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RESEARCH ARTICLE

Can the elimination of cyanobacteria by micro-sieving be an innovative lake purity improvement method?

Agnieszka Napiórkowska-Krzebietke, Marek Łuczyński

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Abstract. The removal of harmful cyanobacteria has recently become an important target in water management strategies. Various methods have been developed to eliminate these microorganisms including: (1) biological methods, especially with floating treatment wetlands and riparian vegetation; (2) physical methods with aeration, mechanical circulation, and hypolimnetic oxygenation; (3) chemical methods with coagulation and flocculation processes; (4) barley straw. We propose that the in situ mechanical-based micro-sieving process provides an opportunity for this to succeed in practice. The appropriate, selective technical parameters and techniques can result in successful water quality improvement, which is essential to meet Water Framework Directive goals and especially for public health. Additionally, micro-sieving used for removing *Gloeotrichia* can contribute to a significant reduction in internal phosphorus loads, a necessary step in lake restoration. The theoretically probable mean cell-bound P-content transferred with *G. echinulata* colonies (during strong blooms) can be as high as 48 mg L^{-1}, and this potential P-load is usually deposited on lake bottoms. The removal of cyanobacterium can result in significant limitations of internal P-sources. The method presented above could be a promising, practical, easy-to-use, and cost-effective method for managing and limiting cyanobacterial blooms.

A. Napiórkowska-Krzebietke [✉], M. Łuczyński
Department of Ichthyology, Hydrobiology and Aquatic Ecology, National Inland Fisheries Research Institute, Olsztyn
Oczapowskiego 10, 10-719 Olsztyn, Poland
E-mail: a.napiorkowska-krzebietke@infish.com.pl

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Introduction

The excessive growth of cyanobacteria has become a global economic problem affecting resources of recreational and potable waters. Under favorable light, temperature, and nutrient conditions, cyanobacteria can cause harmful blooms (cyanobacterial harmful algal blooms – CyanoHABs) with the possible release of cyanotoxins into the water column (Kobos et al. 2013, Napiórkowska-Krzebietke et al. 2015, Mantzouki et al. 2018). This development poses a particular threat to people, domesticated, and wild animals bathing in or drinking such waters. The World Health Organization (WHO 2011) has specified a guideline value of 1.0 µg L^{-1} for microcystin-LR (MC-LR) as being of health significance in drinking water. A poisonous dose of this microcystin could be about 10-times or even higher compared to toxic amounts of arsenic or other naturally occurring chemicals. Mass occurrences of cyanobacteria usually indicate more or less advanced lake eutrophication, including serious ecological deterioration (Napiórkowska-Krzebietke 2015), which often fails to meet the Water Framework Directive

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requirement of having at least a good ecological status (WFD, European Commission 2000). For good water quality, CyanoHABs should be strictly controlled. The findings of Barnard et al. (2021) indicated that nutrient limitation significantly lowered cyanobacteria microcystin and anatoxin production. Thus, it is very important to control nutrients, especially nitrogen and phosphorus (Conley et al. 2009).

A brief overview of the removal of cyanobacteria and cyanotoxins

Many investigations have focused on the efficiency of removing or inactivating cyanobacteria and cyanotoxins, especially from potable water. The review of this topic by Westrick et al. (2010) proved that the efficiency of various treatment technologies commonly used worldwide to remove intact algal cells (such as coagulation/sedimentation, dissolve air flotation/rapid sand filtration, lime precipitation/sedimentation/rapid sand filtration, microfiltration/ultrafiltration) can reach up to 99.5%. Furthermore, this paper gathered information on the cyanotoxin (e.g., microcystins, cylindrospermopsin, anatoxin-a, and saxitoxins) inactivation potential of oxidants such as chlorine and ozone. Very promising results were also obtained by Benoufella et al. (1994), who found that combining the processes of ozoflotation and bilayer filtration could successfully resolve algal bloom problems in waters. Similar findings (i.e., complete filamentous cyanobacteria removal) were achieved by experimentally combining dissolved air flotation and microfiltration (Amaral et al. 2013) and by applying microfiltration and ultrafiltration exclusively (Chów et al. 1997, Huang et al. 2015).

