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Research Paper

Meta-analysis reveals cyanotoxins risk across African inland waters

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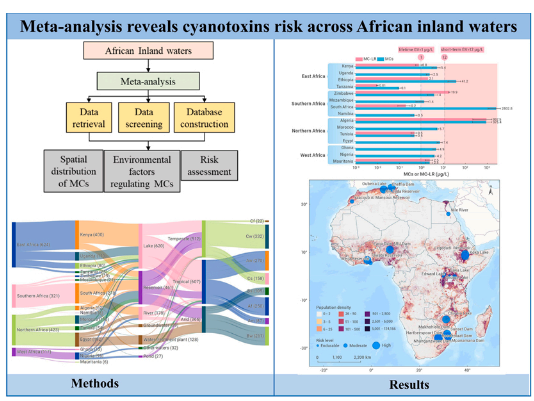
HIGHLIGHTS

- A database was established for microcystins (MCs) in African inland waters.
- In 12 studied countries, MC concentrations exceeded by 1.4–2803 times the guideline.
- MC occurrence is most hazardous in reservoirs and lakes, and in the temperate zone.
- Waterbodies providing drinking water in Africa have a high risk of MC-exposure.
- MCs were significantly positively related to planktonic chlorophyll a concentration.

GRAPHICAL ABSTRACT



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A B S T R A C T

Global eutrophication and climate warming exacerbate production of cyanotoxins such as microcystins (MCs), presenting risks to human and animal health. Africa is a continent suffering from severe environmental crises, including MC intoxication, but with very limited understanding of the occurrence and extent of MCs. By analysing 90 publications from 1989 to 2019, we found that in various water bodies where MCs have been detected so far, the concentrations were 1.4–2803 times higher than the WHO provisional guideline for human lifetime exposure via drinking water (1 μg/L) in 12 of 15 African countries where data were available. MCs were relatively high in the Republic of South Africa (averaged 2803 μg/L) and Southern Africa as a whole (702 μg/L) when compared to other regions. Values were higher in reservoirs (958 μg/L) and lakes (159 μg/L) than in other water types, and much higher in temperate (1381 μg/L) than in arid (161 μg/L) and tropical (4 μg/L) zones. Highly significant positive relationships were found between MCs and planktonic chlorophyll *a*. Further assessment revealed high ecological risk for 14 of the 56 water bodies, with half used as human drinking water sources. Recognizing the extremely high MCs and exposure risk in Africa, we recommend routine monitoring and risk assessment of MCs be prioritized to ensure safe water use and sustainability in this region.

1. Introduction

Eutrophication is a widespread global phenomenon, with the frequency, intensity, duration, and geographical extent of resulting cyanobacterial (blue-green algal) blooms increasing [1,2]. These increases are linked to deterioration of water quality and increased threats to human sustainable development, social and economic welfare, and health. Cyanobacterial blooms are one of the main problems that endanger the ecological function of lakes [3]. They can produce metabolites that are potentially toxic and have distinct odours, such as geosmin and methylisoborneol, and cause night-time oxygen depletion resulting in fish kills and loss of benthic fauna and flora [4]. The production of potent cyanotoxins may threaten the health of animals, including humans [5,6]. Algal toxins can be produced widely along with cyanobacterial blooms in the world [7]. MC-producing species of aquatic bloom-, scum- and mat-forming genera including *Microcystis*, *Dolichospermum*, *Anabaenopsis*, *Planktothrix*, *Aphanizomenon*, *Cylindrospermopsis*, *Raphidiopsis*, and *Nodularia* have been documented [8,9]. Cyanotoxins have been found in fresh, brackish, and marine waters [10, 11]. Based on their modes of action and targets, cyanotoxins can be divided into various types, including hepatotoxins, neurotoxins, dermatotoxins, and cytotoxins [12,13]. According to their chemical structures, the toxins can be divided into different categories, including cyclic peptides, alkaloids, organophosphorus and lipopolysaccharides (LPS) compounds [14].

Microcystins (MCs) are the most frequently reported cyanotoxins found in freshwater, brackish water and marine habitats [11]. *Microcystis* blooms occur in at least 108 countries, and MCs have been reported in at least 79 of them [15]. MCs are primarily produced by *Microcystis* spp., but also by species of other genera, such as *Dolichospermum*, *Oscillatoria*, and *Nostoc* [16]. The continuing re-classification of cyanobacteria and examination of their MCs-producing abilities extend the current known potential of species and genera to produce these toxins, including *Anabaenopsis*, *Dolichospermum*, *Fischerella*, *Leptolyngbya*, *Nostoc*, *Phormidium*, *Planktothrix*, *Radiocystis*, and *Synechococcus* [8]. The most common congeners of the characteristic cyclic heptapeptide structure are MC-leucine-arginine (MC-LR), MC-tyrosine-arginine (MC-YR), MC-arginine-arginine (MC-RR) and MC-leucine-alanine (MC-LA) [17]. Currently, more than 279 structural variants of MCs are known [18], with MC-LR being one of the most toxic and most commonly found variants [19,20]. MCs characteristically display hepatotoxicity, with the liver being the primary target organ in vertebrates [21]. Gastrointestinal effects of MCs typically include enterocyte deformation, gastroenteritis and hemorrhage [22]. MCs can also induce damage to the kidney cortex and medulla [23,24], and to the reproductive system [25]. MCs also appear to have tumor-promoting properties [26]. In addition, these toxins can cause neurotoxicity [27], developmental toxicity [28], and immunotoxicity [29]. MCs-exposure can cause harm to human health to differing extents. One of the most severe incidents causally involving MCs included the deaths of 76 patients in northern Brazil after receiving routine hemodialysis treatment due to intravenous exposure to MCs via the dialysis water [30]. MCs have also been detected in serum samples of fishermen at Lake Chaohu, China [31]. The World Health Organization (WHO) has recommended a provisional guideline value of l μg/L MC-LR in drinking water for human lifetime exposure and 12 μg/L for short-term exposure, respectively [32, 33].

The global climate is warming at an unprecedented rate [34]. Increased global temperatures favor growth of cyanotoxin-producing species and strains [4], and can lead to increased toxin release [35, 36]. Africa is experiencing severe palatable water-depletion, environmental contamination such as eutrophication, and warming. The African continent is also one of the fastest warming regions in the world [37], and the association of key areas where waterborne cyanotoxin poisoning incidents may occur is clear especially in high-risk regions where climate warming has been reported [38].

Africa is a continent where cyanobacterial blooms are common, and from where early reports were published (from 1914 to the 1940, in South Africa) of the deaths of large numbers of farm livestock (sheep, cattle, swine and horses), wild animals and waterbirds, associated with the ingestion of cyanobacterial (mainly *Microcystis*) blooms and scums [39]. It is also notable that the first complete chemical structure of a MCs (MC-LA; initially named as cyanoginosin-LA) was elucidated in South Africa [40]. However, an enquiry to relevant national organizations (e.g. water resource management, public health and agriculture) in 57 countries of Africa revealed wide variations in institutional awareness, and the application of management actions in only a minority of African countries [41,42]. However, there have been continuing reports of cyanotoxins causing poisoning and death in small-bodied African animals (including birds, fish, and turtles) [43-45] as well as the suspected cause of the (mass) mortalities in African medium and large-sized terrestrial mammals [46]. Mammalian victims of cyanotoxin poisoning range from fenced livestock, to fenced wildlife and even non-wading wildlife [38]. The mass mortality of more than 330 African elephants in Botswana in 2020 has been attributed to cyanotoxins [38]. These continuing, although isolated, reports indicate that an updated and systematic assessment and understanding of the status of MCs is needed for African inland waters. However, relevant studies are limited [47,48], and have mostly focused on only a few waterbodies. In a review reporting cyanotoxin distribution in Africa from 2006 to 2016, among 54 studied African countries, only 21 had notable research information concerning cyanobacterial blooms within the last decade; and only 11 out of 21 countries had recorded toxicity accompanied by physico-chemical parameters related to cyanobacterial blooms [49]. The dominant cyanotoxins reported from Africa are MCs (77%; 77 out of 100), which have been identified in 14 countries and in 76 freshwater ecosystems, predominantly in lakes, reservoirs, and ponds [50]. In the context of global warming and accelerating eutrophication, Africa requires more attention, considering its lagging socioeconomic development and insufficient infrastructure [49].

