TECHNICAL BRIEF

WHO/FWC/WSH/15.03

MANAGEMENT OF CYANOBACTERIA IN DRINKING-WATER SUPPLIES: Information for regulators and water suppliers

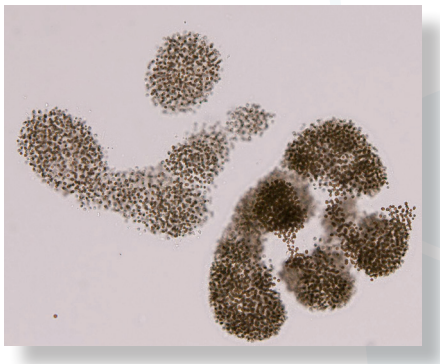
This technical brief provides general information on the management of cyanobacteria in drinking-water supplies to help regulators and water suppliers determine when to take action and what actions to take. It describes a number of measures to prevent the formation of cyanobacterial blooms as well as options to manage such blooms when they occur. Although some of the measures are specific to cyanobacteria, many are equally useful for the management of other hazards. Risks from cyanobacteria should be assessed along with the other microbial, chemical, physical and radiological hazards that may be encountered in a water supply. This can be effectively achieved in the context of developing a water safety plan for the water supply system.

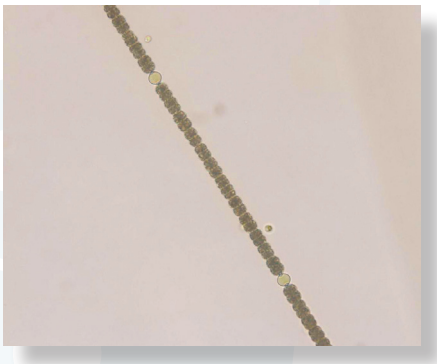
What are cyanobacteria?

Cyanobacteria, also known as blue-green algae, are photosynthetic bacteria naturally present in surface waters in low or moderate numbers; very high numbers are usually caused by human activity enriching the water with phosphorus and nitrogen. Some cyanobacteria produce toxins, called cyanotoxins. Cyanobacteria can occur as single cells or in groups, as colonies or filaments. They can be found in fresh, marine and brackish waters. Frequently occurring genera in surface waters include *Anabaena, Aphanizomenon, Cylindrospermopsis, Lyngbya, Microcystis, Oscillatoria, Phormidium* and *Planktothrix*.

Some cyanobacteria can control their buoyancy and seek water depths with optimal growth conditions. This ability to move within the water column gives cyanobacteria an advantage over other microorganisms that compete for nutrients and light. Buoyant cyanobacteria, such as *Anabaena* and *Microcystis*, may float upward when mixing is weak and accumulate in dense surface blooms (Fig. 1). Other cyanobacteria, such as *Cylindrospermopsis* and *Planktothrix*, stay dispersed, but can reach very high cell densities, causing high turbidity. Still others, such as *Lyngbya, Oscillatoria* and *Phormidium*, grow as benthic populations on sediments or attached to other surfaces, such as piers or submersed rocks (for details, refer to Ministry for the Environment & Ministry of Health, New Zealand, 2009).

Figure 1. Cyanobacterial bloom (left); *Microcystis* sp. (middle; magnified 200-fold); *Anabaena* sp. (right; magnified 400-fold)





World Health Organization

How can cyanobacteria affect drinking-water supplies and human health?

Production of toxins

General information

Cyanobacteria produce a wide range of bioactive substances, some of which are still unknown. A number are toxic to humans – the cyanotoxins – and they have different modes of toxicity. Some cyanotoxins are chiefly contained within the cyanobacterial cell (intracellular cyanotoxins), whereas others are released from the cell into the surrounding water (extracellular cyanotoxins). When the cyanobacteria die, the intracellular cyanotoxins can also be released; this may occur during certain water treatment processes.

Most surface bloom–forming cyanobacterial species can produce toxins; however, not all bloom-forming cyanobacteria are toxic. As a precaution, cyanobacterial blooms should be considered toxic, as evidence shows that up to 75% of blooms are toxic (Chen, Burke & Prepas, 2011). Each type of cyanotoxin can be produced by different genera of cyanobacteria; microcystins, for example, are produced by *Microcystis* and *Planktothrix*, whereas cylindrospermopsin comes from *Cylindrospermopsis* and *Anabaena*. In addition, each genus of cyanobacteria can produce more than one cyanotoxin; *Anabaena* species, for example, produce cylindrospermopsin and anatoxins.