Among the various ways of controlling or even eliminating algal or cyanobacterial blooms (e.g., CyanoHABs), some are based on introducing chemicals such as algaecides that can increase toxicity or coagulants into waters, while others rely on physical control techniques (Newcombe et al. 2010). There are also methods that involve introducing some living organisms. The use of products containing a mixture of bacteria spore forms, vegetative bacteria (non-toxic strains of *Bacillus* and *Pseudomonas*), and fungi that can produce enzymes with increased digestion capacity has become more widespread (Gałczyński and Ociepa 2008). An experimental study by Camacho et al. (2013) revealed that a natural coagulant of horseradish tree, *Moringa oleifera* Lam., seeds (also known from many uses in medicine and also in restoration processes) used in the process of coagulation/flocculation/sedimentation was highly efficient in removing *Microcystis protocystis* W.B.Crow, and included effects such as the lack of cell lysis. Furthermore, the removal efficiency of cyanobacterial cells and microcystins was increased to 100% by adding nanofiltration. Nanofiltration membranes (with mean pore sizes of 0.44 or 0.38 nm) can completely remove cyanotoxins and other organic compounds (López-Muńoz et al. 2009). Thus, in the search for new alternative, effective methods for in situ cyanobacteria removal, we highlight the use of the micro-sieving process that is theoretically appropriate for improving water quality.

Biological methods include (1) floating treatment wetlands (FTW) with emergent plants growing on floating mats that can filter and trap nutrients (especially N and P) and reduce phytoplankton growth including that of cyanobacteria (Jones et al. 2017, Garcia Chanc et al. 2019), and (2) riparian vegetation used as a buffer between open waters and point/non-point sources of pollution.

Physical methods primarily include (1) aeration, (2) mechanical circulation to limit nutrient accessibility to disrupt cyanobacteria migration behavior and reduce their competitive advantage, and (3) hypolimnetic oxygenation to reduce nutrient release rates from sediments (Burford et al. 2019). However, there are more or less popular physical methods.

In addition to biological and physical methods, chemical methods are also used. First, these methods include coagulation and flocculation processes using alum, ferric salts, and clay (Aygun and Yilmaz 2010, Scalize et al. 2019), which are effective for removing suspended solids and can be used effectively to reduce cyanobacteria density and phosphorus levels (EPA 625/1-75-003a. 1975). Secondly, decomposing barley straw, when exposed to sunlight and oxygen, produces chemicals that inhibit algae growth and limits them. This method was used successfully to inhibit the growth of cyanobacteria species of the genera *Microcystis, Anabaena*, and *Aphanizomenon* (Islami et al. 2010). The opposite effect was noted for *Oscillatoria* sp., whereas the growth of *Nostoc* sp. was not affected. Furthermore, light, temperature, and dissolved oxygen also play important roles as does the timing of barley straw removal. However, these results indicated that barley straw could be a promising, easy-to-use, cost-effective, practical method for managing and limiting cyanobacterial blooms.

Micro-sieving in water purity improvement of lakes

Micro-sieving as a pre-filtration process in the purification of water for consumption was first used in the 1940s, originally in England and afterward in other countries (e.g., Germany, Sweden, the Netherlands, New Zealand) (Ljunggren 2006). In Poland, it was first applied in 1994 (Jilek 1994). The application of 23–35 (with a range of 15–60 μm micrometers) micron-net-pore drum-filters with hydraulic loading rates (expressed as the ratio of flow to surface area) of 12–25 m h^{-1} facilitated the removal rates of suspended solids of between 45% and 85%. These findings were reported by Ljunggren (2006), Pfeiffer et al. (2008), Langer and Schermann (2013), and Fernandes et al. (2015) for aquaculture systems or wastewater treatment. The implementation and exploitation of micro-straining (synonymous with micro-sieving) was cost-effective in comparison to other filtration methods.

