RESEARCH ARTICLE

Assessment of microcystins in surface water and irrigated vegetables in Kwaru stream, Hayin Danmani, Kaduna-Nigeria

Halima Abdullahi[1] · Yahuza Tanimu[1] · Suwebat Ayanronke Akinyemi[2] · Maria do Carmo Bittencourt-Oliveira[3] · Mathias Ahii Chia[1] ⓘ

Abstract
Microcystins (MCs) are hepatotoxic secondary metabolites produced by several genera of cyanobacteria. Human exposure routes include drinking contaminated water and consuming contaminated fish, vegetables, crops, and even food supplements that contain cyanotoxin. This study investigated the presence of MCs in a stream with a long history of use as a source of water for irrigation farming. To establish the risk of a lack of monitoring programs, we studied MCs contamination of irrigated vegetables. Toxin levels in the water were generally <0.05 µg L^{-1} in all the investigated stations. Total microcystin concentrations in spinach (0.306 µg Kg^{-1} upstream and 0.217 µg Kg^{-1} downstream), lettuce (0.085 µg Kg^{-1} upstream and 0.462 µg Kg^{-1} downstream), carrot (0.050 µg Kg^{-1} downstream and 0.116 µg Kg^{-1} downstream), cabbage (0.014 µg Kg^{-1} upstream and 0.031 µg Kg^{-1} downstream), tomatoes (0.233 µg Kg^{-1} upstream), and bitter leaf (0.460 µg Kg^{-1} upstream and 0.050 µg Kg^{-1} downstream) collected in March were higher than the levels detected in samples of the same vegetables collected in April. These results highlight Nigeria's severe public health problem, especially in regions with long dry season spells. The level of MCs contamination of irrigated vegetables implies a potential for chronic exposure and associated health challenges.

Keywords Irrigation · Vegetables · Microcystins · Cyanobacteria · Cyanotoxins · Stream water

Introduction

Cyanobacteria, also known as blue-green algae, are microorganisms and autotrophic organisms that are primary producers in aquatic systems; hence, they are categorized as algae (Picardo et al. 2019). Some strains have rich chemistry because they produce various bioactive compounds with varying properties (El Gamal 2010; Picardo et al. 2019). Meanwhile, other forms produce a wide range of toxic and potentially harmful compounds in the form of secondary metabolites known as cyanotoxins, which are regarded as one of the most important groups of natural toxins (Otten and Paerl 2015; Kimambo et al. 2019; Griffith and Gobler 2020).

Microcystins are hepatotoxins primarily found in marine and freshwater habitats worldwide (Liu et al. 2018; Wei et al. 2020). MCs are heat-stable and water-soluble cyclic peptides containing seven amino acids, and over 279 variants of the cyanotoxin have been identified to date (Bouaïcha et al. 2019). They are toxic to humans, domestic animals, livestock, and aquatic organisms because they are potent inhibitors of phosphatases of serine/threonine-protein 1 (PP1) and 2A (PP2A) as well as disruptors of intracellular homeostasis (Fontanillo and Köhn 2018; Massey et al. 2018; Zhao et al. 2021). The inhibition of these phosphatases disarranges the cell cytoskeleton, causes cell death, leads to intrahepatic hemorrhage, and sometimes kills exposed organisms (Carmichael 1992).

MCs are the most ubiquitous and commonly occurring cyanotoxins in freshwater systems (Pham and Utsumi

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✉ Mathias Ahii Chia
chia28us@yahoo.com; amchia@abu.edu.ng

[1] Department of Botany, Ahmadu Bello University, Zaria, Nigeria

[2] Department of Plant Biology, Osun State University, Osogbo, Nigeria

[3] Department of Biological Sciences, Luiz de Queiroz College of Agriculture, University of São Paulo, Av. Pádua Dias, 11, São Dimas, Zip Code 13, Piracicaba, SP 418-900, Brazil

2018). Microcystins can get into the mammalian body when they consume contaminated water, food, and algal dietary supplements, through body contact, hemodialysis, and inhalation to a lesser extent (Massey et al. 2018). Due to MCs' toxic consequences, the International Agency for Research on Cancer (IARC) has categorized this toxin as a possible carcinogen (Cancer 2010). To reduce and prevent MC health hazards, the World Health Organization (WHO) recommended a provisional 1 µg/L MC guideline for drinking water quality (WHO 1998). MCs are carcinogenic because they promote liver tumors (Duy et al. 2000; Falconer and Humpage 2005). Also, there is supporting evidence from China and elsewhere that MCs cause liver cancers in humans (Ueno et al. 1996; Humpage et al. 2000).

Plant irrigation with MCs-contaminated water is an important pathway for human exposure when contaminated food is consumed (Chen et al. 2004). The ability of MCs to bioaccumulate in plant and animal tissues is responsible for the risk involved in consuming contaminated food. Several laboratory and field studies show that several vegetables irrigated with MCs-contaminated water (dissolved MCs) and toxin-producing cyanobacteria strains (particulate MCs) bioaccumulate substantial amounts of this cyanotoxin (Crush et al. 2008; Hereman and do Carmo Bittencourt-Oliveira 2012). The bioaccumulation of MCs in plant and animal tissues led the World Health Organization (WHO) to recommend a maximum daily intake of 0.04 µg Kg^{-1} of body mass (WHO 1998).

