess nutrient enrichment into aquatic systems (Fetahi, 2019; Giri, 2021; Zinabu et al., 2018). Domestic and municipal wastewater, increased applications of chemical fertilizers, and discharging industrial effluents into nearby aquatic systems without adequate treatment have led to increased nutrient loads into surface water resulting in eutrophication (Akale et al., 2018; Lanckriet et al., 2017). About 28% of African waterbodies are seriously impaired by eutrophication due to increased developmental activities with some sort of production work (Nyenje et al., 2010). The concentration of total phosphorus greater than 0.01 mg L^{-1} and total nitrogen above 0.3 mg L^{-1} are enough to cause eutrophication (Tibebe et al., 2022).

In many African countries, recent agricultural intensification with crop–livestock production has led to excess applications of chemical fertilizers along the catchment (Fetahi, 2019; Nyenje et al., 2010; Van Ginkel, 2011). Consequently, runoff from agricultural land washing fertilizers and organic-rich surface soil accelerates the eutrophication of aquatic systems (Lijklema, 1995; Van Ginkel, 2011). Fertilizers applied on farmlands are not completely utilized, a rather large quantity of fertilizer either remain in the soil or gradually washed into aquatic systems due to poor farming practice and reduced water and soil conservation measures (Buratti et al., 2017; Lijklema, 1995). It has been acknowledged that eutrophication is the main factor favoring cyanotoxin production (Chorus et al., 2021; Dolman et al., 2012; Sasner et al., 1981; Tanvir et al., 2021). In various African waterbodies, there are numerous examples of cyanotoxins presence in high concentrations in eutrophic and hypertrophic aquatic systems (Eguzozie et al., 2016; Harding et al., 1995; Masango et al., 2010; Ndlela et al., 2016; Scott et al., 1981, 2018).

Occurrence of cyanotoxins and cyanobacteria in African waterbodies

We documented cyanotoxins occurrence reports on 95 waterbodies (29 lakes, 41 reservoirs, 10 ponds, 9 rivers, 5 coastal waters, and 1 irrigation canal) in 15 African countries (Fig. 2). Svirčev et al. (2019) reviewed publications until 2018 and indicated the presence of cyanotoxins occurrence in fourteen African countries in 76 freshwater ecosystems. In the present review, almost all aquatic ecosystems (98.9%) contained MCs, while ATX-a (5.3%), CYN (2.1%), NOD (2.1), homoanatoxin-a (HTX) (1.1%), and β-*N*-methylamino-L-alanine (BMAA) were reported in few waters. MCs are the most frequently reported toxin (60) in the literature surveyed, while other cyanotoxins such as ATX-a (5), NOD (2), CYN (2), HTX (1), and BMAA (1) have minor contributions. ATX-a was quantified in Kenyan ecosystems only. All concentrated extracts of the Ethiopian Rift Valley Lakes had trace amounts of CYN, but none of the concentrations were high enough to be detected by ELISA (Willén et al., 2011). HTX and BMAA, each were reported in one African aquatic system only. The highest amounts of NOD and MCs were 347,000 μg g^{-1} and 49,410 μg L^{-1} in lakes Zeekoevlei and Nhlanganzwani, South Africa, respectively (Table 3).

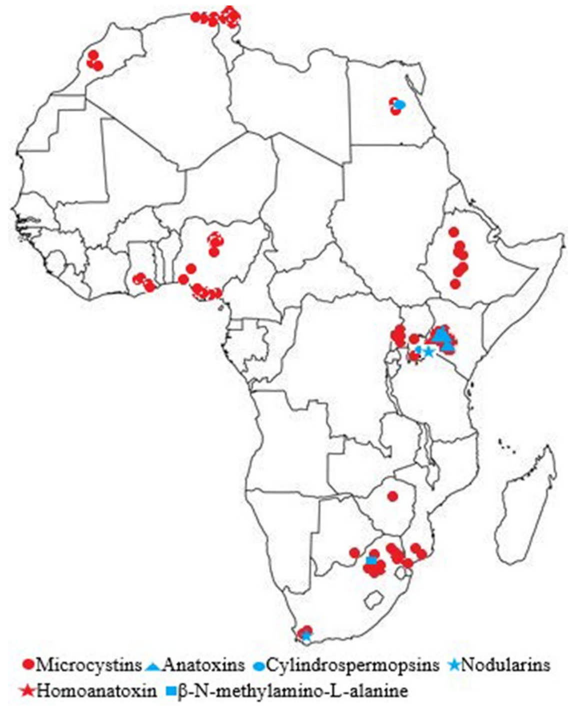

Fig. 2 Geographical distribution of the cyanotoxins reported in African waterbodies

Most of the waterbodies surveyed and reported in μg L^{-1} (83.6%) contained less than 10 μg L^{-1} cyanotoxin from 73 waterbodies. The majority of the toxin content reported as μg g^{-1} (59.1%) was higher than 200 μg g^{-1}. The MCs concentrations in 63% of the water systems were greater than the WHO guideline threshold of lifetime drinking water (1 μg L^{-1}). Twelve waterbodies found in six countries contained MCs concentrations greater than WHO's provisional guideline values for short-term drinking water (12 μg L^{-1}) and recreational water (24 μg L^{-1}) (Tables 1 and 2). The ATX-a, NOD, CYN, HTX, and BMAA concentrations reported did not exceed threshold values of short-term drinking-water and recreational water. However, fish ponds in Sohag province, Egypt, were reported to have CYN amounts (2.76 μg L^{-1}) above the lifetime drinking-water guideline value set by WHO (0.7 μg L^{-1}).

Aquatic ecosystems studied at least twice such as Hartbeespoort Reservoir (South Africa), Nile River (Egypt), Lake Oubeira (Algeria), and Lake Koka (Ethiopia), showed generally declining trends of cyanotoxins concentrations between 1995 and 2015.

Table 1 Maximum values/standards of cyanotoxins concentrations in drinking and recreational water set by WHO (Chorus & Welker, 2021; WHO, 2020)

Cyanotoxin	Type of standard	Value (μg L^{-1})
Microcystins (MC-LR)	Provisional guideline (PG) value for lifetime drinking-water	1
	PG value for short-term drinking-water	12
	PG value for recreational water	24
Nodularin	Health alert level	1
Cylindrospermopsin	Lifetime drinking-water, PG value	0.7
	Short-term drinking-water, PG value	3
	Recreational water, PG value	6
Saxitoxins	Acute guideline value for drinking-water	3
	Guideline value for recreational water	30
Anatoxin-a	Acute health-based reference value for drinking-water	30
	Health-based reference value for recreational water	60

*The health alert level of Nodularin is set by the Australian Government

Lake Victoria's MCs concentration has been steadily increasing until 2017 before it decreased to one of the lowest values (0.02 μg L^{-1}). However, Lake Mburo (Uganda), Lebna Reservoir (Tunisia), Ahmadu Bello University (ABU) Reservoir (Nigeria), Lake Bomo (Nigeria), and Lake Makwaye (Nigeria), have showed increments in MCs content between 2003 and 2013. These variations can be linked to management efforts and nutrient enrichment driven by anthropogenic activities.

