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REVIEW ARTICLE

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# Review of current state of knowledge of microcystin and its impacts on fish in Lake Victoria

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## Abstract

Microcystins are part of algal toxins produced intracellularly within algal cells, being in the family of hepatotoxic cyclic peptides from various species of blue-green algae. Blue-green algae are widely abundant in many equatorial eutrophic lakes, including Lake Victoria, with microcystin mainly from cyanobacterial blooms released into the water column, with different effects along the aquatic ecosystem trophic levels. Depending on the length of exposure and exposure route, microcystin effects on fish can include embryonic hatching perturbations, reduced survival and growth rates, changes in behavior, osmoregulation, increased liver activities and heart rates, as well as histopathological effects. While bioaccumulation is confirmed among fish, biomagnification along food webs is debatable. Lake Victoria the second largest freshwater lake in the world, and the source of livelihoods to millions reported near the gulf and shore MCs of 190 ± 51 to 543 ± 26 ng MC/g DW, respectively. Little is known, however, on the effects of microcystin on the Lake Victoria fishery and, ultimately, on the human population against the WHO recommended human microcystin intake levels of 0.04 μg/kg, thereby being the basis for this review.

**KEYWORDS**
fish, impact, Lake Victoria, microcystin, review

## 1 | INTRODUCTION

Cyanobacteria are gram-negative photosynthetic prokaryotes comprising more than 1,000 species of unicellular and multicellular microorganisms belonging to the class Cyanophyceae under the orders Gloeobacterales, Synechococcales, Oscillatoriales and Nostocales (Komarek, Kastovsky, Mares, & Johansen, 2014). It's dominance in eutrophic aquatic ecosystems is associated with a variety of factors particular to cyanobacteria, including possession of phycobilins (Sobiechowska-Sasim, Ston-Egiert, & Kosakowska, 2014), production of gas vesicles (Walsby, 1994), ability of certain species to fix nitrogen (Fay, 1992), and algae growth inhibition attributable to the ability of cyanobacteria to produce allelopathic chemicals (Gantar et al., 2008; Pflugmacher, 2002). Recent global warming, coupled with nutrient loading in waterbodies, has catalysed the buildup of cyanobacteria blooms resulting in others producing harmful cyanotoxins, such as the genus *Microcystis* (Amorim, de Moura-Falcao, Valenca, de Souza, & do Nascimento Moura, 2019; Sivonen & Jones, 1999). Toxins produced by cyanobacteria are both secondary metabolites and diverse, including microcystin (MC) and nodularins cyclic peptides that inhibit protein phosphatases.

MC, the most frequently occurring and widespread cyanotoxins, are formed within algal cells, mainly from cyanobacterial blooms which are released into the water column (Merel et al., 2013; Sivonen & Jones, 1999). During a cyanobacteria bloom event, MC remain within cells, only being emitted when cells are lysed as a result

  

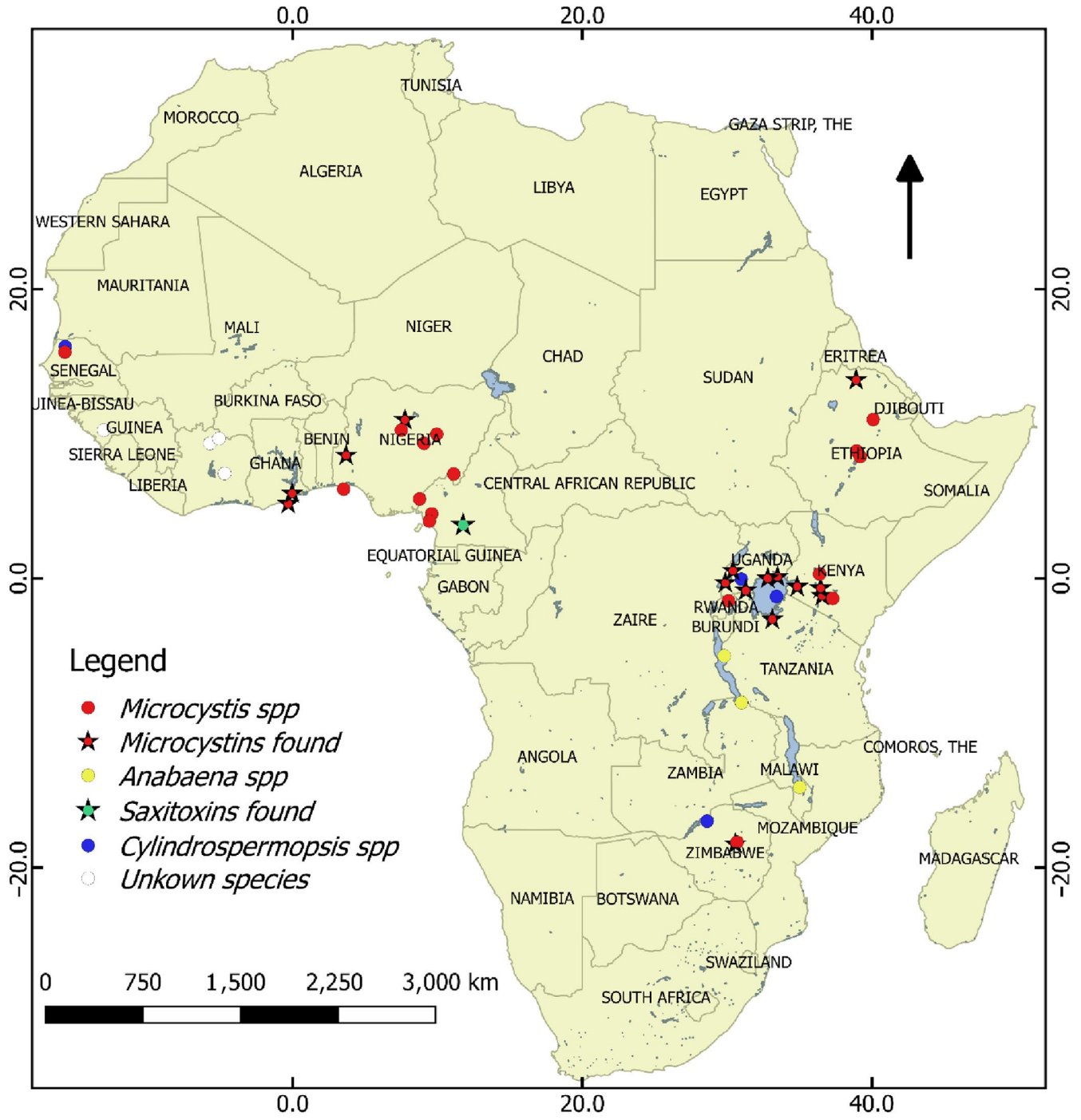


**FIGURE 1** Map of tropical Africa showing locations of cyanobacterial blooms (adapted from Mowe et al. 2015)

of natural cell death and senescence, with neurotoxic, hepatotoxic or dermatotoxic effects. The emission of toxins also may be propagated by evolutionary-derived or environmentally mediated circumstances, including allelopathy or relatively sudden nutrient limitation (Merel et al., 2013).

Cyanobacteria is wildly seen in many equatorial eutrophic lakes, including Lake Victoria, because of elevated temperatures and eutrophication which accelerates algal growth and breakdown, culminating in the release of toxins. The released cyanotoxins, with MC being the most frequently detected, constitute part of the biological water contaminant pathways for fish, livestock and human beings through water, aquatic vegetation and fish intake (Chorus & Bartram, 1999; Sivonen & Jones, 1999; Zhang et al. 2009; Badar et al., 2017). On a global scale, MC exhibits more than 90 variants of toxicity identified to date, with MC-LR being the most toxic and frequent (Pearson, Mihali, Moffitt, Kellmann, & Neilan, 2010). Thus, they have a potential negative impact on the food web with these effects increasing via bioaccumulation in the food web (Chen, Xie, Guo, Zheng, & Ni, 2005). Microcystins-LR, which is a water-soluble MC variant, remains relatively chemically stable in

the water column over time after their release. This can result in increased bioavailable extracellular cyanotoxins that can accumulate along the ecological food chain, resulting in animal poisoning and deaths worldwide (Lambert, Holmes, & Hrudey, 1994; Codd et al. 2005; Nizan, Dimentman, & Shilo, 1986; Fogg, Stewart, Fay, & Walsb, 1973). Depending on the length and route of exposure, MCs effects on fish can include damage or perturbation on the testis and ovaries, the hypothalamic-pituitary-gonadal (HPG) axis, embryonic hatching, survival and growth rate declines, changes in behavior, impaired osmoregulation, increased liver activities and heart rate, and histopathological effects (Lone, Koiri, & Bhide, 2015; Malbrouck & Kestemont, 2006; Svircev et al., 2010). Upon its ingestion, liver, muscle and viscera are the main MC accumulation organs. This can ultimately result in liver failure by inhibiting the protein phosphatases 1 and 2 (PP1 and PP2), leading to cellular toxicity, apoptosis, cancer and structural damage among others (Vaterio, Vasconcelos, & Campos, 2016). Lone et al. (2015) have shown that MCs exhibit genotoxicity attributable to their ability to damage DNA and promote tumor, while Annadotter et al. (1999) and Zhou, Hai, and Kun (2002) reported on the correlation between MC levels in drinking water and incidence of primary liver cancer (PLC).