Based on a meta-analysis of 90 publications, spanning a period from 1989 to 2019, this study explores the effects of different climate types, physical and chemical properties of waterbodies, and lake basin morphology on MCs, aiming to describe the spatial distribution pattern and influencing factors of MCs on the African continent. Optimized risk quotient (RQ_f) was used to study the risks of MCs causing ecological impacts. It is crucial to understand the distribution and environmental drivers of MCs in African inland waters, elucidate the current status of MCs production and fates in these waters, and to formulate effective monitoring and management programs to reduce human and animal health risks.

2. Materials and methods

2.1. Data collection

The geographical coverage in this study was the entire African continent, and the distribution of MCs was considered on both national and regional scales. The publications related to MCs in Africa were retrieved through the Web of Science database. The keywords in the "topic" field included "Africa or African" and "Microcystin or Cyanobacteria or Cyanotoxin", with specific country searches, from 1950 to 2021. The literature collection for this study was carried out in 2021. The retrieved literature was further screened, and the inclusion criterion was quantitative information on the concentration of MCs in the waters. In total, 90 papers from 1989 to 2019 which reported concentrations of MCs in various waterbodies from African countries were found.

Raw data were extracted from available literature sources for subsequent analysis. The data mainly came from text, tables and figures, and the data in the figures were extracted using the GetData Graph Digitizer (version 2.26). The concentrations and type of MCs reported were then recorded, with the time and location of sampling and physio-chemical conditions of the respective waterbodies, and waterbody characteristics.

2.2. Data processing

Google Earth (https://www.google.com/intl/zh-CN/earth/) was used to supplement the data for unrecorded latitude and longitude of sampling points by searching location names. The LakeNet's World Lakes Website (http://www.worldlakes.org/index.asp) was used to supplement information on lake physical characteristics, including volume, surface area, elevation, mean depth, maximum depth, etc. The Köppen climate classification type was determined based on the latitude and longitude coordinates of the study locations [51]. On the African continent, there are 3 climate zones including Arid (B), Tropical (A) and Temperate (C) and 8 climate types, including tropical rainforest climate (Af), tropical monsoon climate (Am), tropical savanna climate (Aw), steppe climate (Bs), desert climate (Bw), warm temperate climate with fully humid (Cf), warm temperate climate with dry summers (Cs), and warm temperate climate with dry winters (Cw) [51].

In total, 90 papers were screened, covering 15 African countries and 133 waterbodies spanning from 1989 to 2019. A total of 1485 data sets was obtained. The collected raw data information and publications are presented in Supplemental Table 1. The data used for analyses follow the principles: (1) MC concentrations were determined by internationally recognized methods with limits of quantification (LOQ) lower than 1 μg/L, including High Performance Liquid Chromatography (HPLC), Liquid Chromatography-Mass Spectrometry (LC-MS), Enzyme-Linked Immunosorbent Assay (ELISA) and Protein Phosphatase Inhibition Assay (PPIA) [33,52]; (2) total MCs (the sum of all dissolved and particulate MCs congeners and total MC-LR (the sum of dissolved and particulate MC-LR) were selected as indicators to assess the occurrence, localization and abundance of MCs; (3) except for the comparison of MCs concentrations in different water categories using all data, only MCs data from lakes, reservoirs and rivers were selected for further analyses.

Figures were drawn with OriginPro 2022, R soft 4.1.3 and ArcGIS Pro 2020. Linear regression analysis was performed to identify relationships between MCs and Chl *a* concentration, physio-chemical conditions of waterbodies, and waterbody characteristics.

2.3. Risk assessment

Assessment of the ecological risk of MCs was based on the optimized risk quotient (RQ_f) [53]. RQ_f based on the detected environmental concentration and toxicity of MCs to representative aquatic organisms at various trophic levels [54]. The RQ_f value was calculated according to the following equation:

$$RQ_f = RQ \times F = (MEC/PNEC) \times F$$

$$F = NO_1/NO_2$$

where RQ is the risk quotient, MEC is the measured environmental concentration (μg/L), PNEC is the predicted no effect concentration (the PNEC of MC-LR is 5.73 μg/L [55]), F is the frequency with which MEC exceeds PNEC, NO_1 is the number of samples greater than PNEC, and NO_2 is the total number of samples. The RQ_f is divided into five risk levels: high risk ($RQ_f \geq 1$), moderate risk ($1 > RQ_f \geq 0.1$), endurable risk ($0.1 > RQ_f \geq 0.01$), negligible risk ($0.01 > RQ_f > 0$), and safe ($RQ_f = 0$).

We downloaded global population distribution data at LandScan (https://landscan.ornl.gov/) (accessed on 13 October 2022). We downloaded lake database at HydroLAKES (https://www.hydrosheds.org/pages/hydrolakes) [56].

3. Results

3.1. Occurrence and distribution of MCs

Ninety publications from 1989 to 2019 reported the concentrations of MCs in various waterbodies from 15 African countries (Fig. 1) (Supplemental Table S2). Table S3 shows the list of dominant phytoplankton species in the lakes and reservoirs where MCs were detected. The dominant species reported were mainly *Microcystis* and *Anabaena*.

Geographically, these 15 countries are located in: (1) Northern Africa (Algeria, Tunisia, Morocco and Egypt); (2) East Africa (Kenya, Uganda, Ethiopia and Tanzania); (3) West Africa (Nigeria, Ghana and Mauritania); and (4) Southern Africa (South Africa, Mozambique, Namibia and Zimbabwe). The size of the data set was largest in East Africa (624) (Fig. 1B), followed by Northern Africa (423), Southern Africa (321), West Africa (117), and Central Africa (0). Nationally, Kenya (400), South Africa (278) and Egypt (192) had the largest data availability.

Lakes (620) and reservoirs (461) were the most studied water types, with ponds (27) being the least studied (Fig. 1B). Most of the data were from the tropical zone (607), followed by the temperate zone (512) and arid zone (366). With reference to climatic types, the data were mainly from the warm temperate climates having dry winters (Cw) (332), tropical savanna climate (Aw) (270), desert climate (Bw) (261), and tropical rainforest climate (Af) (250) (Fig. 1B).

3.2. Concentrations of MCs

The average concentrations of total MCs found in the four regions were arranged in descending order of: (1) Southern Africa (averaged 702 μg/L); (2) Northern Africa (247 μg/L); (3) East Africa (12.3 μg/L); and (4) West Africa (3.9 μg/L) (Supplemental Table S2).

Fig. 2 shows the mean concentrations of MCs recorded in waters of the 15 countries. The highest average concentration of MCs was