Irrigation of vegetables in Northern Nigeria is usually done due to the uneven distribution and sometimes inadequate rainfall for vegetable production. The eutrophication and formation of cyanobacteria blooms in inland waters such as seasonal streams, rivers, and lakes make them unfit for irrigation purposes because of the frequent detection of cyanotoxins (Chia et al. 2009b, 2015). As there are no monitoring programs and management for cyanobacteria blooms and cyanotoxins in most developing countries, investigations highlight the presence, levels, and risk of contamination and consumption of irrigated crops (Peuthert et al. 2015; Cordeiro-Araújo et al. 2016; do Carmo Bittencourt-Oliveira et al. 2016). The investigated area and stream, Kwaru stream, represents a vital ecosystem type that has been poorly investigated. Most studies in Africa and other tropical regions focus on large water supply reservoirs, while less attention has been given to streams and rivers. Therefore, the study aimed to investigate the level of MCs in surface water and some irrigated vegetables at Kwaru stream, Hayin Dan-Mani, Kaduna, Nigeria. We investigated this ecosystem to demonstrate its importance and contributions to MCs as a human exposure pathway.

Materials and methods

Study area

The study was carried out at Kwaru stream, Hayin Dan-Mani, Kaduna. The Kwaru stream is an urban stream that is impacted by many anthropogenic activities such as domestic solid waste dumping, wastewater from residential areas, and car washes, and it is an important source of drinking water for cattle and a variety of irrigated crops during the dry season. Kaduna is located in the northern Guinea savanna region of Nigeria, and it is characterized by two distinct seasons in the year: the dry and rainy seasons. The dry season runs from November to April and is characterized by cold and dry conditions, and the harmattan wind blows from the northeast toward the southwest. On the other hand, the rainy season, which runs from May to early October, is characterized by warm and humid conditions with the wind blowing from the southwest toward the northeast. The average monthly temperature of the region is between 26 and 34 °C (Bununu et al. 2015). Five sampling stations were selected along the irrigated stretch of Kwaru Stream based on the activities along the stream's catchment. Station 1 (10°32′41.5″N, 007°24′26.5″E) is upstream and primarily receives run-off from the farm's upstream stream. Station 2 (10°32′36.0″N, 007°24′25.5″E) is characterized by irrigation farming, dumping, and burning waste. Station 3 (10°32′21.6″N, 007°24′22.6″E) is depicted by dumping waste such as polythene bags, waste food, and cattle grazing and watering. The activities in station 4 (10°32′13.0″N, 007°24′16.4″E) include car and upholstery wash points, irrigation water pump sites, and open human and cattle defecation. At station 5 (10°32′15.5″N, 007°24′12.3″E), we found an inflow of wastewater from residential and agricultural areas.

Water and vegetable sample collection

Surface water from the Kwaru stream and vegetable samples were collected in March and April 2019, representing the driest months and the peak of the dry season. These months also coincide with when most irrigated vegetables attain harvest age and size. The samples of leafy vegetables collected included *Amaranthus hybridus* (spinach), *Brassica oleracea* (cabbage), *Lactuca sativa* (lettuce), *Hibiscus cannabinus* (kenaf), and *Vernonia amygdalina* (bitter leaf). Fruit vegetable samples included *Daucus carota* (carrot) and *Lycopersicum esculentum* (tomatoes). The samples were collected in triplicates upstream (stations 1, 2, and 3) and downstream (stations 4 and 5).

Sample identification was authenticated at the Herbarium of the Department of Botany, Ahmadu Bello University, Zaria, Nigeria.

Cyanobacteria identification and quantification

The Prescott approach, which was adopted by American Public Health Association APHA (2005), Bartram and Rees (1999), and Chia et al. (2009a), was used to analyze cyanobacteria in the lab. The cyanobacteria biomass was determined using the Drop Count Technique (Bartram and Rees 1999). The number of cells in colonies and filaments was counted without separating them and expressed as the number of cells per mL (Chia et al. 2009a).

Analysis of physicochemical parameters

Physicochemical parameters such as water temperature, total dissolved solids, pH, electrical conductivity, water hardness, total alkalinity, dissolved oxygen, biological oxygen demand, chloride, nitrate-nitrogen, and phosphate-phosphorus were analyzed according to standard methods (American Public Health Association APHA 2005).

Microcystins analysis

Aliquots (5 ml) of water samples were frozen and thawed severally to break the cells (Chia and Kwaghe 2015). Following that, the cellular contents were extracted with 75% methanol (Chia and Kwaghe 2015). Next, vegetable samples were rinsed with tap water, followed by distilled water. Then, 2 g of each sample was cut with a razor blade, weighed, and homogenized using a mortar and pestle in 80% methanol to obtain a homogenous mixture (Díez-Quijada et al. 2018). The choice of 80% methanol was to extract the intracellular toxins (Turner et al. 2018). Finally, the homogenate was centrifuged at 2000 rpm (10 min), and the supernatant was extracted and preserved at −40 °C until ready for analysis.

Extracts were subjected to microcystin analysis using a 96-well Abraxis Microcystins-ADDA Enzyme-Linked Immunosorbent Assay (ELISA) kit, following the manufacturer's instructions. The absorbance of the color reaction at the end of the ELISA procedure was read at 450 nm in a Bio-Rad iMark™ Microplate reader (Bio-Rad Laboratories, Inc., Hercules, CA, USA), and the concentrations expressed per cell quota of potential microcystin-producing species (Chia et al. 2019).

Data analyses

The statistical significance of changes in microcystins accumulated in vegetables and total microcystins in water was determined using analysis of variance (ANOVA). When significant differences existed, Tukey's posthoc test was used to perform multiple comparisons. For all analyses, the significance level was set at $p < 0.05$. The total daily intake (TDI) limit of 0.04 g kg^{-1} body weight, determined by the World Health Organization, was used to estimate the risk of eating contaminated vegetables (WHO 2011). The first part of the analysis was based on the premise that an adult weighing 60 kg consumes at least 40 g of vegetables per day and has a microcystin content threshold of 60 µg kg^{-1} in vegetable tissues.

$$TDI_{fish} = MCs_{40g^{-1}}/BM \tag{1}$$

where MCs_{40g}^{-1} is the concentration of MCs per 40g of vegetables, and BM is the body mass of an adult weighing at least 60 kg.