Microcystin can affect various trophic levels in the aquatic ecosystem, with concentrations increasing with exposure period and environmental concentration (Schmidt et al. 2013). An increased periodicity and intensity of harmful algal blooms occurring in many aquatic ecosystems (Figure 1) has attracted global interest regarding the presence of MC (Mowe, Mitrovic, Lim, Furey, & Yeo, 2015). Other studies have further highlighted tropical cyanobacterial genera and cyanobacterial proportionality (Figure 2).

Microcystin persistence and detoxification in aquatic organisms is a critical focus for fishery economics and public health, with several emerging ecological and public health issues focusing on plant and animal communities. This situation is attributed to the anthropogenic effects, mainly nutrient loads to freshwater systems and the related total biomass and composition alteration of algal communities (Beasley, Cook, Dahlem, Lovell, & Valentine, 1989; Galey et al., 1987; Hilborn & Beasley, 2015). Thus, the study of MC in Lake Victoria is critical to its aquatic toxicology and fauna effects in this

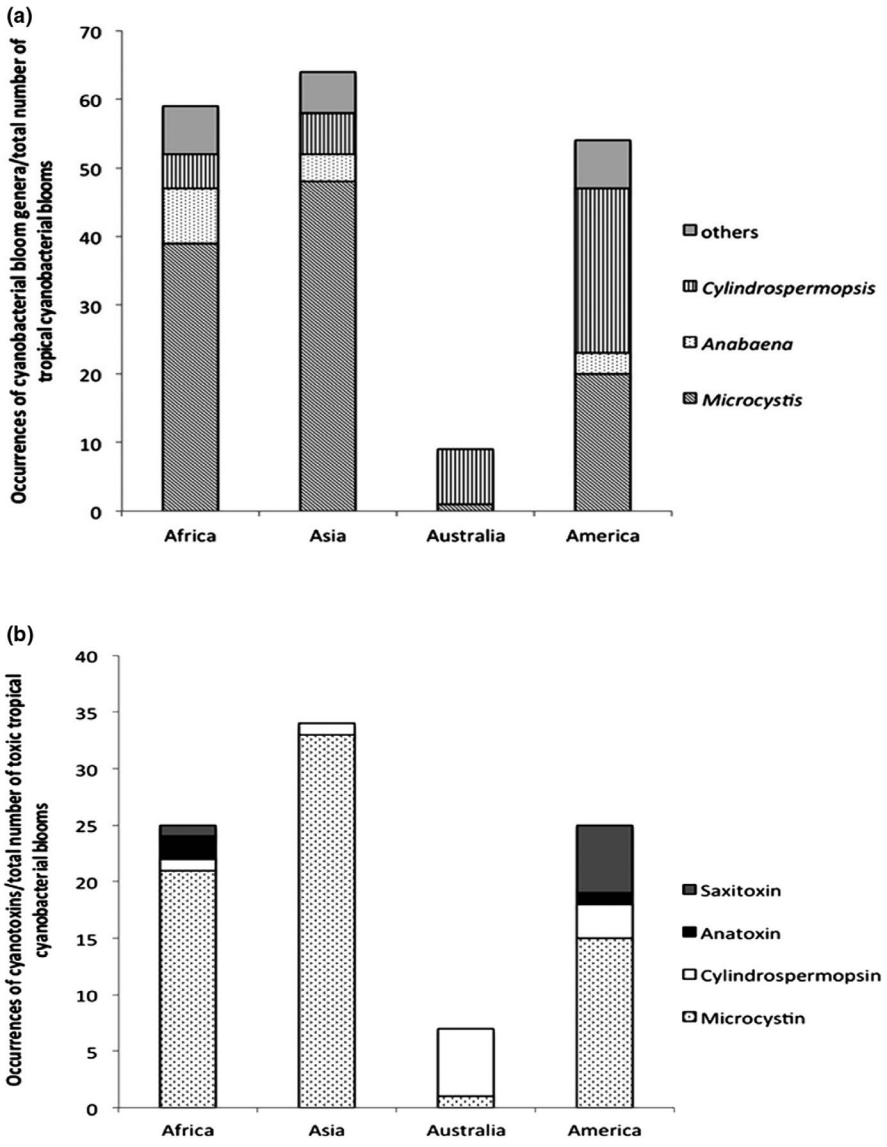


**FIGURE 2** Proportion of tropical cyanobacterial genera out of total tropical cyanobacteria blooms (source: Mowe et al. 2015)

lake. Accordingly, the present study (a) reviews the current state of research regarding microcystis in Nyanza Gulf of Lake Victoria, (b) identifies knowledge gaps and (c) proposes future research directions.

## 2 | MICROCYSTIN IN NYANZA GULF OF LAKE VICTORIA

Over the last three decades, Lake Victoria, the world's second largest freshwater lake, has experienced major water quality deterioration over time attributable mainly to pollution from increased eutrophication, a trend associated with urbanization, agricultural activities and deforestation (Hecky, Muggide, Ramlal, Talbot, & Kling, 2010; Kolding, Medard, Mkumbo, & van Zwieten, 2014). Nyanza Gulf is the most eutrophic bay of Lake Victoria (Simiyu, Oduor, Rohrlack, Sitoki, & Kurmayer, 2018) because of nutrient enrichment originating from subsistence agricultural activities (Gikuma-Njuru, Hecky, Guildford, & MacIntyre, 2013). The high eutrophication levels have resulted in regular cyanobacterial blooms, some with the potential of producing cyanotoxins toxic to fish (Malbrouck & Kestemont, 2006). The most frequently occurring cyanotoxins are the hepatotoxic microcystins (MC) emitted by cyanobacteria (Table 1), including *Microcystis*, *Dolichospermum (Anabaena)*, *Planktothrix (Oscillatoria)* and Nostoc (Meriluoto, Spoof, & Codd, 2017).

MC toxicity is based on the strong inhibition of the protein phosphatases (PP1 and PP2a), disturbing cytoskeleton formation in eukaryotic cells. Microcystin is associated with high eutrophication levels associated with increased nutrient concentrations and phytoplankton growth (Markensten, Moore, & Persson, 2010), resulting in hypoxic conditions in the lake. Several researchers, including Sitoki, Kurmayer and Rott (2012), reported positive results regarding the presence of microcystin in Lake Victoria, linking it with seasonality (Figure 3). Miles et al. (2013) reported the presence of putative microcystin analogues in his study of Mwanza Gulf in Lake Victoria. Recent studies by Simiyu et al. (2018) found the presence of higher microcystin levels (62 ± 7 ng/g fish dry weight) in Nyanza Gulf (Kisumu bay) of Lake Victoria, compared to the open waters of the Rusinga Channel (14 ± 0.8 ng MC/g). These studies confirm higher cyanobacterial blooms within Winam Gulf, Mwanza Gulf and Murchison Bay (Ochumba and Kibbara, 1989; Sekedende et al. 2005; Haande et al., 2007). Semyalo, Rohrlack, Naggawa, and Nyakairu (2009) studied the presence of microcystin in Nile tilapia within Murchison Bay, finding a positive correlation of microcystin in fish gut with that in the water. He also noted an increase in microcystin-emitting cyanobacteria in Lake Victoria may have resulted in increased intake of microcystin in filter-feeding Nile tilapia (Table 2).

It is also worth noting, however, that fish such as tilapia are likely to have a detoxification system able to metabolize ingested toxins to less toxic states (Wiegand et al., 1999). Despite the likelihood of detoxification, other studies also have confirmed toxin accumulation in tissues, especially among planktivorous organisms, through ingestion of toxic microcystis in their diet and via food web transfer (Li, Chung, Kim, & Lee, 2004; Xie et al., 2004). The increased toxins and their effects to human and the aquatic environment are of great concern within freshwater systems. Severe MC exposure to fish has proved to result in high incidences of liver necrosis, growth retardation, impaired reproductive ability and mass mortalities (Malbrouck & Kestemont, 2006; Ochumba, 1990). These effects result from several factors, including reduced oxygen levels in the lake with a negative effect to the overall productivity of the lake. Fish and contaminated water are among the key MC exposure routes to humans, especially when the WHO recommended daily intake limit of 0.04 μg/kg for fish and 1 μg/L for water intake are exceeded (Jia, Luo, Lu, & Giesy, 2014; Okello, Portmann, Erhard, Gademann, & Kurmayer, 2010; WHO, 2003). Microcystin may not immediately pose a health threat to human beings upon consumption, but has potential long-term negative implications.