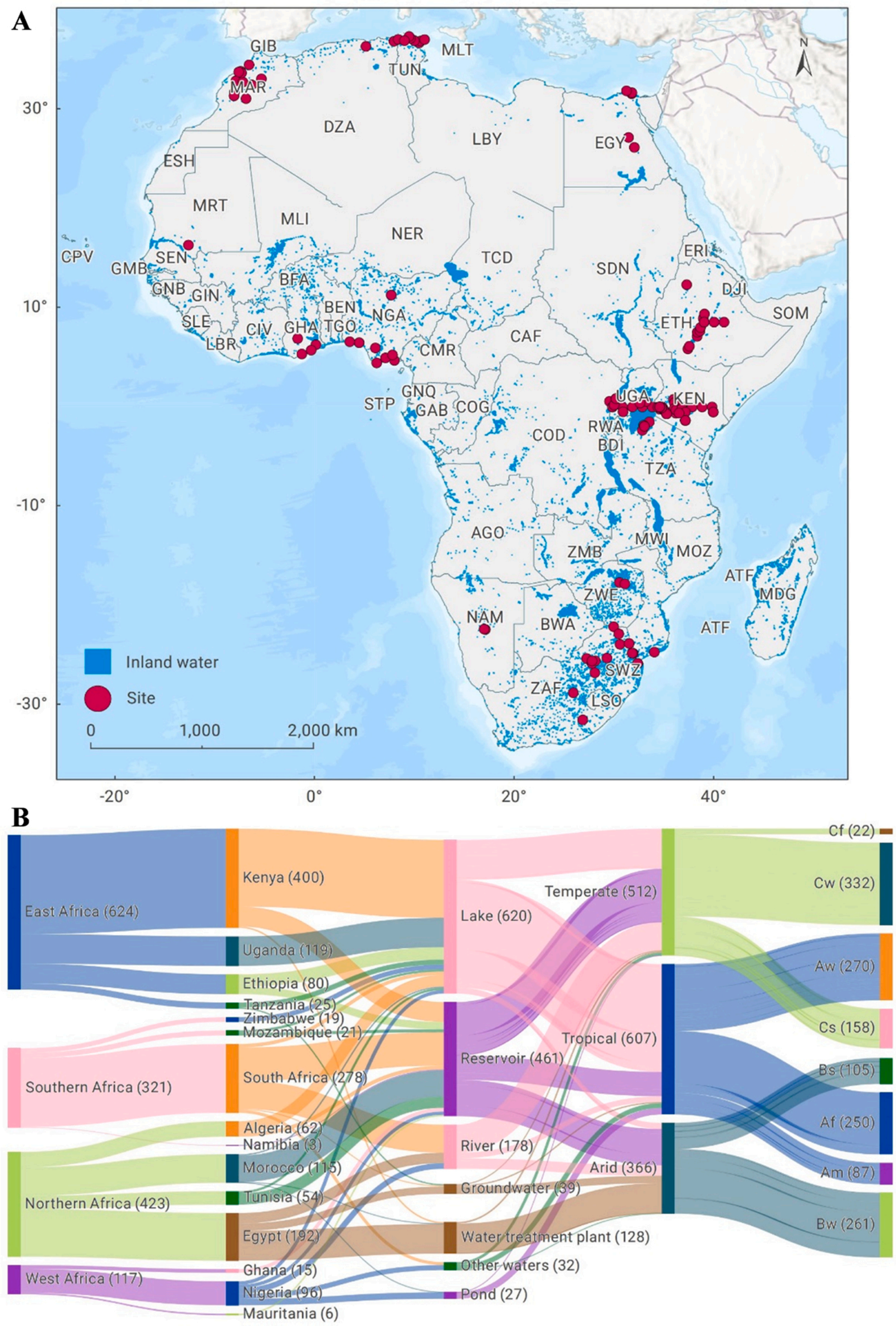

Fig. 1. Geographic distribution of the records of microcystin (MCs) concentration in African waters (A) and Structure (B). Af, tropical rainforest climate; Am, tropical monsoon climate; Aw, tropical savanna climate; Bs, steppe climate; Bw, desert climate; Cf, warm temperate climate with fully humid; Cs, warm temperate climate with dry summer; Cw, warm temperate climate with dry winter.

reported from the Republic of South Africa (average 2803 μg/L), followed by Algeria (975 μg/L), and the lowest average concentration was from Tanzania (0.1 μg/L). Average MC-LR concentrations were only available for eight African countries, being highest in Algeria (998 μg/L), followed by Zimbabwe (19.9 μg/L). The MCs concentrations in three countries, South Africa, Algeria and Ethiopia, exceeded the provisional WHO short-term drinking water guideline value (GV) of 12 μg/L. Except for Tunisia, Namibia, and Tanzania, the concentrations of MCs in all of the other 12 countries exceeded the WHO provisional lifetime drinking-water GV of 1 μg/L. MCs in South Africa were as high as 2803 times the GV.

The concentrations of MCs and MC-LR were compared between different water types, climatic zones, and climate types as shown in Fig. S1. The mean concentrations of MCs and of MC-LR were generally highest in reservoirs and lakes, and in the temperate zone.

3.3. Relationship of MCs with environmental factors

Total MCs concentrations correlated significantly and positively with elevation, mean depth, maximum depth, water temperature, and

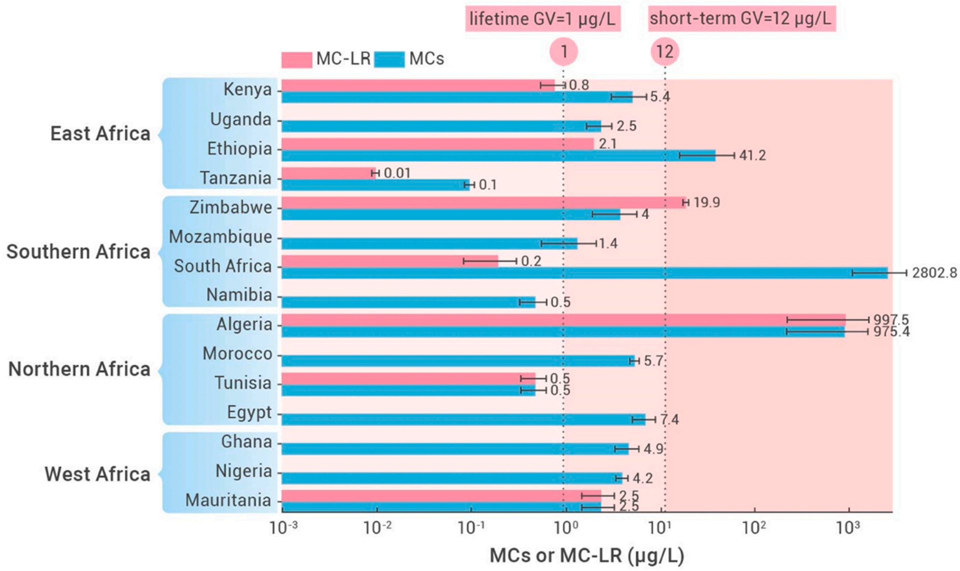

Fig. 2. Concentrations of total microcystins (MCs) and of the MC-leucine-arginine (MC-LR) congener in 15 African countries. The vertical black lines indicate the WHO provisional guideline values (GV) for MCs in drinking water proposed by World Health Organization (WHO) in 2020. Values are presented as the mean ± standard error (SE).

planktonic Chl *a* concentration (Table S4), and negatively with conductivity and soluble reactive phosphorus concentration. MC-LR concentrations correlated significantly and positively with mean depth, surface area, and Chl *a* concentration, and negatively with maximum depth. Fig. 3A and B show the relationships of the concentrations of total MCs and MC-LR with their best predictor, Chl *a*. The linear relationship varied under different water types, climatic zones, mean depths and waterbody surface areas (Fig. S2).

Concentrations of total MCs and of Chl *a* and their ratios in relation to nutrient levels are shown in Fig. S3. Significant relationships only existed between TP and Chl *a* or MCs/Chl *a* (Fig. S3E, H). MCs and Chl *a* concentration and their ratios in relation to lake basin morphology are shown in Fig. S4. Maximum depth and MCs, Chl *a* or MCs/Chl *a* showed significant positive correlations (Fig. S4A, D, G). Mean depth and MCs or MCs/Chl *a* also showed significant positive correlations (Fig. S4B, H), while Chl *a* decreased with increasing mean depth (Fig. S4E). No significant correlation was observed between MCs and volume (Fig. S4C). As volume increased, Chl *a* also increased (Fig. S4F), while MCs/Chl *a* decreased (Fig. S4I).

3.4. Assessing of risks of MCs-exposure

The risks of ecological impacts caused by MCs were assessed for 56 African waterbodies according to optimized risk quotient (RQ_f) (Table S5). In total, 14 waterbodies were at high risk ($RQ_f \geq 1$) and 50% (7/14) of these waterbodies are used as human drinking water supplies, while 29% (4/14) provided irrigation water. Among these, the Nhanganzwane Reservoir in South Africa had the highest ecological risk, with RQ_f of 9513. Seven waterbodies were at medium risk ($1 > RQ_f \geq 0.1$). Minor adverse effects were expected from MCs in 5 waterbodies ($0.1 > RQ_f \geq 0.01$). A strong overlap was found between areas of high and moderate ecological risk for African MCs and areas of high human population density (Fig. 4). MCs were also widely reported to accumulate in various wild animals such as giraffe, rhinoceros, crocodiles, flamingos, terrapins, zebras and fish (Table S6).