The most frequently found cyanobacteria with cyanotoxins in water samples in African aquatic ecosystems were *Microcystis* spp. (73.7%), followed by *Oscillatoria* spp. (35.8%) and *Dolichospermum* spp. (33.7%). Other cyanobacterial genera that were present with cyanotoxins in environmental samples in at least 10% of the waterbodies include *Merismopedia* (24.2%), *Pseudanabaena* (22.1%), *Chroococcus* (17.9%), *Planktothrix* (16.8%), *Spirulina* (14.7%), *Raphidiopsis* (9.5%), and *Synechococcus* (9.5%).

Southern Africa

The occurrence and distribution of cyanotoxins and cyanobacteria have been extensively researched in South African waterbodies. In contrast to NOD, which was only identified in Lake Zeekoevlei, MCs were found in 94.1% of the 17 Southern African aquatic systems surveyed (Table 3). A total of 88.2% of the water systems surveyed had MCs levels over the WHO-recommended limit of 1 μg L^{-1} for drinking water, and of those, 46.2% had levels above the threshold for both short-term drinking water and recreational water use. In Lake Zeekoevlei, Nhlanganzwane Reservoir, and Kruger National Park Reservoirs (Nhlanganzwani, Mpanamana, Makhohlola, and Sunset), the concentration of cyanotoxins (MCs and NOD) was so high (up to 49,410 μg L^{-1}) that it was linked to serious illness and mortality in domestic and wild animals (Harding et al., 1995; Masango et al., 2010; Oberholster et al., 2009). Between 1984 and 2011, Lake Hartbeespoort's particulate MCs remained stable, while its dissolved MCs decreased between 2005 and 2013. This is consistent with a decline in productivity between 2010 and 2018, which is probably caused by a fall in the water temperature (Ali et al., 2022).

MCs measurements in Botswana, Mozambique, and Zimbabwe waterbodies were less than guideline value for short-term drinking water set by WHO (12 μg L^{-1}), although many of them were higher than the limit set by WHO for drinking water (1 μg L^{-1}) (Table 3). *Oreochromis mossambicus* and *Labeo rosae* had estimated daily intake values of MCs concentration in muscle that were 4.1 and 4.6 times, respectively, higher than the recommended tolerable daily intake (TDI) value on 0.04 μg kg^{-1} of body weight (Nchabeleng et al., 2014). In some Southern African water ecosystems that are sources of drinking water, the presence of MCs at concentrations higher than 1 μg L^{-1} is especially worrisome (Mhlanga et al., 2006; Pedro et al., 2012; Recknagel et al., 2017).

Table 2 African waterbodies that contained MCs concentrations greater than the WHO's guideline value for short-term drinking-water and recreational water

Country	Name of water-body	Sampling year	Maximum MCs content	Cyanobacteria	Methods of quantification	References
South Africa	Hartbeespoort Reservoir	2005	3200 μg L^{-1}	*Microcystis* spp. and *Dolichospermum* sp.	ELISA	Conradie and Barnard (2012)
	Roodeplaat Reservoir	2005	217 μg L^{-1}	*Microcystis* spp., *Planktothrix* sp., and *Dolichospermum* sp.	ELISA	Conradie and Barnard (2012)
	Nhlanganzwani Reservoir	2007	49,410 μg L^{-1}	*Microcystis* sp.	ELISA	Masango et al. (2010)
		2007	23,718 μg L^{-1}	*Microcystis* sp.	ELISA	Oberholster et al. (2009)
	Mpanamana Reservoir	2007	1,630 μg L^{-1}	*Microcystis* sp.	ELISA	Masango et al. (2010)
	Makhohlola Reservoir	2007	104 μg L^{-1}	–	ELISA	Masango et al. (2010)
	Sunset Reservoir	2007	253 μg L^{-1}	*Microcystis* sp.	ELISA	Masango et al. (2010)
Ethiopia	Lake Koka	2006	45 μg L^{-1}	*Microcystis* spp. and *Dolichospermum* sp.	HPC-DAD	Willén et al. (2011)
		2013–2014	33 μg L^{-1}	*Microcystis* spp., *Raphidiopsis* (Formerly: *Cylindrospermopsis*) spp., *Dolichospermum* sp., etc.	HPLC–MS/MS	Major et al. (2018)
		2015	27.4 μg L^{-1}	*Microcystis* spp.	HPLC–MS/MS	Tilahun et al. (2019)
	Legedadi Reservoir	2018	453.89 μg L^{-1}	*Microcystis* sp., and *Dolichospermum* spp.	HPLC–MS/MS	Habtemariam et al. (2021)
Kenya	Lake Victoria	2011–2012	2,000 μg L^{-1}	*Microcystis* sp. and *Dolichospermum* sp.	HPLC–DAD	Simiyu et al. (2018)
Algeria	Lake Oubeira	2000–2001	29,163 μg L^{-1}	*Microcystis* sp., *Oscillatoria* sp., *Planktothrix* sp., etc.	HPLC–MS/MS and MALDI-TOF	Nasri et al. (2004)
		2010–2011	13.4 μg L^{-1}	–	HPLC–MS/MS	Amrani et al. (2014)
Egypt	Fish Ponds, Sohag province	2012–2013	44 μg L^{-1}	*Microcystis* sp., *Dolichospermum* sp., *Planktothrix* sp., etc.	ELISA	Mohamed et al. (2020)
Morocco	Lake Lalla Takerkoust	–	22,240 μg L^{-1}	*Microcystis* sp.	HPLC–DAD-MS/MS and MALDI-TOF	El Khalloufi et al. (2012)

HPLC high-performance liquid chromatography, *DAD* diode array detection, *ELISA* enzyme-linked immunosorbent assay, *MS* mass spectrometry, *PP2A* protein phosphatase type 2A

Table 3 Occurrence of cyanotoxins and cyanobacteria in some Southern African waterbodies

