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Impacts of Harmful Algal Blooms (HABs) on Agriculture: A Short Communication

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Abstract. Sustainable agriculture, which requires clean water, healthy soil, and adequate nutrients, is crucial to meet the growing demand for food and fiber. Over application of nutrients to meet demand has degraded surface water quality, leading to accelerated eutrophication. Cultural eutrophication is a process by which aquatic ecosystems such as ponds, lakes, and estuaries become so enriched with nutrients—primarily nitrogen and phosphorus—as to become unusable for safe consumption and ecological purposes. Eutrophication has intensified due to climate change. Increased temperatures, intense storms, and drought can drive the formation of eutrophic and hypereutrophic conditions. Hypereutrophication results in the rapid proliferation of algae and phytoplankton, resulting in algal blooms. Harmful algal blooms (HABs), including the proliferation of cyanobacteria, which can produce cyanotoxins such as microcystins and cylindrospermopsin, can also grow in hypereutrophic conditions. These toxins can detrimentally impact humans, wildlife, and agricultural systems (e.g., fish, livestock, and crops). Fish that ingest algal toxins may suffer from liver damage and oxidative stress, with varying effects depending on the type of fish, the amount of exposure, and the duration of exposure to toxins. Additionally, a few studies report livestock death after drinking water contaminated with byproducts of HABs such as microcystin, nodularin, cylindrospermopsin, anatoxin-a, guanitoxin, and saxitoxin. The available research on the effects of microcystin on crops, vegetables, and fruits consistently demonstrates their negative impact. This short communication article summarizes the literature published between 2012 and 2022 documenting the impact of microcystins on agricultural commodities, particularly livestock and various crops. Although awareness has increased, few publications have discussed microcystin-related livestock deaths in recent years. However, numerous global studies have highlighted the harmful effects of microcystins on crops, fruits, and vegetables. The researchers suggest that in cases where the levels of microcystin exceed the standards established by the World Health Organization, careful monitoring is needed. Human exposure to microcystin may occur through the consumption of livestock, crops, and vegetables contaminated by microcystins through drinking or irrigation. More research is needed to understand the fate and transport mechanisms of microcystins in various agricultural settings, including controlled, simulated, and field experiments.

INTRODUCTION

Excessive nutrients (e.g., nitrogen and phosphorus) (Melaram et al. 2022; Withers et al. 2014; Rabalais et al. 2009) and environmental factors like light and temperature regulate eutrophication in aquatic ecosystems, sometimes leading to the proliferation of algae and aquatic vegetation. Eutrophication frequency, magnitude, and duration have increased globally due to intensive agriculture, urbanization, and climate change (Brooks et al. 2016). While algae and vegetation provide ecological value, excessive growth can harm water quality, leading to decreased dissolved oxygen, taste and odor problems, reduced recreational value, and harmful algal blooms (HABs).

HABs, also called cyanobacterial blooms, typically occur in eutrophic waters, and are caused by multiple cyanobacterial species. Most notable is *Microcystis*, a genus of cyanobacteria (formerly referred to as blue-green algae) capable of producing cyanotoxins. Cyanotoxins are biologically active secondary metabolites that could be fatal to humans, livestock, domesticated animals, and wildlife. Four major cyanotoxins are microcystin (the most widely studied), nodularin, saxitoxin, and cylindrospermopsin (Butler et al. 2009). Toxicologists classify cyanotoxins into four major classes: neurotoxins, hepatotoxins, cytotoxins, and dermatoxins (Pearson et al. 2010). Neurotoxins damage the nervous system, hepatotoxins harm the liver, cytotoxins impact cellular functions, and dermatoxins affect the skin. Nodularin is a potent hepatotoxin to humans, livestock, domesticated animals, and wildlife; saxitoxins are a neurotoxin usually consumed by humans via contaminated shellfish (Pearson et al. 2010). Cylindrospermopsin is hepatotoxic and neurotoxic by nature and can impact the health of mammals by damaging the kidney, liver, and heart.

