CHALLENGES TO TREAT CYANOTOXINS FROM DRINKING WATER ON A LARGE, SMALL AND HOUSEHOLD SCALE

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INTRODUCTION

There is a growing concern to implement strategies to reduce human exposures to cyanobacteria and their toxins from drinking water, as they can cause adverse health effects. When toxin-producing cyanobacteria cells are healthy, cyanotoxins are produced and stored internally. However, aging cells or certain treatment processes cause cells to rupture and release internal toxins. Typically, drinking water treatment processes that are successful at treating intact cyanobacteria cells are ineffective for released cyanotoxins. This poses a challenge for drinking water treatment plants to effectively remove intracellular and extracellular toxins. In addition, some toxins are resistant to certain treatments. This review assesses many drinking water treatment processes on the capacity of inactivating/removing cyanobacteria cells and dissolved cyanotoxins for large and small systems and household units.

WATER TREATMENT TECHNOLOGIES

Drinking water treatment technologies such as conventional treatment, dissolved air flotation, membrane technology, slow sand filtration, oxidation and activated carbon are assessed for treating cyanobacteria cells (intracellular) and released cyanotoxins (extracellular) (Fig. 1).

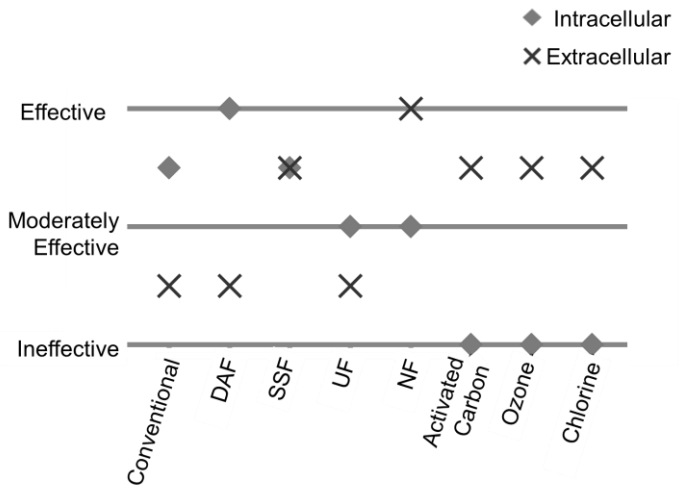

FIGURE 1. OVERVIEW OF THE EFFECTIVENESS OF TREATING INTRACELLULAR AND EXTRACELLULAR CYANOTOXINS WITH WATER TREATMENT TECHNOLOGIES.

Conventional Treatment Processes:

Conventional treatment processes (rapid mixing, flocculation, sedimentation, filtration) remove intact cells; however cells may become trapped in the filters, degrade over time and release toxins (Fig. 1) (Hrudey *et al.* 1999). Also, it is difficult for cells to settle during sedimentation due to low density and floating characteristics of cyanobacteria (Drikas *et al*. 2011).

Conventional treatment processes are not very effective at removing dissolved cyanotoxins, however sufficient dosage and contact time of chlorination step may be effective at inactiving some toxins (Hrudey *et al.* 1999, Sorlini and Collivignarelli 2011).

Dissolved Air Flotation:

Dissolved air flotation may be more effective at removing intact cells than sedimentation (Fig. 1). Bench-top and pilot plant scales of dissolved air flotation studies demonstrated that cyanobacteria were effectively removed with minimal cell damage (Teixeira and Rosa 2006, Teixeira *et al.* 2010). Additional research on a large scale needs to be further investigated.

Slow Sand Filtration:

Slow sand filtration can remove 99% of cyanobacteria cells, however dense cell populations can cause clogged filters, degraded cells and released toxins (Hrudey *et al.* 1999, Zamyadi *et al.* 2011). Removing the bioactive surface layer frequently will

reduce clogging and reduce the chance of released toxins (Hrudey *et al.* 1999). Slow sand filtration can also effectively remove extracellular toxins; however further research in this area needs to be explored (Hrudey *et al*. 1999). A full-scale slow sand filter study found that filtration with lower temperature waters (<4^{0}C) removed fewer microcystins (<85%), which may be due to reduced biodegradation (Grützmacher *et al.* 2002).