Country	Name of water-body	Sampling year	Maximum cyano-toxins content	Cyanobacteria	Methods of quan-tification	References
Botswana	Gaborone Pond	2014–2015	835.87 µg g^{-1} (MCs)	*Microcystis* spp. and *Dolichospermum* spp.	HPLC–MS/MS	Eguzozie et al. (2016)
Mozambique	Lake Nhambavale	2008–2009	7.89 µg L^{-1} (MCs)	*Microcystis* sp.	HPLC–MS/MS	Pedro et al. (2011, 2012)
	Chòkwé Irrigation Canals	2008–2010	0.73 µg L^{-1} (MCs)	*Microcystis* sp.	HPLC–MS/MS	Pedro et al. (2011, 2012)
	Pequenos Libombos Reservoir	2008–2011	0.1 µg L^{-1} (MCs)	*Microcystis* sp.	HPLC–MS/MS	Pedro et al. (2011, 2012)
South Africa	Hartbeespoort Reservoir	1984–1987	415 µg g^{-1} (MCs)	*Microcystis* sp.	HPLC	Wicks and Thiel (1990)
		2005	3,200 µg L^{-1} (MCs)	*Microcystis* spp. and *Dolichospermum* sp.	ELISA	Conradie and Barnard (2012)
		2010	9.1 µg L^{-1} (MCs)	–	ELISA	Mokoena and Mukhola (2019)
		2010–2011	468.04 µg g^{-1} (MCs)	*Microcystis* spp., *Spirulina* sp., and *Planktothrix* spp.	HPLC–MS/MS	Mbukwa et al. (2012)
		2011	3.6 µg L^{-1} (MCs)	*Microcystis* spp., *Sphaerospermopsis* spp., *Raphidiopsis* sp., etc.	HPLC–MS/MS	Ballot et al. (2013)
		2013	0.025 µg g^{-1} (MCs), 1.5 (BMAA) µg g^{-1}	*Microcystis* spp.	ELISA	Scott et al. (2018)
	A reservoir in Paarl District	1994	1,900 µg g^{-1} (MCs)	*Microcystis* sp.	HPLC	Van Halderen et al. (1995)
	Lake Zeekoevlei	1994	347,000 µg g^{-1} (NOD)	*Microcystis* sp. and *Nodularia* sp.	HPLC–DAD	Harding et al. (1995)
	Roodeplaat reservoir	2005	217 µg L^{-1} (MCs)	*Microcystis* spp., *Planktothrix* sp., and *Dolichospermum* sp.	ELISA	Conradie and Barnard (2012)
	Nhlanganzwani Reservoir	2007	49,410 µg L^{-1} (MCs)	*Microcystis* sp.	ELISA	Masango et al. (2010)
		2007	23,718 µg L^{-1} (MCs)	*Microcystis* sp.	ELISA	Oberholster et al. (2009)
	Mpanamana Reservoir	2007	1,630 µg L^{-1} (MCs)	*Microcystis* sp.	ELISA	Masango et al. (2010)
	Makhohlola Reservoir	2007	104 µg L^{-1} (MCs)	–	ELISA	Masango et al. (2010)
	Sunset Reservoir	2007	253 µg L^{-1} (MCs)	*Microcystis* sp.	ELISA	Masango et al. (2010)
	Vaal Reservoir	2007–2015	5 µg L^{-1} (MCs)	–	ELISA	Recknagel et al. (2017)
	Loskop Reservoir	2012	3.25 µg L^{-1} (MCs)	*Microcystis* sp.	ELISA	Nchabeleng et al. (2014)

Table 3 (continued)

Country	Name of water-body	Sampling year	Maximum cyano-toxins content	Cyanobacteria	Methods of quan-tification	References
	Crocodile Breed-ing Reservoir	2014–2015	8.27 μg L^{-1} (MCs)	–	HPLC–MS/MS	Singo et al. (2017)
	Swartspruit River	2014–2015	500.16 μg g^{-1} (MCs)	*Microcystis* spp., *Planktothrix* sp., and *Spirulina* sp.	HPLC–MS/MS	Eguzozie et al. (2016)
Zimbabwe	Lake Chivero	2003–2004	4.2 μg L^{-1} (MCs)	*Microcystis* spp., *Planktothrix* sp., and *Dolichospermum* sp.	ELISA	Mhlanga et al. (2006)

Microcystis is the most frequently reported (82.3%) cyanobacteria together with the cyanotoxin in Southern African water resources. Some South African waterbodies, including the Vaal Reservoir, Theewaterskloof Reservoir, Hartbeespoort Reservoir, Lake Zeekoevlei, and Orange River, have been found to contain potentially toxin-producing cyanobacteria such as *Microcystis aeruginosa*, *Microcystis flos-aquae*, *Dolichospermum* spp., *Oscillatoria* spp., *Nodularin spumigena* and *Raphidiopsis raciborskii*, *Spirulina* spp., and *Planktothrix* (Harding & Paxton, 2001; Scott et al., 1981; Steyn, 1945; Van Halderen et al., 1995).

East Africa

The concentrations of MCs in East African waterbodies ranged from trace to hazardous levels, reaching up to 453.89 μg L^{-1} (Legedadi Reservoir, Ethiopia) and 19,800 μg g^{-1} (Lake Baringo, Kenya) (Table 4). From 33 water resources surveyed, the majority of them (57.6%) had MCs concentrations over the WHO standard for drinking water (1 μg L^{-1}). Lake Koka (Ethiopia), Legedadi Reservoir (Ethiopia), and Lake Victoria (Uganda) contained MCs levels that exceed WHO guideline limits of drinking water for short duration and recreational water. Legedadi Reservoir, a major supply of drinking water for Addis Ababa, Ethiopia, had an extremely high MCs concentration (453.89 μg L^{-1}), which could be hazardous to end users' health (Major et al., 2018). Five lakes in Kenya (Lakes Baringo, Simbi, Sonachi, Bogoria, and Nakuru) contain the neurotoxic ATX-a, with concentrations up to 1260 μg g^{-1} (Lake Baringo).

Lesser Flamingo deaths were associated with the hot spring shore of Lake Bogoria, which had three times more MCs content than the western shore (Ballot et al., 2004; Krienitz et al., 2003). Different MC variants, specifically MC-LR, MC-YR, MC-RR, MC-LA, MC-LF, MC-dmLR, MC-dmRR, LA[NMeSer^7]-MC-YR, [Asp^3]-MC-RY, [MeAsp^3]-MC-RY, and [NMeSer^7]-MC-YR), were found in both the water samples and algal seston (Habtemariam et al., 2021; Major et al., 2018; Okello et al., 2010; Olokotum et al., 2022). CYN was found to be the most prevalent cyanotoxin found around the lakeshores in Lake Victoria, Tanzania, where NOD and MCs also co-occurred (Mchau et al., 2021). HTX was also reported in Lake Victoria, Uganda.

Microcystis dominated the freshwater bodies of East Africa, which occurred in 81.8% of the surveyed waterbodies. The cyanobacterial genera *Merismopedia*, *Dolichospermum*, *Arthrospira*, *Pseudanabaena*, and *Anabaenopsis* are present in at least five water ecosystems of East Africa in the habitats that exhibited detectable cyanotoxins. *Arthrospira fusiformis* dominated three of the five water resources that contained ATX-a (Lakes Simbi, Sonachi, and Bogoria). ATX-a and MC-YR were produced by *A. fusiformis* monocyanobacterial strain that was isolated from Lake Sonachi (Ballot et al., 2005). The *mcyE* gene, a member of the microcystin synthesis gene cluster, in field samples taken from Lake Naivasha in Kenya, and the *mcyB* genotype of *Microcystis* and *Planktothrix* species in freshwater lakes in Uganda were identified to produce cyanotoxins (Krienitz et al., 2013; Okello et al., 2010).