Bottom-dwelling (benthic) cyanobacteria, such as the genera *Lyngbya*, *Oscillatoria* and *Phormidium*, also produce cyanotoxins and therefore may be hazardous if they detach and rise to the surface or disperse in the water.

Potential health effects

Cyanotoxins can have a variety of effects on human health. Acute symptoms range from gastroenteritis, fever and irritation of the skin, eyes, throat and respiratory tract to liver damage and neurotoxicity. Chronic long-term effects include tumour promotion (International Agency for Research on Cancer, 2010). Cyanobacteria do not multiply in the human body and so are not infectious (Chorus & Bartram, 1999).

In an incident in Brazil, more than 50 people died when water contaminated by cyanotoxins (microcystins and probably also cylindrospermopsin) was used for dialysis after insufficient treatment (Jochimsen et al., 1998). Drinking-water should not be used for dialysis without treatment specific for this purpose.

Production of off-flavours and odours

General information

Some genera of cyanobacteria, such as *Anabaena, Phormidium* and *Planktothrix*, produce compounds with unpleasant odours and tastes ("off-flavours"). The two most common compounds are geosmin and 2-methylisoborneol. They impart a musty-earthy odour to drinking-water, which, although unpleasant, is harmless. Although other microorganisms, such as actinomycetes, also produce geosmin and 2-methylisoborneol, cyanobacteria are considered the major source of these compounds in surface waters. Their occurrence can be a sign that toxic cyanobacteria are present. Usually, however, the occurrence of cyanotoxins is not related to taste and odour. Tastes and odours are therefore not reliable signs of a toxin-producing bloom.

Customer complaints and undermining consumer confidence

Taste- and odour-causing compounds can be detected at very low concentrations in water (e.g. a few nanograms per litre), much lower than the concentrations of cyanotoxins that are associated with adverse health effects. These tastes and odours can lead to customer complaints or result in consumers using an aesthetically more acceptable, but potentially less safe, drinking-water source.

Where are cyanobacteria likely to be found, and what causes their growth?

Environmental conditions that favour cyanobacterial growth

Cyanobacterial blooms occur in fresh water in nearly all parts of the world. Environmental conditions that favour cyanobacterial growth tend to occur in late summer and autumn in temperate zones and potentially year-round in productive tropical and subtropical zones. These conditions include:

- high concentrations of nutrients, particularly phosphorus (> 25–50 µg total phosphorus per litre[1]),
- high water temperature (> 25 °C),
- long hydraulic retention time (> 1 month), and
- stable water body stratification (for some cyanobacteria).

Because of these characteristics, planktonic cyanobacteria (those living in the water column) tend to occur more often in reservoirs, dams, lakes, ponds and slow-moving rivers. Benthic cyanobacteria are found on the bottom or in shallow zones of water bodies and tend to stay localized to the area of growth.

If the planktonic or benthic cyanobacteria are disturbed or their mats become detached, their toxins may be released and disperse in the vicinity. Other factors, such as light intensity and wind, affect the growth and accumulation of cyanobacterial blooms. In temperate climates, some filamentous, usually toxic cyanobacteria may produce blooms at the interface between the warm surface water layer and the cold deep layer (e.g. *Planktothrix rubescens*), whereas others may produce high biomass concentrations year-round in well-mixed shallow lakes (e.g. *Planktothrix agardhii*).

Direct and indirect effects of increases in water temperature

Warming of surface water can provide a competitive advantage for cyanobacteria. In temperate regions with seasonal phytoplankton succession, higher winter and spring temperatures may promote the growth of cyanobacteria over that of diatoms, which usually dominate in spring when water bodies are well mixed. Moreover, increased water temperatures further intensify water stratification and lengthen the duration of stratification periods, thus increasing not only the magnitude of the blooms, but also their duration.

Effects of change in patterns of precipitation and storms

Climate change can affect cyanobacterial growth through impacts on both water temperature and precipitation events. Intense rainfall can increase nutrient discharge into water bodies, thus promoting bloom formation, but it may also prevent blooms by increased flushing and mixing. Where water retention time increases as a result of drought, nutrient loads may rise, thus potentially promoting blooms; in contrast, drought may reduce nutrient levels due to reduced influx of water carrying fertilizers. Intense snowfall leading to large spring melt and flooding may also affect cyanobacterial occurrence. Storm events affect water body mixing, with more frequent alternation between stable stratification and mixing interrupting bloom development (see Paerl & Huisman, 2008; Newcombe et al., 2012).