The monthly and seasonal risks of eating microcystin-contaminated vegetables from the study area were predicted using the hierarchical/multilevel modeling method. Equation (2) shows the model that was generated:

$$MCs_{ij} \sim \left(\beta_0 + \beta_j, \sigma_0^2\right), \beta_j \sim N\left(0, \sigma_1^2\right) \tag{2}$$

The vegetables are represented by the MCs. MCs represent the content of the ith observation from the jth group (stream location or month), β_0 represent the overall mean or intercept, β_j represents the group-type mean, σ_0^2 represents within-group variance, and σ_0^2 represents between-group variance. The lmer function of the lme4 package (Bates 2010) of R was used to perform hierarchical modeling, with the restricted maximum likelihood (REML) set to FALSE. Analysis of variance with the ranova function of the jtools package of R was used to determine the significance of the various multilevel tests. Using cumulative distribution functions (CDF), the monthly and stream location risks of consuming contaminated vegetables from the analyzed water source were also demonstrated.

Using Pearson's correlation coefficient and the R base stats function, the correlation between vegetable tissue-bound microcystins and cyanobacterial cell-bound microcystins was found. R (https://www.r-project.org) software for macOS was used for all statistical studies.

Results

Physicochemical conditions of the study area

A summary of the physicochemical characteristics of the investigated water body is given in Table 1. Overall, water temperature, TDS, sulfate, nitrate, and hardness were significantly different between the stations. Specifically, the water temperature was highest in station 1 and lowest in station 3. The changes in phosphate phosphorus were not significant, but nitrate-nitrogen levels were highest in stations 2 and 3 (p

Table 1 Monthly variation of physicochemical parameters of Kwaru stream, Hayin Danmani, Kaduna

Physicochemical	Station				
	1	2	3	4	5
Temperature (°C)	25.27±0.30[a]	25.19±0.34[a]	24.14±0.40[b]	24.67±0.32[ab]	24.72±0.31[ab]
TDS (mg/L)	218.07±35.96[a]	195.53±28.95[a]	205.53±33.21[a]	210.33±32.38[a]	208.73±24.08[a]
EC (µS/cm)	436.87±72.92[a]	396.20±58.92[a]	413.80±64.71[a]	438.73±70.40[a]	405.00±54.56[a]
PH	8.73±0.16[a]	9.03±0.09[a]	9.06±0.09[a]	9.04±0.08[a]	8.74±0.15[a]
DO (mg/L)	2.51±0.19[a]	2.49±0.17[a]	2.42±0.16[a]	2.35±0.12[a]	2.24±0.11[a]
BOD (mg/L)	1.39±0.07[a]	1.39±0.07[a]	1.27±0.08[a]	1.37±0.07[a]	1.26±0.09[a]
Sulfate (mg/L)	146.00±25.43[b]	233.00±23.55[a]	191.67±16.14[a]	201.67±13.59[ab]	196.67±26.20[ab]
Nitrate (mg/L)	20.87±0.38[bc]	23.00±1.19[ab]	24.47±1.13[a]	17.00±0.53[d]	18.80±1.11[cd]
Phosphate (mg/L)	0.127±0.019[a]	0.149±0.027a	0.150±0.031[a]	0.148±0.033[a]	0.115±0.015[a]
Alkalinity (mg/L)	52.73±6.02[a]	55.40±5.85[a]	52.60±5.92[a]	66.53±8.46[a]	57.07±6.29[a]
Hardness (mg/L)	210.93±13.13[a]	200.53±18.66[a]	160.27±15.39[bc]	177.33±13.14[abc]	154.93±11.45[c]
Chloride (mg/L)	121.67±16.52[a]	116.13±12.36[a]	111.87±12.28[a]	124.47±18.14[a]	108.07±9.53[a]

TDS, total dissolved solid; *EC*, electrical conductivity; *pH*, hydrogen ion concentration; *DO*, dissolved oxygen; *BOD*, biological oxygen demand

Means with the same superscript letter(s) per row did not differ significantly ($p > 0.05$)

< 0.05). The first two stations (1 and 2) had the highest water hardness levels, while the lowest values of this parameter were found at station 5. Biochemical oxygen demand and DO were generally uniform across the investigated stations of the water body.

Cyanobacteria composition of the study area

Changes in phytoplankton composition and biomass across stations revealed that the potential microcystin species *Anabaena flos-aquae*, *Microcystis flos-aquae*, and *Planktothrix* spp. were the most abundant in most of the stations sampled (Fig. 1). To be specific, *Planktothrix* spp. had the highest biomass in stations 1, 2, and 5. The total biomass of this species exceeded 500,000 cells mL^{-1}. *A. flos-aquae* was the dominant species in station 2 but was not recorded in the other stations. Other potential microcystin-producing species belonging to the genera *Anabaena*, *Anacystis*, *Lyngbya*, and *Spirulina* had very low biomass at all the investigated stations of the Kwaru stream.