Membrane Technology:

Ultrafiltration and microfiltration can moderately remove intracellular cyanotoxins, due to conflicting studies that state whether the process damages cyanobacteria cells (Fig. 1). Some studies found that ultrafiltration was effective at removing intact cells (*Microcystis aeruginosa* and *Planktothrix agardhii*) without damaging the cells (Campinas and Rosa 2010). Whereas, other studies demonstrated that the ultrafiltration process damaged cells (*Planktothrix agardhii*) and released toxins (Gijsbertsen-Abrahamse *et al.* 2006). Incorporating ultrafiltration with other conventional treatments would provide an effective multi-barrier approach (Hrudey *et al.* 1999, Campinas and Rosa 2010, Gijsbertsen-Abrahamse *et al.* 2006). Ultrafiltration is ineffective at removing extracellular toxins, due to the pore size of ultrafiltration (Campinas and Rosa 2010, Gijsbertsen-Abrahamse *et al.* 2006).

Nanofiltration is more effective than ultrafiltration to remove dissolved toxins (Hrudey *et al*. 1999). It was estimated that a full-scale nanofiltration plant would remove 90% microcystins and anatoxin-a (Gijsbertsen-Abrahamse *et al.* 2006). The nanofiltration process may also rupture intact cells. Therefore, nanofiltration is considered to be only moderately effective at removing intracellular toxins (Fig. 1).

Activated Carbon:

Activated carbon filters can effectively remove intact cells. However, there is a potential for filter clogging, cell degradation and released toxins. In an operational perspective, it is considered to be ineffective for intracellular toxins (Fig. 1).

Powdered activated carbon (PAC) and granular activated carbon (GAC) filters can effectively remove dissolved toxins with high contact time and sufficient doses of activated carbon (Fig. 1) (Hrudey *et al.* 1999).

Some drawbacks include a limited lifespan of activated carbon, variability of removal efficiencies depending on the toxin itself, type of activated carbon and level of dissolved organic carbon (DOC) (Hrudey *et al.* 1999, Newcombe and Burch 2003).

Ozone:

Ozone is not employed to remove particles and therefore it does not remove intact cyanobacteria cells. Ozone increases cell lysis and the toxins released require the use of higher ozone doses than typical water treatment plants (Fig. 1) (Hoeger *et al.* 2002, Rositano *et al.* 1998). To provide safe drinking water from waters with cyanobacteria, it is recommended to apply filtration before ozone, monitor online ozone residual, organic carbon and cell concentrations and change filter media frequently (Hoeger *et al.* 2002). However, ozonation should be followed by biofiltration to reduce the biodegradable organic carbon in order to control the biological growth (or regrowth) in the distribution system.

Ozone can effectively destroy microcystins, anatoxin-a, nodularin PSP and cylindrospermopsin with sufficient ozone residual after 5 minutes, however does not effectively inactivate saxitoxins (Brooke *et al.* 2006, Rositano *et al.* 2001, Westrick *et al*., 2008, Hrudey *et al.* 1999, Newcombe and Burch 2003, Newcombe and Nicholson 2004, Rositano *et al.* 1998). One of the drawbacks to ozonation is that the ozone demand may be affected by DOC and must be satisfied in order to effectively inactivate cyanotoxins (Hrudey *et al.* 1999, Rositano *et al.* 1998).

Chlorine:

Free chlorine is not employed to remove particles and therefore is does not remove intact cyanobacteria cells. Like ozone, it will increase cell rupture and toxin release (Fig. 1).

Free chlorine can effectively inactivate dissolved toxins, depending on pH and contact time (Hrudey *et al.* 1999). Microcystin-LR, nodularin, cylindrospermopsin and saxitoxins is effectively inactivated with sufficient chlorine residual and contact time, whereas anatoxin-a is not effectively inactivated (Hrudey *et al.* 1999, Newcombe and Burch 2003, Ho *et al.* 2008, Newcombe and Nicholson 2004).

HOUSEHOLD TREATMENT

Most of the treatment processes described above can be implemented in large and small drinking water plants; however, applying these technologies to domestic households that are not on municipal water is challenging and is most often not discussed in the literature. Typical household water treatment devices are cartridge filters, ultraviolet (UV) treatment or reverse osmosis (RO) (Hrudey *et al*. 1999).