Occurrence of cyanobacteria in source water

During the last decades, cyanobacterial abundance has increased in many surface waters around the world as a result of various factors, such as increased nutrient concentrations ("eutrophication"). *Cylindrospermopsis raciborskii* has substantially expanded its geographical range: it was initially identified exclusively in tropical and subtropical latitudes, but its prevalence in temperate regions – including northern Europe, southern Australia, New Zealand, the northern United States and southern Canada – has increased over the past two decades. Nonetheless, in most of these regions, other cyanobacteria, particularly *Microcystis* and *Planktothrix*, remain the most frequent causes of heavy blooms.

[1] Note that this is referring to total phosphorus, not to phosphorus dissolved in the water. Detection of dissolved phosphorus at concentrations above 5 µg/L implies excess availability and high bloom potential.

Water bodies that are influenced by discharges of municipal wastewater or subsurface infiltration of groundwater influenced by septic systems are known to carry nutrients at elevated levels that are capable of increasing cyanobacterial growth. These impacts are exacerbated by wastewater treatment systems with poor nutrient removal capacity. Drought conditions can also increase the likelihood of cyanobacterial blooms where wastewater loading remains constant. Runoff from animal feedlots and from fields containing mineral fertilizer or manure can introduce similarly high nutrient loads; in regions with effective phosphorus removal in wastewater treatment but intensive agriculture, the latter tends to be the main cause of eutrophication (see also Merel et al., 2013).

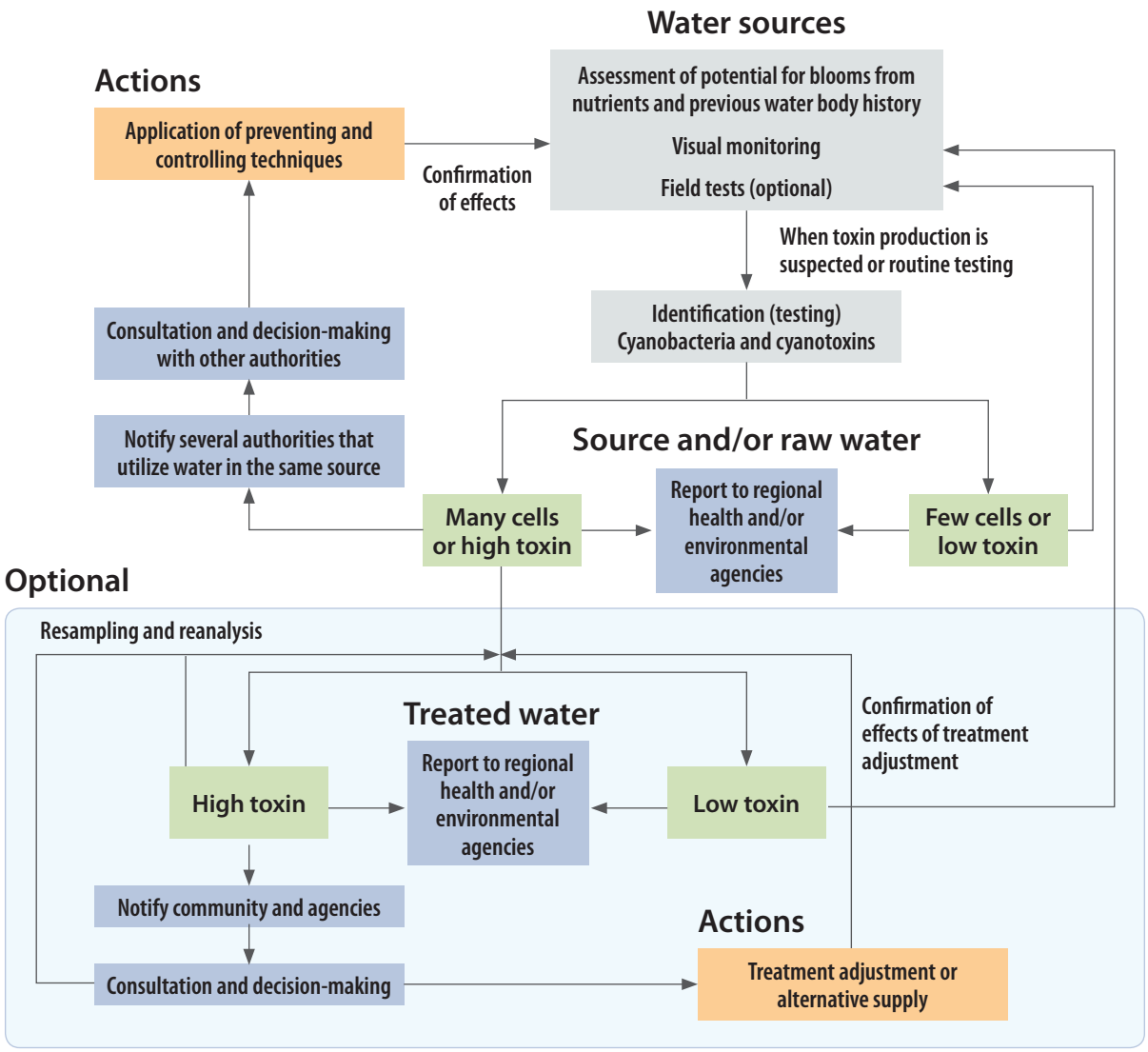
How can the risk associated with cyanobacteria in the water supply be assessed and effectively managed?