Fig. 1 Changes in cyanobacteria composition and abundance at different stations in the Kwaru stream, Hayin Danmani, Kaduna, Kaduna State. For *n* = 3, the values represent the means
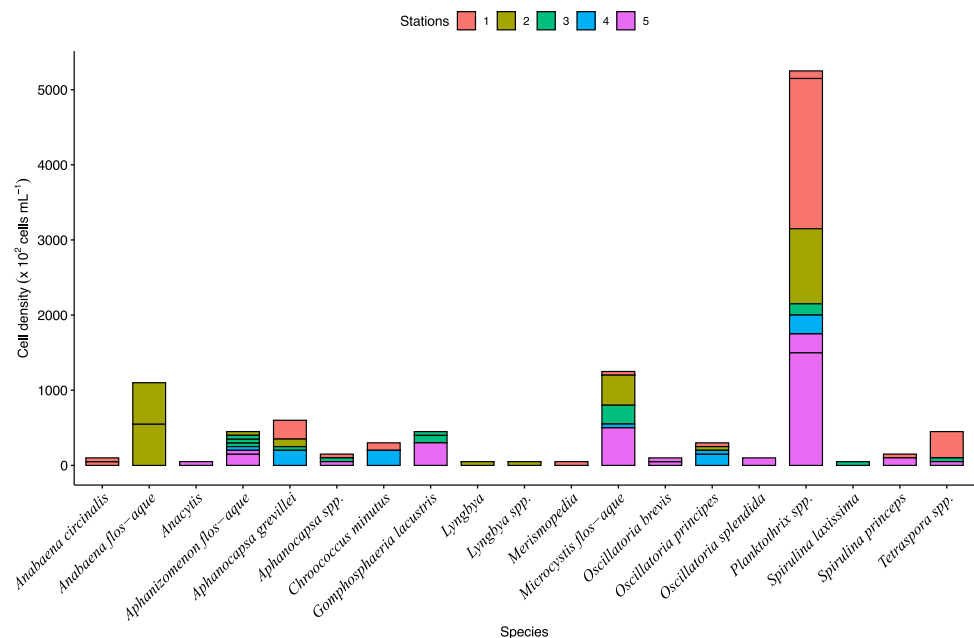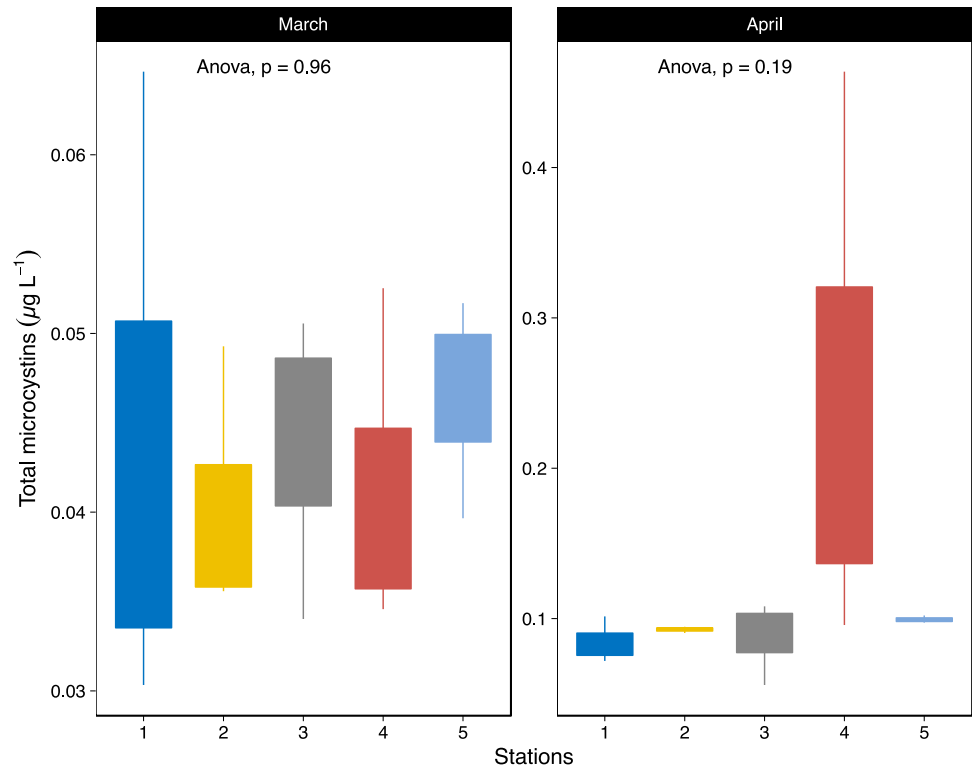
Fig. 2 Monthly variation in total microcystin concentrations in Kwaru stream, Hayin Danmani, Kaduna, Kaduna State. For n = 3, the values represent the mean plus and minus standard deviation

Total microcystin concentrations in water

The total microcystin concentration in the water in the five different stations in March and April varied significantly (Fig. 2). The highest concentration was observed in April in station 4 (0.246 µg L^{-1}), while the lowest was recorded in March (0.040 µg L^{-1}) in station 2. There was no specific trend in the total MCs variation in March. Regardless of the sampling period or sampling station, MC concentrations were lower than 1.0 µg L^{-1}, the maximum permissible level recommended by the WHO.

Total microcystin content of vegetables

On a general note, higher MC levels occurred in vegetables sampled in March than those collected in April (Fig. 3). Per sampling location, the levels of MCs bioaccumulated in the vegetables varied depending on the vegetable. In March upstream, the bitter leaf had the highest bioaccumulated microcystin concentration (0.460 µg Kg^{-1}), while cabbage had the lowest (0.01 µg Kg^{-1}). Downstream, lettuce (0.462 µg Kg^{-1}) had the highest MCs concentration, while cabbage (0.030 µg Kg^{-1}) had the lowest concentration. In April, the highest bioaccumulated microcystins level downstream occurred in spinach (0.217 µg Kg^{-1}), while the lowest was found in cabbage (0.0007 µg Kg^{-1}). In April, kenaf (0.021 µg

Kg^{-1}) had the highest upstream concentration, while the lowest was in cabbage (0.0017 µg Kg^{-1}). There were no detectable levels of MCs in lettuce.

Total daily intake of microcystin-contaminated vegetables and cumulative distribution of tissue-bound microcystins

As MCs TDI calculations are based on bioaccumulated in edible parts of vegetables, higher TDIs were found in March than in April (Fig. 4). Spinach had the highest MCs TDI by an adult (TDIA) and a child (TDIC) throughout the present study (Fig. 4). Also, spinach, lettuce, tomatoes, bitter leaf, and carrots had TDIA and TDIC values greater than 0.04 µg Kg^{-1}, the limit set by the WHO. Contrarily, in April, only spinach had TDIA and TDIC values greater than 0.04 µg Kg^{-1}.