Table 4 Occurrence of cyanotoxins and cyanobacteria in some Eastern African waterbodies

Country	Name of waterbody	Sampling year	Maximum cyanotoxins content	Cyanobacteria	Methods of quantification	References
Ethiopia	Lake Chamo	2006	3.9 μg L^{-1} (MCs)	*Microcystis* spp., *Raphidiopsis* spp., and *Dolichospermum* sp.	HPC-DAD	Willén et al. (2011)
	Lake Langano	2006	1.5 μg L^{-1} (MCs)	*Microcystis* spp.	HPC-DAD	Willén et al. (2011)
	Lake Ziway	2006	1.3 μg L^{-1} (MCs)	*Microcystis* sp.	HPC-DAD	Willén et al. (2011)
	Lake Koka	2006	45 μg L^{-1} (MCs)	*Microcystis* spp. and *Dolichospermum* sp.	HPC-DAD	Willén et al. (2011)
		2013–2014	33 μg L^{-1} (MCs)	*Microcystis* spp., *Raphidiopsis* spp., *Dolichospermum* sp., etc.	HPLC–MS/MS	Major et al. (2018)
		2015	27.4 μg L^{-1} (MCs)	*Microcystis* spp.	HPLC–MS/MS	Tilahun et al. (2019)
	Lake Hora	2008–2009	2.99 μg L^{-1} (MCs)	*Microcystis* sp., *Raphidiopsis* spp., and *Cryptosporiopsis* sp.	HPLC–MS/MS	Zewde et al. (2020)
	Lake Tana	2009–2011	2.65 μg L^{-1} (MCs)	*Microcystis* spp. and *Pseudanabaena* sp.	HPLC–DAD	Mankiewicz-Boczek et al. (2015)
	Legedadi Reservoir	2018	453.89 μg L^{-1} (MCs)	*Microcystis* sp., and *Dolichospermum* spp.	HPLC–MS/MS	Habtemariam et al. (2021)
Kenya	Muruaki Reservoir	1998–2000	1.56 μg L^{-1} (MCs)	*Microcystis* sp.	ELISA	Mwaura et al. (2004)
	Kahuru Reservoir	1998–2001	2.85 μg L^{-1} (MCs)	*Microcystis* sp.	ELISA	Mwaura et al. (2004)
	Murungaru Reservoir	1998–2002	0.33 μg L^{-1} (MCs)	*Microcystis* sp.,	ELISA	Mwaura et al. (2004)
	Lake Victoria	2001	41.4 μg g^{-1} (MCs)	*Microcystis* sp. and *Dolichospermum* spp.	HPLC–DAD and MALDI-TOF	Krienitz et al. (2002)
		2011–2012	2000 μg L^{-1} (MCs)	*Microcystis* sp. and *Dolichospermum* sp.	HPLC–DAD	Simiyu et al. (2018)
	Lake Baringo	2001–2002	19,800 μg g^{-1} (MCs), 1,260 μg g^{-1} (ATX-a)	*Microcystis* sp., *Dolichospermum* spp., *Pseudanabaena* sp., etc.	HPLC–DAD and MALDI-TOF	Ballot et al. (2003)
	Lake Simbi	2001–2002	39 μg g^{-1} (MCs), 1.4 μg g^{-1} (ATX-a)	*Arthrospira* sp., *Anabaenopsis* sp., *Phormidium* sp., etc.	HPLC–DAD and MALDI-TOF	Ballot et al. (2005), Kotut et al. (2006)
	Lake Sonachi	2001–2002	12 μg g^{-1} (MCs), 2 μg g^{-1} (ATX-a)	*Arthrospira* sp., *Anabaenopsis* sp., *Oscillatoria* sp., etc.	HPLC–DAD and MALDI-TOF	Ballot et al. (2005), Kotut et al. (2006)

Table 4 (continued)

Country	Name of water-body	Sampling year	Maximum cyano-toxins content	Cyanobacteria	Methods of quantification	References
	Lake Bogoria	2001–2002	227 μg g^{-1} (MCs), 9 μg g^{-1} (ATX-a)	*Arthrospira* sp., *Synechococcus* spp., *Synechocystis* sp., etc.	HPLC–DAD and MALDI-TOF	Ballot et al. (2004), Kotut et al. (2006)
		2001–2002	155 μg g^{-1} (MCs), 9 μg g^{-1} (ATX-a)	*Arthrospira* sp., *Synechococcus* spp., *Synechocystis* sp., etc.	HPLC–DAD and MALDI-TOF	Ballot et al. (2004), Kotut et al. (2006)
		2001 (Hot spring)	845 μg g^{-1} (MCs), 18 μg g^{-1} (ATX-a)	*Phormidium* sp., *Oscillatoria* sp., *Spirulina* sp., etc.	HPLC–DAD and MALDI-TOF	Krienitz et al. (2003)
	Lake Nakuru	2001–2002	4,594 μg g^{-1} (MCs), 223 μg g^{-1} (ATX-a)	*Arthrospira* sp., *Anabaenopsis* sp., *Synechocystis* sp., etc.	HPLC–DAD and MALDI-TOF	Kotut et al. (2006)
	Lake Elmenteita	2001–2003	202 μg g^{-1} (MCs)	*Arthrospira* sp., *Anabaenopsis* sp., *Synechocystis* sp., etc.	HPLC–DAD and MALDI-TOF	Ballot et al. (2004), Kotut et al. (2006)
	Nakuru Oxidation Ponds	2001–2006	280 μg g^{-1} (MCs)	*Microcystis* sp. and *Arthrospira* sp.	HPLC–DAD and MALDI-TOF	Kotut et al. (2010)
	Ngeki Reservoir	2007–2008	0.14 μg L^{-1} (MCs)	*Microcystis* sp., *Anabaenopsis* sp., and *Merismopedia* sp.	HPLC–DAD	Kaggwa et al. (2018), Straubinger-Gansberger et al. (2014)
	Ngei Reservoir	2007–2008	0.22 μg L^{-1} (MCs)	*Microcystis* sp. and *Merismopedia* sp.	HPLC–DAD	Kaggwa et al. (2018), Straubinger-Gansberger et al. (2014)
	Lukenya Reservoir	2007–2008	0.70 μg L^{-1} (MCs)	*Microcystis* sp.	HPLC–DAD	Kaggwa et al. (2018)
	Ruthagati Reservoir	2007–2008	0.46 μg L^{-1} (MCs)	*Microcystis* sp.	HPLC–DAD	Kaggwa et al. (2018)
	Mailo Reservoir	2007–2008	0.61 μg L^{-1} (MCs)	*Microcystis* sp., *Aphanocapsa* sp., and *Merismopedia* sp.	HPLC–DAD	Kaggwa et al. (2018), Straubinger-Gansberger et al. (2014)
	Sagana Reservoir	2007–2008	0.18 μg L^{-1} (MCs)	*Microcystis* sp., *Aphanocapsa* sp., and *Merismopedia* sp.	HPLC–DAD	Kaggwa et al. (2018), Straubinger-Gansberger et al. (2014)
	Harambe Reservoir	2007–2008	0.13 μg L^{-1} (MCs)	*Microcystis* sp.	HPLC–DAD	Kaggwa et al. (2018)
	Bomet Reservoir	2007–2008	0.89 μg L^{-1} (MCs)	*Microcystis* sp. *Planktolyngbya* sp., and *Merismopedia* sp.	HPLC–DAD	Kaggwa et al. (2018), Straubinger-Gansberger et al. (2014)
	Lake Naivasha	2008–2013	0.3 μg g^{-1}	*Microcystis* sp., *Planktothrix* sp.	HPLC–PDA and HPLC–MS/ MS	Krienitz et al. (2013)

