CYANOBACTERIA – THE PROBLEM OF THE MODERN WORLD

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Abstract

Cyanobacteria are a very expansive group of microorganisms, showing a number of adaptations, allowing them to live in various environmental conditions. Cyanobacteria are characterized by massive growth which manifests itself as water blooms. Blooms are stimulated by environmental factors, including high concentration of biogenic compounds, high water temperature. Blooming is a major threat because it has many negative consequences, including disturbance of the entire ecosystem and the production of toxins by cyanobacteria. Contact with cyanotoxins is extremely dangerous, both for humans and animals. Cyanotoxins can be divided according to the nature of their interaction. There are: neurotoxins, dermatotoxins, hepatotoxins and cytotoxins. Each of these groups has a different mechanism of action and causes different effects in the body. There are many possible routes of exposure to toxins. Toxins can also bioaccumulate leading to risk of consuming fish caught in bloomed water bodies. At the moment, there are no effective ways to combat water blooms or clean them of toxins. The aim of this study is to draw attention to the problem posed by mass blooms of cyanobacteria in water reservoirs.

Key words: cyanobacterial blooms, bioaccumulation, toxins.

General characteristics of cyanobacteria

Cyanobacteria are gram-negative prokaryotes with the ability to carry out the photosynthetic process. They form a very expansive group of microorganisms, occurring mainly in aquatic environments. The feature that offers a significant advantage to the growth of cyanobacterial cells, compared to other phytoplankton organisms, is the ability to perform photosynthesis at low concentrations of carbon dioxide and pH in the range of 7-9 (Błaszczyk et al. 2010). They also have a mechanism for fixing atmospheric nitrogen. Nitrogen fixation takes place in special cells called heterocytes; inside them molecular nitrogen is reduced to ammonia (Błaszczyk et al. 2010). This process takes place under anaerobic conditions with the participation of the enzyme nitrogenase. In addition, some species of cyanobacteria produce aerotopes, structures consisting of numerous cylindrical gas bubbles that allow vertical movement in the water column, thereby optimizing access to light and biogenic compounds (Błaszczyk et al. 2010). Cyanobacteria reproduce in a vegetative way, through cell division or disruption of a thread formed by a group of cells. Bloom-forming cyanobacteria are remarkably resistant to environmental extremes. This group of organisms manages to tolerate huge changes in salinity and temperature and their ability to survive low light intensity gives them an extremely large competitive advantage in numerous environments. Due to the formation of large aggregates, ranging from 0.2 mm to 5.0 mm, cyanobacteria cannot be eaten by zooplankton, which results in a lack of natural enemies (Błaszczyk et al. 2010).

Cyanobacterial blooms

Definition of cyanobacterial blooms

Cyanobacteria are characterized by rapid and massive growth, which is called bloom. Water blooms consist of massive phytoplankton growth, accompanied by a characteristic smell, strong turbidity and intense color of the water. Blooms are commonly observed worldwide in seas and oceans, lakes and other bodies of water. In temperate climates, they occur most frequently in the summer. Furthermore, recent studies have reported that global climate change can also favor hazardous cyanobacterial species, increasing their growth rate, dominance, persistence, geographical distribution, and activity. Among the species that create blooms, we can distinguish unicellular and colony forms of picoplankton, nanoplankton and microplankton. On the basis of such features as: size, shape, and method of cell division, we distinguish five orders: *Chroococcales, Pleurocapsales, Oscillatoriales ,Nostocales, Stigonematales* with main representatives listed in Table 1.

Table 1. Examples of bloom-forming cyanobacteria.

Order	Representative of the species
Chroococcales	*Microcystis aeruginosa,* *Microcystis flos-aquae,*
Oscillatoriales	*Planktothrix agardhii,* *Planktothrix rubenscens*
Nostocales	*Nodularia spumigena,* *Dolichospermum lemmermannii*