The CDFs of MCs in water showed marked variations in the risk of consuming untreated water from the stream (Fig. 5). The risk of drinking less than 0.1 µg L^{-1} MC-contaminated water was more than 75% across most stations (Fig. 5a). On the other hand, drinking water from station 4 posed the highest risk to humans and animals because more than 40% of the samples collected from the station had MC levels of more than 0.1 µg L^{-1}. In line with the levels of MCs detected in water, the lowest risk of drinking contaminated water was in station 4.

Fig. 3 Total microcystin concentration in vegetables from Kwaru stream, Hayin Danmani, Kaduna, Kaduna State. Values represent mean plus and minus standard deviation for $n = 3$. Values with asterisks are significantly different at $p < 0.05$
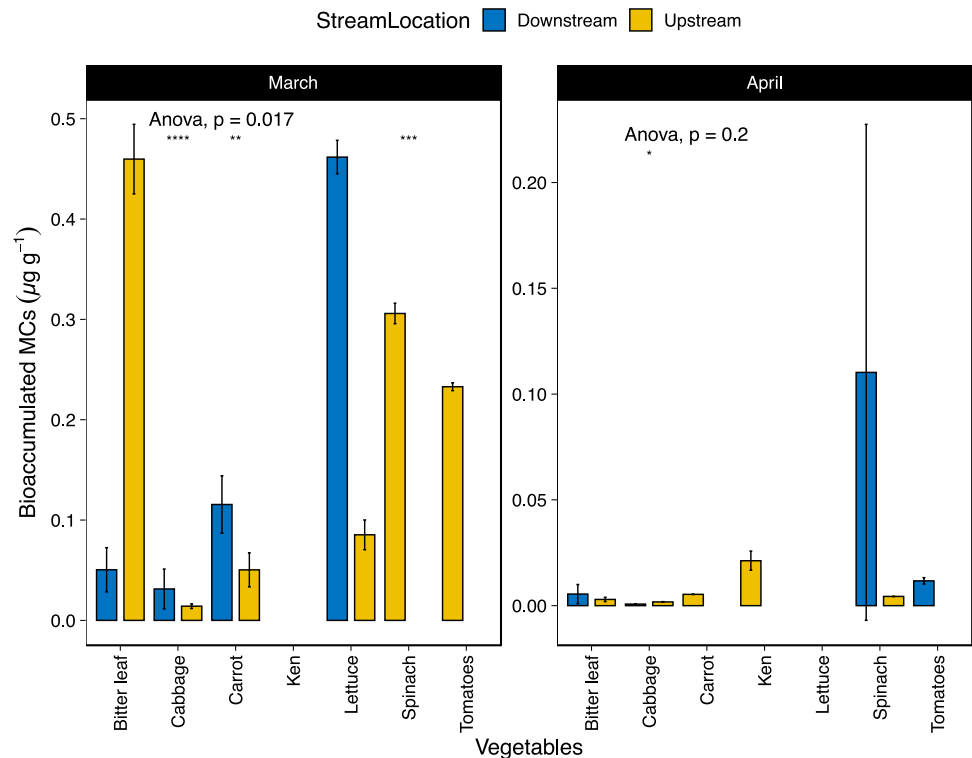
Furthermore, there was a 75% chance of consuming water containing more than 0.1 μg L^{-1} MC in April, whereas there was a 75% chance of consuming less than this amount in March (Fig. 5b).

The risk of consuming MC-contaminated vegetables was not significantly different in vegetables irrigated upstream and downstream (Fig. 6a). Regardless of the collection point of vegetables, the chance of consuming vegetables containing more than 0.1 μg g^{-1} MC was *ca.* 30%. Unlike the case of drinking MC-contaminated water, where the risk was higher in April, in terms of consuming contaminated vegetables, the risk was higher in March than in April (Fig. 6b). Specifically, there was a less than 10% chance of consuming vegetables containing more than 0.1 μg g^{-1} MC in April, whereas the reverse was observed in March. A more than 50% chance of consuming vegetables containing more than 0.1 μg g^{-1} MC was observed in March, indicating substantially different risk levels between the months. The CDFs of the investigated vegetables showed distinct differences, showing that risk differs between them (Fig. 6c). Specifically, consuming vegetables such as kenaf and cabbage posed the lowest risks, followed by bitter leaf and carrot. The vegetables with the highest risk of exposure to MC levels greater than 0.1 μg g^{-1} MC were spinach, tomatoes, and lettuce (Fig. 6c).

Discussion

Microcystins concentration in stream water

Most developed countries recognize the risk associated with the excessive proliferation of cyanobacteria and cyanotoxins, while the reverse is the case for most developing countries. Sadly, global climate change and eutrophication of aquatic ecosystems that promote the excessive proliferation of cyanobacteria and cyanotoxins are independent of the economic status of any country and continue to pose significant risks to humans and wildlife. Therefore, the increased occurrence of MCs in aquatic ecosystems and the contamination of irrigated crops pose currently unquantifiable health risks, particularly in developing countries due to a lack of data. The present study results demonstrate the need to generate data from tropical developing countries where conditions are highly suitable for the formation of harmful cyanobacterial blooms. The physicochemical characteristics of the Kwaru stream fell within the range of those reported for other water bodies in Nigeria and other tropical regions with a history of cyanobacterial blooms. We found detectable levels of MCs in the Kwaru stream with concentrations peaking at the end of the dry season, which is in line with generally