Table 4 (continued)

Country	Name of waterbody	Sampling year	Maximum cyanotoxins content	Cyanobacteria	Methods of quantification	References
		2010–2011	0.08 μg L^{-1} (MCs)	*Microcystis* sp., *Dolichospermum* sp., *Spirulina* sp., etc.	ELISA	Raffoul et al. (2020)
Tanzania	Lake Victoria	2018	0.02 μg L^{-1} (MCs), 0.01 μg L^{-1} (NOD), and 0.01 μg L^{-1} (CYN)	–	HPLC–MS/MS	Mchau et al. (2021)
Uganda	Lake Victoria	2004–2005	0.7 μg L^{-1} (MCs)	–	HPLC–MS/MS	Semyalo et al. (2010)
		2007–2008	1.6 μg L^{-1} (MCs)	–	HPLC–DAD and MALDI-TOF–MS	Okello et al. (2010)
		2016–2017	15 μg L^{-1} (MCs), 0.04 μg L^{-1} (HTX)	*Microcystis* spp., *Chroococcus* spp., and *Dolichospermum* spp.	HPLC–DAD-MS	Olokotum et al. (2022)
	Lake Mburo	2004–2005	0.26 μg L^{-1} (MCs)	–	HPLC–MS/MS	Semyalo et al. (2010)
		2007–2008	3.2 μg L^{-1} (MCs)	*Microcystis* sp. and *Dolichospermum* sp.	HPLC–DAD and MALDI-TOF–MS	Okello et al. (2010)
	Lake Saka	2007–2008	10.2 μg L^{-1} (MCs)	*Microcystis* sp., and *Planktothrix* sp.	HPLC–DAD and MALDI-TOF–MS	Okello et al. (2010)
	Lake George	2007–2008	0.5 μg L^{-1} (MCs)	*Microcystis* sp.	HPLC–DAD and MALDI-TOF MS	Okello et al. (2010)
	Lake Edward	2007–2008	1.5 μg L^{-1} (MCs)	*Microcystis* sp.	HPLC–DAD and MALDI-TOF MS	Okello et al. (2010)

North Africa

MCs occurred in all of the North African waterbodies surveyed, with many congeners detected from various ecosystems (up to 21 in Lake des Oiseaux) (Bouhaddada et al., 2016). Of the 19 aquatic ecosystems documented, 63.2% had MCs concentrations higher than the WHO's provisional recommendation limit of 1 μg L^{-1} for drinking water (Table 5). Fish ponds in the Sohag province (Egypt), Lalla Takerkoust Reservoir (Morocco), and Lake Oubeira (Algeria) have cyanotoxins levels beyond the WHO guidelines for short-term drinking water use and recreational water. In the province of Sohag, a fish pond with a high concentration of CYN (2.76 μg L^{-1}) may cause the accumulation of the toxin in fish, putting consumers at risk. The main sources of drinking water, Lake Oubeira and Lalla Takerkoust Reservoir contained extremely high levels of MCs up to 29,163 μg L^{-1}. The presence of high concentrations of MCs was linked to turtle deaths that occurred during a *Microcystis* spp. bloom in Lake Oubeira (Nasri et al., 2008). Tomato plants exposed to a crude extract of a harmful cyanobacterial bloom from Lalla Takerkoust Reservoir experienced leaf tissue necrosis (El Khalloufi et al., 2012).

There are a few instances in Egypt and elsewhere where water treatment plants not only failed to completely remove cyanobacterial cells and degrade toxins, but also lysed the cyanobacteria's cells and

Table 5 Occurrence of cyanotoxins and cyanobacteria in some Northern African waterbodies

Country	Name of waterbody	Sampling year	Maximum cyanotoxins content	Cyanobacteria	Methods of quantification	References
Algeria	Lake Oubeira	2000–2001	29,163 μg L^{-1} (MCs)	*Microcystis* sp., *Oscillatoria* sp., *Planktothrix* sp., etc.	HPLC–MS/MS and MALDI-TOF	Nasri et al. (2004)
		2005	1120 μg g^{-1} (MCs)	*Microcystis* spp.	HPLC–MS/MS	Nasri et al. (2008)
		2010–2011	13.4 μg L^{-1} (MCs)	–	HPLC–MS/MS	Amrani et al. (2014)
	Cheffia Reservoir	2004	28.9 μg g^{-1} (MCs)	*Microcystis* sp., *Dolichospermum* sp., and *Oscillatoria* sp.	HPLC–MS/MS	Nasri et al. (2007)
	Lake des Oiseaux	2013	62 μg g^{-1} (MCs)	*Microcystis* spp. and *Dolichospermum* sp.	HPLC–MS/MS	Bouhaddada et al. (2016)
	Guenitra Reservoir	2016	1.5 μg L^{-1} (MCs)	*Microcystis* sp., *Limnococcus* sp., *Coelomoron* sp. etc.	ELISA	Boufligha et al. (2021)
Egypt	Nile River	1999	0.78 μg L^{-1} (MCs)	*Oscillatoria* sp., *Microcystis* sp., *Merismopedia* sp., etc.	ELISA	Mohamed and Carmichael (2000)
		2013	4.5 μg L^{-1} (MCs)	*Microcystis* sp., *Gloeocapsa* sp., *Gomphosphaeria* sp., etc.	ELISA	Mohamed et al. (2015)
		2013	0.8 μg g^{-1} (MCs)	*Oscillatoria* sp., *Merismopedia* sp., and *Gomphosphaera* sp.	ELISA	Mohamed (2016a, 2016b)
	El-Dowyrat Fish Ponds	2000	1120 μg g^{-1} (MCs)	*Microcystis* sp., *Merismopedia* sp., *Oscillatoria* sp., etc.	ELISA	Mohamed et al. (2003)
	Fish Ponds, Sohag province	2012–2013	2.76 μg L^{-1} (CYN)	*Dolichospermum* sp., *Lyngbya* sp., *Planktothrix* sp., etc.	HPLC–DAD	Mohamed and Bakr (2018)
		2012–2013	44 μg L^{-1} (MCs)	*Microcystis* sp., *Dolichospermum* sp., *Planktothrix* sp., etc.	ELISA	Mohamed et al. (2020)
Morocco	Lake Lalla Takerkoust	1994–1997	1777.64 μg g^{-1} (MCs)	*Microcystis* sp. and *Pseudoanabaena* sp.	HPLC–DAD	Oudra et al. (2002)
		–	22,240 μg L^{-1} (MCs)	*Microcystis* sp.	HPLC–DAD-MS/MS and MALDI-TOF	El Khalloufi et al. (2012)
	Mansour Eddahbi Reservoir	2004	64.4 μg g^{-1} (MCs)	*Microcystis sp.*, *Pseudanabaena* sp. and *Oscillatoria* sp.	HPLC- DAD-MS	Douma et al. (2010)

Table 5 (continued)