The most effective means of consistently ensuring the safety of a drinking-water supply is through the use of a comprehensive risk assessment and risk management approach that encompasses all steps in the water supply, from catchment to consumer. For this purpose, the World Health Organization (WHO) recommends the development of water safety plans (Davison et al., 2005; WHO, 2011).

Water safety plan development draws on the principles and concepts of both a multiple-barrier approach and the hazard assessment and critical control points approach. The primary objective of a water safety plan is ensuring good drinking-water supply through the identification of risks from hazards and hazardous events, the prevention or minimization of contamination of source waters, the reduction or removal of contamination through treatment processes and the prevention of recontamination in the distribution system.

An example of a flow chart to guide water suppliers in determining when to take action to manage cyanobacteria and what actions to perform is provided in Fig. 2 (see also Chorus & Bartram, 1999; Health Canada, 2002; Newcombe, 2012).

Figure 2. Example flow chart of the management of cyanobacteria in water



Source: Adapted from Health Canada (2002).

Assessing the potential of water sources to support cyanobacterial blooms

Understanding the conditions that promote the growth of cyanobacteria in water bodies is useful for predicting whether cyanobacterial problems are likely to occur. A fundamental basis for cyanobacterial growth is the concentration of total phosphorus, as the total amount of phosphorus in the system limits the total amount of biomass that can occur. Water temperature is also an important factor for assessing the potential for cyanobacterial growth, as shown in Table 1. Data on additional factors, such as chlorophyll *a*, thermal stratification, local weather conditions influencing stratification and concentrations of nitrogen, can improve the assessment.

Table 1. Example assessment of the potential for high biomass of cyanobacteria based on environmental conditions[a]

Indicator	Very low	Potential for high biomass of cyanobacteria (blooms)			Very high
Total phosphorus (µg/L)	< 10	10–25	> 25–50	> 50–100	> 100
Water residence time	River with visible current	< 1 month		≥ 1 month	
pH	< 5–6	> 6–7	> 7		
Secchi disc transparency[b] during season typical for cyanobacteria	≥ 2 m	< 2–1 m	< 1–0.5 m		< 0.5 m
Temperature (°C)	< 10	10 – < 15	15 – < 20	20 – < 25	≥ 25

[a] The higher the number of these conditions that are fulfilled, the higher the potential for high biomass of cyanobacteria.
[b] Determined as the depth at which a white disc of 20 cm diameter lowered into the water is no longer visible.
Source: Adapted from Umweltbundesamt (2014).

Monitoring and testing in water sources

Several-year data sets on the occurrence of cyanobacteria are valuable for cyanobacterial risk assessment and management. In many water bodies, cyanobacteria occur with quite regular annual patterns. Once these patterns are understood, monitoring can be specifically targeted to critical time periods. Monitoring cyanobacteria also provides information for tracking the development of cyanobacterial blooms as well as for early warning for water source management and drinking-water treatment plants. Monitoring is most effectively based on surveillance of source water for evidence of cyanobacterial bloom–forming potential, such as the concentration of total phosphorus. Effective monitoring is useful for improving the identification of water bodies at risk of blooms, particularly as, in many cases, data from a single point in time (e.g. spring overturn or end of dry season) serve to characterize bloom potential. On-site visual assessment of water body turbidity and scouting for surface blooms are effective, low-cost, direct methods that can trigger increased vigilance where such events occur.