The presence of a *Microcystis* bloom does not necessarily indicate microcystin production or an exposure concentration dangerous to human health, livestock, domesticated animals, wildlife, or crops (Redouane et al. 2019). Cyanobacterial cells do not continuously secrete microcystin (Malik et al. 2020); instead, environmental conditions must be optimal to trigger the release of microcystins. Toxin production is thought to be a function of nutrients, ambient temperature, light quality, and pH (Neilan et al. 2013; Song et al. 1998; Lukac and Aegerter 1993; Sivonen 1990). However, research on conditions that induce toxin production remains inconclusive. Researchers are unsure of the conditions that consistently induce microcystin release during cyanobacterial blooms, as the environmental and physicochemical factors that influence a cyanobacteria bloom are interrelated (Neilan et al. 2013; Oh et al. 2000; Rastogi et al. 2014).

Multiple studies have assessed the impacts of microcystins, as a byproduct of HABs, on human health. Still, very little information is available on their impact on agriculture, particularly livestock and crops. This short communication provides an overview of the impacts of microcystins on agriculture by synthesizing literature from the past ten years. This short review is of interest to research, engineering, and farming communities.

METHODS

To assess the impact of microcystins on agriculture, an exhaustive literature search was conducted via Google Scholar using relevant terms. Single keywords or a combination of keywords, such as microcystins, agriculture, crop, and livestock, were used during the search. Articles published before 2012 were not included in the analysis. Once the search was completed, the articles were sorted into two categories of agriculture based on the affected target: 1) cattle and livestock or 2) crops and vegetables. Each article was reviewed to comprehend the goal(s), the geographical location, and the findings of each study. In conclusion, the outcomes of the review were summarized, and their relevance for South Carolina (SC) was evaluated.

RESULTS AND DISCUSSION

Toxins, in general, are hazardous to living and agricultural systems. Livestock may be exposed to microcystins through drinking water, such as ponds containing microcystins. Similarly, microcystins typically enter plants through irrigation water or soil contaminated with microcystins. While microcystin contamination of surface waters (e.g., irrigation reservoirs and livestock ponds) is straightforward, groundwater pollution from microcystin occurs through accumulation of microcystins in soil. Through the movement of soil moisture, the toxin moves through the vadose zone and reaches the groundwater zone (Melaram et al. 2022). Other possible sources of microcystins could be the applications of cyanobacterial fertilizer in conjunction with manure applied for plant growth (Corbel 2014; Melaram et al. 2022). Table 1 summarizes information on each of the articles reviewed.

IMPACTS ON LIVESTOCK

Negative impacts of HABs on animal health have been recorded over decades (Hilborn and Beasley 2015); however, in recent years, the impact on livestock has been less documented, whether due to lack of farmer willingness to report such an event, absence of understanding of HAB impact on livestock, or the lack of affordable detection technologies for microcystin. Microcystins can enter the body through various routes, such as dermal contact, oral exposure, ingestion, etc. Cattle can show symptoms such as coughing, throat irritation, and nasal exudates.

Menezes et al. (2019) discussed the likely impacts of *Microcystis* on a herd of cows in the South of Portugal. The study reported that 20 of 54 Angus × Charolais crossbred cows died within 19 hours of exposure to stagnant water. Five additional cows displayed symptoms of illness (e.g., diarrhea) and died later, while 29 stayed healthy. After necropsy, the clinical and pathological analysis indicated hepatic and renal necrosis. Various cyanobacterial species, mainly *Microcystis,* were identified in the water sample, and microcystin-LR was detected in the kidney of one necropsied animal.

Dreher et al. (2019) documented an incident in Oregon where 32 steers died in June 2017 after consuming water from Junipers Reservoir contaminated with microcystins. Blood samples were collected from the cattle for pathological analysis. Water samples were collected from the reservoir for toxin analysis. Results indicated that the deaths were likely the result of acute liver poisoning by microcystin. The presence of microcystin in nearby waterbodies further reinforced the likely cause of death. A study was conducted by Badar et al. (2017) to understand the impact of microcystins in drinking water on animals' health. Water samples were collected from groundwater, canal water, and storage tanks; blood samples were collected from cows and buffa-

Table 1. Overview of the articles reviewed for the current objectives.