Fig. 4 Total daily intake (TDI) of microcystins by an adult and a child following consumption of different vegetables irrigated with contaminated water from Kwaru stream, Kaduna. Values represent mean plus and minus standard deviation for $n = 3$. Values with asterisks are significantly different at $p < 0.05$
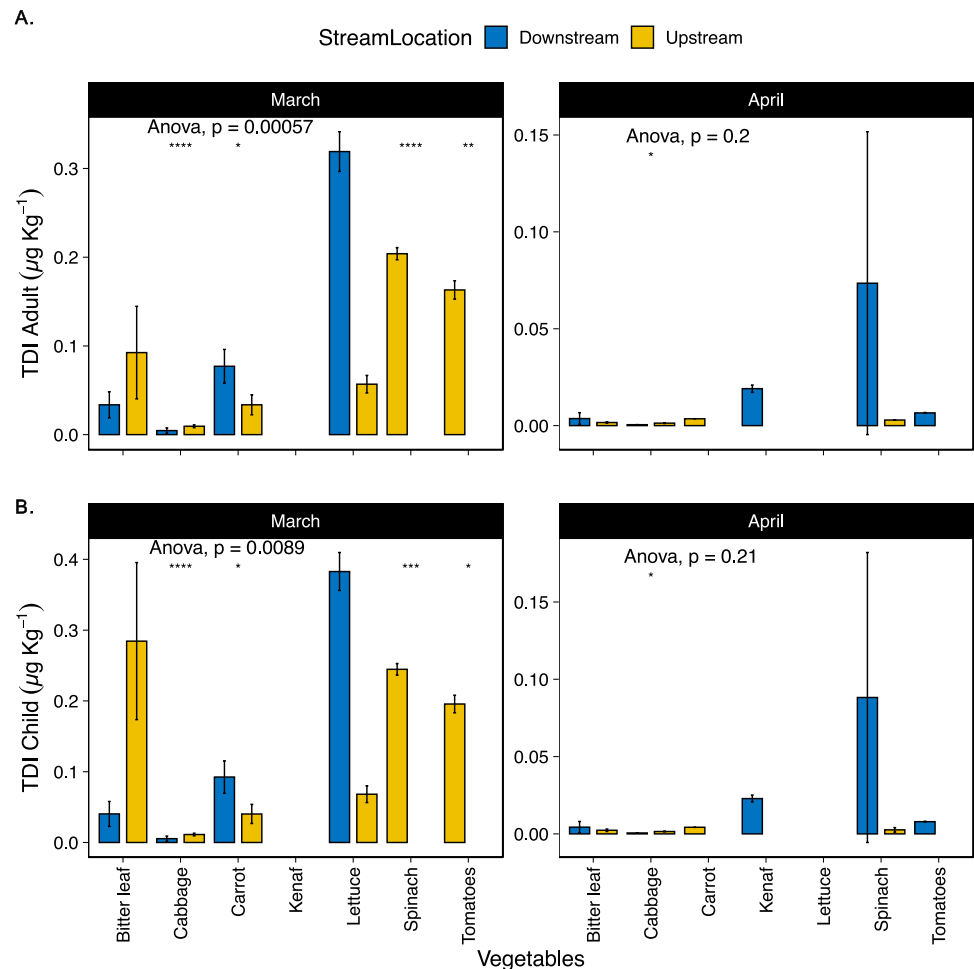
reported changes in water quality, weather, and cyanotoxins content in Northern Nigeria (Chia et al. 2009b; Chia and Kwaghe 2015). Specifically, these changes could be attributed to increased daytime temperatures, reduced water levels, increased nutrients, and solar irradiation, favoring the proliferation of cyanobacteria and the production of cyanotoxins like microcystins (Mohamed et al. 2020; Chia et al. 2021). This hypothesis is supported by the presence of microcystin-producing cyanobacteria taxa such as *Anabaena, Microcystis,* and *Planktothrix* in the stream during the investigation. Similar amounts of microcystins (0.01–7.50 µg L^{-1}) and the same microcystin-producing taxa were detected in freshwater and marine habitats in Nigeria by Chia et al. (2009a, b, 2021) and Kadiri et al. (2020).

There is a general water scarcity problem in several developing tropical countries, and northern Nigeria is no exception. This information is critical because people around the catchment of water bodies like Kwaru Stream drink the water without prior treatment. Fortunately, the detected levels of total MCs in the present study were lower than the recommended (WHO) guideline value of 1.00 µg L^{-1} for drinking water. However, there were marked differences between the risk of exposure to MCs dependent on the station and the month of water collection. These changes can be linked to the differences in anthropogenic activities along the stream's catchment.

Microcystin content in vegetables

The amount of MCs bioaccumulated in irrigated vegetables varied significantly. These differences are dependent on the levels of MCs in the environment, prevailing environmental conditions, species of vegetable, the nature and size of their leaves, and their physiological and biochemical adaptations to the presence of MCs (Chia et al. 2019). For example, higher evapotranspiration rates taking place on leaf surfaces than on other organs not directly exposed to solar irradiation result in substantial variations in the concentrations of MCs bioaccumulated by plants (Constable and Rawson 1980). The present study's findings collaborate with those of Chia et al. (2019), who observed

Fig. 5 Monthly and station variation in estimated cumulative distribution functions (CDF) of mean microcystin content in water collected from the Kwaru stream in Kaduna, Nigeria

A.