Grochowiecka et al. (2009) and Piontek and Czyżewska (2012) published results that indicated the high removal efficiency of phytoplankton including cyanobacteria (21–93%) with the application of micro-sieving as a step in water treatment. When cyanobacteria abundance was very low, removal efficiency was as high as 100%. Considering the technical options of micro-sieving, companies specializing in water technologies offer various types of drums with sieve systems in which the pore size range is 5–250 microns (even up to 1,000 microns) with throughput capacities of up to 7,500 m^3 h^{-1}. The Water Treatment Plant in Zawada has installed three 10-micron-net-pore drum-sieves with an efficiency of 292–720 m^3 h^{-1} (Grochowiecka et al. 2009, Piontek and Czyżewska 2012). Other studies have focused on using particle-filtration processes to eliminate phytoplankton, especially cyanobacteria with *Limnothrix redekei* as the dominant species (Czyżewska and Piontek 2019). The effect of removal was statistically significant, and the process also contributed to decreased contents of intracellular microcystins from the reduction of cyanobacteria.

A conceptual approach to using micro-sieving

The highly successful removal of cyanobacteria cells and cellular debris before cyanotoxin is released into the water should be the highest priority for improving water quality and achieving WFD targets for lake restoration. Furthermore, cyanobacteria removal should also ensure the partial elimination of nutrients and consequently contribute to significant water quality improvement.

Properly planned, well-organized in situ micro-sieving should guarantee highly efficient cyanobacteria removal. Thus, we hypothesized that in situ micro-sieving is effective for cyanobacteria removal and can be used as a purity improvement method (PIM) for lake restoration. To assess the effectiveness of micro-sieving, a feasibility study should be performed based on the following SMART criteria:

- Specific – micro-sieves with the appropriate pore size (e.g. 5–10 μm or more) should include separating out micro-sized organisms and initial flocculation, if necessary;
- Measurable – cyanobacteria analyses should be done before and after micro-sieving to determine the immediate effects;
- Achievable – properly working micro-sieving and flocculation processes, with frequent micro-sieve

flushing to avoid any clogging, i.e., with good self-cleaning;

- Relevant – the method should be used at appropriate times, i.e., during the first peaks of cyanobacteria biomass;
- Timetabled – purity improvement measures should be implemented throughout the cyanobacteria growth season, and they can be repeated the following year to compare results.

Cyanobacteria removal efficiency depends on various technical and technological factors and even weather conditions. Optimizing micro-sieving is highly recommended. For example, the flocculation process can be used as a pre-treatment step designed to remove effectively single, very small-sized cyanobacteria cells or those dispersed throughout the water column. Frequently flushing out micro-sieves can help to minimize clogging and ensure good self-cleaning. According to Ljunggren (2006), clogging is the major drawback of micro-sieving. Immediately isolating flushed water should help to avoid any additional risk of cyanotoxin being released from possibly damaged cells into lakes. However, mechanical cell damage depends also on other factors including increased turbulence or pressure in drums.

What is important? Micro-sieve technology can facilitate water quality improvement to a degree comparable with geoengineering technologies (Mackay et al. 2014), and it can produce good results. The technical methods should ensure high hydraulic capacity to guarantee adequate precision of cyanobacteria removal and to minimize cyanotoxin risks that endanger human safety. Furthermore, micro-sieving is a non-invasive, effective way to eliminate algae and cyanobacteria from freshwaters. Capital expenditures and operating costs can be lower than those of other improvement methods; therefore, micro-sieving is a rather cost- and energy-efficient technology.