	Authors, Year	Location of the study	Species of interest
Cattle and Livestock	Badar et al. 2017	Unknown	Cows and Buffalos
	Menezes et al. 2019	Almodôvar, Portugal	Cows
	Dreher et al. 2019	Oregon, USA	Steers
Crops and Vegetables	Liang et al. 2016	Taihu Lake, China	Rice
	Liang and Liu 2020	Taihu Lake, China	Rice
	Liang et al. 2021	Taihu Lake, China	Rice
	Gu and Liang 2020	Taihu Lake, China	Rice, Cucumber
	Wijewickrama and Manage 2019	North Central Province, Sri Lanka	Rice, Leafy green vegetable
	Zhu et al. 2018	Taihu Lake, China	Cucumber
	Bakr et al. 2022	Sohag District, Egypt	Leafy green vegetable
	Lee et al. 2021	Ohio, USA	Leafy green vegetable
	Xiang et al. 2019	Dianchi Lake, Xingyun Lake, and Dashahe Reservoir, China	Leafy vegetables, fruit vegetables, root vegetables
	Tsoumalakou et al. 2021	Karla Reservoir, Greece	Spinach
	do Carmo Bittencourt-Oliveira et al. 2016	São Paulo, Brazil	Lettuce
	El Khalloufi et al. 2012	Lalla Takerkoust Reservoir, Morocco	Tomato
	Gutiérrez-Praena et al. 2014		Tomato
	Corbel et al. 2016	Paris, France	Tomato
	Lahrouni et al. 2012	Marrakesh Region, Morocco	Faba bean

los. Drinking water supplies were contaminated with cyanobacteria toxins; these toxins were the predominant cause of health hazards in cattle.

IMPACTS ON CROPS AND VEGETABLES

Agricultural producers rely on water from ponds, reservoirs, canals, rivers, or wells to meet their irrigation water demand. If the irrigation water is contaminated by microcystin, it can impact the performance of the crops, contaminate soil, and influence groundwater quality. Of late, irrigation water contaminated with microcystins has been an increasing research focus. The World Health Organization (WHO) established a tolerable daily intake limit for microcystin-LR of 0.04 μg/kg body weight/day, assuming consumption of 300 g of fresh plant matter or 400 g of rice consumed by a 60 kg person (Chorus and Welker 2021).

Liang et al. (2021) exposed rice (*Oryza sativa*) to microcystins at various stages (e.g., seedling, booting, and filling). Irrigation water was spiked with ascending concentrations of microcystins. Exposures were made over seven days for each stage of growth. Exposure to high concentrations (100, 1000 μg/L) of microcystins during the seeding or booting stage reduced the nutritional value and yield of rice more than exposure during the filling stage. Liang et al. (2021) also conducted a health risk assessment. They determined that microcystin exposure via irrigation water at 100 μg/L during the booting stage would result in filled rice grains that exceeded the tolerable daily intake. In another study, Liang and Liu (2020) studied the response of hormones (abscisic acid, gibberellin, indole-3-acetic acid, and zeatin) in rice seedlings to microcystin-contaminated irrigation water. The researchers assessed the relationship between hormone ratios and rice growth exposed to microcystins. They reported that low concentrations of microcystins promoted rice growth; however, higher concentrations of microcystins altered the plant hormone balance, and inhibited rice growth. Liang et al. (2016) exposed rice tissues to microcystin-contaminated irrigation water for seven days. They concluded that while low concentrations had insignificant effects, high concentrations of microcystins (≥1000 μg/L) reduced rice growth and yield due to photosynthetic inhibition.