Causes of cyanobacterial blooms

The massive growth of cyanobacteria is influenced by environmental factors, such as high nutrient content, low nitrogen to phosphorus ratio, water temperature exceeding 20 °C, intense sunlight, no wind (Rzymski 2009, Sierosławska et al. 2012). The rate of multiplication is most strongly related to the temperature and length of the day. Increasing the content of biogenic compounds in the water with a longer period of warm, sunny weather contributes to the appearance of blooms (Błaszczyk et al. 2010). High concentrations of biogenic compounds in water have an anthropogenic source. Cultural eutrophication from domestic, industrial, and agricultural wastes as well as global climate change can play a major role in the global expansion of harmful algal blooms. Most often we are dealing here with irrational agriculture, too intensive fertilization of farmland (Rastogi et al. 2015). The water eutrophication process is also influenced by soil water erosion and the increasing emission of nitrogen oxides to the atmosphere and their increased content in rainfall. The growth and composition of blooms is also influenced by xenobiotics entering the environment, e.g. heavy metals, antibiotics and other synthetic growth regulators (Rzymski 2009).

Blooms can be divided into two types: appearing on the surface and those that occur in the deeper layers of the water column (Błaszczyk et al. 2010). Surface blooms are most often formed by the species *Microcystis spp., Dolichospermum spp., Nodularia spumigena,* while the deep-sea blooms are *Planktothrix rubenscens* and *Limnothrix redeckei* (Błaszczyk et al. 2010). Cyanobacterial blooms cause many adverse effects, including changes in the abiotic conditions in reservoirs, e.g. a decrease in the concentration of oxygen dissolved in water, a change in pH, water turbidity. This causes changes in the structure of aquatic ecosystems, the structure of the food chain, and loss of biodiversity (Sierosławska et al. 2012). There is a change in the biomass and species composition of zooplankton, which is food for pelagic fish, including herring and sprat (Pastuszak et al. 2015). Areas inhabited by zoobenthos, which are a very important part of the diet of cod, are being reduced. This leads to a reduction in the cod breeding areas. Massive development of cyanobacteria reduces the transmittance of sunlight, which deteriorates the light conditions of deeper water layers and leads to the disappearance of vegetation from the coastal zone. As a result, the plant composition of the reservoir changes (Pastuszak et al. 2015).

Cyanobacteria vs human and animal health

Cyanobacteria can interact directly with the organisms found in blooming water bodies by producing and releasing toxins (Sierosławska et al.2012). Due to the nature of the impact, toxins can be divided into four groups: neurotoxins, hepatotoxins, dermatotoxins and cytotoxins. Examples of illnesses caused by cyanobacterial toxins are presented in Table 2. Neurotoxins damage the central and peripheral nervous systems and they are the most toxic compounds produced by cyanobacteria. They interfere with the neuromuscular system, causing paralysis of respiratory muscles, and death by respiratory failure in rats after only a few minutes. Hepatotoxins impair activity of hepatocytes, leading to extensive liver injury. Dermatotoxins cause irritation and damage to the skin and mucous membranes. Cytotoxins disrupt the course of metabolic processes in cells, which leads to disturbances in a whole range of biochemical pathways (Adamski et al. 2016). Toxins most often find their way into the water during the lysis of cyanobacterial cells, which in the case of intensive blooms can cause high concentrations of them when mass cell death occurs (Adamski et al. 2016). It can happen that we do not see the characteristic features of the bloom in the water, such as changed color, smell, but toxins are present in it anyway. Due to the fact that the toxins are odorless and colorless, it is not possible to observe them directly (Zanchett and Oliviera-Filho 2013).

Table 2. Reports of animal illnesses and deaths that serve as sentinel events for cyanobacteria-associated human health risk between 1989 and 2010. Based on Hilborn and Beasley 2015.

Location	Year	Cyanobacteria	Toxin	Animal illness	Human illness
Lake Rutland Water in Leicestershire, United Kingdom	1989	*Microcystis aeruginosa*	Microcystin	Dog and sheep deaths	Gastroenteritis, dermatitis among those who recreated in water
Zeekoevlei Lake, South Africa	1994	*Nodularia spumigena* and *Microcystis aeruginosa*	Microcystin Nodularin	Dog and livestock deaths	None reported
Pond in Mymensingh, Bangladesh	2002	*Anabaena flos-aquae* and *Microcystis aeruginosa*	Unknown	Fish and goat deaths	Rash, eye and ear irritation
River Meuse, Venlo Municipality, Netherlands	2003	Unspecified cyanobacteria	Unknown	Fish and bird deaths	Rash
Buccaneer Bay Lake, Eastern Nebraska, United States	2004	*Anabaena, Microcystis, Oscillatoria*	Microcystin	Dog, livestock, wildlife deaths	More than 50 reports of rash, skin lesions, headache and/or gastroenteritis
Lakes, Ohio, United States	2010	*Anabaena, Aphanizomeno, Planktolyngbya limnetica*	Microcystin Anatoxin-a	Dog, fish deaths, bird illness	Multiple effects including dermatologic, respiratory, neurologic illness and/or gastroenteritis