Theoretical approach to using micro-sieving in situ to remove internal phosphorus loads from lake sediments

Micro-sieving technology combined with chemical pre-treatment is used in wastewater treatment plants to ensure good, reliable phosphorus removal (Langer and Schermann 2013), and it has also been proven highly efficient at cyanobacteria removal (Grochowiecka et al. 2009, Piontek and Czyżewska 2012). Lakes dominated by the cyanobacterium *Gloeotrichia* could be chosen since their condition is of special concern in attempts to improve water quality. The dominance of G*loeotrichia echinulata* J. S. Smith ex Richt (Fig. 1) is usually connected with nutrient-rich lake sediments, and it can be a visible symptom of the progressive deterioration of the ecological and trophic conditions of lakes (Napiórkowska-Krzebietke and Hutorowicz 2015). *G. echinulata* can transport effectively phosphorus from nutrient-rich sediments (benthic life stage) to pelagic waters (pelagic life stage) (Pettersson et al. 1993, Tymowski and Duthie 2000), which can accelerate lake eutrophication. Istvánovics et al. (1993) reported that as *G. echinulata* migrated to epilimnetic waters, it could transport from approximately 2.5 mg P m^{-2} d^{-1} (Pettersson et al. 1993) to as much as 3.8 mg P m^{-2} d^{-1}, which was estimated to correspond to 66% of the total annual internal phosphorus load in the lake studied. Furthermore, this study suggested that the amount of 49 ng P $colony^{-1}$ (even up to 81 ng P $colony^{-1}$) could be expected as the mean phosphorus content in benthic *Gloeotrichia* colonies. Thus, calculated as dry weight, this would equal approximately 5.2 μg P per mg dw and as much as 8.5 μg P per mg dw.

Assuming the phosphorus content above as that of *G. echinulata* colonies, it was possible to calculate the probable theoretical P content that could be transported from sediments in Lake Wulpińskie (20.39547 E, 53.70494 N, 706.7 ha surface area, maximum and mean depths of 54.6 m and 10.6 m, respectively), which was the subject of our study. During *Gloeotrichia* blooms, when colonies (1–3 mm in diameter) migrated from sediments to the surface layer (more or less dispersed in the water column) (Fig. 2), the probable mean transferred cell-bound phosphorus content would be 48 mg L^{-1} (Table 1).

The application of the micro-sieving method in situ to remove *Gloeotrichia* can also remove cell-bound phosphorus from aquatic ecosystems.