Gu and Liang (2020) investigated how increasing microcystin concentration influenced relative growth rate, reactive oxygen species, malondialdehyde content, and antioxidative enzyme activities of rice and cucumber (*Cucumis sativus*) during stress and recovery periods. Cucumber was more susceptible to microcystin-induced stress than rice. Similarly, Zhu et al. (2018) evaluated the effect of 7-day microcystin exposures to cucumber at various stages of growth (e.g., seedling, early flowering, fruiting) and exposure impact on growth, yield, and quality. Irrigation solutions with 10 μg/L of microcystin suppressed different stages of the growth of cucumber. Cucumber growth and yield were reduced if applications were made at the fruiting stage at 100 or 1000 μg/L of microcystin. Cucumbers from plants exposed to 100 or 1,000 μg/L microcystins accumulated 0.103 μg/kg and 0.198 μg/kg microcystins, exceeding WHO guidelines; thus, human consumption of exposed cucumbers was cautioned.

Wijewickrama and Manage (2019) evaluated the potential transfer mechanisms of microcystins to humans by crops through irrigation waters and the relative risk associated with that exposure. Two rice varieties (BG358 and Suwandel) and water spinach (*Ipomoea aquatica*) were used in a lab-scale experiment treated with *Microcystis aeruginosa* sourced from a hypereutrophic lake. Field samples of the two rice varieties and water lettuce were also collected from a field irrigated with water from the same lake. Results indicated potential health risks for humans for rice consumption (*O. sativa,* BG358) as the concentration of microcystin-LR detected in the sample was high enough that daily consumption of contaminated rice could impact human health. Human exposure to microcystin-LR from Suwandel rice or water spinach was below the total daily intake associated with risk by the WHO.

El Khalloufi et al. (2012) conducted a study to understand the effect of microcystin extracts on tomato (*Solanum lycopersicum*) growth outcomes. Germination of tomato seeds exposed to a microcystins extract (22.2 μg/mL) was reduced by 85%. After a 30-day exposure to microcystins, tomato growth and productivity were also inhibited. Gutiérrez-Praena et al. (2014) exposed tomato plants to cyanobacterial extracts (100 μg/L microcystin-LR) for two weeks to determine the toxicity effect and accumulation of microcystin. While no physical or physiological changes were observed, microcystin-LR was detected in green and mature tomatoes (5.15-5.41 μg/kg and 10.5-10.8 μg/kg, respectively) and shoots and roots (1,635 and 12,298, respectively) at concentrations exceeding the WHO-established limit, suggesting a risk to human health. Corbel et al. (2016) assessed the transfer and accumulation of microcystins in tomato (*S. lycopersicum* 'MicroTom') tissues using extracts containing microcystins. Tomato plants were exposed to *Microcystis aeruginosa* crude extracts (up to 100 μg/microcystin-LR) and radiolabeled 14C-microcystin-LR for 90 days and 48 hours, respectively. Microcystin-LR was present in both the roots and shoots; however, unlike Gutiérrez-Praena et al. (2014), no toxin accumulation was detected in the tomato.

Bakr et al. (2022) observed microcystin accumulation in the tissues of lettuce (*Lactuca sativa*, 1044 μg/kg) and arugula (*Eruca sativa*, 1089 μg/kg) irrigated with microcystin-contaminated water (45.0–600 μg/L). Exceedances of daily intake guidelines for microcystins are possible, and regular microcystin monitoring of irrigation water used for crops intended for human consumption is warranted (Bakr et al., 2022). In another study, do Carmo Bittencourt-Oliveira et al. (2016) conducted a 15-day experiment with lettuce irrigated with microcystin-contaminated water. Microcystin bioaccumulation by lettuce increased with exposure concentration. Lee et al. (2021) examined the colonization of lettuce by *Microcystis* through simulated spray irrigation and airborne deposits. Crop productivity declined, and microcystins accumulated in various edible parts of lettuce, suggesting new exposure routes for humans and animals.

Xiang et al. (2019) studied microcystins in irrigation water, soils, and vegetables (detailed species list in Table 1) using field sampling and coupled risk models. Irrigation waters contaminated with microcystins were the primary source of contamination for soil and vegetables. Most of the vegetables screened, particularly celery, posed a moderate to high health risk for human consumption. Tsoumalakou et al. (2021) used spray and drip irrigation dosed with microcystins on spinach to understand how irrigation style influenced microcystin uptake. Though microcystin concentrations were lower in drip-irrigated spinach, microcystins bioaccumulated in tissues to concentrations of concern for livestock or human consumption. Lahrouni et al. (2012) quantified the effects of microcystin exposures on growth, nodulation, and nitrogen uptake by Faba bean (*Vicia faba*). Microcystin exposure (50 and 100 μg/L) reduced rhizobial growth, germination rate (decreased by 25-32%), shoot and root growth, and nodule number.