Country	Name of waterbody	Sampling year	Maximum cyanotoxins content	Cyanobacteria	Methods of quantification	References
	Almassira Reservoir	2004	9.9 μg g^{-1} (MCs)	*Microcystis* sp., *Pseudanabaena* sp., *Oscillatoria* spp., etc.	HPLC- DAD-MS	Douma et al. (2010)
Tunisia	Chiba River	2003	0.67 μg L^{-1} (MCs)	*Oscillatoria* sp., *Pseudanabaena* sp., *Merismopedia* sp., etc.	PP2A	Jenhani et al. (2006)
	Mlaabi Reservoir	2003	1.55 μg L^{-1} (MCs)	*Oscillatoria* spp., *Pseudanabaena* sp., *Merismopedia* sp., etc.	PP2A	Jenhani et al. (2006)
	Bezirk Reservoir	2003	1.15 μg L^{-1} (MCs)	*Oscillatoria* sp., *Pseudanabaena* sp., *Merismopedia* sp., etc.	PP2A	Jenhani et al. (2006)
	Bir Mcherga Reservoir	2004	0.95 μg L^{-1} (MCs)	*Microcystis* sp., *Oscillatoria* spp., *Planktothrix* sp., etc.	PP2A	Jenhani et al. (2006)
	Masri Reservoir	2003	0.8 μg L^{-1} (MCs)	*Oscillatoria* spp., *Merismopedia* sp., and *Chroococcus* sp.	PP2A	Jenhani et al. (2006)
	Sejnène Reservoir	2001–2002	0.85 μg L^{-1} (MCs)	*Oscillatoria* spp., *Phormidium* sp., *Pseudanabaena* sp., etc.	PP2A	Jenhani et al. (2006)
	Joumine Reservoir	2001–2002	0.18 μg L^{-1} (MCs)	*Oscillatoria* spp. and *Merismopedia* sp.	PP2A	Jenhani et al. (2006)
	Hjar Reservoir	2003	7.95 μg L^{-1} (MCs)	*Microcystis* sp., *Oscillatoria* spp., *Pseudanabaena* sp., etc.	PP2A	Jenhani et al. (2006)
		2003	7.46 μg L^{-1} (MCs)	*Oscillatoria* spp. and *Pseudanabaena* sp.	PP2A	El Herry et al. (2007)
	Lebna Reservoir	2003	1 μg L^{-1} (MCs)	*Microcystis* sp., *Oscillatoria* spp., *Pseudanabaena* sp., etc.	PP2A	Jenhani et al. (2006)
		2005	5.57 μg L^{-1} (MCs)	*Microcystis* spp., *Oscillatoria* sp., *Phormidium* sp., etc.	PP2A	El Herry et al. (2008)

released significant amounts of MCs (Eynard et al., 2000; Ling, 2000; Mohamed et al., 2015; Mohamed, 2016a). The final treated water's MCs concentration was 3.8 μg L^{-1}, much higher than the quantity found in the untreated water source from Egypt's Nile River (Mohamed, 2016a). Fishponds in Egypt contained considerably high concentrations of MCs and CYN that exceed WHO guideline values of 1 μg L^{-1}. The muscle of common carp from Lake Oubeira exceeded the WHO lifetime limit for the tolerated daily consumption of MCs (Amrani et al., 2014).

Oscillatoria was the most frequently reported (84.2%) cyanobacteria found with the cyanotoxins in water samples from North African waterbodies surveyed. Other cyanobacteria with a smaller frequency of occurrence include *Microcystis* (73.7%), *Pseudanabaena* (57.9%), *Merismopedia* (57.9%), *Chroococcus* (47.4%), *Dolichospermum* (36.8%), and *Planktothrix* (31.6%). The cyanobacterial cell density of some North African water systems positively correlated with MCs contents (Mohamed & Bakr, 2018; Mohamed et al., 2015; Nasri et al., 2007). *Anabaena affinis*, *Planktothrix agardhii*, *Raphidiopsis catemaco*, and *Capillaria philippinensis* were assigned as CYN producers for the first time in Egyptian fishponds (Mohamed & Bakr, 2018). The presence of the MCs synthetase genes (*mcyA*, *-B*, *-C*, *-D*, *-E,* and *-G*) in the *Microcystis* spp. isolates indicate that these species are responsible for the MCs production in a few North African water ecosystems (El Herry et al., 2008; Fathalli et al., 2011).

West Africa

All of the 26 waterbodies of three surveyed West African nations (Ghana, Nigeria, and Zimbabwe) contained MCs (Table 6). Major congeners of MCs such as MC-LR, MC-LF, MC-RR, and MC-YR were reported (Addico et al., 2017; Chia & Kwaghe, 2015). The WHO's guideline limit of drinking water 1 µg L^{-1} for MCs concentration was exceeded in 76.9% of the aquatic ecosystems. None of the water bodies' MCs levels, however, rose above the WHO threshold limits for recreation usage and drinking water for short periods. The Owabi Reservoir in Ghana, which provides drinking water to the Kumasi metropolitan area, had the highest MCs content (8.73 µg L^{-1}) of all the West African waters examined (Addico et al., 2017). The presence of MCs levels exceeding 1 µg L^{-1} in about ten coastal ecosystems in Nigeria shows that cyanotoxins are a concern that is not just present in inland waters. In Nigeria, Kwaru stream irrigated vegetables and the fish from some fish ponds in Zaria contained MCs values that exceed WHO recommended total daily intake value (0.04 µg kg^{-1} body weight) (Abdullahi et al., 2022; Chia et al., 2021).

Dolichospermum is the most frequently found (61.5%) cyanobacteria in the surveyed West African waterbodies where cyantoxins were measured. Other cyanobacterial genera found in at least 5 ecosystems examined include *Microcystis* (57.7%), *Oscillatoria* (57.7%), *Spirulina* (26.9%), *Chroococcus* (26.9%), *Marssoniella* (26.9%), *Planktothrix* (23%), *Trichodesmium* (23.1%), and *Merismopedia*(19.2%). All of the samples examined from 11 Nigerian coastal waters that contained the *mcy*E gene of the MC synthetase (*mcy*) cluster showed the presence of toxic strains of cyanobacteria (Kadiri et al., 2020). Many West African water systems showed a substantial positive association between MCs concentration and cyanobacterial density (Addico et al., 2017; Chia & Kwaghe, 2015; Chia et al., 2021).

Adverse effects of cyanotoxins in Africa

Research on the Vaal Reservoir, South Africa is the earliest known study on animal toxicity caused by algal blooms in Africa (Steyn, 1945). According to Steyn (1945), the algal-infested water was poisonous, and the degree of poisoning depended upon the number of algae consumed. Since then, many scholars have linked the poisoning of humans and animals in Africa to cyanotoxins (Harding et al., 1995; Krienitz et al., 2005; Nasri et al., 2008; Scott et al., 1981; Soll & Williams, 1985; Van Halderen et al., 1995; Zilberg, 1966).