Monitoring of cyanobacteria, cyanotoxins and taste- and odour-causing compounds

Timing, frequency and depth of sampling are best adapted to the (sometimes rapid) variation of cyanobacterial densities between locations within the water body. Densities are influenced by local factors, such as changes in wind direction. The appropriate frequency of sampling will be influenced by a number of factors, including the cost of monitoring, the season, the growth rate of the cyanobacteria and methods employed in preventing and controlling cyanobacteria.

Chlorophyll *a* is a good indicator for overall phytoplankton biomass, and monitoring chlorophyll *a* is a direct way to provide a semi-quantitative estimate of cyanobacterial biomass, particularly if performed in combination with a brief check in the microscope as to whether it chiefly originates from cyanobacteria (Chorus & Bartram, 1999; Health Canada, 2002; Newcombe et al., 2010; Newcombe, 2012).

To determine whether cyanobacteria are present in source waters and how concentrated they are, direct visual inspection for discoloration or surface scums of cyanobacteria in water sources is an effective first check. A typical colour of bloom is green with an olive hue; however, the colours can range from grey or tan to blue-green or reddish; during short periods of lysis, the bloom may also be bright turquoise or blue. If cyanobacteria are suspected, species identification and cell count by microscopic observation are recommended. It is not difficult to identify cyanobacteria at the genus level for staff with some experience in microscopy, and this can be sufficient to detect a potential cyanotoxin hazard, particularly from the genera *Anabaena, Aphanizomenon*, *Microcystis* and *Planktothrix*.

Field test kits can be useful for screening for specific cyanotoxins; however, more sophisticated laboratory testing should be considered to confirm the identification of the toxins and their concentrations. The absence of one cyanotoxin does not guarantee the absence of all cyanotoxins. Testing for cyanotoxins in the treated drinking-water is useful to validate and optimize the efficacy of treatment processes (Chorus & Bartram, 1999; Japan Water Works Association, 2000; Nicholson & Burch, 2001; American Water Works Association, 2004; Newcombe, 2012).

The presence of geosmin and 2-methylisoborneol can be recognized by the musty smell of the water. Analytical confirmation and quantification require specific equipment and skills that often are not routinely present in water utilities (see also Jüttner & Watson, 2007).

How can cyanobacterial growth in water sources be prevented or controlled?

There are a number of approaches and techniques to prevent or control the growth of cyanobacteria in water sources. Preventive programmes to manage cyanobacteria in water should be developed in coordination with those agencies with the responsibility for managing water resources, including environmental, agricultural and health authorities. The appropriate technique will depend on a number of factors, including local environmental conditions, cost of the technique, target periods, ecological condition of the respective water source and effects on other water uses (e.g. agricultural and recreational uses) (National Rivers Authority, 1990; Chorus & Bartram, 1999; Newcombe, 2012; Water Research Foundation, 2012).

Nutrient level control

Control of the levels of nutrients – specifically phosphorus, which is usually critical in promoting bloom growth and formation – is a key factor for sustainable long-term management of cyanobacterial growth in drinking-water sources. Nutrient control can be achieved through good watershed management practices, such as limiting the input of nutrients from wastewater effluent and agricultural runoff (including minimizing use of fertilizers in the catchment) and controlling erosion through improved techniques of ploughing and by maintaining a densely vegetated buffer strip a few metres wide around the water body and its tributaries.

Artificial mixing/aerating of source waters

Artificial mixing/aerating is an intermediate-term or long-term technique to manage the growth of scum-forming cyanobacteria, such as the genera *Anabaena* and *Microcystis*, in water sources with stable thermal stratification, present in many reservoirs. Mixing the water column can disrupt thermal stratification at least partially and thus inhibit the movement of cyanobacteria through the water column into optimal light conditions. However, it requires a sufficiently deep water body, energy, sophisticated equipment, excellent planning, monitoring of the impact and adjustment of the mixing regime. Thus, it may be uneconomical. In addition, once aeration ceases, blooms can return. In addition, mixing can cause other cyanobacteria – adapted to mixing – to replace the previously prevalent species.