Despite the likelihood of continued ingestion of cyanobacteria by fish, even in the presence of microcystin which ultimately accumulates in fish tissue (Zhao, Zhu, Yang, Gan, & Song, 2006), research has confirmed that fish have the ability to physiologically deal with microcystin through biliary excretion (Sahin, Tencalla, Dietrich, & Naegeli, 1996), and behaviorally through lowering their feeding rate in the existence of toxic algae (Keshavanath et al., 1994). On the other hand, fish may change their behaviour to consume large amounts of cyanobacteria as a means of controlling the blooms in the lake (Datta & Jana, 1998). Substantial ingested quantities, however, may accumulate in fish livers and muscles, subsequently being transferred along the food web (Lance et al., 2014). Semyalo et al. (2009) recommended examination of microcystin accumulation at different levels in the fish food web in order to better understand the effects. Nile tilapia, being a generalist feeder, usually accumulates substantial quantities of microcystin in its diet. Previous research on tilapia diets in Lake Victoria have demonstrated cyanobacteria (especially *microcystis* sp.) can constitute about 30% of the phytoplankton community (Haande et al., 2007; Semyalo et al., 2009). Simiyu et al. (2018) noted the level of microcystin in Lake Victoria depends on the location, with open waters containing lower concentrations (56 ± 56 ng MC/g DW), compared to gulfs and shore areas (190 ± 51 to 543 ± 26 ng MC/g DW). Substantial quantities of microcystin absorbed by fish accumulates in the liver and muscles, subsequently being transferred up the food chain.

## 3 | BIOACCUMULATION AND BIOMAGNIFICATION

Bioaccumulation refers to the buildup of substances such as toxins or other chemicals in the body of an organism. It occurs when an organism ingests a substance at a rate faster than which it is eliminated through catabolism and excretion. This means the longer the biological half-life of a toxic substance, the higher the risk of chronic poisoning, even in spite low levels of the toxin in the environment. Studies have confirmed the intensity of toxin accumulation is not only based on a species feeding guild but is also dependent on

**TABLE 1** Summary of cyanobacterial blooms, prevalence and toxins reported in tropical Africa (Mowe et al., 2015)

| Country | Potential toxic species found | Toxin test | Toxins found | Quantity of toxins | References |
|---|---|---|---|---|---|
| Cameroon | *Planktothrix mougeotii, Oscillatoria putrida* & *Microcystis spp. (M. aeruginosa, M. wesenbergii)* | Not tested | Not tested | Not tested | Kemka *et al.* (2013), Green (2010) |
| Cote d'Ivoire | Unknown bloom-forming species | Not tested | Not tested | Not tested | Bouvy *et al.* (1998), Arfi *et al.* (2001) |
| Ethiopia (2011) | *Microcystis* sp.* | ELISA | No MC found | No MC found | Gremberghe *et al.* (2011) |
| Ghana | *Microcystis aeruginosa** & *Anabaena flos-aquae* | HPLC | MC-RR | 0.03–3.21 μg/L | Addico, Hardege, Komarek, Babica, & de Graft-Johnson, (2006) |
| Kenya | *Microcystis aeruginosa**, *Arthrospira fusiformis** & *Anabaenopsis abijatae** | ELISA/HPLC-MALDI-TOF | MS MC-LR & Anatoxin-a | MC: 1.6–39.0 μg/L Anatoxin:o.5–2.0 μg/L | Ballot, Krienitz, Kotut, Wiegand and Pflugmacher (2005), Haande et al.(2007), Kotut, Ballot, Wiegand and Krienitz (2010) |
| Malawi | *Anabaena sp.* | Not tested | Not tested | Not tested | Gondwe, Guildford and Heck (2007) |
| Nigeria | *Cylindrospemopsis sp.**, *Anabaena sp.**, *Microcystis sp.**(*Microcystis aeruginosa, M. flos-aquae, M. wesenbergii), Lyngbya sp.**, *Aphanizomenon flos-aquae, Oscillatoria limnetica* & *Anabaena spiroides* | ELISA/HPLC-MALDI-TOF | MC, CYN, Anatoxin-a, Anatoxin-a (S),STX | MC:1.4– 3.8 μg/L | Anadu, Obiaha and Ejike (1990), Kemdirim (2000), Ezra and Nwankwo (2001), Akin-Oriola (2003), Akin-Oriola, Anetekhai and Oriola (2006), Odokuma and Isirima 2007), Chia, Abolude, Ladan and Kalaboms (2009), Okechukwu and Ugwumba (2009), Onyema (2010), Ajuzie (2012) |
| Senegal | *Microcystis aeruginosa &(2006);Cylindrospermopsis raciborskii* | Mouse bioassay | No CYN/STX found | No CYN/STX found | Berger *et al.* (2006), Bouvy *et al.* (2006), Dufour, Sarazin, Quiblier, Sane and Leboulanger (2006) |
| Tanzania | *Anabaena sp.,Microcystis sp.** | HPLC-DAD/-MALDI-TOF | MC-RR | 0–1.0 μg/L | Sekadende, Lyimo and Kurmayer (2005) |
| Uganda | *Microcystis aeruginosa, M. flos-aquae, Anabaenopsis spp., Aphanizomenon sp., Anabaena sp.* & *Cylindrospermopsis raciborskii* | ELISA,HPLC/ MALDI-TOF&LC-MS/MS | MC-RR,($Asp^3$)MC-RR, MC-YR,($ASP^3$) MC-YR, MC-LR, MC-RY,($Asp^3$) MC-RY | 0.2–61.2 μg/L | Ganf (1974), Komarek and Kling (1991), Oliver and Ganf (2000); Haande et al. (2007); Haande *et al.* (2007), Green (2010), Okello et al.(2010), Okello and Kurmayer (2011), Poste, Hecky and Guildford (2013) |
| Zimbabwe | *Microcystis aeruginosa**, *M. wesenbergii, M. novacekii, C. raciborskii, Lyngbya sp., Anabaena sp., Aphanizomenon sp.* & *Oscillatoria sp.* | ELISA | MC-LR | 0.2–22.48 μg/L | Ramberg (1987), Magadza (2006), Mhlanga, Day, Chimbari, Siziba and Cronberg (2006a), Mhlanga *et al.* (2006b), Magadza (2008-2009), Kunz (2011), Tendaupenyu (2012) |

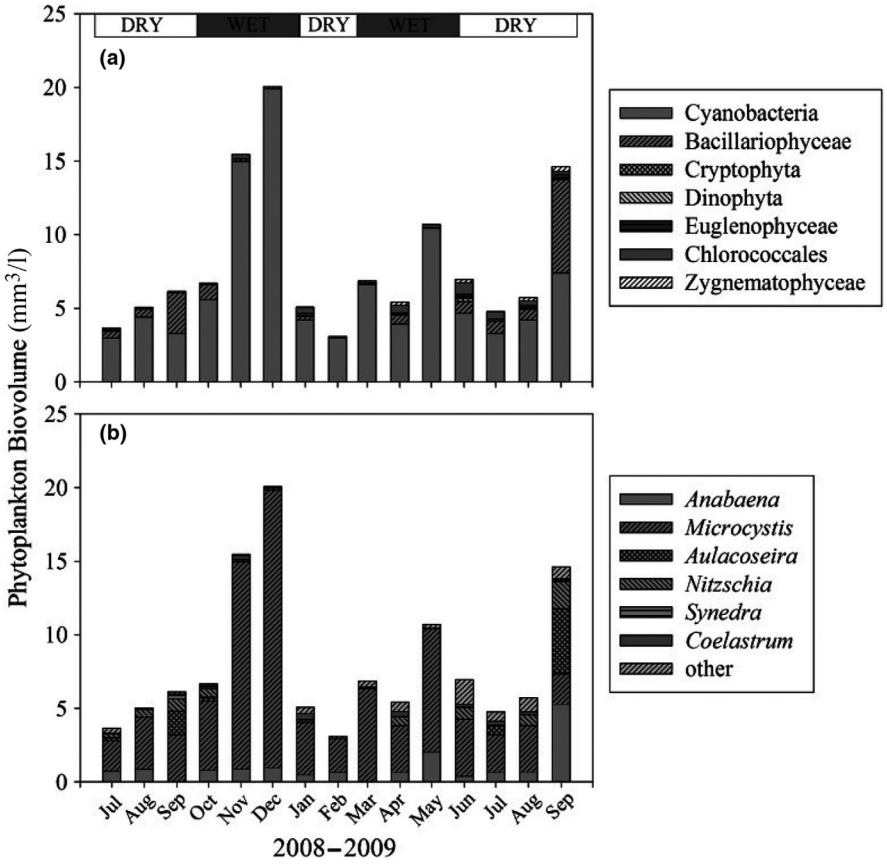


**FIGURE 3** Proportion of different cyanobacterial toxins out of total number of tropical toxic cyanobacterial blooms (source: Mowe et al. 2015)

**TABLE 2** Selectivity index log *Q* of major cyanobacteria groups found in the diets of Nile tilapia fish in Lake Mburo (*n* = 22) and Murchison Bay, Lake Victoria (*n* = 44; N/A = not available; Source: Semyalo et al., 2011)

| | Selectivity index (log *Q*) | | | | | |
|---|---|---|---|---|---|---|
| | Lake Mburo | | | Murchison Bay | | |
| Genus | Minimum | Mean | Maximum | Minimum | Mean | Maximum |
| *Microcystis* | 3.56 | 3.92 | 3.99 | 2.99 | 3.87 | 3.99 |
| *Anabaena* | − 1.26 | 0.93 | 3.06 | −1.22 | 1.75 | 3.64 |
| *Aphanocapsa* | 2.06 | 2.14 | 2.21 | N/A | N/A | N/A |
| *Other cyanobacteria* | − 0.39 | 0.89 | 3.48 | −0.22 | −0.11 | 0 |

the environmental toxin concentration and rate of accumulation in a fish relative to depuration (Ibelings & Chorus, 2007; Kozlowsky-Suzuki, Wilson, & da Ferrão-Filho, 2012). MC bioaccumulation has been confirmed to exhibit different pathological effects on different fish species, with phytoplanktivorous species being more tolerant to MC effects (Xie et al., 2004).