4. Discussion

In this study, a systematic review was conducted of reported MCs in African waterbodies through a critical literature evaluation. A database

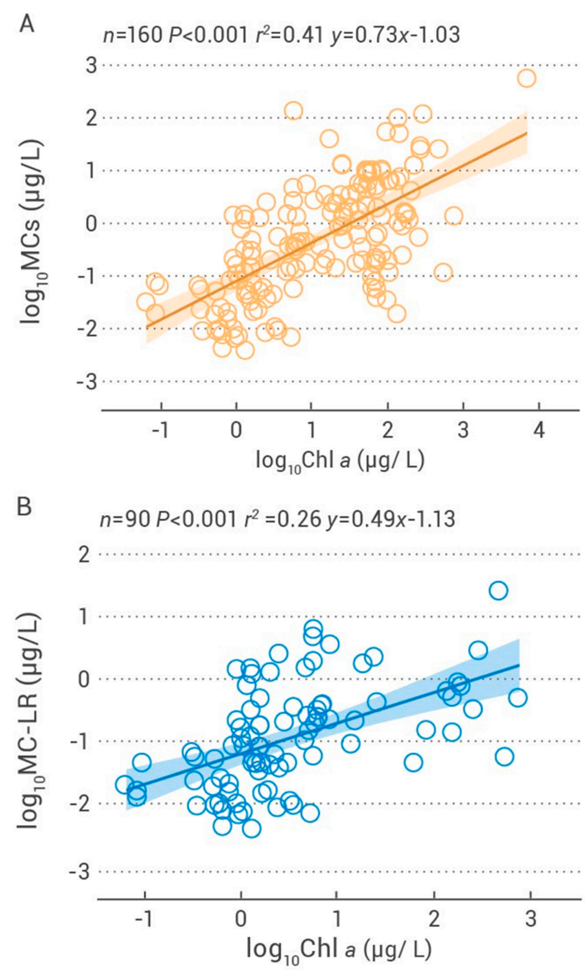

Fig. 3. Relationship between total microcystins (MCs) and MC-leucine-arginine (MC-LR) congener concentrations and planktonic chlorophyll *a* (Chl *a*) concentrations. Total (A), MC-LR (B). Shading indicates 95% confidence interval.

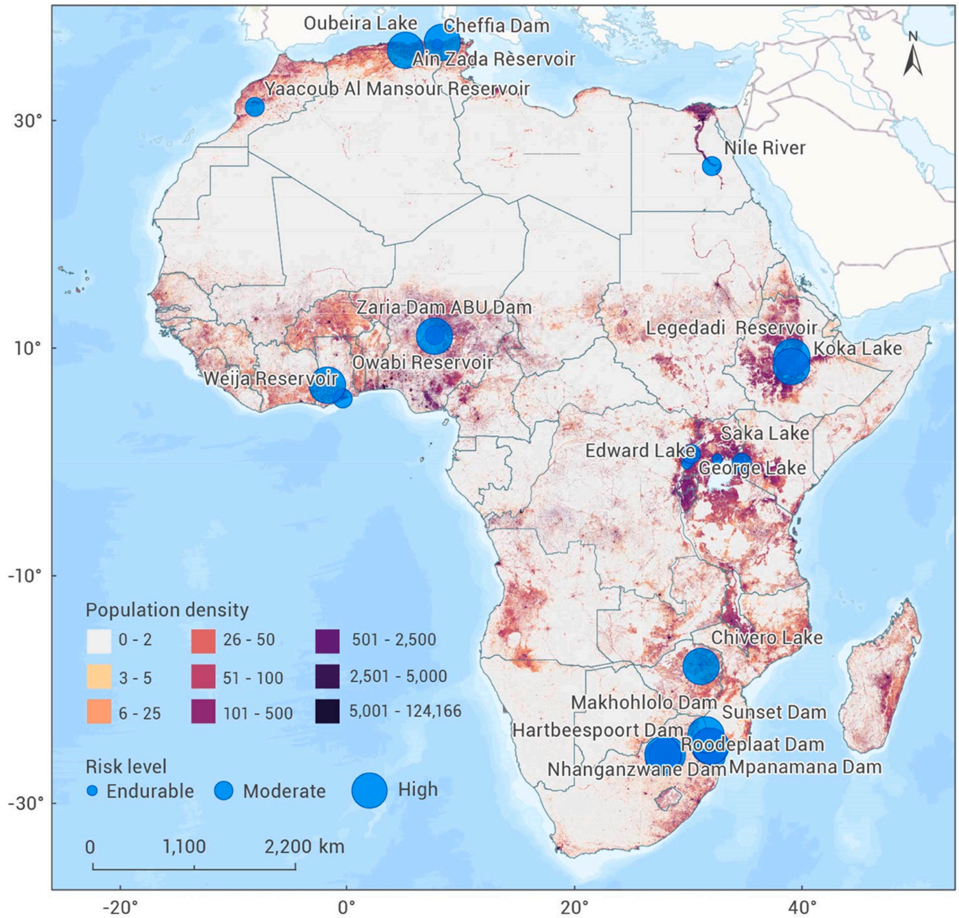

Fig. 4. Location of waterbodies for ecological risk assessment of MCs in Africa and population density (From LandScan Global in 2021).

on MCs for various African inland waters was established, covering 133 ecosystems in 15 African countries, with a total of 1485 data sets from publications spanning from 1989 to 2019. A strong geographic heterogeneity was found in MCs in these waters.

The extremely high concentration of MCs reported in many African inland waters provides a warning of the severe situation of MCs occurrence throughout the continent. Among the 15 countries with available data, 12 countries (80%) yielded an average total MCs concentration value exceeding the provisional guideline value of 1 μg MC-LR/L for potential lifetime human exposure via drinking water derived by the WHO [32,33]. Reported concentrations of total MCs in the waters in the 15 countries (averaged as 257 μg/L, ranging 0.1–2803 μg/L are much higher than those reported for 32 European freshwater ecosystems, including 20 lakes and 12 reservoirs (mean: 14.8 μg/L, range: 0.0034–100 μg/L) [57]. The reported total MCs concentrations in lakes and reservoirs in Africa (averaged 158 μg/L from 52 lakes, $n = 253$, and 957 μg/L from 42 reservoirs, $n = 206$) were also much higher than those reported from other regions, for example in China (averaged 4.0 μg/L from 22 lakes, $n = 652$, and 1.8 μg/L from 14 reservoirs, $n = 105$) [53]. In Australia, MCs concentrations also reached very high levels (MCs in scum samples: 0.5–8429 μg/L from 13 lakes; MCs: 0.5–1645 μg/L from 19 wetlands) [58,59]. In Africa, lakes and reservoirs are important freshwater resources [60], providing major drinking water sources for human beings [61] and acting as vital habitats for various wildlife particularly megafauna such as African savanna elephants (*Loxodonta africana*) and hippopotami (*Hippopotamus amphibius*) [62-64].

High concentrations of MCs in African waters imply a high risk of MCs exposure for both people and wildlife. Our assessment revealed that 14 out of 26 analyzed waterbodies were at high ecological risk (RQ_f 1.1–9513), including sources of drinking water and irrigation water. Among these, the Nhanganzwane Reservoir in South Africa had the highest ecological risk (RQ_f 9513), which may explain the massive puzzling death of wild animals reported from South Africa [44]. The known cases of wildlife mortality caused by waterborne MCs appear to be relatively common on the African continent [65,66]. Humans can also be affected by exposure to MCs via drinking water, recreational activities and the consumption of foods containing cyanotoxins [67]. MCs can accumulate in fruits and vegetables irrigated with MCs-contaminated water, posing health risks to humans [68,69]. The situation is particularly severe when it coincides with water scarcity, which is one of the most concerning issues threating sustainability and stability in African societies [70]. Africa is one of three global "hotspots" of water scarcity [70], with at least 580 million people lacking access to improved sanitation facilities [71]. In sub-Saharan Africa, 40% of the population in urban areas still lack safely managed drinking water, and the proportion in rural areas is as high as 75% [72]. Furthermore, the hotspots of cyanotoxin exposure risks in southeastern Africa are also areas of high megafauna diversity [38]. Therefore, frequent monitoring of water quality and cyanotoxin concentrations in African waters is urgently needed to inform national water management, environmental and health protection authorities to help to protect the health and sustainability of environments and societies within this area.