CONCLUSION AND FUTURE DIRECTIONS

The environmental drivers of *Microcystins*, such as rising temperatures, urbanization, and intensive agriculture, are expected to persist in the future. As a result, the global and regional issues of the associated toxins are likely to increase, including in South Carolina.

Only three peer-refereed articles documented reports of HAB exposures and livestock death. Anecdotal evidence suggests that livestock farmers may either lack an understanding of the impact of microcystins or the technologies to detect them, or farmers may resist reporting due to perceived impacts on the marketability of their product. This lack of knowledge and resources can make investigating the actual reasons for livestock fatalities challenging. Livestock commonly depends on local water resources such as ponds or a slow-moving water system to fulfill their water demands. If the pond is contaminated with microcystins, the cattle have various pathways for exposure to microcystins (e.g., drinking, wading, licking fur). These pathways should be carefully studied, and proper risk assessments performed to understand linkages among the pathways, livestock, and human exposure. A deeper understanding of these links will aid in designing and implementing appropriate responses to microcystin-related livestock issues.

This review of the impact of microcystins on crop and vegetable health identified various pathways of exposure and bioaccumulation. Also, it highlighted the potential to exceed WHO-recommended daily intake limits for rice and vegetables. Most microcystin food-safety research has been conducted by investigators outside the US, particularly in Asian countries. One possible reason for this trend is the degradation of water quality in the region over the past several decades, caused by rapid population growth and development (Evans et al. 2012). The research community could also focus on understanding the effect of microcystins on specialty crops that rely on irrigation reservoirs.

SC's agriculture industry is worth $45B and includes livestock farming and the cultivation of various crops and vegetables, including rice, tomatoes, spinach, peppers, cucumbers, and more. In addition to various water sources such as rivers, farmers commonly rely on livestock ponds and irrigation ponds to meet their water demand. The state experiences various climate extremes, such as droughts and hurricanes, that could potentially fuel cyanobacterial blooms and microcystin release. SC Department of Health and Environmental Control samples larger, public-recreation lakes for microcystin presence (Bores and Lachenmyer 2020). However, sampling of privately-owned ponds is the responsibility of the property owner. Smaller, private ponds, potentially used for agricultural purposes, are also likely to contain microcystins. With the wealth of research on the effects of microcystins on livestock, crops, and fruits that have emerged globally in the past decade, the agricultural community in SC could use this knowledge to refine their farming practices to avoid using microcystin-contaminated water sources. While no microcystin standards exist for agricultural products, SC adopted recreational and drinking water standards for microcystins and cylindrospermopsin in 2020. The US Environmental Protection Agency implemented a similar standard in 2015. The US Food and Drug Administration screens for microcystin in various dietary supplements and food items; when unsafe microcystin levels are detected, the items are removed from the market. Therefore, to address food and water security issues, researchers, agencies, and the farming community in SC should work together to develop standards and to understand the risk associated with microcystins to the livestock, crops, and citizens in SC.

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REFERENCES

Badar M, Batool F, Khan SS, Khokhar I, Qamar MK, Yasir C. Effects of microcystins toxins contaminated drinking water on hepatic problems in animals (cows and buffalos) and toxins removal chemical method. Buffalo Bulletin. 2017;36:43–56.

Bakr A, Alzain MN, Alzamel NM, Loutfy N. Accumulation of microcystin from *Oscillatoria limnetica* Lemmermann and *Microcystis aeruginosa* (Kützing) in two leafy green vegetable crop plants *Lactuca sativa* L. and *Eruca sativa*. Plants. 2022;11:1733.