In contrast, biomagnification refers to the increasing concentration of a substance within the tissues of organisms existing at successively higher levels in a food chain. This occurs as a result of persistence of the substance, food chain energetics and/or or low or non-existent rates of internal degradation or excretion. The toxin levels usually build up along the food chain. Nevertheless, there is inadequate knowledge on toxin biomagnification (Flores, Miller, & Stockwell, 2018; Kozlowsky-Suzuki et al., 2012). Although recent studies have proved fish and human accumulation of toxins is associated with the environmental concentration of particular toxins, coupled with the exposure period (Gurbuz, Uzunmehmetoglu, Diler, Metcalf, & Codd, 2016; Jia et al., 2014), the MCs concentration up the trophic level is limited because of toxin depuration (Ferrao-Filho and Kozlowsky-Suzuki, 2011; Zhang et al. 2009). It is important to note, however, that different studies have resulted in conflicting outcomes in relation to microcystin accumulation up the trophic levels because of their spatial temporal trends (Snyder, 2015; Xie et al., 2005; Zhang et al.2009).

## 4 | MICROCYSTIN IMPACTS IN FISH

Enhanced production of cyanotoxin-producing cyanobacteria is associated with nutrient loading into waterbodies primarily resulting from human activities. Anthropogenic nutrient inputs to freshwater systems has continued to shift the total biomass and composition of algal communities and subsequently fish, particularly for eutrophic freshwater lakes. Cyanobacteria blooms

in highly eutrophic lakes can provide a rich and abundant source of nutrients for fish, including Roach (*Rutilus rutilus*), Silver carp (*Hypophthalmichthys molitrix)* and Nile tilapia (*Oreochromis niloticus*) (Bwanika, Chapman, Kizito, & Balirwa, 2006; Chen, Xie, Zhang, Ke, & Yang, 2006; Kamujunke, Schmidt, Pflugmacher, & Mehner, 2002). This is not always the case (Bednarska, 2006), however, since blooms are often dominated by colonial and filamentous forms that can cause mechanical interference for zooplankton grazers and clogging of gills in fish (Landsberg, 2002), leading to a decreased food web and subsequent fish population. The presence of aqueous and cell-bound cyanotoxins in a fish diet is not good for their morphology, physiology, behaviour and ultimately their survival (Malbrouck & Kestemont, 2006). The presence of cyanotoxins such as microcystins can induce stress in fish (Baganz, Staaks, Pflugmacher, & Steinberg, 2004) that can in turn lead to low foraging rates (Beveridge et al., 1993). Different effects

**TABLE 3** Microcystins detected by LC–$MS^2$ (Method A) with and without thiol derivatization in standards and in extracts from *Microcystis* bloom in Lake Victoria (BSA6)[a]

| Underivatized sample | | | | Mercaptoethanol derivative | | MEMHEG derivative | | Abundance in sample | |
|---|---|---|---|---|---|---|---|---|---|
| Rt (min) | $[MH]^+ m/z$ | Microcystin | Status | Rt (min) | $[MH]^+ m/z$ | Rt (min) | $[MH]^+ m/z$ | Standard | BSA6 |
| 1.8 | 1,038.5 | MC-RR (**3**) | Confirmed | 1.81 | 1,116.5 | 2.59 | 1,394.5 | Major | Major |
| 3.3 | 1,031.5 | [$Asp^3$]MC-YR (**20**) | Tentative | 3.35 | 1,109.5 | 4.1 | 1,387.5 | ND | Minor |
| 3.46 | 1,063.5 | [$Mser^7$]MC-YR (**14**) | Tentative | NR | – | NR | – | ND | Major |
| 3.51 | 1,013.5 | [$Mser^7$]MC-LR (**15**) | Tentative | NR | – | NR | – | ND | Major |
| 3.59 | 1,031.5 | [$Dha^7$]MC-YR (**21**) | Tentative | 3.49 | 1,109.5 | – | 1,387.5 | Minor | Minor |
| 3.61 | 1,045.5 | MC-YR (**2**) | Confirmed | 3.63 | 1,123.5 | 4.33 | 1,401.5 | Major | Major |
| 3.68 | 981.5 | [$Asp^3$]MC-LR (**17**) | Tentative | 3.69 | 1,059.5 | 4.26 | 1,337.5 | Minor | Minor |
| 3.77 | 995.5 | MC-LR (**1**) | Confirmed | 3.71 | 1,073.5 | 4.47 | 1,351.5 | Major | Major |
| 3.79 | 981.5 | [$Dha^7$]MC-LR (**8**) | Confirmed | 3.84 | 1,059.5 | 4.5 | 1,337.5 | Minor | Minor |
| 4.02 | 1,009.5 | MC-HilR (**11**) | Tentative | 3.93 | 1,087.5 | 4.68 | 1,365.5 | ND | Minor |
| 4.05 | 1,029.5 | MC-FR (**12**) | Tentative | 3.97 | 1,107.5 | ND | 1,385.5 | ND | Minor |
| 4.9 | 953.5 | MC-RA (**10**) | Tentative | 4.78 | 1,031.5 | 5.44 | 1,309.5 | ND | Major |
| 5.01 | 1,031.5 | [$Asp^3$]MC-RY (**16**) | Tentative | 4.86 | 1,109.5 | 5.41 | 1,387.5 | ND | Minor |
| 5.07 | 1,063.5 | [$Mser^7$]MC-RY (**22**) | Tentative | NR | – | NR | – | ND | Minor |
| 5.12 | 1,031.5 | [$Dha^7$]MC-RY (**23**) | Tentative | 4.94 | 1,109.5 | 5.56 | 1,387.5 | ND | Minor |
| 5.29 | 1,045.5 | MC-RY (**9**) | Confirmed | 5.22 | 1,123.5 | 5.79 | 1,401.5 | ND | Major |
| 5.37 | 1,075.5 | MC-RY(OMe) (**24**) | Tentative | 5.3 | 1,153.5 | 5.88 | 1,431.5 | ND | ND |
| 5.44 | 967.5 | MC-RAba (**25**) | Tentative | 5.29 | 1,045.5 | 5.92 | 1,323.5 | ND | Minor |
| 5.93 | 981.5 | MC-RApa(1) (**26**) | Tentative | 5.76 | 1,059.5 | 6.34 | 1,337.5 | ND | Minor |
| 6.09 | 981.5 | MC-RApa(2) (**27**) | Tentative | 5.89 | 1,059.5 | 6.48 | 1,337.5 | ND | Minor |
| 6.34 | 995.5 | MC-RL (**28**) | Tentative | 6.15 | 1,073.5 | 6.71 | 1,351.5 | ND | Minor |
| 6.37 | 1,029.5 | MC-RF (**13**) | Tentative | 6.22 | 1,107.5 | 6.74 | 1,385.5 | ND | Major |
| 8.09 | 960.5 | MC-YA (**29**) | Tentative | 7.83 | 1,038.5 | 8.52 | 1,316.5 | ND | Minor |
| 8.36 | 910.5 | MC-LA (**4**) | Confirmed | 7.83 | 988.5 | 8.58 | 1,266.5 | Major | Minor |
| 8.55 | 1,002.5 | MC-LY (**6**) | Confirmed | 8.1 | 1,080.5 | 8.72 | 1,358.5 | Major | ND |
| 8.7 | 1,032.5 | MC-LY(OMe) (**18**) | Tentative | 8.23 | 1,110.5 | 8.84 | 1,388.5 | Minor | ND |
| 8.91 | 974.5 | MC-YAba (**30**) | Tentative | 8.58 | 1,052.5 | 9.23 | 1,330.5 | ND | Minor |
| 9.15 | 924.5 | MC-LAba (**31**) | Tentative | 8.5 | 1,002.5 | 9.18 | 1,280.5 | ND | Minor |
| 9.8 | 1,025.5 | MC-LW (**7**) | Confirmed | 9.28 | 1,103.5 | 9.84 | 1,381.5 | Major | ND |
| 10.3 | 986.5 | MC-LF (**5**) | Confirmed | 9.59 | 1,064.5 | 10.13 | 1,342.5 | Major | ND |
| 10.45 | 952.5 | MC-LL (**19**) | Tentative | 9.8 | 1,030.5 | 10.21 | 1,308.5 | Minor | ND |

[a]NR, no reaction; ND, not detected; identities considered confirmed only when peaks possessed identical retention time and mass spectral fragmentation to authentic standards and were considered tentative when these properties were consistent with proposed structure in absence of standard; retention times for thiol derivatives are for most abundanst diastereoisomer; compounds were denoted as "Major" when they constituted more than ca 10% of most abundant microcystin in sample; Source: Miles et al. (2013).