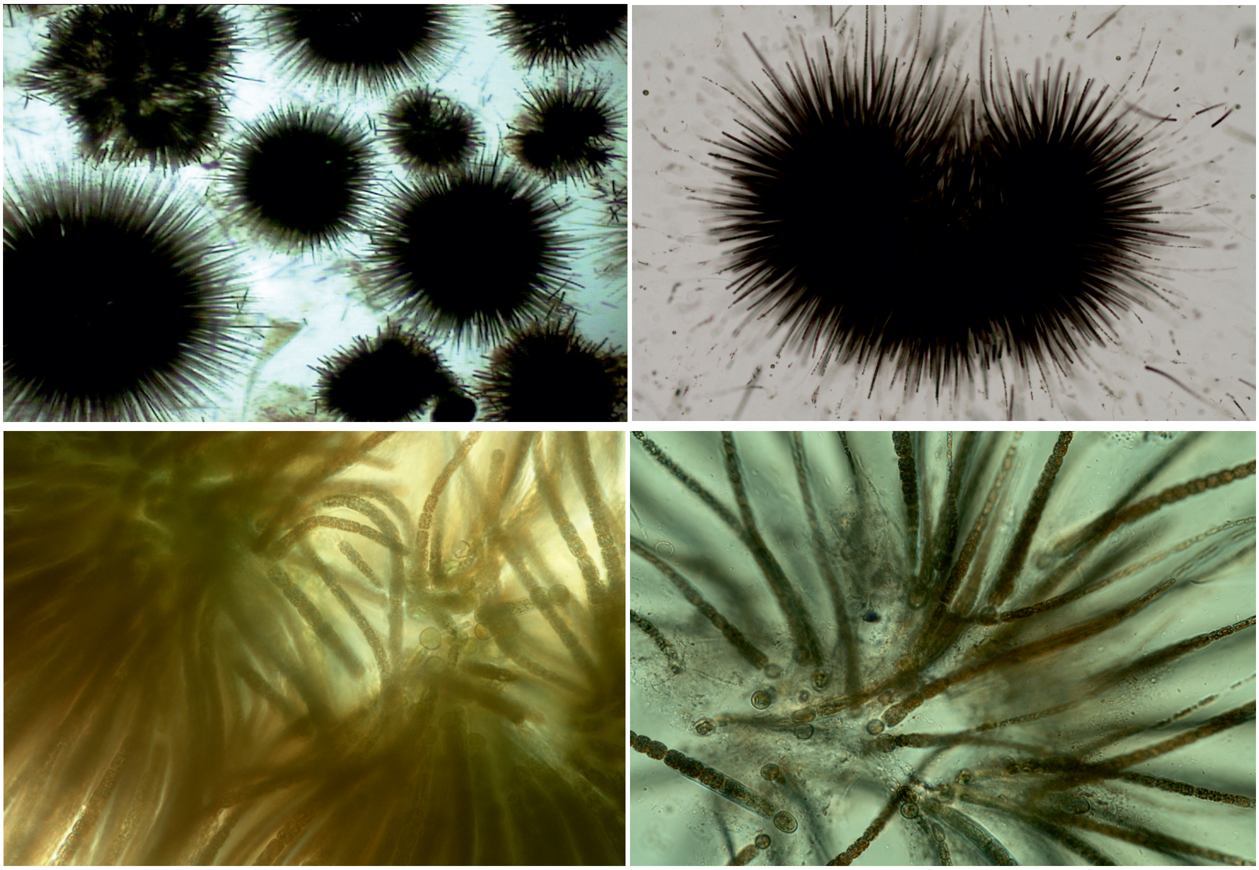

Figure 1. *Gloeotrichia echinulata* bloom and single colony (views at magnifications of 100x, 200x, 400x).

Table 1
Probability of cell-bound phosphorus transport by benthic *G. echinulata* colonies from lake sediments, calculations based on data from Lake Wulpińskie (own data)

Term	Sampling site and depth	Gloeotrichia echinulata (colony L^{-1})		Probable content of cell-bound phosphorus (mg P L^{-1}) mean[1]	maximum[2]
July 29, 2020	littoral/pelagic zone, surface layer (0-0.5 m)	min	12500	0.613	1.013
		max	16667	0.817	1.350
		mean	14375	0.704	1.164
		SD	1751	0.086	0.142
		CV%	12.18		
July 22, 2021	littoral/pelagic zone, surface layer (0-0.5 m)	min	139583	6.840	11.306
		max	159375	7.809	12.909
		mean	147292	7.217	11.931
		SD	8156	0.400	0.661
		CV%	5.54		
July 29, 2021	littoral zone, Gloeotrichia scum (0-0.025 m)	min	398437	19.523	32.273
		max	766145	37.541	62.058
		mean	587358	28.781	47.576
		SD	151608	7.429	12.280
		CV%	25.81		

[1]assuming 49 ng P colony^{-1} as the mean P content in benthic *Gloeotrichia* colonies (according to Pettersson et al. 1993)
[2]assuming 81 ng P colony^{-1} as the maximal P content in benthic *Gloeotrichia* colonies (according to Pettersson et al. 1993)

