Food crops irrigated with cyanobacteria-contaminated water: an emerging public health issue in Canada

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Cyanobacteria, commonly but inaccurately known as blue-green algae, are naturally occurring, single-celled organisms (prokaryotes) (Whitton and Potts, 2012) found in fresh, brackish, and marine waters (Backer et al., 2015) and some soils. It is estimated that there are between 2000 and 8000 species worldwide (Nabout et al., 2013). Cyanobacteria produce oxygen during photosynthesis and were thus fundamental in helping to create the oxygen-rich atmosphere on earth today (Schopf, 2012). Cyanobacteria are also the primary nitrogen fixers in the ocean (Diez et al., 2008). The presence of some secondary metabolites produced by cyanobacteria may enhance productivity of certain agricultural crops (Machado et al., 2017b).

However, cyanobacteria are better known for their detrimental impacts on aquatic ecosystems and human health. Under certain conditions including, but not limited to, warmer water temperatures and high nutrient loads, cyanobacteria can rapidly proliferate and create blooms known as cyanoblooms, harmful algal blooms (HABs), or cyanoHABs. Cyanoblooms can be unsightly, impacting popular tourist destinations, e.g., Lake Erie (Levy, 2017). Their presence can impart an unpleasant odour or taste to the water, and as the bloom dies it may smell of rotting plants.

Even more concerning is the production of cyanotoxins. There are many different types of cyanotoxins; however, some cause more of a public health risk than others. These include nodularin, saxitoxin, cylindrospermopin, and microcystins of which there are almost 100 different variants (Qi et al., 2015). Cyanotoxins are harmful to human health; different toxins target different organ systems, e.g., liver, kidneys, nervous system, and skin (Svircev et al., 2017). Acute exposure causes symptoms such as vomiting, diarrhoea, nausea, skin irritation, rash, fever, headache, weakness, numbness of lips and mouth, incoordination, respiratory and muscular paralyses, and in rare cases death (Svircev et al., 2017). Chronic exposure to microcystins and nodularin can induce tumour-promoting activity, often but not always resulting in liver tumours (IARC Monographs 94, 2010). Microcystin-LR (MC-LR), the most common microcystin

variant, has been classified as Group 2B, possibly carcinogenic to humans (IARC Monographs 94, 2010). Exposure to cyanotoxins occurs via drinking contaminated water, inhalation of steam and aerosolized droplets of contaminated water during showering, skin contact during swimming or showering, consumption of fish or shellfish grown in contaminated water bodies, or consumption of food crops irrigated with contaminated water (Svircev et al., 2017).

Cyanotoxins can bioaccumulate in various food crops irrigated with cyanobacteria-contaminated water (Table 1). There are many variables that can determine to what concentration cyanotoxins bioaccumulate, such as the plant stage when exposed to cyanotoxins (e.g., germination, growing, fruiting adult plant), composition of soil bacteria, concentration of cyanotoxin in the water, amount of water used for irrigation, length of exposure via irrigation, etc. However, the fact that bioaccumulation can occur has raised the question of whether there is a public health risk for people consuming food crops grown under these conditions.

Produce as a vehicle for foodborne illnesses

Over the last 50 years, food crops have been implicated in an ever-increasing number of foodborne illnesses. Between the 1970s and 1990s in the United States, the percentage of outbreaks involving fresh produce increased from 0.7% to 6% (Sivapalasingam et al., 2004). In the United States between 1998 and 2008, fresh produce was responsible for 46% of foodborne illnesses (Painter et al., 2013). There is clearly an increasing risk of foodborne illnesses via food crops, and due consideration should thus be given to the water used to irrigate crops. While this risk has historically been due to the role fresh produce plays in the transmission of enteric pathogens, there is a growing body of evidence showing the potential for food crops to bioaccumulate cyanotoxins (Codd et al., 1999; McElhiney et al., 2001; Mohamed and Al Shehri, 2009; Hereman and Bittencourt-Oliveira, 2012; Freitas et al., 2015; Liang and Wang, 2015; Bittencourt-Oliveira et al., 2016; Cordeiro-Araújo et al., 2016; Machado et al., 2017a), potentially resulting in consumer exposure.

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Table 1. Accumulation of microcystins in food crops via irrigation with cyanobacteria-contaminated water. Control doses are not shown.