A significant positive relationship was found between total MCs and planktonic Chl *a* concentration. Similar positive correlations have been reported in Lake Erhai, China and in Lake Erie, USA-Canada [73,74]. Some studies have established predictive models for MCs concentrations based on Chl *a* [74]. Historical data of Chl *a* concentrations in waterbodies are much more abundant than those for MCs. It is more feasible to obtain phytoplankton pigment data as a routine parameter in water quality monitoring than MCs data which require specialist cyanotoxin expertise and facilities [75,76]. Therefore, the reasonably good linear relationship found in this study between total MCs and planktonic Chl *a* concentration for African waters allows estimates of potential MCs concentrations for waters where data for MCs are lacking or difficult to obtain, though such relationships may depend on the relative dominance of cyanobacteria in total phytoplankton biomass.

The limited amount of MCs data collected in this comprehensive literature search confirms and extends earlier assessments of cyanotoxin occurrence throughout the African continent [42,77,50], indicating that the number of published studies of waterborne cyanotoxins, and specifically of MCs, throughout African waters remains low. The 15 countries with available data on MCs concentrations represent only 28% of the 54 sovereign countries in Africa [78]. Although research on MCs in waterbodies has progressed in recent years with economic development and technological advances [49,79], there are generally fewer studies related to MCs in inland waters throughout all of Africa, compared to other continents [50,80]. Thus, Africa accounts for 11.7% (55 of 468) of the global published literature on cyanotoxin distribution and cyanotoxin poisoning incidents, only higher than Oceania (10.9%, 51) but clearly lower than South America (13.5%, 63), Asia (16.7%, 78), North and Central America (19.8%, 93), and Europe (27.4%, 128) [50]. Africa accounts for only 2% (1 of 42) of the global literature on epidemiological studies of cyanotoxins in connection with the etiology of adverse human health effects, much lower than reported for South America (14.3%, 6), North America (14.3%, 6), Oceania (19%, 8), Europe (21.4%, 9), and Asia (29%, 12) [77]. The investment in, and intensity of research on MCs in African waterbodies appears to be influenced by the level of economic development of individual countries. Among the top 10 African countries in terms of GDP, only Angola yielded no MCs data in the present study. 12 countries (80%) with MCs data in this study are ranked in the top 20 in Africa in terms of GDP [81]. The research focus on MCs is also related to the geographical location of waterbodies, with reports on these toxins being mainly from East Africa and least from West Africa. East Africa supports the densest lake clusters in the tropics [82]. This region contains more than 25% of the Earth's, and more than 90% of Africa's surface freshwater resources [83]. Major watersheds in Africa are experiencing high year-on-year population growth [84] and surface and groundwaters are heavily polluted due to agricultural and industrial activities [85]. The MCs in Lake Victoria, the largest lake in Africa, can mainly be attributed to high nutrient loading caused by the intensification of urbanization and agricultural activities [86]. Due to point-source pollution (wastewater discharged from 16 sewage treatment plants), the nutrient load of the Hartbeespoort reservoir in Africa is increasing, resulting in very high MCs concentrations [87]. Therefore, in future studies, more attention should be paid to the occurrence and fates of MCs in drinking water sources in rural and undeveloped areas.

Ongoing climate change is also affecting water quality and safety by stimulating cyanobacterial growth and cyanotoxin production [1,88] and hence the risk of poisoning in animals and humans [38]. It is projected that the temperature increases in Africa will be higher than the global average [37,89], increasing the probability of future extreme climate events in the future. Of additional concern is the expected faster temperature increase in west and central Africa [89], where least research has been done on cyanotoxins as revealed in this study, leaving vast uncertainty of cyanotoxin production and exposure risk. Increased attention to MCs production and the impacts of these persistent and potent cyanotoxins on health. Therefore, is particularly needed on the African continent, including: 1) strengthening and extending epidemiological research on MCs throughout the continent to better understand current and emerging threats to human health, wildlife and farmed animals; 2) use of multi-scale, multi-method, multi-disciplinary monitoring and quantitative analysis of MCs in inland waters to reduce and prevent human and animal exposure to hazardous MCs concentrations; 3) strengthening the research on small waterbodies such as ponds, to be able to better control the exposure risk of MCs in future warming scenarios.

5. Conclusions

Based on an extensive literature review, a database was established for the microcystins (MCs) and related environmental characteristics of 133 freshwater ecosystems in 15 African countries from 1989 to 2019. The data available, while modest compared to other continents except for Oceania, showed strong spatial heterogeneity between regions and countries within the African continent. Strong spatial variation was also found for MCs concentrations, being the highest in Southern Africa and the lowest in West Africa. MCs concentrations in African inland waters were much higher than those in waterbodies in other continents and countries. Among the 15 African countries with available MCs data, 12 countries (80%) included average MCs which were 1.4–2803 times higher than the provisional drinking water guideline value of 1 μg/L of the WHO for human health protection during chronic (lifetime) exposure. MCs concentrations in lakes and reservoirs were significantly higher than those in other freshwater ecosystems and were highest in the temperate zone. A highly significant, positive linear regression was found between concentrations of total MCs and planktonic chlorophyll *a*. Fourteen of the 56 African waterbodies were assessed as presenting a high ecological risk of MCs intoxication, with 7 of the 14 being sources of drinking water. The relatively low frequency of research on MCs but high risks of human and animal exposure to these cyanotoxins, together demonstrate a rising need for research and for the development and application of risk management measures. A further major challenge is to coordinate aquatic environmental pollution and sustainable development, particularly in a future of accelerating climate warming and eutrophication. Therefore, we recommend frequent monitoring of water quality, particularly of MCs, and guideline establishment, based on international prior experience and recommendations, plus relevant local/national water-usage practices, toxicity tests, and epidemiological studies on the exposure risks and health impacts of MCs, to ensure human and wildlife health and sustainability within the African continent.

Environmental implication

Cyanobacteria can produce a wide range of toxins called cyanotoxins. Microcystins (MCs) are among the most toxic and widely distributed of the cyanotoxins. MCs are a group of cyclic heptapeptides which may lead to toxicity in humans, including hepatotoxicity, nephrotoxicity, neurotoxicity, and reproductive toxicity [1,10].

Based on a meta-analysis of 90 publications, a database was established for the MCs and related environmental characteristics of 133 freshwater ecosystems in 15 African countries from 1989 to 2019. This study explored the spatial distribution pattern, exposure risk, and environmental factors influencing waterborne MCs on the African continent.

CRediT authorship contribution statement

H.W., P.X., and X.Z. designed the study. X.Z. searched and collected data. X.Z., Y.L., Y.W., P.W., L.Y., L.Z., S.X. did the data analyses. X.Z. performed the data interpretation and wrote the manuscript. Y.G., C.X., L.C., G.C., J.C., Y.L., H.P., E.J., H.W., and X.Z. reviewed and revised the manuscript. All authors discussed the results and commented on the manuscript.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jhazmat.2023.131160.

References

[1] Huisman, J., Codd, G.A., Paerl, H.W., Ibelings, B.W., Verspagen, J.M.H., Visser, P. M., 2018. Cyanobacterial blooms. Nat Rev Microbiol 16, 471–483. https://doi.org/10.1038/s41579-018-0040-1.

[2] Yang, X., Wu, X., Hao, H., He, Z., 2008. Mechanisms and assessment of water eutrophication. J Zhejiang Univ Sci B 9, 197–209. https://doi.org/10.1631/jzus.B0710626.

[3] Ibelings, B.W., Fastner, J., Bormans, M., Visser, P.M., 2016. Cyanobacterial blooms. Ecology, prevention, mitigation and control: Editorial to a CYANOCOST special issue. Aquat Ecol 50, 327. https://doi.org/10.1007/s10452-016-9595-y.