of microcystin and the potential consequences to fish have been reported for aquatic food webs. Malbrouck and Kestemont (2006), for example, reported that fish exposure to microcystin in a dose-dependent manner in early life stages can results in perturbations to embryonic hatching, decreased survival and growth rates, and histopathological effects, including enlarged and opaque yolk sac, small heads, curved body and tail. They also reported that ingested microcystin accumulates in the liver, muscle and viscera of juveniles and adults and can affect fish behavior, growth rate and osmoregulation. Depending on the microcystin exposure route, the effects of microcystin concentration in the water and the food chain can be many and varied. Sonia and Ramanibai (2015) found a decrease in the body weight and death after eight days in *Poecilia sphenops* after exposing them to the cyanobacteria *Microcystis aeruginosa* in the diet at a concentration of $6 \times 10^4$ cells/ml to each individual fish. Exposure to microcystin can produce architectural changes in the liver, disturb parenchyma formation of the liver and enlarged hepatocytes with granular cytoplasm. Fish exposure to this microcystis concentration resulted in hepatocyte necrosis, further displaying ruptured follicle walls in the oocyte, while the compactness of the tissue also was disturbed. There was less yolk in the developing oocyte, deformed follicle cells and incidences of ovary necrosis. Weight loss and fish mortality was likely a result of a combination of stress and organ damage.

Microcystins, particularly MC-LR, a monocyclic peptide hepatotoxin, was found to accumulate mainly in the liver of fish, as well as in the kidneys, gills and intestines (Mohammed & Hussein, 2006; Radbergh, Bylund, & Erikkson, 1991; Zurawell, Chen, Burke, & Prepas, 2005). Ayles et al. (1986) noted the impacts of cyanobacteria on fish populations is not due only to the toxins they release, but also to reduced oxygen levels in the waterbody resulting from as well as the collapse of the algal bloom. Shebulsky (1951), however, proved that fish death occurred even in the presence of an adequate oxygen supply, indicating toxins contributed partly to the death of fish. With the current human health movement toward consuming leaner meat, many people in Kenya have embraced fish eating, particularly the communities living along Lake Victoria, which are known to depend highly on fish as one of their staple meals, which could result in human exceedance of the average daily tolerance intake limit provided by World Health Organization of 0.04 μg/kg body mass per day for MC-LR (WHO, 1998; Chorus & Bartram, 1999). Thus, it is critical to assess microcystin exposure risks to human via fish consumption, especially among the traditional fish-eating communities.

MCs detected by LC–$MS^2$, with and without thiol derivatization in standards, have confirmed the presence of MC-LR, a lethal microcystin, in Lake Victoria (Table 3). Among other organs, the effects of MC-LR on fish livers has also been noted to extend its human health effects, with almost similar organs affected. As fish consumption grows in the country against a declining fisheries capture, the risk of exposure to MCs through fish intake are real (Poste, Hecky, & Guildford, 2011). Assessment of human health impacts associated with limited water supply and sanitation within a given area requires epidemiological studies to establish dose-response relationships (DRRs). Although often expensive and resource demanding, this will link environmental variables with observable health impacts (World Bank, 1998). In cases where drinking water is contaminated by cyanotoxins, however, bottled water or different sources of water are likely alternatives, even though they may require more time, energy and possibly funds to obtain such alternatives. Three categories of impacts are used to estimate the monetary consequences of illness to society attributable to water pollution, including (a) income losses due to illness, (b) health care expenditures to society and/or affected individuals, and (c) pain, suffering and/or inconvenience experienced by affected individuals. The costs associated with the two first categories can be determining by directly observing these factors (Ready et al., 2004). Establishing quantitative epidemiological relationships is the main data-demanding task in comparing the benefits and costs of measures to reduce algal toxins. Concluding whether or not liver damages within a given population is a result of cyanobacterial intoxication requires determining which drinking water sources is contaminated, who drinks it, and the particular population risk levels of suffering liver disease, compared to those drinking water from different water sources (Kuiper-Goodman, Falconer & Fitzgerald, 1999). Losses from fish sales also have direct effects on both national and individual revenues, as well as household nutritional requirements particularly around the affected areas. Monitoring of toxigenic and non-toxigenic algae are very costly to any nation's GDP (Reichwaldt and Ghadouani, 2012; Falconer & Humpage, 2005). However, the implications of unmonitored cyanotoxin emissions, particularly MC in eutrophic freshwater bodies that include Lake Victoria, can have far-reaching effects on aquatic ecosystem balances and human health.

## 5 | CONCLUSIONS AND RECOMMENDATIONS

Lake Victoria, like other freshwater eutrophic lakes, is experiencing cyanobacterial build-up resulting from increased nutrient loads associated with poor agricultural practices and domestic and industrial wastes. Being the second largest freshwater lake in the world, and the largest in Africa, the lake contributes significantly to food security and fish species richness. There is great risk of losing the diversity of fish species in the lake to the effects of cyanotoxins and further impact human health through fish consumption and contaminated water use. The commercially important fish species of the lake, with the exception of *Lates niloticus*, are herbivorous, thereby being predisposed to high levels of cyanobacterial microcystis, despite biodilution capability along food web. There is a paucity of information on microcystin biomagnification in fish. There is evidence of microcystin bioaccumulation in the muscle, liver and viscera of fish, therefore posing a health risk not only to fish performance and species diversity through disrupted food webs, but also to human health. With people embracing a healthier diet, they tend to consume more fish, a lean and healthy protein source. Thus, depending on the intake level, they may end up exceeding the average daily

tolerance limit of 0.04 μg/kg body weight recommended by the World Health Organization. Thus, it is critical to assess the seasonal concentration levels of various microcystin species in Lake Victoria and their bioaccumulation pathways, especially for commercially-important fish species, in order to inform lake management and the fish food industry.

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## REFERENCES

Addico, G., Hardege, J., Komarek, J., Babica, P., & de Graft-Johnson, K. A. A. (2006). Cyanobacteria species identified in the Weija and Kpong reservoirs, Ghana, and their implications for drinking water quality with respect to microcystin. *African Journal of Marine Science*, *28*, 451–456. https://doi.org/10.2989/18142320609504196.

Akin-Oriola, G. A. (2003). On the phytoplankton of Awba reservoir, Ibadan, Nigeria. *Revista de Biologia Tropical*, *51*, 1–6.

Akin-Oriola, G. A., Anetekhai, M. A., & Oriola, A. (2006). Algal blooms in Nigerian waters: an overview. *African Journal of Marine Science*, *28*, 219–224.

Ajuzie, C. C. (2012). A first survey of phytoplankton community richness in Lamingo Reservoir, Jos, Nigeria: A wake-up call for the continuous monitoring of microalgae in surface waters serving as drinking water sources in Nigeria. *New York Science Journal*, *5*, 1–8.

Amorim, C. A., de Moura-Falcao, R. H., Valenca, C. R., de Souza, V. R., & do Nascimento Moura, A. (2019). Allelopathic effects of the aquatic macrophyte *Ceratophyllum demersum* L. on phytoplankton species: Contrasting effects between cyanobacteria and chlorophytes. *Acta Limnologica Brasiliensia*, *31*, e21.

Anadu, D. I., Obiaha, A., & Ejike, C. (1990). Water quality and plankton periodicity in two contrasting mine lakes in Jos, Nigeria. *Hydrobiologia*, *208*, 17–25.

Annadotter, H., Cronberg, G., Johansson, S., & Olsson, M. (1999). The occurrence of toxin-producing blue-green algae (cyanobacteria) in the sub-tropical drinking water reservoir Lake Chivero, Zimbabwe. Paper presented at International Conference on Shallow Tropical Waters and Humans, 11–16 April 1999, KWSTI Naivasha, Kenya.

Arfi, R., Bouvy, M., Cecchi, P., Pagnao, M., & Thomas, S. (2001). Factors limiting phytoplankton productivity in 49 shallow reservoirs of North Côte d'Ivoire (West Africa). *Aquatic Ecosystem Health and Management*, *4*, 123–138. https://doi.org/10.1080/14634980127706.

Ayles, G. B., Lark, J. G. I., Barica, J., & Kling, H. (1986). Seasonal mortality in Rainbow trout (*Salmogairdneri*) planted in small eutrophic lakes of central Canada. *Journal of the Fisheries Research Board of Canada*, *37*, 647–655.

Badar, M., Batool, F., Khan, S. S., Khokhar, I., Qamar, M. K., & Yasir, C. (2017). Effects of microcystin toxins contaminated drinking water on hepatic problems in animals (Cowsa and Buffalos) and toxins removal. *Buffalo Bulletin*, *36*, 43–55.

Baganz, G., Staaks, S., Pflugmacher, S., & Steinberg, C. E. W. (2004). A comparative study on the microcystin induced behavioural changes of two fish species, *Danio rerio* and *Leucaspius delineatus*. *Environmental Toxicology*, *19*, 564–570.

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.