Bores E, Lachenmyer L. 2020 South Carolina cyanotoxin distribution project. Technical Report No. 004-2022.

Brooks BW, Lazorchak JM, Howard DAM, Johnson MVV, Morton SL, Perkins DAK, Reavie ED, Scott GI, Smith SA, Steevens JA. Are harmful algal blooms becoming the greatest inland water quality threat to public health and aquatic ecosystems? Environmental Toxicology and Chemistry. 2016;35:6–13.

Butler N, Carlisle JC, Linville R, Washburn B. Microcystins: A brief overview of their toxicity and effects, with special reference to fish, wildlife, and livestock. OEHHA Ecotoxicology, California Environmental Protection Agency, Department of Water Resources Agency; 2009.

Chorus I, Welker M. eds. Toxic cyanobacteria in water. 2nd edition. Boca Raton (FL): CRC Press; 2021 [on behalf of the World Health Organization, Geneva, CH].

Corbel S, Mougin C, Bouaïcha N. Cyanobacterial toxins: Modes of actions, fate in aquatic and soil ecosystems, phytotoxicity and bioaccumulation in agricultural crops. Chemosphere. 2014;96:1–5.

Corbel S, Mougin C, Nélieu S, Delarue G, Bouaïcha N. Evaluation of the transfer and the accumulation of microcystins in tomato (*Solanum lycopersicum* cultivar MicroTom) tissues using a cyanobacterial extract containing microcystins and the radiolabeled microcystin-LR (14C-MC-LR). Science of the Total Environment. 2016;541:1052–1058.

do Carmo Bittencourt-Oliveira M, Cordeiro-Araújo MK, Chia MA, de Toledo Arruda-Neto JD, de Oliveira ÊT, dos Santos F. Lettuce irrigated with contaminated water: Photosynthetic effects, antioxidative response and bioaccumulation of microcystin congeners. Ecotoxicology and Environmental Safety. 2016;128:83–90.

Dreher TW, Collart LP, Mueller RS, Halsey KH, Bildfell RJ, Schreder P, Sobhakumari A, Ferry R. Anabaena/Dolichospermum as the source of lethal microcystin levels responsible for a large cattle toxicosis event. Toxicon. 2019;1:100003.

El Khalloufi F, El Ghazali I, Saqrane S, Oufdou K, Vasconcelos V, Oudra B. Phytotoxic effects of a natural bloom extract containing microcystins on *Lycopersicon esculentum*. Ecotoxicology and environmental safety. 2012;79:199–205.

Gu Y, Liang C. Responses of antioxidative enzymes and gene expression in *Oryza sativa* L and *Cucumis sativus*

L seedlings to microcystins stress. Ecotoxicology and Environmental Safety. 2020;193:110351.

Gutiérrez-Praena D, Campos A, Azevedo J, Neves J, Freitas M, Guzmán-Guillén R, Cameán AM, Renaut J, Vasconcelos V. Exposure of *Lycopersicon esculentum* to microcystin-LR: Effects in the leaf proteome and toxin translocation from water to leaves and fruits. Toxins. 2014;6:1837–1854.

Hilborn ED, Beasley VR. One health and cyanobacteria in freshwater systems: Animal illnesses and deaths are sentinel events for human health risks. Toxins. 2015;7:1374–95.

Lahrouni M, Oufdou K, Faghire M, Peix A, El Khalloufi F, Vasconcelos V, Oudra B. Cyanobacterial extracts containing microcystins affect the growth, nodulation process and nitrogen uptake of faba bean (*Vicia faba* L., Fabaceae). Ecotoxicology. 2012;21:681–7.

Lee S, Kim J, Lee J. Colonization of toxic cyanobacteria on the surface and inside of leafy green: A hidden source of cyanotoxin production and exposure. Food Microbiology. 2021;94:103655.

Liang C, Wang W, Wang Y. Effect of irrigation with microcystins-contaminated water on growth, yield, and grain quality of rice (*Oryza sativa*). Environmental Earth Sciences. 2016;75:1–10.

