Beneath the Surface: Exploring the Impact of Cyanobacterial Harmful Algal Blooms on Aquatic Ecosystems, Fish Nutritional Composition, and Human Health

Olivia Cheung
Cornell University

Cyanobacteria are photosynthetic prokaryotes that form part of the base of aquatic food webs. They are often referred to as blue-green algae, and when they grow on the water's surface they may resemble scum (EPA, 2023). As primary producers, they convert sunlight and carbon dioxide into carbohydrates, lipids, and protein that are vital nutritional components for aquatic animals. Primary consumers (also known as grazers or herbivores) pass these nutrients onward to upper trophic levels, where they may ultimately reach mammals including humans (Jónasdóttir et al., 2019). However, cyanobacteria also produce microcystin toxins that pose dangerous health effects for organisms throughout the aquatic ecosystem as well as those that depend on lake insects or fish as their food source.

Cyanobacterial harmful algal blooms (cyanoHABs) result from the excessive growth of cyanobacteria. A cyanoHAB can damage ecosystems and potentially produce toxins (NIEHS, 2023). In recent years, the incidence of cyanoHABs has surged due to global environmental changes, reflecting an escalation in their intensity, frequency, duration, and geographic range (Gobler et al., 2017). In 2019, an Intergovernmental Panel on Climate Change (IPCC) report confirmed that "Harmful algal blooms display range expansion and increased frequency in coastal areas since the 1980s in response to both climatic and non-climatic drivers such as increased riverine nutrients run-off." It also stated that "harmful algal blooms have had negative impacts on food security, tourism, local economy, and human health" (IPCC, 2019).

Nutrient loading and warming from anthropogenic activity and climate change are the main drivers of cyanoHABs (O'Neil et al., 2012). Nutrient runoff from agricultural, industrial, and sewage waste raises the concentrations of phosphorus and nitrogen which promote algal blooms (Kaebernick and Neilan, 2001). Changing weather patterns and increasing frequency and intensity of storms also affect the flow of nutrients into bodies of water (Coffey et al., 2018). Dense layers of cyanoHABs on the water's surface prevent sunlight from reaching algae below, thereby reducing oxygen production. At the same time, dying algae depletes deep-water oxygen and clogs fish gills, sometimes leading to stress or even mass mortality of fish and other animals (NIEHS, 2023). **In the face of increasing global environmental change, understanding the consequences of cyanoHABs on aquatic ecosystems, fish nutritional composition, and human health remains a critical pursuit.**

Impact of Microcystins and cyanoHABs on Aquatic Ecosystems

Numerous reports detail microcystin-related fatalities across many types of animals including wild, domestic, terrestrial, and aquatic (Rastogi et al., 2014). A study in 2010 found connections between the death of over 20 sea otters and microcystin intoxication that accumulated in shellfish, the sea otters' main food source (Miller et al., 2010). For fish, microcystins have been found to affect the development and organ function of young fish and accumulate in the liver and muscle of juveniles and adults (Malbrouck and Kestemont, 2006). The vast literature on the harmful effects of microcystins at all levels of the aquatic ecosystem confirms the need to mitigate the increasing presence of cyanoHABs that threaten food systems and have implications for human nutrition since humans depend on fish as a major food source.

Fish Nutritional Composition and Toxins

Fish are a primary source of essential nutrients such as fatty acids, proteins, and vitamins for human communities across the globe. In West African countries such as Senegal and Ghana and in Asian countries such as Cambodia and Bangladesh, fish account for over 50 percent of people's average per capita intake of animal protein (FAO, 2014). In fishing communities in particular, fish are the primary source of these vital nutrients. Notably, fish are a unique protein source due to their rich nutrient content. Essential n-3 polyunsaturated fatty acids (n-3 PUFAs) including eicosapentaenoic (EPA) and docosahexaenoic acids (DHA) are prevalent in fish (Brenna et al., 2014). DHA is important for an infant's eye, brain, immune, metabolic, and autonomic nervous system development (Lauritzen et al., 2002). Fish eaten by mothers has been associated with high concentrations of long-chain PUFAs in breast milk, which is the main way infants receive fatty acids (Lauritzen et al., 2002). A study in Lake Victoria, Kenya found that the fatty acid content of breast milk was influenced by the species of fish consumed indicating that access to affordable fish plays a major role in breast-milk fatty acid concentrations (Fiorella et al., 2018). Consuming PUFAs from small servings of fish is associated with lowering congenital heart disease mortality risk by 17% (König et al., 2005). Fish are also important sources of nutrients such as calcium, iron, selenium, zinc, vitamin A, and proteins which are essential for human physiological function (Hicks et al., 2019). Since fish consumption covers approximately 20% of the average protein intake for around 30% of the world population, fish significantly contribute to human nutrition, food security, and poverty alleviation (Nong et al., 2021).