In South Africa, between 1973 and 1974, cattle kills around Hartbeespoort Reservoir was linked to *M. aeruginosa* toxicity (Scott et al., 1981). In 1979, three white rhinoceroses (*Ceratotherium simum*) died related to *Microcystis* toxicity from Klipvoor Reservoir, Barakologadi Game Reserve (Soll & Williams, 1985). Postmortem macroscopic and microscopic pathology revealed acute hepatotoxicity, hepatomegaly with hemorrhage, severe liver necrosis, numerous ecchymoses, and petechiae. In 1994, a dog died after drinking water from Lake Zeekoevlei. Histopathological examination of the liver revealed periacinar fibrosis with duplication of the central veins, degeneration of hepatocytes, and the distention of the bile canuliculi with bile pigment (Van Halderen et al., 1995). The water contained cyanobacterial bloom of *Nodularia spumigena* (95%) and *Microcystis aeruginosa* that produced 3479 µg g^{-1} nodularin.

Table 6 Occurrence of cyanotoxins and cyanobacteria in some Western African waterbodies

Country	Name of waterbody	Sampling year	Maximum cyanotoxins content	Cyanobacteria	Methods of quantification	References
Ghana	Barekese Reservoir	2005	0.46 μg L^{-1} (MCs)	*Cyanogranis* sp., *Dolichospermum* spp., *Merismopedia* spp., etc.	HPLC–DAD	Addico et al. (2017)
	Owabi Reservoir	2005	8.73 μg L^{-1} (MCs)	*Cyanogranis* sp., *Planktolyngbya* spp., *Aphanocapsa* sp., etc.	HPLC–DAD	Addico et al. (2017)
	Kpong Reservoir	2005	4.69 μg L^{-1} (MCs)	*Geitlerinema* sp., *Planktothrix* sp., *Raphidiopsis* spp., etc.	HPLC–DAD	Addico et al. (2017)
	Weija Reservoir	2005	8.56 μg L^{-1} (MCs)	*Aphanocapsa* spp., *Merismopedia* spp., *Pseudanabaena* sp., etc.	HPLC–DAD	Addico et al. (2017)
Nigeria	Ahmadu Bello University (ABU) Reservoir	2008	2.4 μg L^{-1} (MCs)	*Marssoniella* sp., *Dolichospermum* sp., *Spirulina* sp., etc.	ELISA	Chia et al. (2009), Chia and Kwaghe (2015)
		2013	7.4 μg L^{-1} (MCs)	*Microcystis* sp., *Dolichospermum* sp., *Marssoniella* sp., etc.	ELISA	Chia and Kwaghe (2015)
	Lake Bomo	2008	3.8 μg L^{-1} (MCs)	*Marssoniella* sp., *Dolichospermum* sp., *Microcystis* sp., etc.	ELISA	Chia et al. (2009), Chia and Kwaghe (2015)
		2013	5.04 μg L^{-1} (MCs)	*Microcystis* sp., *Dolichospermum* sp., *Oscillatoria* sp., etc.	ELISA	Chia and Kwaghe (2015)
	Lake Makwaye	2008	2 μg L^{-1} (MCs)	*Microcystis* sp., *Spirulina* sp., *Marssoniella* sp., etc.	ELISA	Chia et al. (2009), Chia and Kwaghe (2015)
		2013	5.25 μg L^{-1} (MCs)	*Microcystis* sp., *Dolichospermum* sp., *Trichodesmium* sp., etc.	ELISA	Chia and Kwaghe (2015)
	Living Faith Church Zaria Pond 2	2008	1.6 μg L^{-1} (MCs)	*Microcystis* sp., *Spirulina* sp., *Marssoniella* sp., etc.	ELISA	Chia et al. (2009)
	Jim Harrison Pond	2008	1.4 μg L^{-1} (MCs)	*Dolichospermum* sp., *Microcystis* sp., *Marssoniella* sp., sp., etc.	ELISA	Chia et al. (2009)
	Mairabo Pond 1	2008	0.15 μg L^{-1} (MCs)	*Spirulina* sp. and *Marssoniella* sp.,	ELISA	Chia et al. (2009)
	Zaria Reservoir	2013	6.25 μg L^{-1} (MCs)	*Microcystis* sp., *Dolichospermum* sp., *Synechococcus* sp., etc.	ELISA	Chia and Kwaghe (2015)

Table 6 (continued)

Country	Name of waterbody	Sampling year	Maximum cyanotoxins content	Cyanobacteria	Methods of quantification	References
	Cross River	2014–2015	2.6 μg L^{-1} (MCs)	–	ELISA	Kadiri et al. (2020)
	Akwa Ibom Ocean	2014–2015	1.18 μg L^{-1} (MCs)	*Oscillatoria* sp.	ELISA	Kadiri et al. (2020)
	Eleme River	2014–2015	7.44 μg L^{-1} (MCs)	*Lyngbya* sp. and *Oscillatoria* spp.	ELISA	Kadiri et al. (2020)
	Brass River Bayelsa	2014–2015	2.31 μg L^{-1} (MCs)	–	ELISA	Kadiri et al. (2020)
	Delta Ocean	2014–2015	5.08 μg L^{-1} (MCs)	*Microcystis* sp., *Lyngbya* sp., *Dolichospermum* sp., etc.	ELISA	Kadiri et al. (2020)
	Obineyin Estuary Ondo	2014–2015	3.92 μg L^{-1} (MCs)	*Oscillatoria* sp.	ELISA	Kadiri et al. (2020)
	Ogun Ocean	2014–2015	4.79 μg L^{-1} (MCs)	*Dolichospermum* sp., *Oscillatoria* spp., and *Planktothrix* sp.	ELISA	Kadiri et al. (2020)
	Ikota River	2014–2015	7.75 μg L^{-1} (MCs)	*Trichodesmium* sp. and *Oscillatoria* spp.	ELISA	Kadiri et al. (2020)
	Bar Beach Ocean	2014–2015	4.31 μg L^{-1} (MCs)	*Trichodesmium* sp., *Oscillatoria* spp., *Lyngbya* sp., etc.	ELISA	Kadiri et al. (2020)
	Gbaji River	2014–2015	3.81 μg L^{-1} (MCs)	*Oscillatoria* spp.	ELISA	Kadiri et al. (2020)
	Nagoyi Fish Pond	2018	0.2 μg L^{-1} (MCs)	*Microcystis* spp., *Nostoc* sp., *Chroococcus* sp., etc.	ELISA	Chia et al. (2021)
	Danlami Fish Pond	2018	0.3 μg L^{-1} (MCs)	*Microcystis* spp., *Nostoc* sp., *Chroococcus* sp., etc.	ELISA	Chia et al. (2021)
	Bal & Kol Fish Ponds	2018	0.303 μg L^{-1} (MCs)	*Microcystis* spp., *Nostoc* sp., *Calothrix* sp., etc.	ELISA	Chia et al. (2021)
	Kwaru stream	2019	0.05 μg L^{-1} (MCs)	*Planktothrix* sp., *Microcystis* sp., *Dolichospermum* sp., etc.	ELISA	Abdullahi et al. (2022)

Oberholster et al. (2009) associated the possible cause of the mortalities of the white rhinoceroses, zebra, wildebeest, and other wild animals in Nhlanganzwane Reservoir, South Africa with acute exposure to MCs toxins. Similarly, the wildlife mortality near four South African reservoirs (Nhlanganzwani, Mpanamana, Makhohlola, and Sunset) in Kruger National Park was also associated with *Microcystis* blooms, which were confirmed to be toxic using mouse and fish (*Clarias gariepinus*) bioassays (Masango et al., 2010). Animal (e.g., fish, giraffes, cows, sheep, etc.) poisoning and deaths around some South African waterbodies, including the Vaal Reservoir, Eastern Transvaal Reservoir, Bloemh Reservoir, Klipdrif Reservoir, Theewaterskloof Reservoir, Erfenis Reservoir, and Orange River, were linked to the toxicity of cyanotoxins (Harding, 1997; Harding & Paxton, 2001; Scott, 1991; Theron, 1990a, 1990b; Van Ginkel & Hohls, 1999).