[4] Paerl, H.W., Huisman, J., 2009. Climate change: A catalyst for global expansion of harmful cyanobacterial. blooms. Environ Microbiol Rep 1, 27–37. https://doi.org/10.1111/j.1758-2229.2008.00004.x.

[5] Gorham, P.R., Carmichael, W.W., 1988. Hazards of freshwater blue-green algae (cyanobacteria). In: Lembe, C.A., Waaland, J.R. (Eds.), Algae and Human Affairs. University Press, Cambridge, UK, pp. 403–431.

[6] Metcalf, J.S., Codd, G.A., 2012. Ecology of Cyanobacteria II: Their Diversity in Space and Time. In: Whitton, B.A. (Ed.), Cyanotoxins. Springer Dordrecht Netherlands, 651–575.

[7] Chorus, I., 2001. Introduction: Cyanotoxins — Research for Environmental Safety and Human Health. In: Chorus, I. (Ed.), Cyanotoxins. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 1–4. https://doi.org/10.1007/978-3-642-59514-1_1.

[8] Bernard, C., Ballot, A., Thomazeau, S., Maloufi, S., Furey, A., Mankiewicz-Boczek, J., et al., 2017. Cyanobacteria associated with the production of cyanotoxins. In: Meriluoto, J., Spoof, L., Codd, G.A. (Eds.), Handbook of Cyanobacterial Monitoring and Cyanotoxin Analysis. Wiley, Chichester UK, pp. 501–525.

[9] Codd, G.A., Morrison, L.F., Metcalf, J.S., 2005. Cyanobacterial toxins: risk management for health protection. Toxicol Appl Pharmacol 203, 264–272. https://doi.org/10.1016/j.taap.2004.02.016.

[10] Codd, G.A., 1995. Cyanobacterial toxins: occurrence, properties and biological significance. Water Sci Technol 32, 149–156. https://doi.org/10.2166/wst.1995.0177.

[11] Massey, I.Y., Al osman, M., Yang, F., 2022. An overview on cyanobacterial blooms and toxins production: their occurrence and influencing factors. Toxin Rev 41, 326–346. https://doi.org/10.1080/15569543.2020.1843060.

[12] Falconer, I.R., 1999. An overview of problems caused by toxic blue-green algae (cyanobacteria) in drinking and recreational water. Environ Toxicol 14, 5–12. https://doi.org/10.1002/(SICI)1522-7278(199902)14:1<5::AID-TOX3>3.0.CO;2-0.

[13] Rastogi, R.P., Sinha, R.P., Incharoensakdi, A., 2014. The cyanotoxin-microcystins: current overview. Rev Environ Sci Biotechnol 13, 215–249. https://doi.org/10.1007/s11157-014-9334-6.

[14] van Apeldoorn, M.E., van Egmond, H.P., Speijers, G.J.A., Bakker, G.J.I., 2007. Toxins of cyanobacteria. Mol Nutr Food Res 51, 7–60. https://doi.org/10.1002/mnfr.200600185.

[15] Harke, M.J., Steffen, M.M., Gobler, C.J., Otten, T.G., Wilhelm, S.W., Wood, S.A., et al., 2016. A review of the global ecology, genomics, and biogeography of the toxic cyanobacterium, *Microcystis* spp. Harmful Algae 54, 4–20. https://doi.org/10.1016/j.hal.2015.12.007.

[16] Dawson, R.M., 1998. The toxicology of microcystins. Toxicon 36, 953–962. https://doi.org/10.1016/S0041-0101(97)00102-5.

[17] Brena, B.M., Font, E., Pírez Schirmer, M., Badagian, N., Cardozo, E., Pérez Parada, A., et al., 2021. Microcystin ELISA in water and animal serum for an integrated environmental monitoring strategy. Int J Environ Anal Chem 1–13. https://doi.org/10.1080/03067319.2021.1881073.

[18] Jaeger-Honz, S., Nitschke, J., Altaner, S., Klein, K., Dietrich, D.R., Schreiber, F., 2022. Investigation of microcystin conformation and binding towards PPP1 by molecular dynamics simulation. Chem -Biol Interact 351, 109766. https://doi.org/10.1016/j.cbi.2021.109766.

[19] Chen, L., Giesy, J.P., Adamovsky, O., Svirčev, Z., Meriluoto, J., Codd, G.A., et al., 2021. Challenges of using blooms of *Microcystis* spp. in animal feeds: a comprehensive review of nutritional, toxicological and microbial health evaluation. Sci Total Environ 764, 142319. https://doi.org/10.1016/j.scitotenv.2020.142319.

[20] Funari, E., Testai, E., 2008. Human health risk assessment related to cyanotoxins exposure. Crit Rev Toxicol 38, 97–125. https://doi.org/10.1080/10408440701749454.

[21] Svirčev, Z., Baltić, V., Gantar, M., Juković, M., Stojanović, D., Baltić, M., 2010. Molecular aspects of microcystin-induced hepatotoxicity and hepatocarcinogenesis. J Environ Sci Heal C 28, 39–59. https://doi.org/10.1080/10590500903585382.

[22] Liu, Y., Qi, C.-L., Li, D.-W., Li, H.-Y., Li, R.-M., Yang, W.-D., 2023. Microcystin-LR exposure interfered maintenance of colonic microenvironmental homeostasis in rat. Food Chem Toxicol 173, 113611. https://doi.org/10.1016/j.fct.2023.113611.

[23] Milutinović, A., Sedmak, B., Horvat-Znidarsic, I., Suput, D., 2002. Renal injuries induced by chronic intoxication with microcystins. Cell Mol Biol Lett 7, 139–141. https://doi.org/10.1046/j.1462-5822.2002.00165.x.

[24] Zhang, D., Yuan, L., Zhang, L., Qiu, T., Liao, Q., Xiang, J., et al., 2022. Pathological and biochemical characterizations of microcystin-LR-induced liver and kidney damage in chickens after acute exposure. Toxicon 220, 106952. https://doi.org/10.1016/j.toxicon.2022.106952.

[25] Chen, L., Chen, J., Zhang, X., Xie, P., 2016. A review of reproductive toxicity of microcystins. J Hazard Mater 301, 381–399. https://doi.org/10.1016/j.jhazmat.2015.08.041.

[26] Žegura, B., 2016. An overview of the mechanisms of microcystin-LR genotoxicity and potential carcinogenicity. Mini-Rev Med Chem 16, 1042–1062. https://doi.org/10.2174/1389557516666160308141549.

[27] Hu, Y., Chen, J., Fan, H., Xie, P., He, J., 2016. A review of neurotoxicity of microcystins. Environ Sci Pollut Res 23, 7211–7219. https://doi.org/10.1007/s11356-016-6073-y.

[28] Qi, M., Dang, Y., Xu, Q., Yu, L., Liu, C., Yuan, Y., et al., 2016. Microcystin-LR induced developmental toxicity and apoptosis in zebrafish (*Danio rerio*) larvae by activation of ER stress response. Chemosphere 157, 166–173. https://doi.org/10.1016/j.chemosphere.2016.05.038.

[29] Lin, W., Hung, T.-C., Kurobe, T., Wang, Y., Yang, P., 2021. Microcystin-Induced Immunotoxicity in Fishes: A Scoping Review. Toxins 13, 765. https://doi.org/10.3390/toxins13110765.

[30] Carmichael, W.W., Lau, S., Rinehart, K.L., Shaw, G.R., Eaglesham, G.K., 2001. Human fatalities from cyanobacteria: chemical and biological evidence for cyanotoxins. Environ Health Perspect 109, 6. https://doi.org/10.1289/ehp.01109663.

[31] Chen, J., Xie, P., Li, L., Xu, J., 2009. First Identification of the hepatotoxic microcystins in the serum of a chronically exposed human population together with indication of hepatocellular damage. Toxicol Sci 108, 81–89. https://doi.org/10.1093/toxsci/kfp009.