Although there are many nutritional benefits from fish consumption, there is also the risk of exposure to harmful metals and toxins that fish accumulate from the surrounding environment. Metals are naturally found in ecosystems, but pollution and industrial activity have increased the presence of contaminants in toxic concentrations. Not all metals are dangerous to fish and humans, and toxicity can depend on concentration. Elements such as iron (Fe), copper (Cu), zinc (Zn), and selenium (Se) are essential elements necessary for body metabolism. However, some essential elements like Se can become toxic when consumed in higher concentrations. Toxic elements including chromium (Cr), nickel (Ni), cadmium (Cd), mercury (Hg), and lead (Pb) are always harmful, and mainly come from pollution (Bosch et al., 2015). Metals have been found to accumulate at different rates and concentrations depending on fish species and size (Canli et al., 2003). The presence of trace metals from anthropogenic activity stimulates cyanoHAB growth and heightens the risk of metals accumulating at dangerous concentrations in organisms (Facey et al., 2019).

The effects of the toxic mercury and microcystins have been studied in the context of fish consumption. Mercury (Hg) is a heavy metal neurotoxin that is naturally found in rock from the Earth's crust. In aquatic environments, the main form of Hg is methylmercury (MeHg), which is of great concern because it accumulates up the food web. The increase in industrial Hg pollution from 1950 to 1970 by atmospheric emissions and chemical spills led to an increased incidence of mercury poisoning from seafood consumption around the world (US Environmental Protection Agency, 1997). Exposure to methylmercury is associated with human death and neurological disease as it is absorbed into the bloodstream and spread to tissue and organs (US Environmental Protection Agency, 1997). While there are fish consumption guidelines to limit Hg exposure, nutritional benefits such as fatty acids might offset the negative effects depending on the concentrations of each. Scientists are still determining the best method to analyze the complex relationship between beneficial and harmful nutritional traits to inform the fish consumption guidelines. For example, a risk-benefit assessment was performed on farmed fish from the eutrophic Wujiangdu Reservoir (Jing et al., 2021). They found that the n-3 PUFA benefits outweighed the negative effects of MeHg. However, microcystin levels in the fish samples indicated a high risk from that different toxin pathway (Jing et al., 2021). Monitoring of all nutritional traits at a species-specific level is crucial for determining consumer safety guidelines. Instead of restricting all fish consumption, the United States Food and Drug Administration recommends eating certain species of seafood based on their Hg levels. Swordfish and king mackerel at a high trophic level have larger Hg concentrations and should be eaten in small quantities (FDA, 2023). Further research on the nutritional-toxicological conflict at an individual species level is necessary, particularly now with increasing microcystins from cyanoHABs.

As previously discussed, fish living in areas at risk for cyanoHABs can accumulate microcystins. In the U.S., a study on fish in Lake Erie found that microcystins are present in fish livers after cyanoHAB events which pose a threat to fish health but were not present in concentrations that pose a risk to human health (Shahmohamadloo et al., 2023). However, as cyanoHABs recur, increase in severity, and continue to affect fish, the risk to humans must be studied. Global environmental changes will not only magnify the risk of contaminants and toxins in fish but also may impact their nutritional benefits with significant downstream effects on human health. At the base of the food web, phytoplankton produce nutritious polyunsaturated fatty acids (PUFAs) that are transferred to larger organisms. Cyanobacteria have been found to produce less PUFAs compared to other phytoplankton species, so their quality as food for herbivores may be lower, with consequences for the rest of the food web, including humans (Jónasdóttir et al., 2019). When creating fish consumption guidelines, it is necessary to create joint advisories that account for both the negative impact of cyanoHABs and the positive nutritional benefits, variation among species, and the balance between the two. Comprehensive research is required to ascertain how global environmental changes influence fish nutritional composition and its subsequent implications for human health. The Cornell faculty who I work with are striving to fill this major knowledge gap for the largest lake fishery in the world: Lake Victoria in East Africa.

Impact of Microcystins and cyanoHABs on Human Health

Harmful algal blooms are a risk to human health due to their production of microcystins. Understanding how cyanobacterial blooms and toxins impact the food web and human consumption of water and fish is important. Microcystins belong to the genus *Microcystis* and are cyclic peptides that damage the liver of organisms and are thus classified as hepatotoxins. There are over 100 types of known microcystins with the same general structure but different amino acid compositions (Puddick et al., 2015). At a cellular level, microcystins can inhibit enzyme activity, disrupt the structure and function of the cytoskeleton, and damage cells and DNA which increases the risk of cancer and apoptosis (Rastogi et al., 2014).

There have been *Microcystis* blooms on every continent along with reports of their toxic effects (Rastogi et al., 2014). CyanoHABs are most common in tropical and subtropical areas (Rastogi et al., 2014). Global warming and eutrophication may intensify cyanobacteria growth, and thereby stimulate higher levels of hepatotoxin production (El-Shehawy et al., 2012). The bioaccumulation of microcystins in water sources and the organisms that live there also pose a threat to human and ecosystem health. Bioaccumulation starts at the bottom of the food chain when organisms that feed on cyanobacteria or have contact with or drink contaminated water ingest the microcystins (Rastogi et al., 2014). Toxins may accumulate in fish if they feed on phytoplankton, take in toxins through their gills or skin, or ingest filter feeders (such as zooplankton) that are heavily exposed to cyanobacteria through their feeding mechanism (Ibelings et al., 2007).