Use of algicides and agents to precipitate cyanobacteria

The use of algicides to kill cyanobacteria is a technique for the short-term management of cyanobacterial growth in reservoirs (not in rivers). It can be useful at the beginning of bloom development. The most common algicide is copper sulfate; however, alternative algicides, such as copper chelates and hydrogen peroxide, have been applied. As some cyanotoxins and taste- and odour-causing compounds are intracellular, algicide application causing the sudden death of many cells can result in substantial release of cyanotoxins. Although drinking-water treatment would have removed the cells with the toxins, dissolved cyanotoxins are more likely to break through. Therefore, algicides are best applied while cell numbers are still low, to avoid the release of significant concentrations of intracellular toxins and taste- and odour-causing compounds.

Algicides may be used at higher cell numbers only if the reservoir can be taken out of supply until the toxins or taste- and odour-causing compounds degrade or if treatment for their removal is available. In addition, algicide use requires monitoring to minimize impacts on the agricultural use of water and on ecosystems, as well as precaution to ensure that algicides are not released into water sources, which may result in other health impacts or downstream environmental impacts. Operators must follow manufacturers' instructions when they use algicides.

Alum and gypsum work differently, precipitating rather than quickly killing the cells, and precipitating phosphorus as well. These may be feasible options where costs need to be kept low, as in the case of small water utilities.

Other options

Other techniques, such as decreasing the hydraulic retention time of reservoirs, maintaining flow in regulated rivers and biomanipulation (i.e. managing ecosystem components that compete with cyanobacteria, such as submersed aquatic plants), are also useful in some cases. Their success depends on excellent planning, monitoring and maintenance, based on an in-depth understanding of the ecosystem (National Rivers Authority, 1990; Newcombe, 2012).

How can intake of cyanobacteria be avoided? How can cyanobacteria, cyanotoxins and taste- and odour-causing compounds be removed through drinking-water treatment?

If significant amounts of cyanobacterial cells, cyanotoxins and taste- and odour-causing compounds are present in water sources and if prevention and control strategies cannot be implemented sufficiently quickly, a number of methods are available to prevent exposure to cyanotoxins or taste- and odour-causing compounds. For microcystins, the most effective control is the removal of the intact cells, as any cell damage in the drinking-water treatment plant may lead to toxin release and an increase in dissolved toxin entering the distribution system. For other cyanotoxins, this would be only partially effective, as higher proportions of the toxins occur dissolved in the water.

The appropriate technique will depend on a number of factors, including the hydrogeological situation, current treatment processes, cost of the technique and types of cyanobacteria, cyanotoxins and taste- and odour-causing compounds, as well as further microbial, chemical and physical hazards in the water supply that also require removal by treatment (Chorus & Bartram, 1999; Water Research Foundation, 2010; Newcombe, 2012; Odel, 2012).

A brief description of the treatment methods for cyanobacteria, cyanotoxins and taste- and odour-causing compounds follows. The treatment performance for cyanobacterial cells, intracellular/extracellular cyanotoxins, geosmin and 2-methylisoborneol is summarized in Table 2.

Table 2. Treatment performance for cyanobacterial cells, intracellular/extracellular cyanotoxins, geosmin and 2-methylisoborneol

Treatment processes	Cyanobacterial cells, intracellular cyanotoxins, geosmin and 2-methylisoborneol	Extracellular (free) cyanotoxins	Extracellular (free) geosmin and 2-methylisoborneol
Coagulation/sedimentation	+	–	–
Riverbank and slow sand filtration	+	+	+
Membrane filtration	+	–[a]	–[a]
Dissolved air flotation	+	–	–
Activated carbon	–	+	+
Ozonation[b]	–	+	+
Chlorination (free chlorine)[c]	–	+	–
Chloramination and chlorine dioxide	–	–	–
Preoxidation	–	–	–

+: 80% or more removal, although it depends on treatment conditions and types of cyanobacteria and toxins; –: not so effective.
[a] Depends on pore size of membranes. Nanofiltration is effective.
[b] Ozonation may release cyanotoxins and is not effective for saxitoxins.
[c] Chlorination may release cyanotoxins and is not effective for anatoxin-a.

Water abstraction at variable depths or sites

As concentrations of cyanobacteria can occur on the surface or at depth, variable abstraction depths may be useful for decreasing cyanobacterial cells and their toxins in the raw water for drinking-water production. Where scums tend to accumulate at a specific shoreline of the water body owing to a prevailing wind, choosing the off-take site away from this area can be useful. If cells accumulate at varying sites of a reservoir (e.g. in different bays, depending on the wind direction), it may also be useful to shift abstraction sites, if technically feasible.