[32] World Health Organization (WHO)., 1998. Guidlines for drinking-water quality. Vol. 2, Health criteria and other supporting information, 2nd ed. WHO, Geneva.

[33] World Health Organization (WHO)., 2020. Cyanobacterial toxins: Microcystins. Background document for development of WHO guidelines for drinking-water quality and guidelines for safe recreational water environments. WHO, Geneva.

[34] Ji, F., Wu, Z., Huang, J., Chassignet, E.P., 2014. Evolution of land surface air temperature trend. Nat Clim Chang 4, 462–466. https://doi.org/10.1038/nclimate2223.

[35] Mantzouki, E., et al., 2018. Temperature effects explain continental scale distribution of cyanobacterial toxins. Toxins 10, 156. https://doi.org/10.3390/toxins10040156.

[36] Walls, J.T., Wyatt, K.H., Doll, J.C., Rubenstein, E.M., Rober, A.R., 2018. Hot and toxic: Temperature regulates microcystin release from cyanobacteria. Sci Total Environ 610, 786–795. https://doi.org/10.1016/j.scitotenv.2017.08.149.

[37] Collier, P., Conway, G., Venables, T., 2008. Climate change and Africa. Oxf Rev Econ Policy 24, 337–353. https://doi.org/10.1093/oxrep/grn019.

[38] Wang, H., Xu, C., Liu, Y., Jeppesen, E., Svenning, J.-C., Wu, J., et al., 2021. From unusual suspect to serial killer: Cyanotoxins boosted by climate change may jeopardize megafauna. Innovation 2, 100092. https://doi.org/10.1016/j.xinn.2021.100092.

[39] Schwimmer, M., Schwimmer, D., 1986. Medical aspects of phycology. In: Jackson, D.E. (Ed.), Algae, Man and the Environment. Syracuse University Press, Syracuse, New York, pp. 278–358.

[40] Botes, D.P., Tuinman, A.A., Wessels, P.L., Viljoen, C.C., Kruger, H., Williams, D.H., et al., 1984. The structure of cyanoginosin-LA, a cyclic heptapeptide toxin from the cyanobacterium *Microcystis aeruginosa*. J Chem Soc Perkin Trans 1 (1), 2311–2318. https://doi.org/10.1039/P19840002311.

[41] Harding, W., Downing, T., Van Ginkel, C., Moolman, A., 2009. An overview of cyanobacterial research and management in South Africa post-2000. Water SA 35, 479–484. https://doi.org/10.4314/wsa.v35i4.76792.

[42] Harding, W.R., 2005. Africa: Situation Assessment., in: Codd, G.A. et al. (Eds.), CYANONET: A Global Network for Cyanobacterial Bloom and Toxin Risk Management., No. 76. UNESCO International Hydrological Programme, Technical Documents in Hydrology, Paris, pp. 9–20.

[43] Krienitz, L., Ballot, A., Kotut, K., Wiegand, C., Pütz, S., Metcalf, J.S., et al., 2003. Contribution of hot spring cyanobacteria to the mysterious deaths of Lesser