Humans may be exposed to toxins by three different pathways: contaminated drinking water, eating contaminated fish, or direct contact with water or inhalation of aerosol particles. Microcystins from eating fish are dispersed in the body through the bile acid transport system, which absorbs the toxins into bile and spreads them to the brain, gastrointestinal tract, and kidney (Eriksson et al. 1990; Fischer et al. 2005). Ingesting water contaminated with microcystins has been associated with liver failure, nausea, vomiting, diarrhea, and risk for liver and colorectal cancer in humans (Pouria et al., 1998). In 1996, a hemodialysis center in Brazil used water from a reservoir with cyanobacterial blooms causing 89% of patients to experience these symptoms, 100 patients to develop acute liver failure, and 52 deaths (Azevedo et al., 2002). Scientists concluded that intravenous contact with microcystins contributed to the symptoms and death (Azevedo et al., 2002). Microcystin exposure can also cause eye, ear, and skin irritation and allergies (Codd et al., 2005).

Harmful Algal Blooms in Lake Victoria, Kenya

Africa’s Lake Victoria is the second-largest freshwater lake in the world and is bordered by Kenya, Uganda, and Tanzania. Lake Victoria can serve as a model to study the nutritional impact of cyanoHABs on the ecosystem and human health. Over 42 million people depend on the lake for water and food. CyanoHABs are increasingly prevalent throughout the lake with detrimental effects on food and water sources and the local economy. Lake Victoria is also the largest lake fishery in the world and is home to many small-scale fishing communities (Roegner et al., 2023). The fishing industry provides jobs and income for the riparian communities that rely on fish for sources of protein, fatty acids, and other essential nutrients. However, fishing communities are often food insecure with limited alternatives for nutritious food making them most vulnerable to environmental change such as cyanoHABs. In tropical regions like Lake Victoria, freshwater cyanoHABs occur year-round and for longer periods than in temperate regions (Mowe et al. 2015). Historically, cyanoHABs in Lake Victoria occurred during the long dry season from December to March (Roegner et al., 2023). With rising temperatures and excess nutrients from industrial waste, sewage, and agricultural runoff, cyanoHABs now persist year-round in some sheltered bays (Roegner et al., 2023).

Lake Victoria's fish are a main source of food and nutrition but also a main microcystin exposure pathway. There are a growing number of studies on microcystin bioaccumulation in food fish from tropical freshwaters (Zewde et al., 2018; Zamora-Barrios et al., 2019). Three species of fish are commonly found in Lake Victoria's commercial fish markets: Nile perch, tilapia, and dagaa (*R. argentea*). Dagaa, a small pelagic fish, is an affordable protein source for food-insecure and low-income communities (Matsuishi et al., 2006). A study in Kisumu Bay found microcystins in dagaa tissue which is a potential health concern due to their high consumption (Simiyu et al., 2018). A 2023 study found that fishers in Kisumu Bay and Homa Bay noted negative effects of cyanoHABs including a decline in fish catch or profit, worsening water quality, and their ability to sustain their livelihoods. In those locations, microcystin concentrations found in fish and water also surpassed World Health Organization (WHO) intake guidelines (Roegner et al., 2023). Toxins from cyanoHABs threaten fishing communities already facing high rates of poverty, food insecurity, and health issues including HIV/AIDS, malaria, and cholera (Omwega et al. 2006). Since fish are the most nutritious food source available, it is important to understand how environmental change will impact their nutritional value. However, the spatiotemporal variability in the distribution of microcystins poses a challenge for monitoring food and water sources (Roegner et al., 2023). Further research on microcystin production in tropical freshwater lakes is required to address human health risks.

Future Directions

To gain deeper insights into global environmental change, further research is needed to elucidate the effects of harmful algal blooms on fish nutritional value, ecosystem health, and the public perception and use of natural resources. Quantitative analysis of microcystins as well as fatty acids, protein, and other nutrients in fish tissue will provide insight into how cyanoHABs impact the essential nutritional traits of fish. Analyzing fish samples from varying trophic levels, commonly consumed species, and tropical freshwater environments will provide a comprehensive understanding of microcystin accumulation across the food web, addressing current knowledge gaps. In addition, studying cyanoHAB dynamics over space and time will provide more information on how ecosystems respond to the blooms. Lastly, analyzing community perceptions and concerns of the blooms could help inform research and policy and could help build an understanding of the history and pattern of blooms.

Heightened public awareness and education on cyanoHABs and associated health risks are pivotal to guiding appropriate behavioral responses. CyanoHABs provide a model of how environmental change affects human perceptions of natural resources and informs consumer behavior. As ecosystems evolve and knowledge changes, effective dissemination of scientific findings and policy to the public will be increasingly vital. CyanoHABs challenge conventional single-stressor approaches to communicating environmental risks to the public, so I am excited to be contributing to an international research project that is addressing that challenge in a nation where so many people depend heavily on the lake and its fish.

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