Toxins of cyanobacteria

In the Baltic Sea, the toxin producing species are *Nodularia spumigena, Dolichospermum lemmermannii,* and *Dolichospermum flos-aquae.* Species of the genus *Dolichospermum* are massively present in the Gulf of Gdańsk, they produce microcystins. *Nodularia spumigena* is responsible for the production of nodularins. Both nodularins and microcystins are hepatotoxins (Trevino-Garrison et al. 2015). Microcystins and nodularins are very similar in structure and biological activity and are among the most commonly synthesized cyanobacterial toxins (Błaszczyk et al. 2010). Their toxic effects result from the strong binding of serine-threonine phosphotases in the cytosol of liver cells. This reaction inhibits the activity of phosphatases, leading to hyperphosphorylation of proteins, including intermediate filaments and microfilaments, and damage to the cytoskeleton of liver cells (Błaszczyk et al. 2010, Rzymski 2009). Moreover, microcystins and nodularins induce apoptosis and necrosis of hepatocytes, they can also be promoters of cancerous tumors (Błaszczyk et al. 2010). The characteristic symptoms of poisoning are: fever, vomiting, diarrhea, while skin exposure causes symptoms of irritation, rash or dermatitis (Rzymski 2009). Both microcystins and nodularins bioaccumulate in the food chain. Microcystins have been found in the tissues of zooplankton crustaceans, snails, crab larvae, clams and fish. Nodularins are detected in the tissues of animals intended for consumption, e.g. clams, shrimps, flounder, cod. It has also been found that cooking does not break down these toxins (Rzymski 2009). Another toxin produced by species of the genus *Dolichospermum* is anatoxin-a. In Poland, the presence of this toxin during blooms was detected in the water of the Gulf of Gdańsk (Sierosławska et al.2012). It is a neurotoxin. The main toxic effect is disturbance of the transmission of nerve impulses (Sierosławska et al. 2012). This is caused by the binding of the anatoxin-a to the nicotinic receptor, to which it has a greater affinity than acetylcholine. This leads to the opening of ion channels and depolarization of the muscle cell membrane. Acetylcholinesterase does not break down toxins, so there is a constant depolarization of the neuromuscular synapse, causing contractions (Rzymski 2009). A characteristic symptom of anatoxin-a poisoning is salivation (Błaszczyk et al. 2010). The toxin was originally called "the factor causing rapid death", because of the very vigorous effects after intraperitoneal administration of toxic cyanobacterial cells or filtrates from their cultures to mice (Sierosławska et al. 2012). Contact with the toxin caused seizures and paralysis, followed by death within minutes (Sierosławska et al. 2012).

Cyanobacteria of the genus *Dolichospermum* also produce lipopolysaccharides (LPS) classified as endotoxins, which are a component of the cell wall and occur in all cyanobacteria (Błaszczyk et al. 2010). Lipopolysaccharides are dermatotoxins and irritants (Rzymski 2009). Contact with LPS in humans and animals may cause septic shock. Other symptoms are: fever, chills, cough, sore throat (Błaszczyk et al. 2010). Moreover, LPS may cause skin and eye irritation (Rzymski 2009).

Routes of exposure to toxins

The most important route of exposure of humans and animals to cyanobacterial toxins is through water intake (Sierosławska et al. 2012). Domestic and wild animals are endangered due to drinking water directly from blooming reservoirs and numerous cases of fatal poisoning of cattle, dogs and horses have been reported (Błaszczyk et al. 2010). In recreational reservoirs, where massive water blooms occur, there is a risk of accidental ingestion of cyanotoxin water, as well as of the cells themselves, which may contain much higher concentrations of toxins than water (Zanchett and Oliviera-Filho 2013, Sierosławska et al. 2012). There is also the possibility of intoxication by inhalation with aerosols containing cyanotoxins while swimming or practicing other water sports (Sierosławska et al. 2012, Błaszczyk et al. 2006). Another route of exposure is skin contact with contaminated water, causing skin irritation and allergies. Consuming fish and aquatic invertebrates such as clams, snails and shrimp, caught in ecosystems susceptible to cyanobacterial blooms, can also be hazardous to health (Rzymski 2009).