Flamingos at Lake Bogoria, Kenya. FEMS Microbiol Ecol 43, 141–148. https://doi.org/10.1111/j.1574-6941.2003.tb01053.x.
[44] Masango, M.G., Myburgh, J.G., Labuschagne, L., Govender, D., Bengis, R.G., Naicker, D., 2010. Assessment of *Microcystis* bloom toxicity associated with wildlife mortality in the Kruger National Park, South Africa. J Wildl Dis 46, 95–102. https://doi.org/10.7589/0090-3558-46.1.95.
[45] Nasri, H., El Herry, S., Bouaïcha, N., 2008. First reported case of turtle deaths during a toxic *Microcystis* spp. bloom in Lake Oubeira. Algeria Ecotox Environ Safe 71, 535–544. https://doi.org/10.1016/j.ecoenv.2007.12.009.
[46] Bengis, R., Govender, D., Lane, E., Myburgh, J., Oberholster, P., Buss, P., et al., 2016. Eco-epidemiological and pathological features of wildlife mortality events related to cyanobacterial bio-intoxication in the Kruger National Park, South Africa. J S Afr Vet Assoc 87, a1391. https://doi.org/10.4102/jsava.v87i1.1391.
[47] Ballot, A., Krienitz, L., Kotut, K., Wiegand, C., Pflugmacher, S., 2005. Cyanobacteria and cyanobacterial toxins in the alkaline crater lakes Sonachi and Simbi, Kenya. Harmful Algae 4, 139–150. https://doi.org/10.1016/j.hal.2004.01.001.
[48] Chia, A.M., Oniye, S.J., Ladan, Z., Lado, Z., Pila, A.E., lnekwe, V.U., et al., 2009. A survey for the presence of microcystins in aquaculture ponds in Zaria, Northern-Nigeria: possible public health implication. Afr J Biotechnol 8, 6282–6289. https://doi.org/10.5897/AJB09.1263.
[49] Ndlela, L.L., Oberholster, P.J., Van Wyk, J.H., Cheng, P.H., 2016. An overview of cyanobacterial bloom occurrences and research in Africa over the last decade. Harmful Algae 60, 11–26. https://doi.org/10.1016/j.hal.2016.10.001.
[50] Svirčev, Z., Lalić, D., Bojadžija Savić, G., Tokodi, N., Drobac Backović, D., Chen, L., et al., 2019. Global geographical and historical overview of cyanotoxin distribution and cyanobacterial poisonings. Arch Toxicol 93, 2429–2481. https://doi.org/10.1007/s00204-019-02524-4.
[51] Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F., 2006. World Map of the Köppen-Geiger climate classification updated. Meteorol Z 15, 259–263. https://doi.org/10.1127/0941-2948/2006/0130.
[52] Massey, I.Y., Wu, P., Wei, J., Luo, J., Ding, P., Wei, H., et al., 2020. A mini-review on detection methods of microcystins. Toxins 12, 641. https://doi.org/10.3390/toxins12100641.
[53] Wei, H., Jia, Y., Wang, Z., 2022. Microcystin pollution in lakes and reservoirs: a nationwide meta-analysis and assessment in China. Environ Pollut 309, 119791. https://doi.org/10.1016/j.envpol.2022.119791.
[54] Zhou, S., Di Paolo, C., Wu, X., Shao, Y., Seiler, T.-B., Hollert, H., 2019. Optimization of screening-level risk assessment and priority selection of emerging pollutants – The case of pharmaceuticals in European surface waters. Environ Int 128, 1–10. https://doi.org/10.1016/j.envint.2019.04.034.
[55] Niu, Z., Du, L., Li, J., Zhang, Y., Lv, Z., 2018. Ecological risk assessment of microcystin-LR in the upstream section of the Haihe River based on a species sensitivity distribution model. Chemosphere 193, 403–411. https://doi.org/10.1016/j.chemosphere.2017.11.037.
[56] Messager, M.L., Lehner, B., Grill, G., Nedeva, I., Schmitt, O., 2016. Estimating the volume and age of water stored in global lakes using a geo-statistical approach. Nat Commun 7, 13603. https://doi.org/10.1038/ncomms13603.
[57] Filatova, D., Picardo, M., Núñez, O., Farré, M., 2020. Analysis, levels and seasonal variation of cyanotoxins in freshwater ecosystems. Trends Environ Anal Chem 26, e00091. https://doi.org/10.1016/j.teac.2020.e00091.
[58] John, J., Kemp, A., 2006. Cyanobacterial Blooms in the Wetlands of the Perth region, Taxonomy and Distribution: an Overview. J R Soc West Aust 89, 51–56.
[59] Kemp, A., John, J., 2006. Microcystins associated with *Microcystis* dominated blooms in the Southwest wetlands, Western Australia. Environ Toxicol 21, 125–130. https://doi.org/10.1002/tox.20164.
[60] Song, C., Zhan, P., Ma, R., 2020. Progress in remote sensing study on lake hydrologic regime. Lake Sci 32, 1406–1420. https://doi.org/10.18307/2020.0514.
[61] Siriwardana, C., Cooray, A.T., Liyanage, S.S., Koliyabandara, S.M.P.A., 2019. Seasonal and spatial variation of dissolved oxygen and nutrients in Padaviya Reservoir, Sri Lanka. J Chem 2019, 1–11. https://doi.org/10.1155/2019/5405016.
[62] Redfern, J.V., Grant, C.C., Gaylard, A., Getz, W.M., 2005. Surface water availability and the management of herbivore distributions in an African savanna ecosystem. J Arid Environ 63, 406–424. https://doi.org/10.1016/j.jaridenv.2005.03.016.
[63] Ryan, S., Getz, W., 2005. A spatial location-allocation GIS framework for managing water sources in a savanna nature reserve. South Afr J Wildl Res 35, 153–178.
[64] Sutherland, K., Ndlovu, M., Pérez-Rodríguez, A., 2018. Use of artificial waterholes by animals in the southern region of the Kruger National Park, South Africa. Afr J Wildl Res 48, 023003. https://doi.org/10.3957/056.048.023003.
[65] Matsunaga, H. , Harada, K.-I. , Senma, M. , Ito, Y. , Yasuda, N. , Ushida, S. , et al. , 1999. Possible cause of unnatural mass death of wild birds in a pond in Nishinomiya, Japan: Sudden appearance of toxic cyanobacteria. Nat. Toxins. 7, 81–84. https://doi.org/10.1002/(SICI)1522–7189(199903/04)7:23.0.CO;2-O.
[66] Mez, K., Beattie, K.A., Codd, G.A., Hanselmann, K., Hauser, B., Naegeli, H., et al., 1997. Identification of a microcystin in benthic cyanobacteria linked to cattle deaths on alpine pastures in Switzerland. Eur J Phycol 32, 111–117. https://doi.org/10.1080/09670269710001737029.
[67] de la Cruz, A.A., Hiskia, A., Kaloudis, T., Chernoff, N., Hill, D., Antoniou, M.G., et al., 2013. A review on cylindrospermopsin: the global occurrence, detection, toxicity and degradation of a potent cyanotoxin. Environ Sci-Proc Imp 15, 1979–2003. https://doi.org/10.1039/C3EM00353A.
[68] Codd, G.A., Metcalf, J.S., Beattie, K.A., 1999. Retention of *Microcystis aeruginosa* and microcystin by salad lettuce (Lactuca sativa) after spray irrigation with water containing cyanobacteria. Toxicon 37, 1181–1185. https://doi.org/10.1016/S0041-0101(98)00244-X.
[69] Melaram, R., Newton, A.R., Chafin, J., 2022. Microcystin contamination and toxicity: implications for agriculture and public health. Toxins 14, 350. https://doi.org/10.3390/toxins14050350.
[70] United Nations Environment Programme (UNEP)., 2010. Africa Water Atlas. Division of Early Warning and Assessment. UNEP, Nairobi, Kenya.
[71] World Health Organization (WHO)., United Nations International Children's Emergency Fund (UNICEF)., 2010. Joint Monitoring Programme for Water Supply and Sanitation. Progress on sanitation and drinking-water: 2010 update. WHO, UNICEF.
[72] World Health Organization (WHO), United Nations International Children's Emergency Fund (UNICEF)., World Bank., 2022. State of the world's drinking water: an urgent call to action to accelerate progress on ensuring safe drinking water for all. Licence: CC BY-NC-SA 3.0 IGO. WHO, Geneva.
[73] Qian, S.S., Stow, C.A., Rowland, F.E., Liu, Q., Rowe, M.D., Anderson, E.J., et al., 2021. Chlorophyll *a* as an indicator of microcystin: Short-term forecasting and risk assessment in Lake Erie. Ecol Indic 130, 108055. https://doi.org/10.1016/j.ecolind.2021.108055.
[74] Yu, G., Jiang, Y., Song, G., Tan, W., Zhu, M., Li, R., 2014. Variation of *Microcystis* and microcystins coupling nitrogen and phosphorus nutrients in Lake Erhai, a drinking-water source in Southwest Plateau, China. Environ Sci Pollut Res 21, 9887–9898. https://doi.org/10.1007/s11356-014-2937-1.
[75] Meriluoto, J., Spoof, L., Codd, G.A. (Eds.), 2017. Handbook of Cyanobacterial Monitoring and Cyanotoxin Analysis, 1st ed. Wiley, Chichester UK. 〈https://doi.org/10.1002/9781119068761〉.
[76] Ogashawara, I., Moreno-Madriñán, M., 2014. Improving inland water quality monitoring through remote sensing techniques. ISPRS Int J Geo-Inf 3, 1234–1255. https://doi.org/10.3390/ijgi3041234.
[77] Svirčev, Z., Drobac, D., Tokodi, N., Mijović, B., Codd, G.A., Meriluoto, J., 2017. Toxicology of microcystins with reference to cases of human intoxications and epidemiological investigations of exposures to cyanobacteria and cyanotoxins. Arch Toxicol 91, 621–650. https://doi.org/10.1007/s00204-016-1921-6.
[78] Iyawe, E.P., Idowu, B.M., Omoleye, O.J., 2021. Radiology subspecialisation in Africa: A review of the current status. SA J Radiol 25, a2168. https://doi.org/10.4102/sajr.v25i1.2168.
[79] Merel, S., Walker, D., Chicana, R., Snyder, S., Baurès, E., Thomas, O., 2013. State of knowledge and concerns on cyanobacterial blooms and cyanotoxins. Environ Int 59, 303–327. https://doi.org/10.1016/j.envint.2013.06.013.
[80] Zurawell, R.W., Chen, H., Burke, J.M., Prepas, E.E., 2005. Hepatotoxic cyanobacteria: a review of the biological importance of microcystins in freshwater environments. J Toxicol Environ Heal B 8, 1–37. https://doi.org/10.1080/10937400590889412.
[81] International Monetary Fund (IMF)., 2021. Regional economic outlook. Sub-Saharan Africa: navigating a long pandemic. IMF, Washington D.C.
[82] Bootsma, H.A., Hecky, R.E., 2003. A comparative introduction to the biology and limnology of the African great lakes. J Gt Lakes Res 29, 3–18. https://doi.org/10.1016/S0380-1330(03)70535-8.
[83] Salzburger, W., Van Bocxlaer, B., Cohen, A.S., 2014. Ecology and evolution of the African great lakes and their faunas. Annu Rev Ecol Evol Syst 45, 519–545. https://doi.org/10.1146/annurev-ecolsys-120213-091804.
[84] Olokotum, M., Mitroi, V., Troussellier, M., Semyalo, R., Bernard, C., Montuelle, B., et al., 2020. A review of the socioecological causes and consequences of cyanobacterial blooms in Lake Victoria. Harmful Algae 96, 101829. https://doi.org/10.1016/j.hal.2020.101829.
[85] Fayiga, A.O., Ipinmoroti, M.O., Chirenje, T., 2018. Environmental pollution in Africa. Environ Dev Sustain 20, 41–73. https://doi.org/10.1007/s10668-016-9894-4.
[86] Onyango, D.M., Orina, P.S., Ramkat, R.C., Kowenje, C., Githukia, C.M., Lusweti, D., et al., 2020. Review of current state of knowledge of microcystin and its impacts on fish in Lake Victoria. Lakes Reserv 25, 350–361. https://doi.org/10.1111/lre.12328.
[87] Oberholster, P., Cloete, T., van Ginkel, C., Botha, A.-M., Ashton, P., 2008. The use of remote sensing and molecular markers as early warning indicators of the development of cyanobacterial hyperscum crust and microcystin- producing genotypes in the hypertrophic Lake Hartbeespoort. South Afr Pretoria Counc Sci Ind Res CSIR 15.
[88] Lürling, M., Van Oosterhout, F., Faassen, E., 2017. Eutrophication and warming boost cyanobacterial biomass and microcystins. Toxins 9, 64. https://doi.org/10.3390/toxins9020064.
[89] Diffenbaugh, N.S., Burke, M., 2019. Global warming has increased global economic inequality. Proc. Natl. Acad. Sci. U. S. A. 116, 9808–9813. 〈https://doi.org/10.1073/pnas.1816020116〉.