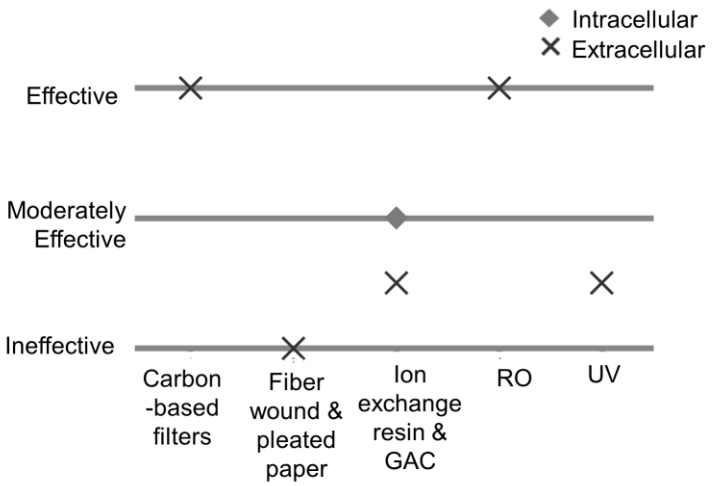

FIGURE 2. OVERVIEW OF THE EFFECTIVENESS OF TREATING INTRACELLULAR AND EXTRACELLULAR MICROCYSTIN WITH HOUSEHOLD TREATMENT TECHNOLOGIES.

Cartridge Filtration:

When comparing the effect of filter types on microcystin-LR removal, carbon block and carbon-wrapped filters removed the highest amount of microcystin-LR (99% removal), whereas fiber wound and pleated paper filters only removed 5.84% and 4.65% of microcystin-LR, respectively (Fig. 2) (Pawlowicz *et al.* 2006).

Due to operational drawbacks, intact cellular removal with ion exchange and GAC cartridge filters has low removal effectiveness (Fig. 2). Ion exchange and GAC cartridge filters were tested with intact cyanobacteria cells (*Microcystis aeruginosa*, *Anabaena flos-aquae* and *Oscillatoria agardhii*) and found that filamentous cells (*A. flos-aquae* and *O. agardhii*) were removed more effectively (60% removal) than single cells (*M. aeruginosa*) (10% removal) (Lawton *et al.* 1998). Trapped cells in the filter could degrade and release toxins; therefore it is suggested to pre-rinse filters and filter repeatedly, which may not be feasible (Lawton *et al.* 1998). Extracellular microcystin removal was also assessed and was found to be less than moderately effective because it did not remove all microcystin variants completely (Fig. 2) (Lawton *et al.* 1998).

Ultraviolet Treatment:

UV light can degrade microcystins, at a specific wavelength and sufficient light intensity (Tsuji *et al.* 1995). However, the required light intensity may be impractically high, which indicates overall low effectiveness (147 $\mu W/cm^2$). In addition, organics can interfere with effective UV treatment (Tsuji *et al.* 1995). This

suggests that UV light can be used to degrade dissolved microcystins from raw water, if raw water has low organics and sufficient UV light intensity and exposure time (Tsuji *et al.* 1995).

Reverse Osmosis:

It is assumed that reverse osmosis (RO) can remove microcystins; however few studies have assessed RO for cyanotoxin removal (Lawton and Robertson 1999). A study by Neumann and Weckesser (1998) confirmed this assumption, indicating that 96.7-99.9% of microcystin-LR was removed by RO. One of the challenges is that toxins are only removed and not destroyed, therefore waste from the system contains toxins that will need to be discarded properly (Lawton and Robertson 1999).

CONCLUSION

Overall, additional research is needed to help large and small water treatment plants address challenges associated with cyanobacteria and cyanotoxin treatment using conventional, dissolved air flotation, membrane filtration, slow sand filtration, oxidation and activated carbon treatment options. Each technology has a different degree of effectiveness on removing/inactivating intact cyanobacteria cells and dissolved cyanotoxins. Because various toxins react to treatments differently, it is important to study the effects of water treatment on different cyanotoxin variants.

Limited studies have tested the effectiveness of cyanotoxin removal using household treatments such as, cartridge filters, UV treatment or reverse osmosis. Cartridge filters have been shown to remove intact cyanobacteria cells. Pre-rinsing or filtering repeatedly is recommended to reduce the risk of cell rupture, which may be operationally impractical. UV treatment on inactivating dissolved cyanotoxins depends on organic matter, UV light intensity and exposure time. Reverse osmosis has removed microcystin-LR effectively. To our knowledge, these household treatments have only been tested with microcystin. Full-scale *in-situ* and long-term studies are needed to support these findings from previous studies.

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