Plant species	Irrigation doses and details	Outcome	Author
Lettuce (<i>Lactuca sativa</i>)	MC-LR 0.5, 2, 5, 10 µg/L MC-RR 0.15, 0.5, .5, 3 µg/L Total MC 0.65, 2.5, 6.5, 13 µg/L Thirty day old plants given 100 mL of water daily for 15 days. Lettuce leaf tissue analyzed.	No bioaccumulation at lowest doses. MC-LR: 32 – 143 µg/kg FW MC-RR: 6 – 15 µg/kg FW Total MC: 39 – 158 µg/kg FW	Bittencourt-Oliveira et al., 2016
Lettuce (<i>Lactuca sativa</i>)	Specific doses unknown. Irrigation in a commercial horticulture unit. MC-LR (bloom and scum): 3.23±0.11 µg/mg Lettuce leaf tissue analyzed.	MC-LR: 94 – 2487 µg/kg DW Cyanobacterial cells not removed from lettuce leaves by washing/rinsing. Crop removed from sale.	Codd et al., 1999
Lettuce (<i>Lactuca sativa</i>), arugula (<i>Eruca sativa</i>)	MC-LR 5, 10 µg/L Arugula (30 day old plants) lettuce (40 day old plants) irrigated daily with 100 mL water for 7 days, followed by 7 days depuration. Lettuce leaf tissue analyzed.	MC-LR: 50 – 100 µg/kg FW (After depuration) MC-LR: decreased to 30 µg/kg FW MC-LR not detected in arugula.	Cordeiro-Araújo et al., 2016
Lettuce (<i>Lactuca sativa</i>)	Total MC 2100 µg/L (from contaminated lake water). Irrigated every 2 nd or 3 rd day for 12 days with 100 mL water. Leaf and roots analyzed.	MC-LR: 300 – 870 µg/kg DW (roots) 740 – 840 µg/kg DW (shoots)	Crush et al., 2008
Lettuce (<i>Lactuca sativa</i>)	Total MC 0.62, 2.5, 6.23, 12.5 µg/L Fully grown plants sprayed with 100 mL water daily for 15 days. Lettuce leaf tissue analyzed.	MC-LR: 8.31 – 177.8 µg/kg FW Greater accumulation at higher doses.	Hereman and Bittencourt-Oliveira, 2012
Lettuce (<i>Lactuca sativa</i>), arugula (<i>Eruca sativa</i>), cabbage (<i>Brassica</i> sp.), radish (<i>Raphanus</i> sp.), dill (<i>Anethum graveolens</i>), parsley (<i>Petroselinum crispum</i>)	Contaminated groundwater from wells used, (probably MC-YR) ranged from 0.3 to 1.8 µg/L. Leaves and roots of all plants analyzed.	Lettuce: <100 – ~400 µg/kg FW Arugula: <100 – ~400 µg/kg FW Cabbage: <100 – ~800 µg/kg FW Radish: <300 – 1200 µg/kg FW Dill: ~150 – 800 µg/kg FW Parsley: 300 – 800 µg/kg FW Roots accumulated higher concentrations compared to leaves, with the exception of dill.	Mohamed and Al Shehri, 2009
Broccoli (<i>Brassica oleracea</i>), mustard (<i>Sinapis alba</i>)	Total MC (LR and RR) 1, 10 µg/L Mustard exposure 19 days Broccoli exposure 20 days	Only MC-LR detected in plant roots. Broccoli: 0.9 – 2.4 µg/kg FW Mustard: 2.5 – 2.6 µg/kg FW	Järvenpää et al., 2007
Rice (<i>Oryza sativa</i>)	MC-LR 24, 120, 600, 3000 µg/L Germination tests. Rice seeds soaked for 24 hrs then laid in boxes lined with paper saturated with 10 mL of each dose. 4 mL of each dose was added at 3 day intervals. Continued for 10 days. Seedlings analyzed.	MC-LR (lowest dose) not detected (highest dose) 29.4 – 54 µg/kg FW	Chen et al., 2004
Tomatoes (<i>Lycopersicon esculentum</i>)	MC-LR 100 µg/L Plants irrigated every 3 rd day for 2 weeks with 500 mL water. Leaves, fruit (green and mature), roots were collected and analyzed after 2 weeks.	MC-LR (after 1 week) only detected in green and mature tomato: 5.4 and 10.8 µg/kg FW, respectively. MC-LR below detection limit after 2 weeks of irrigation in all measured parts of the plant.	Gutiérrez-Praena et al., 2014
Carrots (<i>Daucus carota</i>)	MC-LR 10, 50 µg/L. Carrots grown for 1 month and then irrigated for 32 days.	MC-LR: 5 µg/kg FW	Machado et al., 2017a

Note: MC, microcystin; MC-LR, MC-YR, and MC-RR, variants of microcystin; FW, fresh weight; DW, dry weight.