B.
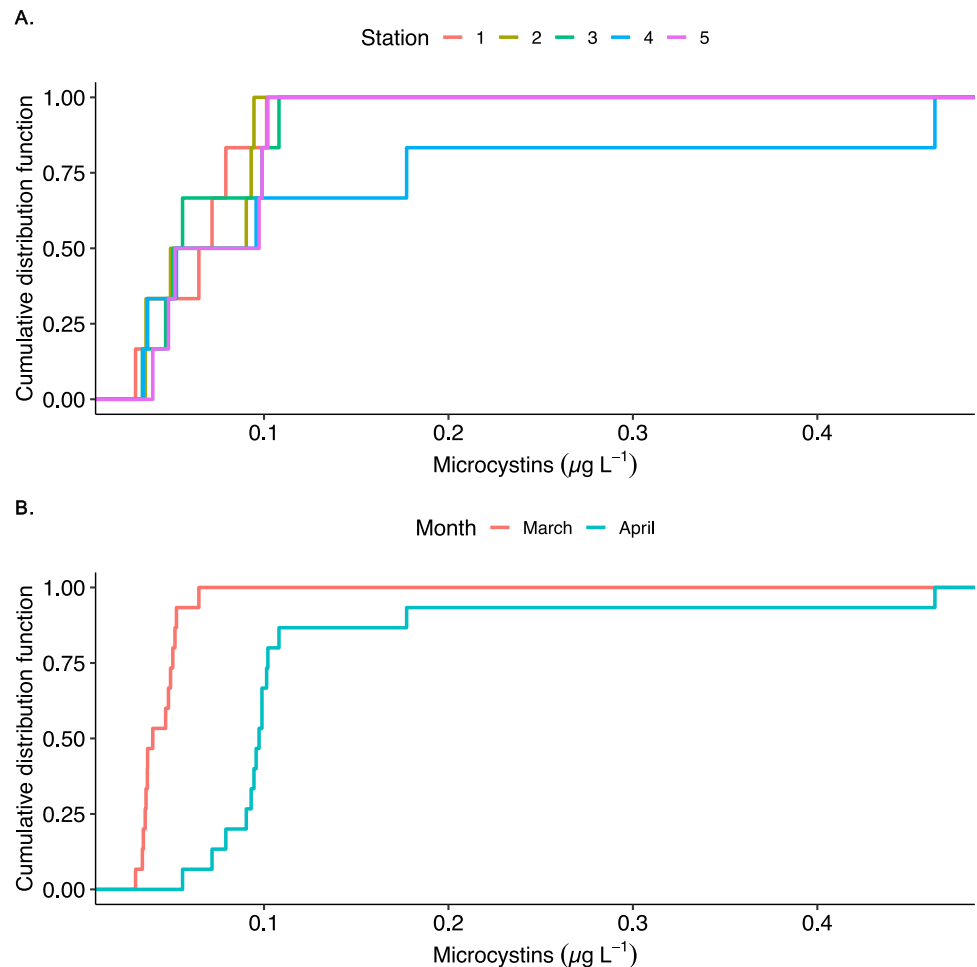
higher MC in the leaves of irrigated vegetables than in other plant parts. Also, Mohamed and Al Shehri (2009) and Chia et al. (2019) found the highest levels of MCs in *Amaranthus hybridus* (spinach) compared to other irrigated vegetables.

Furthermore, Crush et al. (2008) demonstrated that higher concentrations of MCs were detected in *Lactiva sativa* and *Trifolium repens* with broader leaves than in *Brassica napus* and *Lolium perenne* with smaller leaves. This contrasts with a study (Machado et al. 2017) that detected MC-LR in carrots at 5 μg kg^{-1} fresh weight, where the root is the edible portion. Finally, it is essential to note that fruits or vegetables like tomatoes had substantially high levels of MCs comparable to other broad-leaf vegetables, an indication that microcystin accumulation in fruits represents a significant exposure pathway.

In April, only spinach had a high MC concentration compared to other vegetables. The lower MCs' bioaccumulated levels in all the vegetables in April negatively correlated with the highest MCs' levels found in the water in the same month. This observation implies that when the length of irrigation, which leads to bioaccumulation of significant amounts in vegetable tissues, is not taken into account, having low MCs levels in water does not necessarily imply minimal risk. Previously, we showed that microcystin congeners vary in their bioaccumulation rates. The bioaccumulation and depuration of MC-LR depend on its saturation concentrations, irrigation duration, plant species, and exposure concentration (Cordeiro-Araújo et al. 2016; do Carmo Bittencourt-Oliveira et al. 2016). Also, the differences observed in the MC content of the investigated vegetables are not surprising as plants have different physiological, biochemical, and morphological adaptations that determine the rate at which they uptake and bioaccumulate MCs (Cordeiro-Araújo et al. 2016; do Carmo Bittencourt-Oliveira et al. 2016). Plants also differ in the rates at which they can excrete or depurate MCs and chemically detoxify MCs with antioxidant enzymes (Cordeiro-Araújo et al. 2016). This difference may also account for variations in bioaccumulated MCs in the investigated vegetables.