Beasley, V. R., Cook, W. O., Dahlem, A. M., Lovell, R. A., & Valentine, W. M. (1989). Algae intoxications in livestock and waterfowl. *Veterinary Clinics of North America: Food Animal Practice*, *5*(2), 345–361.

Bednarska, A. (2006). Cyanobacteria and their influence on herbivore zooplankton. *Wiadomosci Ekologiczne*, *52*(2), 59–87.

Berger, C., Ba, N., Gugger, M., Bouvy, M., Rusconi, F., Coute, A., … Bernard, C. (2006). Seasonal dynamics and toxicity of Cylindrospermopsis raciborskii in Lake Guiers (Senegal, West Africa). *Microbiology Ecology*, *57*, 355–366.

Beveridge, M. C. M., Baird, D. J., Rahmatullah, S. M., Lawton, L. A., Beattie, K. A., & Codd, G. A. (1993). Grazing Rates on Toxic and Nontoxic Strains of Cyanobacteria by Hypophthalmichthys molitrix and *Oreochromis niloticus*. *Journal of Fish Biology*, *43*, 901–907.

Bouvy, M., Arfi, R., Cecch, P., Corbin, D., Pagano, M., Saint-Jean, L., & Thomas, S. (1998). Trophiccoupling between bacterial and phytoplanktonic compartments in shallow tropical reservoirs (Ivory Coast, West Africa). *Aquatic Microbial Ecology*, *15*, 25–37.

Bouvy, M., Ba, N., Ka, S., Sane, S., Pagano, M., & Arfi, R. (2006). Phytoplankton community structure and species assemblage succession in a shallow tropical lake (Lake Guiers, Senegal). *Aquatic Microbial Ecology*, *45*, 147–161.

Bwanika, G. N., Chapman, L. J., Kizito, Y., & Balirwa, J. (2006). Cascading effects of introduced Nile Perch (*Lates niloticus*) on the foraging ecology of Nile tilapia (*Oreochromis niloticus*). *Ecology of Fresh Water Fish*, *15*, 470–481.

Chen, J., Xie, P., Guo, L., Zheng, L., & Ni, L. (2005). Tissue Distribution and Seasonal Dynamics of the Hepatotoxic Microcystins-LR and RR in Fresh Water Snail (*Bellmya aeruginosa*) from a Large Shallow Trophic Lake of the Subtropical China. *Environmental Pollution*, *134*, 423–430.

Chen, J., Xie, P., Zhang, D. W., Ke, Z. X., & Yang, H. (2006). *In situ* studies on the bioaccumulation of microcystins in the phytoplanktivorous Silver carp (*Hypophthalmichthys molitrix*) stocked in Lake Taihu with dense toxic Microcystis blooms. *Aquaculture*, *261*, 1026–1038.

Chia, A. M., Abolude, D. S., Ladan, Z., & Kalaboms, A. (2009). The presence of microcystins in aquatic ecosystems in Northern Nigeria: Zaria as a case study. *Research Journal of Environmental Toxicology*, *3*, 170–178. https://doi.org/10.3923/rjet.2009.170.178.

Chorus, I., & Bartram, J. (1999). *Toxic Cyanobacteria in Water: A Guide to Their Public Health Consequences, Monitoring, and Management*. London: E & FN Spon. Codd, G. A. A. Zendo (2005). ISBN 0-419-23930-8.

Codd, G. A., Lindsay, J., Young, F. M., Morrison, L. F., & Metcalf, J. S. (2005). Cyanobacterial toxins. In J. Huisman, H. C. P. Matthijs, & P. M. Visser (Eds.), *Harmful cyanobacteria*, pp. 1–23. Berlin, Germany: Springer-Verlag.

Datta, S., & Jana, B. B. (1998). Control of bloom in a tropical lake: Grazing efficiency of some herbivorous fishes. *Journal of Fish Biology*, *53*(1), 12–24. https://doi.org/10.1111/j.1095-8649.1998.tb00104.x

Dufour, P., Sarazin, G., Quiblier, C., Sane, S., & Leboulanger, C. (2006). Cascading nutrient limitation of the cyanobacterium Cylindrospermopsis raciborskii in a Sahelian lake (North Senegal). *Aquatic Microbial Ecology*, *44*, 219–230.

Ezra, A. G., & Nwankwo, D. I. (2001). Composition of phytoplankton algae in Gubi reservoir, Bauchi, Nigeria. *Journal of Aquatic Sciences*, *16*, 115–118.

Falconer, I. R., & Humpage, A. R. (2005). Health risk assessment of cyanobacterial (blue-green algal) toxins in drinking water. *International Journal of Environmental Research and Public Health*, *2*(1), 43–50. https://doi.org/10.3390/ijerph2005010043

Fay, P. (1992). Oxygen relations of nitrogen fixation in cyanobacteria. *Microbiology Reviews*, *56*, 340–373.

Ferrao-Filho, A. S., & Kozlowsky-Suzuki, B. (2011). Cyanotoxins: Bioaccumulation and effects on aquatic animals. *Marine Drugs*, *9*(12), 2729–2772. https://doi.org/10.3390/md9122729

Flores, N. M., Miller, T. R., & Stockwell, J. D. (2018). A global analysis of the relationship of concentration of microcystins in water and fish. *Frontiers in Marine Science*, *5*(30). https://doi.org/10.3389/fmars.2018.00030

Fogg, G. E., Stewart, W. D. P., Fay, P., & Walsb, A. E. (1973). *The Blue-Green Algae*. London: Academic Press. https://doi.org/10.1002/jobm.19750150115

Galey, F. D., Beasley, V. R., Carmichael, W. W., Kleppe, G., Hooser, S. B., & Haschek, W. M. (1987). Blue-green algae (*Microcystis aeruginosa*) hepatotoxicosis in dairy cows. *American Journal of Veterinary Research*, *48*(9), 1415–1420.

Ganf, G. G. (1974). Phytoplankton biomass and distribution in a shallow eutrophic lake (Lake George, Uganda). *Oecologia*, *16*, 9–29.

Gantar, M., Berry, J. P., Thomas, S., Wang, M., Perez, R., & Rein, K. (2008). Allelopathic activity among cyanobacteria and microalgae isolated from Florida freshwater habitats. *FEMS Microbiology Ecology*, *64*, 55–64. https://doi.org/10.1111/j.1574-6941.2008.00439.x

Gikuma-Njuru, P., Hecky, R. E., Guildford, S. J., & MacIntyre, S. (2013). Spatial variability of nutrient concentrations, fluxes, and ecosystem metabolism in Nyanza Gulf and Rusinga Channel, L. Victoria (East Africa). *Limnology and Oceanography*, *58*(3), 774–789.

Gondwe, M. J., Guildford, S. J., & Hecky, R. E. (2007). Planktonic nitrogen fixation in Lake Malawi/Nyasa. *Hydrobiologia*, *596*, 251–267.

Green, J. (2010). Geographical variation in rotifers associated with Microcystis blooms. *Hydrobiologia*, *662*, 197–204.

Gremberghe, I., Gucht, K., Vanormelingen, P., Asmelash, T., Dejenie, T., D'hondt, S., … Vyverman, W. (2011). Genetic diversity of Microcystis blooms (Cyanobacteria) in recently constructed reservoirs in Tigray (Northern Ethiopia) assessed by rDNA ITS. *Aquatic Ecology*, *45*(2), 289–306. https://doi.org/10.1007/s10452-011-9354-z.

Gurbuz, F., Uzunmehmetoglu, O. Y., Diler, O., Metcalf, J. S., & Codd, G. A. (2016). Occurrence of microcystins in water, bloom, sediment and fish from a public water supply. *Science of Total Environment*, *562*, 860–868. https://doi.org/10.1016/j.scitotenv.2016.04.027

Haande, S., Ballot, A., Rohrlack, T., Fastner, J., Wiedner, C., & Edvardsen, B. (2007). Diversity of *Microcystis aeruginosa* isolates (Chroococcales, cyanobacteria) from East African water bodies. *Archives of Microbiology*, *188*(1), 15–25. https://doi.org/10.1007/s00203-007-0219-8

Haande, S., Rohrlack, T., Ballot, A., Røberg, K., Skulberg, R., Beck, M., & Wiedner, C. (2008). Genetic characterisation of Cylindrospermopsis raciborskii (Nostocales, Cyanobacteria) isolates from Africa and Europe. *Harmful Algae*, *7*, 692–701.

Hecky, R. E., Muggide, R., Ramlal, P. S., Talbot, M. R., & Kling, G. W. (2010). Multiple stressors cause rapid ecosystem change in L. *Victoria*. *Freshwater Biology*, *55*(1), 19–42. https://doi.org/10.1111/j.1365-2427.2009.02374.x

Hilborn, E. D., & Beasley, V. R. (2015). One health and cyanobacteria in freshwater systems: Animal illnesses and deaths are sentinel events for human health risks. *Toxins*, *7*(4), 1374–1395. https://doi.org/10.3390/toxins7041374

Ibelings, B. W., & Chorus, I. (2007). Accumulation of cyanobacterial toxins in freshwater "seafood" and its consequences for public health: A review. *Environmental Pollution*, *150*(1), 177–192. https://doi.org/10.1016/j.envpol.2007.04.012

Jia, J., Luo, W., Lu, Y., & Giesy, J. P. (2014). Bioaccumulation of microcystins (MCs) in four fish species from Lake Taihu, China: Assessment of risks to humans. *Science of Total Environment*, *487*, 224–232. https://doi.org/10.1016/j.scitotenv.2014.04.037

Kamujunke, N., Schmidt, K., Pflugmacher, S., & Mehner, T. (2002). Consumption of cyanobacteria by roach (*Rutilus rutilus*) useful or harmful to the fish? *Freshwater Biology*, *47*(2), 243–250. https://doi.org/10.1046/j.1365-2427.2002.00800.x

Kemdirim, E. C. (2000). Diel rythym of plankton and physicochemical parameters in Kangimi reservoir, Kaduna State Nigeria. *Journal Aquatic Science*, *15*, 35–39.