Cyanotoxins can bioaccumulate in food crops

Cyanobacteria, specifically MC-LR, can bioaccumulate in various food crops irrigated with cyanobacteria-contaminated water (Codd et al., 1999; Chen et al., 2004; Järvenpää et al., 2007; Crush et al., 2008; Mohamed and Al Shehri, 2009; Hereman and Bittencourt-Oliveira, 2012; Gutierrez-Praena et al., 2014; Bittencourt-Oliveira et al., 2016; Cordeiro-Araújo et al., 2016; Machado et al., 2017a). Concentrations measured in plants are dependent on the concentrations in the water used for irrigation (Hereman and Bittencourt-Oliveira, 2012). For example, MC-LR accumulated in lettuce leaf tissue grown in potted soil under laboratory conditions at concentrations of up to 143 µg/kg after irrigation for 15 days with 100 mL water containing 10 µg/L MC-LR. However, very low doses, i.e., 0.5 and 0.65 µg/L, did not show bioaccumulation of MC-LR in lettuce leaf tissue (Bittencourt-Oliveira et al., 2016). After only 7 days of irrigation with 100 mL water containing 10 µg/L MC-LR in a laboratory setting, lettuce leaf tissue concentrations of up to 100 µg/kg fresh weight were seen (Cordeiro-Araújo et al., 2016). Researchers were made aware of a situation where crops were being spray irrigated with contaminated water under actual farm conditions. Accordingly, actual concentrations in the irrigation water were not reported. Nonetheless, MC-LR in lettuce leaf tissue reached between 94 and 2,487 µg/kg dry weight (1 g of dry weight is equivalent to 10 g fresh weight), and cyanobacterial cells were not able to be washed off the lettuce leaves, thus reporting in dry weight increases observed concentrations. Subsequently, this batch of produce was not sold (Codd, 1999).

Studies of broccoli and mustard (*Sinapis alba*) showed MC-LR was only detected in the roots of the plants at low concentrations, e.g., 2.4 and 2.6 µg/g fresh weight, respectively (Järvenpää et al., 2007). Considering the part of the plant that is consumable, these concentrations would not pose a health risk. In contrast, Machado et al. (2017a) detected MC-LR in carrots at 5 µg/kg fresh weight, where the root is the edible portion. Mohamed and Al Shehri (2009) detected total MC in both leaves and roots of the plants they examined. Overall, the roots accumulated much higher concentrations of MC compared with the leaves; however, for some plants, e.g., radish, carrot, yams, beets, it is the root that is consumed, thus presenting a greater risk.

Clear differences in study conditions exist, which may explain some of the observed results. For example, only one study was under natural conditions (Codd et al., 1999). One germination experiment irrigated seedlings with MC-LR concentrations that do not reflect ecologically relevant concentrations, i.e., the highest dose used was 3000 µg/L (Chen et al., 2004). Some studies were conducted under hydroponic conditions (Gutierrez-Praena et al., 2014), whereas others used potted soil or sand (Järvenpää et al., 2007; Crush et al., 2008; Hereman and Bittencourt-Oliveira, 2012; Bittencourt-Oliveira et al., 2016; Cordeiro-Araújo et al., 2016; Machado et al., 2017a). Soil can retain up to 57% of the toxin bioavailable to the plant (Machado et al., 2017b); however, there is a lack of controlled studies conducted under field conditions using ecologically relevant concentrations.

Lack of policy and regulation in Canada

Health Canada has set a maximum acceptable concentration (MAC) of 1.5 µg/L for MC-LR in drinking water and 20 µg/L

for MC-LR in recreational water bodies (Health Canada, 2016). There are no MACs set for any other cyanotoxin in drinking water and no guidelines or regulations set on MC-LR in water used for the irrigation of food crops. Of the small volume of primary research conducted within the examined period on bioaccumulation of MC-LR in food crops, none has been conducted in Canada.