Fig. 6 Monthly, location, and vegetable variation in the estimated cumulative distribution functions (CDF) of mean microcystin content in vegetables irrigated with water from Kwaru stream, Kaduna, Nigeria
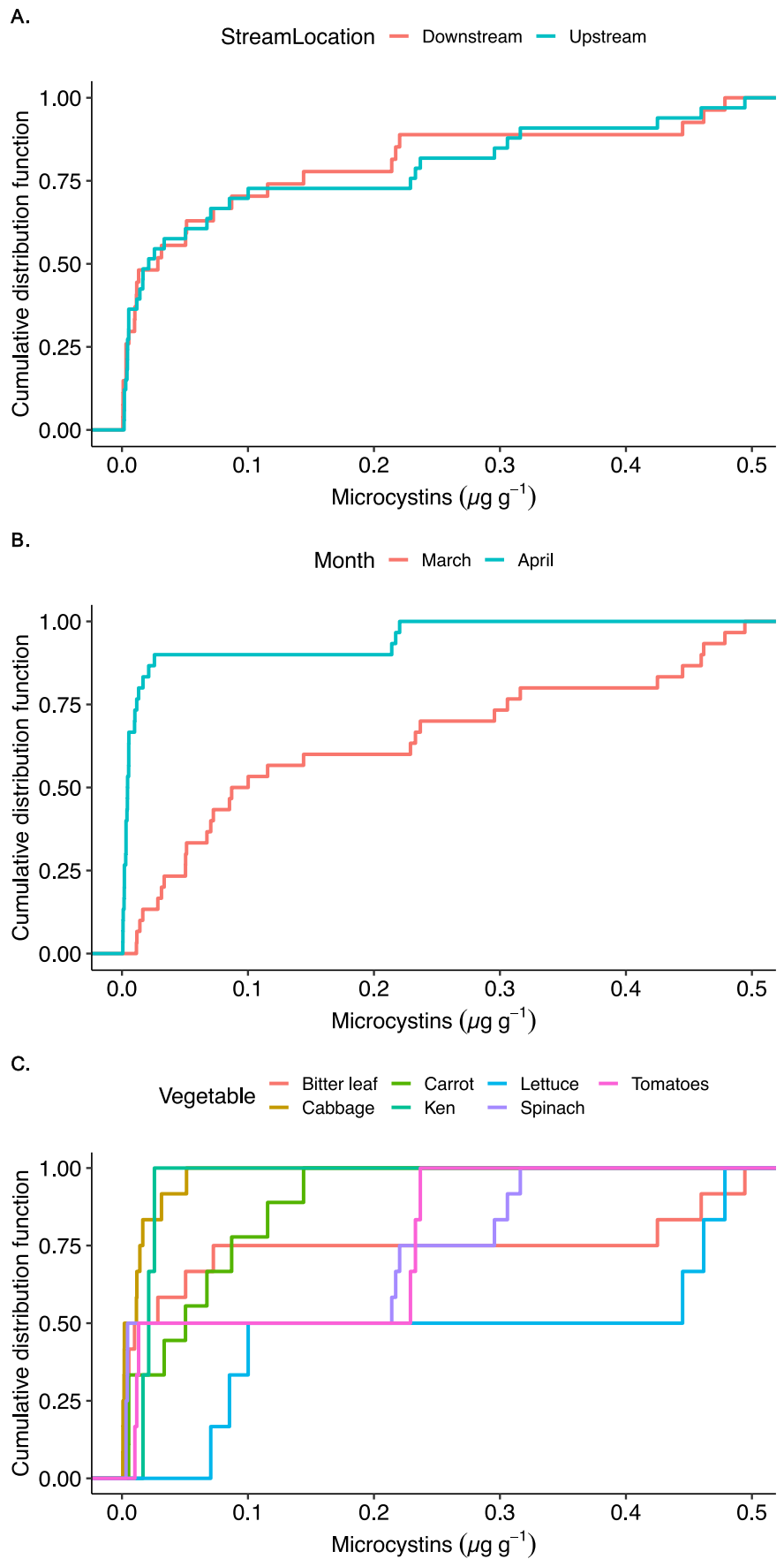
Total daily intake of MCs by humans (adults and children) and risk assessment

The concentration of MCs in vegetable tissues is usually directly proportional to the TDI by humans (Chia et al. 2019). Therefore, higher concentrations of MCs in vegetables resulted in higher TDI and risks for adults and children in the present study. A link between cumulative levels of microcystins and TDI has also been found in other crops, such as *Phaseolus vulgaris*, with values ranging from 0.125 to 0.391 µg Kg^{-1} body weight (Mohamed et al. 2022). Based on our findings, cabbage (March and April), lettuce (April), carrot (April), bitter leaf (April), tomatoes (April), and kenaf (April) posed no significant acute and chronic risk to humans since the TDI did not exceed the TDI limit set by WHO (0.04 µg per kg body weight per day). However, the TDI of MC in spinach in March and April and in lettuce, carrot, bitter leaf, and tomato in March exceeded the TDI limit. Thus, the risk of exposure to MCs is highest in March, as indicated by the CDF. While the risk may appear to be higher in March than in April, the chance of consuming high levels of MCs is dependent on the type of vegetable consumed. This outcome agrees with Chia et al. (2019)'s findings that irrigated vegetables in northern Nigeria have very high levels of microcystins. The result is also in line with previous studies indicating MCs accumulate differentially in various crops irrigated with water contaminated with blue-green algae or MCs (Cordeiro-Araújo et al. 2016; do Carmo Bittencourt-Oliveira et al. 2016; Machado et al. 2017). According to Wood et al. (2004), the WHO's maximum daily intake of MC-LR is a suggested limit for healthy adults, meaning that children, the elderly, and sensitive/unhealthy people are more susceptible to the adverse effects of MC consumption. Thus, lower TDI than the WHO recommended levels may not necessarily mean lower risk, as vulnerable and unhealthy people may suffer severe ailments post-exposure to MC via this exposure route.

The human health risks from the TDI of MCs are plant-specific (Cordeiro-Araújo et al. 2016) and proportional to the degree and rate of bioaccumulation (Crush et al. 2008). Leafy vegetables, especially spinach and lettuce, showed the highest health risk among the various vegetables. Unfortunately, spinach and lettuce are among the most consumed vegetables worldwide, emphasizing the gravity of potential long-term health challenges (Zhang et al. 2010). Likewise, many studies have shown that MC-LR is resistant to heat, being stable at temperatures as high as 300 °C (Bruno et al. 2012).

Conclusion

Our study revealed that having low MCs levels in water does not necessarily translate to low risk when considerations are not given to the duration of irrigation that leads to bioaccumulation of substantial amounts in vegetable tissues. Specifically, total

MCs in water during the months in all the stations were lower than the recommended (WHO) guideline value of 1.00 µg L^{-1} for drinking water. Also, the detected levels of MCs in irrigated vegetables were high, leading to higher TDIs than the 0.04 µg kg^{-1} body weight set by the WHO in March. This study demonstrates the need to develop management strategies for MCs in water bodies used for irrigation farming and the need to screen crops or vegetables harvested from farms before human consumption in developing tropical countries. In addition, consumer education must be encouraged and aggressively pursued to ensure they understand the consequences of MCs' contamination of drinking water and irrigated vegetables.

Declarations

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