Water abstraction through bank filtration or slow sand filtration

Slow sand filtration and riverbank filtration are effective not only for cyanobacterial cells, but also for extracellular cyanotoxins, geosmin and 2-methylisoborneol, as these undergo biodegradation during such processes. For slow sand filters, frequent scraping of surface layer or backwashing may be necessary if filter media clog rapidly due to the high load of organic matter. If sand filter clogging occurs frequently, it is effective to couple the sand with anthracite, whose diameter is larger than that of sand. Efficacy may be reduced if the water temperature is low or the filtration rate is high. These methods are not costly and are fairly easy to apply, even where resources are limited. Abstraction through riverbank filtration is possible where the underground is not rocky but consists of sufficiently permeable sediment.

Water treatment to remove cyanobacterial cells and intracellular cyanotoxins, geosmin and 2-methylisoborneol

Dissolved air flotation is effective particularly for light cells and species containing gas vesicles, which typically form surface scums. Waters of high colour and low turbidity are best suited for flotation processes.

Coagulation/sedimentation/filtration is effective to remove many species of cyanobacteria and cell-bound cyanotoxins, particularly microcystins, and taste- and odour-causing compounds, depending on pH, coagulant type and dose. It is ineffective in removing cyanotoxins that largely occur extracellularly and thus may be present even after the producing cyanobacteria have disappeared from the water body. Sediments (sludge) should be rapidly removed from the treatment system (e.g. from the clarifier) to avoid the release of cyanotoxins and taste- and odour-causing compounds. Backwashing should be done frequently to reduce the release of dissolved toxins to the filtered water. Post-coagulation (i.e. the addition of coagulants after sedimentation) is effective for some small and light cyanobacteria – such as *Synechococcus* spp. – that may be difficult to remove using normal coagulation/sedimentation and that increase the turbidity and colour of treated water. Preoxidation (chlorination or ozonation before coagulation/sedimentation/filtration) also increases the coagulation performance; however, it carries a risk of cyanobacterial cell disruption and release of cyanotoxins or taste- and odour-causing compounds. Validation of performance should include toxin analysis, particularly in situations where high cell densities reach the treatment system, and post-treatment for the removal of extracellular cyanotoxins and taste- and odour-causing compounds may need to be augmented with preoxidation. A further limitation to the application of preoxidation is that it can increase the production of disinfection by-products, particularly considering the high load of organic material introduced by a bloom.

Membrane filtration (microfiltration, ultrafiltration, nanofiltration and reverse osmosis) is effective for removing cyanobacterial cells. Its efficiency depends on the pore size of the membranes – usually less than 1 µm – and on the membrane materials. Frequent backwashing and removal of backwash water from the plant are recommended for avoiding the release of cyanotoxins and taste- and odour-causing compounds. Pretreatment of the raw water is also recommended to prevent fouling and optimize membrane performance.

Removal of extracellular (free) cyanotoxins

Powdered activated carbon and granular activated carbon are very effective, depending on the carbon dose, the type of carbon (wood-based powdered activated carbon for microcystin and cylindrospermopsin) and contact time (> 30 minutes recommended); however, they are expensive. Coupling peroxidation with activated carbon is an effective way to remove both cyanotoxins and their potential transformation products. Moreover, the carbon must be regenerated or replaced at routine intervals, often based on the breakthrough of total organic carbon; however, toxin breakthrough may occur before significant total organic carbon breakthrough is detected.

Chlorination can be effective against many cyanotoxins (with the exception of anatoxin-a) in water where the pH is not very high (< 8), the free chlorine concentration is sufficiently high (> 0.5 mg/L residual) and the contact time is sufficiently long (> 30 minutes). Chloramine and chlorine dioxide are not effective. Chlorination can be followed by activated carbon treatment to remove chlorination by-products (for further information, see Newcombe, 2012).

Preoxidation with other oxidants, such as potassium permanganate, can be effective against microcystins and anatoxin-a, but limited or no data are available for other cyanotoxins.

Ozonation may very effectively degrade cyanobacteria, depending on characteristics of the raw water, such as the concentration of natural organic matter and pH (> 7). Ozonation can be followed by activated carbon treatment to remove ozonation by-products.

Other options include advanced oxidation processes, ultraviolet irradiation with hydrogen peroxide, but only at impractically high doses or in the presence of a catalyst (e.g. titanium), and nanofiltration/reverse osmosis, which are effective, but generally expensive.