The *Canadian Water Quality Guidelines* (Canadian Council of Ministers of the Environment, 2008) provide some guidance for irrigation water quality. However, their focus is primarily on physical and chemical parameters, e.g., heavy metals; plant, human, and animal pathogens; and how these affect crops. Emerging toxins, such as MC-LR, are not discussed. However, there is a framework in place for developing new guidelines that could be included in future updates (Canadian Council of Ministers of the Environment, 1999).

Furthermore, in Canada, legislation that addresses the quality of irrigation water is lacking. For example, the *Fresh Fruit and Vegetable Regulations* (C.R.C., c. 285) under the *Agricultural Products Act* stipulates that water used for post-harvest washing and rinsing must be potable, but it does not provide any requirements for irrigation water. This federal legislation applies to produce that is imported, exported, or shipped between provinces. Where there is a lack of legislation, producers are encouraged to follow better practices. A brief survey of materials from various provinces yielded documents that provided similar advice, with a focus on microbial quality and emphasis on the washing and rinsing stages (British Columbia Ministry of Agriculture, 2009; Jones and Shortt, 2010; Alberta Agriculture and Forestry, 2012).

In 1999, the World Health Organization (WHO) established a tolerable daily intake (TDI) of 0.04 µg MC-LR/kg body weight (BW) (World Health Organization et al., 1999). Some of the studies mentioned above (Mohamed and Al Shehri, 2009; Hereman and Bittencourt-Oliveira, 2012; Machado et al., 2017a) found MC-LR concentrations in food crops at levels high enough to exceed the WHO TDI, raising concerns about public health risks from consuming food crops irrigated with MC-LR contaminated water. The US FDA guidelines on agricultural water used for irrigation refer only to *E. coli* and microbial quality, not to cyanobacteria-contaminated water (US Food and Drug Administration, 2017). However, frequently asked questions about cyanobacteria posted by Oregon Public Health (Oregon Health Authority, 2015) noted that if any of the four cyanotoxins they monitor (anatoxin-a, cylindrospermopsin, microcystins, or saxitoxins) are above their drinking water guidelines, then the water should not be used for washing, preparing, or cooking food, nor should it be used for irrigating food crops. However, if below their guidelines (1.6 µg/L for microcystins for people over 6 years old), water can be used to irrigate food crops as long as contaminated water on any crops is allowed to dry completely in sunlight before consuming and measures are taken to ensure no children or animals drink the water.

Climate change as an exacerbating factor

Certain climactic conditions can facilitate the formation of cyanoblooms. These include warmer water temperatures, a condition under which cyanobacteria can rapidly proliferate; a decrease in water stratification, which favours cyanobacterial growth and survival; and longer cyanobacterial growing seasons

(Pick, 2016). An increase in extreme weather events, such as droughts, introduces competition for scarce water resources and drives cyanobacterial growth in diminished water bodies. Resource competition may lead to an increase in greywater use for food crop irrigation, which may improve household food security (Rodda et al., 2011) but can also result in irrigation with microbially contaminated water.

Flooding from increased precipitation (Trenberth, 2011) can increase terrestrial run-off, including sewage overflows into water bodies, thus increasing nutrient loads (Hamilton et al., 2016), driving cyanobacterial growth. Climate change is also implicated in the range expansion of cyanobacteria species (Pick, 2016); blooms and toxins that did not previously occur begin to appear where they were never before observed. In Canada, rapid warming of northern latitudes means areas once largely unaffected by cyanobacteria may now be at risk (Pick, 2016). However, to date research examining the impact of climate change on cyanobacteria in the context of food crop irrigation and within a Canadian context, i.e., the northern latitude, is lacking.

Knowledge gaps

There is a lack of field-based experiments examining irrigation of food crops under real conditions. Some research indicates various soil types adsorb cyanotoxins, reducing toxin bioavailability to plants, and that certain soil bacteria species can biodegrade cyanotoxins (Corbel et al., 2014). However, whether or not there are geographic differences in soil bacteria species present in Canada and if they are capable of degrading cyanotoxins requires further investigation.