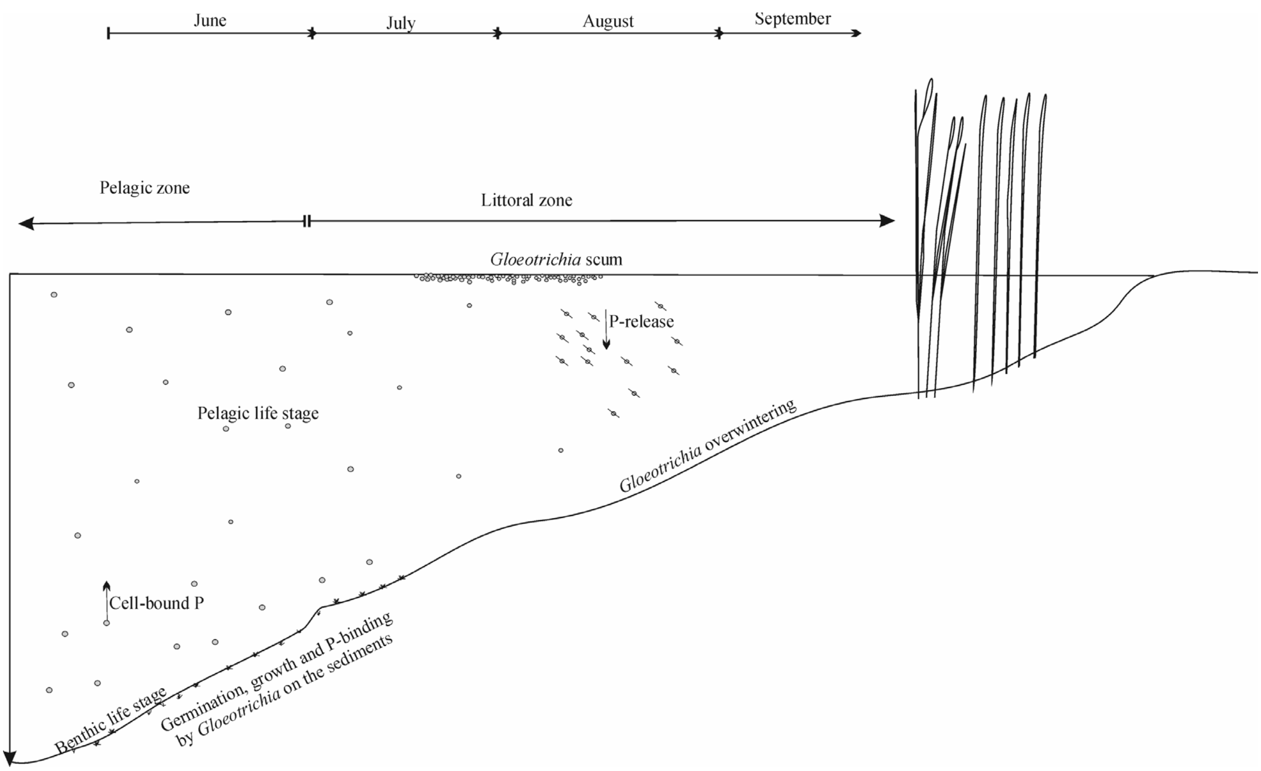

Figure 2. Benthic and pelagic life stages of *Gloeotrichia echinulata* in a Gloeotrichia-dominated lake including the phosphorus (P) internal cycling.

The best time for the in situ application of micro-sieving is late July/early August, when *G. echinulata* migrate intensely. Assuming high removal efficiency of up to 93% (or in some cases even 100%), this will facilitate a significant reduction in internal P loads along with reduced *Gloeotrichia* colonies. Cyanobacterial biomass obtained from micro-sieving can be used as biofertilizers in agriculture and in the production of energy and secondary metabolites of nutritional, cosmetic, and medicinal importance (Pathak 2018, Chittora 2020).

Conclusions

Properly planned, well executed in situ micro-sieving offers unique opportunities for success. The choice of the best technical parameters and methods combined other processes (e.g., flocculation) can provide satisfactory water quality improvement, which is important for public users. The elimination or reduction of a cyanobacteria bloom levels will also decrease the risk of their toxic effects. Furthermore, the role of the cyanobacterium *Gloeotrichia* in sediment-phosphorus translocation is one of the major factors affecting the reduction of internal phosphorus loads in some type of lakes; therefore it can be helpful for lake restoration.

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ORCiD

Agnieszka Napiórkowska-Krzebietke
https://orcid.org/0000-0001-8361-0290
Marek Łuczyński https://orcid.org/0000-0001-5243-7309

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