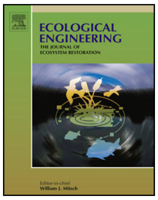
Ecological Engineering 87 (2016) 246–253

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng



In situ enclosure experiments on the occurrence, development and decline of black bloom and the dynamics of its associated taste and odor compounds

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ARTICLE INFO

Article history:
Received 24 July 2015
Received in revised form 31 October 2015
Accepted 21 November 2015
Available online 22 December 2015

Keywords:
Taste and odor compounds
Black bloom
Cyanobacterial biomass
Dissolved oxygen
Lake Taihu

ABSTRACT

Black bloom has an offensive odor (caused by, e.g., dimethyl sulfide, DMS; dimethyl disulfide, DMDS; and dimethyl trisulfide, DMTS) and disastrous consequences for natural limnic ecosystems worldwide. However, research on black bloom and its taste and odor (T&O) compounds has been limited by the difficulty of predicting the time and location of black bloom events. Therefore, the occurrence, development and decline of black bloom and the dynamics of T&O compounds in each stage of black bloom were examined in Meiliang Bay, Lake Taihu, through an in situ enclosure (2.5 m × 2.5 m) simulation experiment with various levels of cyanobacterial biomass ($0\,g\,m^{-2}$, $1500\,g\,m^{-2}$, $7500\,g\,m^{-2}$ and $15{,}000\,g\,m^{-2}$, fresh weight). The principal odor-related substances and the physicochemical parameters were analyzed every two or three days. Black blooms occurred in the moderate ($7500\,g\,m^{-2}$) and high ($15{,}000\,g\,m^{-2}$) cyanobacterial biomass treatments concurrently on day 5 but did not occur in the low cyanobacterial biomass ($1500\,g\,m^{-2}$) treatment or in the control group ($0\,g\,m^{-2}$). Thus, black bloom could be induced by the decay of dense cyanobacterial populations under suitable meteorological and hydrographic conditions. As the extent of black bloom increased, the concentrations of nutrients (e.g., ammonium nitrogen and total phosphorus), odorous compounds, and total divalent anionic sulfur and the duration of low dissolved oxygen levels increased, whereas the pH decreased. In addition, linear regression analysis revealed that the concentrations of odorous compounds in the water column were significantly correlated with changes in certain physicochemical parameters (e.g., chlorophyll *a*, pH) and these changes were mainly induced by the breakdown of the cyanobacterial bloom. Overall, our study revealed that (i) the extent of black bloom (e.g., level of black water color, concentrations of offensive odor compounds and duration) is strongly influenced by cyanobacterial biomass; and (ii) extremely high concentrations of T&O compounds may originate from the decomposition of cyanobacteria.

1. Introduction

Black bloom, also known as black water agglomerate, is a serious natural ecosystem disaster that occurs worldwide in freshwater lakes and along seashores (Berthon and Zibordi, 2010; Pucciarelli et al., 2008). This phenomenon often occurs during the summer (Lu and Ma, 2009). Public concern about black bloom was triggered by the recent potable water crisis in the city of Wuxi. A black color and a strong offensive odor are the two most characteristic features of black bloom (Zhang et al., 2010). The offensive odorous compounds can lead to worse economic losses (Freuze et al., 2004). However, research on black bloom and its associated taste and odor (T&O) compounds has been limited by the difficulty of predicting the time and location of black bloom events (He et al., 2013).

Studies have suggested that β-cyclocitral, β-ionone and volatile organic sulfur compounds (VOSCs), such as dimethyl sulfide (DMS), dimethyl disulfide (DMDS) and dimethyl trisulfide (DMTS), are the major compounds responsible for the strong offensive odor of black bloom (Duval and Ludlam, 2001; Shen et al., 2014). Zhang et al. (2010) reported that DMS, DMDS, DMTS and β-cyclocitral reached the notably high concentrations of 93.9, 46.1, 17.2 and 21.0 $\mu g\,L^{-1}$, respectively, during the water crisis in Wuxi City, and Yang et al.

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http://dx.doi.org/10.1016/j.ecoleng.2015.11.039
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Fig. 1. The black bloom that occurred in Lake Taihu.

(2008) reported that DMTS reached 11.7 and 1.8 $\mu g\,L^{-1}$ at two separate sampling sites on another sampling day. Additionally, a high concentration of DMS was also detected in black bloom induced by submerged plants (Shen et al., 2014). However, these reports were based on casual field follow-up investigations without continuous monitoring. Little is known about the dynamics of T&O compounds during the entire black bloom process.