The literature focuses on microcystin research and largely neglects the bioaccumulation of other cyanotoxins into food crops, because microcystins are generally regarded as the most important of the cyanotoxins (Health Canada, 2016). Research is lacking on the frequency and intensity of watering; different delivery methods, e.g., spray, drip, or sprinkle irrigation; as well as risks to farm workers from these delivery methods, i.e., inhalation of water from spray irrigation. Only one study on depuration (the excretion or metabolic breakdown of toxins) was found and this examined only two species, lettuce and arugula (Cordeiro-Araújo et al., 2016). Further depuration work on a wider range of food crops is necessary. Given the variability in results presented above, a wider range of food crops, including fruit and berries, should be examined, preferably with a focus on the edible portions. Work to investigate possible biotransformation of cyanotoxins would also be of use.

It should be noted that research on irrigation of food crops with cyanobacteria-contaminated water is lacking in a Canadian context within the examined period. None of the studies on bioaccumulation in food crops were conducted within Canada. Microcystins have now been detected in lakes in every Canadian province over the last decade (Orihel et al., 2012), thus there is a need for evidence to inform us as we move forward.

Future directions

The consumption of food crops irrigated with cyanobacteria (MC-LR)-contaminated water is an emergent area with public

health implications. Not enough is known about how this issue might affect Canadian consumers, especially in regard to changing climactic conditions; thus, it seems timely to address the issue with Canadian research and knowledge synthesis. Moving forward, suggested research and policy-enabling directions may include:

- research addressing issues specific to Canadian geography, climate, and physical conditions around the contamination of food crops irrigated with cyanobacteria-contaminated water;
- the development of Canadian regulations or guidelines for MC-LR in irrigation water intended for food crops;
- to increase awareness among food producers of the emerging risk that cyanobacterial toxins such as MC-LR pose to their consumers;
- to increase knowledge through education campaigns among food producers that helps them to determine when an irrigation water source may be at risk of containing cyanotoxins, how to use test kits to check for their presence, and next steps to take if cyanotoxins are detected; and
- to highlight the role that environmental health officers (EHO) and public health professionals have in aiding this effort through education and consultation.

Practical recommendations cannot be made until evidence-based research, preferably conducted in Canada, is available to inform us. For example, research on the use of different irrigation systems, e.g., use of drip irrigation or canals, rather than spray irrigation; refraining from use of contaminated water for set periods prior to harvesting to allow depuration; or treatment of water used for irrigation. In the meantime, increasing awareness and education amongst food producers, EHOs, and other public health professionals, of the risk posed by the use of cyanobacteria-contaminated irrigation water is suggested.

Methods

To inform this article, recently published scientific literature and relevant government, agency, and grey literature was scoped using the following methods.

Literature was identified through Medline, CINAHL, Biomedical Reference Collection, Web of Science, and Google Scholar. Emphasis was placed on scientific articles published within the last five years; however, older articles were included if they appeared relevant. An initial search was conducted within the context of cyanobacteria and health, using the terms:

- Cyanobacteri OR Cyanophyta OR “blue-green bacteria” OR cyanoHAB OR “harmful algal bloom” OR cyanotoxin OR microcystin OR “Anatoxin-a producing Tychonema”) AND (health OR illness disease OR e-coli OR legionnaire OR crypto OR shigell* OR fowleri OR amoeba OR norovirus OR bacterium OR endotoxin OR respiratory OR cancer OR inflammation)
- (rule OR guidance OR guideline OR regulation OR operation OR legislation)
- (advisory OR notification OR restriction OR limit OR response)
- (risk OR assessment OR mitigation OR management).

This search turned up 117 related articles/documents. The titles and abstracts were scanned to assess their relevance to this context. A second, more context-specific search was conducted. Terms included:

- Cyanobacteri OR Cyanophyta OR “blue-green bacteria” OR cyanoHAB OR “harmful algal bloom” OR cyanotoxin OR microcystin OR “Anatoxin-a producing Tychonema”) AND agricultur* OR farming OR vegetable OR garden OR irrigat* OR harvest

This search turned up 28 related articles, of which 10 specifically examined the bioaccumulation of cyanotoxins in food crops.

One further search was conducted to look for Canadian-specific literature, using the terms:

- (cyanobacteria OR cyanophyta OR “blue-green bacteria” OR cyanohab OR “harmful algal bloom” OR cytotoxin OR microcystin OR “Anatoxin-a producing Tychonema”) AND (canad* OR “british columbia” OR coast OR atlantic) AND (agricultur* OR farming OR vegetable OR garden OR irrigat* OR crop OR harvest OR plant).

This search turned up 6 articles, which were not specifically relevant to this context.

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