Cyanotoxins (MCs and ATX-a) ingestion was associated with the mass mortality of lesser flamingos at Lake Bogoria, Kenya (Krienitz et al., 2003, 2005). Death of lesser flamingos related to cyanotoxins is also reported in Lakes Big and Manyara, Tanzania

(Lugomela et al., 2006). The mortality of freshwater turtles (*Emys orbicularis* and *Mauremys leprosa*) was associated with MCs in Lake Oubeira, Algeria (Nasri et al., 2008). Similarly, deaths and illnesses in wild and domestic animals in the Ethiopian Rift Valley lake areas were also linked to cyanotoxins (Willén et al., 2011). Moreover, Zilberg (1966) related gastroenteritis, skin rashes, itching, and sore eyes of children to the production of algal toxins from Lake Mcllwaine, Salisbury (now Harare).

Awareness, efforts of control, and possible solutions

Several efforts have been made to lessen eutrophication in South Africa since the 1970s (Van Ginkel, 2010, 2011). As a result, many eutrophication control strategies were put into practice, including biomanipulation, lowering detergent P levels, predicting cyanobacterial blooms, and disrupting epilimnion by laminar flow (Van Ginkel, 2011). Lake McIlwaine (now Lake Chivero) in Zimbabwe is an example of a successful eutrophication recovery. The long-term research by the Hydrobiology Research Unit of the University of Rhodesia (now the University of Zimbabwe) since 1967 was combined with intensive monitoring efforts by the City of Salisbury. These efforts included diverting nutrients to pasture irrigation schemes, extensive publicity and developing water pollution control legislation and control of the water hyacinth. As a result, the lake was changed to mesotrophy by the end of the 1970s from hypereutrophic condition in 1971 (Thornton, 1982).

Many African countries have legislations that set standards for effluent discharges including the Republic of South Africa Water Act; Zimbabwe Water Act; Kenyan Water Act; Malawian Water Resources Act; Zambian Natural Resources Conservation Act and Water Pollution Control Act (Brown et al., 2020; Thornton & Boddington, 1989). For instance, South Africa limits ammonia release to water resources to less than 6 mg L^{-1}, whereas Zimbabwe limits nitrate, ammonia, and phosphorus concentrations to under 10, 0.5, and 1 mg L^{-1}, respectively (McKendrick, 1982; NWA, 1998; Wiechers & Heynike, 1986). The Ethiopian Environmental Protection Authority has set the concentrations of ammonia, nitrate, and dissolved phosphorus to be less than 5, 20, and 5 mg L^{-1}, respectively, before discharge to inland waters (EEPA, 2011; FDRE, 2002). Additionally, numerous measures for soil and water conservation have been put into place, but it is important to regularly examine how they will affect the improvement of water quality (Reij, 1991).

Different approaches are used worldwide to control cyanotoxin concentration below acceptable drinking and recreational water limits. These approaches prevent bloom occurrence and eradicate cyanobacterial blooms (Merel et al., 2013). To prevent cyanobacterial blooms occurrence, monitoring the quantity of nutrients (C, N, and P), sediment dredging, sediment inactivation (usually by using aluminum sulfate), dosing with aluminum sulfate (to bind P and make it limiting for cyanobacterial growth), biomanipulation of the food web (using microorganisms such as viruses, fungi, bacteria, zooplankton, and algae), accurate prediction of cyanobacterial growth cycles, and mechanical disturbance of the epilimnion are essential (Harding & Paxton, 2001; Merel et al., 2013; Van Ginkel, 2011). On the other hand, eradication of occurring cyanobacterial blooms requires applying an algaecide, usually copper sulfate (Hrudey et al., 1999). However, this technique should be applied with caution since it releases intracellular toxins as a result of cell lysis (Jones & Orr, 1994; Peterson et al., 1995) and induce Cu^{2+} accumulation on the sediment causing copper toxicity that allows cyanobacterial blooms a few weeks later (Merel et al., 2013).

Regular monitoring of nutrient, cyanobacteria and cyanotoxin load is required in African waterbodies. Waterbody management, watershed management, and land-use planning are necessary to reduce nutrient enrichment of water ecosystems (Chorus & Welker, 2021; WHO, 2016). Controlling human exposure is the only remaining option for management if control measures on these levels are absent or fall short of their goals(Chorus & Welker, 2021). Options for addressing this range from educating users—that is, raising knowledge and guiding personal reactions to bloom situations—to temporarily limiting access to aquatic ecosystems during the bloom (Chorus, 2005; Stauffer et al., 2019).

Contrary to freshwaters, the public is generally well aware about algal toxins for the marine environment (Chorus & Welker, 2021). Even though scientific understanding has been expanding in Africa for decades (Harding & Paxton, 2001), the general public does not seem to be sufficiently informed about cyanotoxins (Harding et al., 2009; Mohamed, 2016a). Therefore, public gatherings, radio broadcasts, warning signs near impacted waterbodies and the dispersal of information booklets must be used to distribute pertinent information.

Conclusions

This meta-analysis review documented occurrences of cyanobacteria and cyanotoxins among African waterbodies. It showed how widely cyanotoxins have spread throughout African aquatic ecosystems and the resulting health dangers to people and animals. MCs were reported in at least 95 African water resources. ATX-a, CYN, NOD, and HTX were quantified in few aquatic ecosystems. *Microcystis* spp. dominated the East and Southern African water systems with cyanotoxins in water samples, while *Oscillatoria* spp. and *Dolichospermum* spp. were most frequently found in North and West African waters. Extremely high concentrations of MCs are reported from African aquatic resources and large concentrations of cyanotoxins have been linked to animal mass mortalities. Most of the water resources examined had MCs concentrations higher than the WHO recommendation of drinking water (1 μg L^{-1}). This indicates a high potential risk to public health when exposed to the toxins during recreational, domestic, and daily activities. Therefore, it is crucial to regularly monitor cyanotoxins in fish, treatment centers, and drinking water sources. Watershed management activities and point-source pollution control are essential for reducing the excessive levels of nutrients loading and eutrophication into the African waterbodies. Furthermore, the standards set in relation to nutrients' concentration for African waterbodies should be revised to adopt the international standards.

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