Liang C, Liu H. Response of hormone in rice seedlings to irrigation contaminated with cyanobacterial extract containing microcystins. Chemosphere. 2020;256:127157.

Liang C, Ma X, Liu H. Effect of microcystins at different rice growth stages on its yield, quality, and safety. Environmental Science and Pollution Research. 2021;28:13942–13954.

Lukač M, Aegerter R. Influence of trace metals on growth and toxin production of *Microcystis aeruginosa*. Toxicon. 1993;31:293–305.

Malik JK, Bharti VK, Rahal A, Kumar D, Gupta RC. Cyanobacterial (blue-green algae) toxins. Handbook of Toxicology of Chemical Warfare Agents. 2020; 467–478.

Melaram R, Newton AR, Chafin J. Microcystins contamination and toxicity: Implications for agriculture and public health. Toxins. 2022;14:350.

Menezes C, Nova R, Vale M, Azevdo J, Vasconcelos V, Pinto C. First description of an outbreak of cattle intoxication by cyanobacteria (blue-green algae) in the South of Portugal. The Bovine Practitioner. 2019;1:66–70.

Neilan BA, Pearson LA, Muenchhoff J, Moffitt MC, Dittman E. Environmental conditions that influence toxin biosynthesis in cyanobacteria. Environmental Microbiology. 2013;15:1239–1253.

Oh HM, Lee SJ, Jang MH, Yoon BD. Microcystin production by *Microcystis aeruginosa* in a phosphorus-limited chemostat. Applied and Environmental Microbiology. 2000;66:176–9.

Pearson L, Mihali T, Moffitt M, Kellmann R, Neilan B. On the chemistry, toxicology, and genetics of the cyanobacterial toxins, microcystin, nodularin, saxitoxin and cylindrospermopsin. Marine Drugs. 2010;8:1650–80.

Rabalais NN, Turner RE, Diaz RJ, Justić D. Global change and eutrophication of coastal waters. Journal of Marine Science. 2009;66:1528–1537.

Rastogi PR, Sinha RP, Moh SH, Lee TK, Kottuparambil S, Kim YJ, Rhee JS, Choi EM, Brown MT, Hader DP et al. Ultraviolet radiation and cyanobacteria. Journal of Photochemistry and Photobiology B: Biology. 2014;141:154–169.

Redouane EM, Zerrifi SE, El Khalloufi F, Oufdou K, Oudra B, Lahrouni M, Campos A, Vasconcelos V. Mode of action and fate of microcystins in the complex soil-plant ecosystems. Chemosphere. 2019;225:270–281.

Sivonen K. Effects of light, temperature, nitrate, orthophosphate, and bacteria on growth of and hepatotoxin production by *Oscillatoria agardhii* strains. Applied and Environmental Microbiology. 1990;56:2658–2666.

Song L, Sano T, Li R, Watanabe MM, Liu Y, Kaya K. Microcystin production of Microcystis viridis (cyanobacteria) under different culture conditions. Phycological Research. 1998;46:19–23.

Tsoumalakou E, Papadimitriou T, Berillis P, Kormas KA, Levizou E. Spray irrigation with microcystins-rich water affects plant performance from the microscopic to the functional level and food safety of spinach (*Spinacia oleracea* L.). Science of the Total Environment. 2021;789:147948.

Wijewickrama MM, Manage PM. Accumulation of Microcystin-LR in grains of two rice varieties (*Oryza sativa* L.) and a leafy vegetable, *Ipomoea aquatica*. Toxins. 2019;11:432.

Withers PJA, Neal C, Jarvie HP, Doody DG. Agriculture and eutrophication: Where do we go from here? Sustainability. 2014;6:5853–5875.

Xiang L, Li YW, Liu BL, Zhao HM, Li H, Cai QY, Mo CH, Wong MH, Li QX. High ecological and human health risks from microcystins in vegetable fields in southern China. Environment International. 2019;133:105142.

Zhu J, Ren X, Liu H, Liang C. Effect of irrigation with microcystins-contaminated water on growth and fruit quality of *Cucumis sativus L.* and the health risk. Agricultural Water Management. 2018;204:91–9.