Bioaccumulation of toxins

Invertebrates are less susceptible to the effects of cyanotoxins, but have the ability to accumulate them in their tissues (Rzymski 2009). The literature shows the phenomenon of accumulation of microcystins and nodularins in zooplankton and benthic organisms, as well as in muscles and organs of fish (Błaszczyk et al. 2010). The accumulation of hepatotoxins in zooplankton organisms indicates that they constitute an important link in the transport of these compounds to higher levels of the food chain (Błaszczyk et al. 2010). Studies confirm the increased rate of toxin accumulation during the increase in cyanobacteria. In the case of fish, the source of cyanotoxin contamination may be their food, i.e. mollusks, smaller fish. The highest concentrations of microcystins and nodularins were detected in the liver, the organ which is the main site of hepatotoxin action. Nodularin has been identified in samples of many different Baltic fish, including: salmon, herring, stickleback, cod. The presence of hepatotoxins in the muscles of bream, zander and roach caught from the Gulf of Gdańsk has been demonstrated (Błaszczyk et al. 2010). Microcystins can also accumulate in other parts of the fish's body: gills, kidneys, gonads and the digestive tract. Some of the toxins have even been detected in the silver crucian brain, suggesting the ability to cross the blood-brain barrier. Drinking water is considered to be the main source of danger cyanobacterial toxin poisoning for humans. However, bearing in mind the increasing number of studies proving the high levels of cyanotoxins in fish, shrimp and other edible aquatic organisms, we can conclude that this is another, no less important source of risk (Błaszczyk et al. 2010).

Environmental factors of toxin synthesis

An important aspect to pay attention to is what the synthesis of toxins is dependent on. The production of cyanobacterial toxins is regulated by environmental factors. Studies have shown that the cultivation of cyanobacteria under conditions of elevated temperature promoted an increase in the amount of produced toxins, even under conditions of nutrient limitation. Cyanobacteria that produce toxins, not only withstand various stressors in the environment, but also increase the level of toxin production in response to them. It has also been found that toxins play a role in the growth rate of cyanobacterial cells (Boopathi and Ki 2014).

Conclusions

Cyanobacterial toxins pose a real threat to human health, moreover, this threat manifests itself on many levels. For this reason, it is necessary to constantly control aquatic ecosystems for the occurrence of blooms. The blooms should be investigated, the species of cyanobacteria that compose them should be observed and the level of cyanotoxins monitored. Strategies based on physical, chemical and biological manipulation can reduce the amount of harmful cyanobacteria. However, these strategies are largely confined to relatively small ecosystems and some of them can cause ecological and environmental damage, including disturbances of plankton and benthic populations and fish habitats. Due to the lack of an effective and side-effect free method enabling the removal of cyanobacteria from water reservoirs, research should be conducted towards the development of such a method. Endangered ecosystems should be strictly excluded from recreational use and fishing for aquatic organisms. Bathing in reservoirs exposed to cyanobacterial blooms should be strictly avoided. Reclamation of degraded water reservoirs, where conditions may favor the formation of cyanobacterial blooms, is also very important. Efforts should be made to eliminate the causes of this degradation by introducing changes to the irrational agricultural economy, which is mainly responsible for the excessive introduction of nitrogen and phosphorus compounds into the waters. The ecological state of the Baltic Sea also depends on the ecological state of the natural environment in the river basins that constitute the sea basin. For this reason, the protection of the Baltic Sea must be closely related to the protection of inland waters, which in turn requires the reduction of nitrogen and phosphorus compounds pollution in the river basins. Research into cyanobacterial toxins and the role of environmental factors in their production must be continued to fully understand their environmental impact. Much field research is still needed to tackle the problem of cyanobacteria in the Baltic Sea and other bodies of water.

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