Kemka, N., Njine, T., Zebaze, T. S. H., Niyitegeka, D., Monkiedje, A., Foto, M. S., … Compere, P. (2003). Quantitative importance of cyanobacteria populations in a hypertrophic shallow lake in the subequatorial African region (Yaounde Municipal Lake, Cameroon). *Archiv fur Hydrobiologie*, *156*, 495–510. https://doi.org/10.1127/0003-9136/2003/0156-0495.

Keshavanath, P., Beveridge, M. C. M., Baird, D. J., Lawton, L. A., Nimmo, A., & Codd, G. A. (1994). The functional grazing response of a phytoplantivorous fish *Oreochromis niloticus* to mixtures of toxic and nontoxic strains of the cyanobacterium *Microcystis aeruginosa*. *Fish Biology*, *45*(1), 123–129. https://doi.org/10.1111/j.1095-8649.1994.tb01291.x

Kolding, J., Medard, M., Mkumbo, O., & van Zwieten, P. (2014). *Status, trends and management of the L. Victoria fisheries*. Rome, Italy: FAO.

Komarek, J., Kastovsky, J., Mares, J., & Johansen, J. R. (2014). Taxonomic classification of Cyanoprokaryotes (Cyanobacterial genera) using a polyphasic approach. *Preslia*, *86*, 295–335.

Komarek, J., & Kling, H. (1991). Variation in six planktonic cyanophyte genera in Lake Victoria (East Africa). *Algological Studies*, *61*, 21–45.

Kotut, K., Ballot, A., Wiegand, C., & Krienitz, L. (2010). Toxic cyanobacteria at Nakuru sewage oxidation ponds - A potential threat to wildlife. *Limnologica*, *40*, 47–53.

Kozlowsky-Suzuki, B., Wilson, A. E., & da Ferrão-Filho, A. S. (2012). Biomagnification or biodilution of microcystins in aquatic foodwebs? Meta-analyses of laboratory and field studies. *Harmful Algae*, *18*, 47–55. https://doi.org/10.1016/j.hal.2012.04.002

Kuiper-Goodman, T., Falconer, I., & Fitzgerald, J. (1999). Human health aspects. In I. Chorus, & J. Bartram (Eds.), *Toxic cyanobacteria in Water: A Guide to their Public Health, Consequences, Monitoring and Management* (pp. 113–153). London, UK: World Health Organization (WHO).

Kunz, M. J. (2011). Effect of large dams in the Zambezi River basin: changes in sediment, carbon and nutrient fluxes. Ph.D. Thesis, Swiss Federal Institute of Technology, Zurich. Diss. ETH No. 19441.

Lambert, T. W., Holmes, C. F. B., & Hrudey, S. E. (1994). Microcystin class of toxins: Health effects and safety of drinking water supplies. *Environmental Review*, *2*, 167–186.

Lance, E., Petit, A., Sanchez, W., Paty, C., Gerard, C., & Bormans, M. (2014). Evidence of trophic transfer of microcystins from the gastropod *Lymnaea stagnalis* to the fish *Gasterosteus aculeatus*. *Harmful Algae*, *31*, 9–17. https://doi.org/10.1016/j.hal.2013.09.006

Landsberg, J. H. (2002). The effects of harmful algal blooms on aquatic organisms. *Reviews in Fisheries Science*, *10*(2), 113–390.

Li, X. Y., Chung, I. K., Kim, J. I., & Lee, J. A. (2004). Subchronic oral toxicity of microcystin in common carp (Cyprinus carpio L.) exposed to Microcystis under laboratory conditions. *Toxicon*, *44*, 821–7. https://doi.org/10.1016/j.toxicon.2004.06.010.

Lone, Y., Koiri, R. K., & Bhide, M. (2015). An overview of toxic effect of potential human carcinogen Microcystin-LR on testis. *Toxicology Reports*, *2*, 289–296. https://doi.org/10.1016/jtoxrep.2015.01.008

Magadza, C. H. D. (2006). Kariba reservoir: experience and lessons learned. *Lakes and Reservoirs Management*, *11*, 271–286.

Magadza, C. H. D. (2008–2009). Re-eutrophication and pathenogenic contamination of Lake Chivero. In: M. Nakamura (ed.), Integrated lake basin management. International Lake Environment Committee.

Malbrouck, C., & Kestemont, P. (2006). Effects of microcystins on fish. *Environmental Toxicology and Chemistry*, *25*(1), 72–86.

Markensten, H., Moore, K., & Persson, I. (2010). Simulated lake phytoplankton composition shifts toward cyanobacteria dominance in a future warmer climate. *Ecological Applications*, *20*, 752–767.

Merel, S., Walker, D., Chihana, R., Snyder, S., Baures, E., & Thomas, O. (2013). State of knowledge and concerns on cyanobacterial blooms and cyanotoxins. *Environment International*, *59*, 303–327.

Meriluoto, J., Spoof, L., & Codd, G. A. (2017). *Handbook of cyanobacterial monitoring and cyanotoxin analysis* (pp. 576). Chichester, UK: John Wiley & Sons Ltd.

Miles, C. O., Sandvik, M., Nonga, H. E., Rundberget, T., Wilkins, A. L., Rise, F., & Ballot, A. (2013). Identification of microcystins in a L. Victoria cyanobacterial bloom using LC-MS with thiol derivation. *Toxicon*, *70*, 21–31.

Mhlanga, L., Day, J., Chimbari, M., Siziba, N., & Cronberg, G. (2006a). Observations on limnological conditions associated with a fish kill of Oreochromis niloticus in Lake Chivero following collapse of analgal bloom. *African Journal of Ecology*, *44*, 199–208.

Mhlanga, L., Day, J., Cronberg, G., Chimbari, M., Siziba, N., & Annadotter, H. (2006b). Cyanobacteria and cyanotoxins in the source water from Lake Chivero, Harare, Zimbabwe, and the presence of cyanotoxins in drinking water. *African Journal of Ecology*, *31*, 165–173.

Mohammed, Z. A., & Hussein, A. A. (2006). Depuration of microcystins in Tilapia fish exposed to natural populations of toxic cyanobacteria: A laboratory study. *Ecotoxicology and Environmental Safety*, *63*(3), 424–429.

Mowe, M. A. D., Mitrovic, S. M., Lim, R. P., Furey, A., & Yeo, D. C. J. (2015). Tropical cyanobacterial blooms: A review of prevalence, problem taxa, toxins and influencing environmental factors. *Journal of Limnology*, *74*(2), 205–224.

Nizan, S., Dimentman, C., & Shilo, M. (1986). Acute toxic effects of the cyanobacterium *Microcystis aeruginosa* Daphnia magna. *Limnology and Oceanography*, *31*(3), 497–502. https://doi.org/10.4319/lo.1986.31.3.0497

Ochumba, P. B. O. (1990). Massive fish kills in Nyanza Gulf of L. Victoria, Kenya. *Hydrobiologia*, *208*(1), 93–99. https://doi.org/10.1007/BF00008448

Ochumba, P. B. O., & Kibbara, D. I. (1989). Observations on blue-green algal blooms in the open waters of Lake Victoria. *Kenya. African Journal of Ecology*, *27*(1), 23–34. https://doi.org/10.1111/j.1365-2028.1989.tb00925.x

Odokuma, L. O., & Isirima, J. C. (2007). Distribution of cyanotoxins in aquatic environments in the Niger Delta. *African Journal of Biotechnology.*, *6*, 2375–2385.

Okechukwu, O., & Ugwumba, A. (2009). Cyanobacteria abundance and its relationship to water quality in the Mid-Cross River floodplain, Nigeria. *International Journal of Tropical Biology*, *57*, 33–43.

Okello, W., & Kurmayer, R. (2011). Seasonal development of cyanobacteria and microcystin production in Ugandan freshwater lakes. *Lakes and Reservoirs Management*, *16*(2), 123–135.

Okello, W., Portmann, C., Erhard, M., Gademann, K., & Kurmayer, R. (2010). Occurrence of microcystin-producing cyanobacteria in Ugandan freshwater habitats. *Environmental Toxicology*, *25*, 367–438.

Oliver, R. L., & Ganf, G. G. (2000). Freshwater Blooms. In B. A. Whitton, & M. Potts (Eds.), *The ecology of cyanobacteria: their diversity in time and space* (pp. 149–194). Dordrecht: Kluwer Academic Publisher.