Removal of extracellular (free) geosmin and 2-methylisoborneol

Powered activated carbon and granular activated carbon are very effective, depending on the dose and type of activated carbon (wood, coal and coconut-based carbons) and contact time (> 30 minutes recommended); however, they are expensive. Geosmin can be more easily removed (adsorbed) than 2-methylisoborneol. Coupling of activated carbon with preoxidation may be effective to remove extracellular geosmin and 2-methylisoborneol.

Ozonation is very effective and best followed by activated carbon treatment to remove ozonation by-products. Compared with 2-methylisoborneol, geosmin is much more effectively oxidized by ozone; therefore, some utilities may consider the addition of hydrogen peroxide to increase the reaction kinetics in order to remove 2-methylisoborneol.

What are the important issues in treating drinking-water containing cyanobacteria?

Inhibition of coagulation

Some cyanobacteria, such as the genus *Microcystis*, produce coagulation inhibitor proteins, which cause a decrease in removal efficiencies of particulates and dissolved organic matter, such as disinfection by-product precursors, in the coagulation/sedimentation processes.

Filter clogging and breakthrough

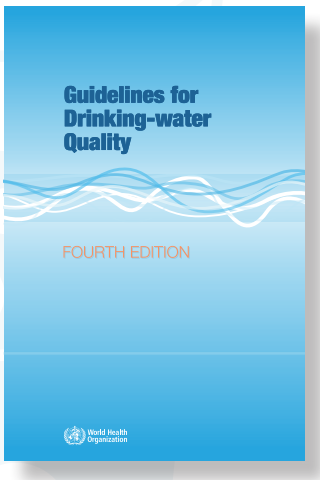
Larger-sized cyanobacteria can clog filters when present in high numbers, increasing the need for washing or exchanging filters and potentially leading to the release of cyanotoxins and taste- and odour-causing compounds from trapped cyanobacterial cells due to cell damage. Small cyanobacteria, such as *Synechococcus*, and filamentous cyanobacteria, such as *Aphanizomenon* and *Planktothrix*, may be poorly retained on filters and can visibly break through or increase turbidity and colour in treated water when present in high numbers.

Interference with disinfection

Disinfectant demand and disinfection by-product formation increase when cyanobacterial cells are present in high numbers.

Does the World Health Organization have guideline values for cyanotoxins, geosmin and 2-methylisoborneol?

The WHO *Guidelines for Drinking-water Quality* (WHO, 2011) provide the scientific point of departure for the establishment of national standards and regulations. The Guidelines include a provisional guideline value of 1 µg/L for total microcystin-LR (free plus cell-bound) – the most toxic compound in a large family of microcystins – in drinking-water. The guideline value is provisional, as it covers only microcystin-LR, the database is limited and new data on the toxicity of cyanobacterial toxins are being generated.



Other cyanotoxins are not included in the *Guidelines for Drinking-water Quality*, as data on their health effects are insufficient for a stringent toxicological derivation of a guideline value, although further research is being carried out. For other cyanotoxins, a number of countries have used default assumptions to derive and implement provisional maximum acceptable concentrations.

The *Guidelines for Drinking-water Quality* do not include guideline values for geosmin or 2-methylisoborneol, which are aesthetic concerns, not public health issues.

Overall conclusions

Management of cyanobacteria is most effective when focusing on bloom prevention through catchment and water source management as part of a water safety plan approach to managing risks to a water supply system. The adoption of the water safety plan approach includes establishing a cross-sectoral team to analyse the local situation, assessing the health risks and developing management plans. Water safety plans provide a valuable platform to facilitate communication between stakeholders in the catchment, which may be subject to different legislation (e.g. agriculture, wastewater, water management, health).

As part of a water safety plan, it is important to determine bloom potential or track bloom development through biomass determination and nutrient monitoring at regular intervals. If possible, cell counts and species identification may be necessary to determine the potential presence of cyanotoxins.

Preventive approaches may not always be effective in the short term, particularly where nutrient loads are high and where implementation of measures to reduce nutrient loads sufficiently for effective control of cyanobacterial biomass takes time. In such situations, treatment processes need to be optimized, taking into consideration the types of cyanobacteria, cyanotoxins and taste- and odour-causing compounds, as well as microbial, chemical and physical hazards in the water supply.

Combining monitoring techniques with toxin testing will assess the effectiveness of the barriers in place – from the catchment to the treatment plant outlet. Periodic testing for selected cyanotoxins (e.g. during a bloom and as it declines) is also valuable to verify whether there is a potential health concern during that event.

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