Black bloom may be induced by algal blooms (Lu and Ma, 2009). Ma et al. (2013) showed that the decay of cyanobacterial blooms could induce anoxic water conditions, decrease pH, and increase nutrient loading in the lake water. The water in the enclosures was black and malodorous. Moreover, DMS, DMTS and β-cyclocitral simultaneously reached extremely high levels, with maxima of 62.33, 12.41 and 1.37 $\mu g\,L^{-1}$, respectively. Liu et al. (2015) suggested that sediment dredging at an appropriate depth could suppress the occurrence of black bloom but could not suppress the offensive odor. Feng et al. (2014) suggested that sulfide-reducing bacteria (SRB) and protein are the principal biological and organic factors, respectively, that contribute to the occurrence of black bloom. Most studies have primarily focused on the mechanism of black bloom occurrence. However, the development and decline of black bloom and the related T&O compounds in each stage remain unclear. Furthermore, little is known about how cyanobacterial biomass affects black bloom and T&O compounds.

The present study sought to address these knowledge gaps by conducting black bloom simulation experiments in Meiliang Bay, Lake Taihu, China, using various levels of cyanobacterial biomass. The dynamics of the T&O compounds, as well as those of water quality parameters, were continuously monitored in all enclosures until the black bloom disappeared. We also compared these findings to results that were previously collected from a natural black bloom (Fig. 1) in the mid- to late stage in June 2013 in Gonghu Bay, Lake Taihu. Fortunately, the development and decline of black bloom and the related T&O compounds in the in situ simulation experiment were consistent with the survey results from the natural black bloom. These results provide new insights that may help clarify the relationship between T&O compounds and factors relevant for better incident prediction, warning and prevention in the future.

2. Materials and methods

2.1. Study site

Lake Taihu (30°55′40″-31°32′58″N, 119°52′32″-120°36′10″E), the third largest freshwater lake in China, is a typical large and shallow eutrophic subtropical lake (surface area: 2338 km^2, mean depth: 1.9 m). Many serious black bloom incidents have recently occurred in Lake Taihu, particularly along the western and northern shorelines (Duan et al., 2014). In Meiliang Bay, in the northern part of Lake Taihu, enclosures have been deployed approximately 200 m away from the eastern shoreline. As a result of nutrient pollution, Meiliang Bay is eutrophic and experiences intensive blooms of algae (mostly cyanobacteria) during summer (Tang et al., 2014).

2.2. Experimental design

Twelve enclosures (2.5 m × 2.5 m) were constructed from waterproof polyvinyl chloride. The enclosures were open to the atmosphere and to the bottom sediment and were supported by four rigid horizontal hoops. The mean water depth in all enclosures was approximately 1.5 m. To prevent waves and rising water from entering, the enclosure walls were extended approximately 1 m above the mean water level. To minimize the artificial disturbances of the enclosure construction, the enclosures were left untreated for two weeks before the addition of cyanobacteria. Samples were collected from each enclosure on July 31, 2014, one day before adding cyanobacteria as a reference. The bloom cyanobacteria used in this work were collected from a cove on Meiliang Bay. The fresh cyanobacteria were centrifuged at 1500 r/min for 5 min, yielding a water content of approximately 65%, calculated according to previously reported methods (Liu et al., 2010). The cyanobacteria were alive when they were added to the enclosures. Four treatments with different levels of cyanobacterial biomass were applied: control (0 $g\,m^{-2}$, C), low cyanobacterial biomass (1500 $g\,m^{-2}$, L), moderate cyanobacterial biomass (7500 $g\,m^{-2}$, M), and high cyanobacterial biomass (15,000 $g\,m^{-2}$, H). Each treatment was performed in triplicate. Immediately after the addition of the cyanobacteria, the water in the enclosures was mixed by stirring with an oar. Experiments were terminated when the water column became colorless in all enclosures. Samples were collected every two or three days based on the changes in water quality parameters during the study period, beginning on day 1 (1 August, 2014).

2.3. Sampling and analyses

Samples were obtained between 10:00 AM and 1:00 PM at a single depth (0.5 m below the water surface) in the center of each enclosure. Samples for the analysis of total divalent anionic sulfur ($\sum S^{2-}$) were immediately transferred into bottles containing zinc acetate to prevent oxidation. Samples for evaluating T&O compounds and inorganic nutrients were collected in 1-L narrow-neck PE bottles with no headspace and stored immediately in a portable refrigerator at approximately 4 °C before transport to the laboratory. Upon arrival in the laboratory, all samples for the analysis of off-flavor were stored at −20 °C for no more than 5 days before analysis.

Water temperature, dissolved oxygen (DO), pH and total dissolved solid (TDS) were measured in situ using a HORIBA water quality monitor (HORIBA, Ltd. Kyoto Japan). Total nitrogen (TN), ammonium nitrogen (NH_4-N), total phosphorus (TP), $\sum S^{2-}$ ($\Sigma S^{2-} = H_2S + HS^- + S^{2-}$) and chlorophyll *a* were analyzed according to standard methods (Jin and Tu, 1990).

To estimate the T&O compounds, a 300-mL water sample was filtered through a Whatman GF/C fiberglass filter. The filtrate was analyzed for dissolved T&O compounds in water. The T&O compounds were analyzed with a P&T extraction device coupled with GC–MS according to Chen et al. (2010a) and Deng et al. (2011).

2.4. Statistical analysis

Correlations between water quality variables and T&O compounds were identified using Pearson's correlation coefficient