Onyema, I. C. (2010). Phytoplankton diversity and succession in the Iyagbe lagoon, Lagos. *European Journal of Scientific Research*, *43*, 61–74.

Pearson, L., Mihali, T., Moffitt, M., Kellmann, R., & Neilan, B. (2010). On the chemistry, toxicology and genetics of the cyanobacterial toxins, microcystin, nodularin, saxitoxin and cylindrospermopsin. *Marine Drugs*, *8*(5), 1650–1680. https://doi.org/10.3390/md8051650

Pflugmacher, S. (2002). Possible allelopathic effects of cyanotoxins, with reference to microcystin- LR, in aquatic ecosystems. *Environmental Toxicology*, *17*(4), 407–413. https://doi.org/10.1002/tox.10071

Poste, A. E., Hecky, R. E., & Guildford, S. J. (2011). Evaluating Microcystin Exposure Risk through Fish Consumption. *Environmental Science and Technology*, *45*(13), 5806–5811. https://doi.org/10.1021/es200285c

Poste, A. E., Hecky, R. E., & Guildford, S. J. (2013). Phosphorus enrichment and carbon depletion contribute to high Microcystis biomass and microcystin concentrations in Ugandan lakes. *Limnology and Oceanography*, *58*, 1075–1088. https://doi.org/10.4319/lo.2013.58.3.1075.

Radbergh, C. M. I., Bylund, G., & Erikkson, J. E. (1991). Histopathological effects of microcystin LR a cyclic peptide toxin from the cyanobacterium (Blue green algae) *Microcystis aeruginosa* in common carp (*Cyprinus carpio*). *Aquatic Toxicology*, *20*, 131–146.

Ramberg, L. (1987). Phytoplankton succession in the Sanyati basin, Lake Kariba. *Hydrobiologia*, *153*, 193–202.

Ready, R. C., Navrud, S., Day, B., Dubourg, R., Machado, F., Mourato, S., & Rodriquez, M. X. V. (2004). Benefit transfer in Europe. Are values consistent across countries? *Environmental and Resource Economics*, *29*(1), 67–82.

Reichwaldt, E. S., & Ghadouani, A. (2012). Effects of rainfall patterns on toxic Cyanobacterial blooms in a changing climate: Between simplistic scenarios and complex dynamics. *Water Research*, *46*, 1372–1393.

Sahin, A., Tencalla, F. G., Dietrich, D. R., & Naegeli, H. (1996). Billiary excretion of biochemically active cyanobacteria (blue-green algae) hepatotoxins in fish. *Toxicology*, *106*(1–3), 123–130.

Schmidt, J. R., Shaskus, M., Estenik, J. F., Oesch, C., Khidekel, R., & Boyer, G. L. (2013). Variations in the Microcystin Content of Different Fish Species Collected from a Eutrophic Lake. *Toxins*, *5*, 992–1009. https://doi.org/10.3390/toxins5050992.

Sekadende, B. C., Lyimo, T. J., & Kurmayer, R. (2005). Microcystin production by cyanobacteria in the Mwanza Gulf (Lake Victoria, Tanzania). *Hydrobiologia*, *543*, 299–304.

Semyalo, R., Rohrlack, T., Kayiira, D., Kizito, Y. S., Byarujali, S., Nyakairu, G., & Larsson, P. (2011). On the diet of Nile tilapia in two eutrophic tropical lakes containing toxin producing cyanobacteria. *Limnologica*, *41*(2011), 36–41.

Semyalo, R., Rohrlack, T., Naggawa, C., & Nyakairu, G. W. (2009). Microcystin concentrations in Nile Tilapia (*Oreochromis niloticus*) caught from Murchison Bay, L. Victoria and Lake Mburo: Uganda. *Hydrobiologia*, *638*, 235–244.

Shebulsky, M. (1951). Observations on the properties of a toxin produced by Microcystis. *Verhandlungen Des Internationalen Verein Limnologie*, *11*, 363–366.

Simiyu, B. M., Oduor, S. O., Rohrlack, T., Sitoki, L., & Kurmayer, R. (2018). Microcystin content in phytoplankton and in small fish from Eutrophic Nyanza Gulf, L. Victoria, Kenya. *Toxins*, *10*(7), 275. https://doi.org/10.3390/toxins10070275.

Sitoki, L., Kurmayer, R., & Rott, E. (2012). Spatial variation of phytoplankton composition, biovolume, and resulting microcystin concentrations in the Nyanza Gulf (L. Victoria, Kenya). *Hydrobiologia*, *691*, 109–122.

Sivonen, K., & Jones, G. (1999). Cyanobacterial toxins (Chapter 3). In I. Chorus, & J. Bartram (Eds.), *Toxic cyanobacteria in water: A guide to their public health consequences, monitoring and management* (pp. 41–11). London, UK: F & FN Spon for WHO.

Snyder, H. (2015). Microcystin accumulation in fish muscle tissue: Exploring the safety of fish consumption in several Michigan water bodies. Masters Theses. 774. http://scholarworks.gvsu.edu/theses/774.

Sobiechowska-Sasim, M., Ston-Egiert, J., & Kosakowska, A. (2014). Quantitative analysis of extracted phycobilin pigments in cyanobacteria-an assessment of spectrophotometric and spectrofluorometric methods. *Journal of Applied Phycology*, *26*, 2065–2074. https://doi.org/10.1007/s10811-014-0244-3.

Sonia, R., & Ramanibai, R. (2015). Effects of microcystin on hepatotoxicity of Molly Fish (*Poecilia spenops*). *International Journal of Innovative*

*Research in Science, Engineering and Technology*, *4*(4), 2361–2366. https://doi.org/10.15680/ijirset.2015.0404097

Svircev, Z., Baltic, V., Gantar, M., Jukovic, M., Stojanovic, D., & Baltic, M. (2010). Molecular aspects of microcystin-induced hepatotoxicity and hepatocarcinogenesis. *Journal of Environmental Science and Health - Part C: Environmental Carcinogenesis & Ecotoxicology Reviews*, *28*, 39–59. https://doi.org/10.1080/10590500903585382

Tendaupenyu, P. (2012). Nutrient limitation of phytoplankton in five impoundments on the Manyame River, Zimbabwe. *Water S A*, *38*, 97–104. https://doi.org/10.4314/wsa.v38i1.12.

Vaterio, E., Vasconcelos, V., & Campos, A. (2016). New insights on the mode of action of microcystins in animal cells - A Review. *Mini-reviews in Medical Chemistry*, *16*(13), 1032–1041. https://doi.org/10.2174/1389557516666160219130553

Walsby, A. E. (1994). Gas vesicles. *Microbiological Reviews*, *58*(1), 94–144. https://doi.org/10.1128/MMBR.58.1.94-144.1994

WHO. (1998). *Guidelines for drinking-water quality. Vol. 2*, *Health criteria and other supporting information: Addendum* (2nd Ed.). World Health Organization. http://www.who.int/iris/handle/10665/63844

WHO (2003). *Guidelines for safe recreational water environments volume 1: Coastal and fresh waters*. World Health Organization, Water Sanitation and Health.

Wiegand, C., Pflugmacher, S., Oberemm, A., Meems, N., Beattie, K. A., Steinberg, C. E. W., & Codd, G. A. (1999). Stages of Zebra fish Daniorerio. *Environmental Toxicology*, *14*, 89–95.

World Bank. (1998). The effects of pollution on health: The economic toll. In: *Pollution Prevention Handbook*, *Toward Cleaner Production*. Washington D.C.: World Bank Group.

Xie, L. Q., Xie, P., Guo, L., Li, L., Miyabara, Y., & Park, H. (2005). Organ distribution and bioaccumulation of microcystins in freshwater fish at different trophic levels from the eutrophic Lake Chaohu, China. *Environmental Toxicology*, *20*(3), 293–300. https://doi.org/10.1002/tox.20120

Xie, L. Q., Xie, P., Ozawa, K., Honma, T., Yokoyama, A., & Park, H. D. (2004). Dynamics of microcystins-LR and -RR in the phytoplanktivorous silver carp in a sub-chronic toxicity experiment. *Environmental Pollution*, *127*(3), 431–439. https://doi.org/10.1016/j.envpol.2003.08.011

Zhang, D. W., Xie, P., Liu, Y. Q., & Qiu, T. (2009). Transfer, distribution and bioaccumulation of microcystins in the aquatic food web in Lake Taihu, China, with potential risks to human health. *Science Total Environment*, *407*, 2191–2199.

Zhao, M. S. Q., Zhu, V. X. M., Yang, Y. X., Gan, N. Q., & Song, L. R. (2006). Effect of dietary cyanobacteria on growth and accumulation of microcystis in Nile tilapia (*Oreochromis niloticus*). *Aquaculture*, *261*, 960–966.

Zhou, I., Hai, Y., & Kun, C. (2002). Relationship between microcystin in drinking water and colorectal cancer. *Biomedical and Environmental Sciences*, *15*, 166–171.

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. *Journal of Toxicology and Environmental Health Part B*, *8*, 1–37. https://doi.org/10.1080/10937400590889412

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