Mitigating harmful cyanobacterial blooms in drinking water reservoirs through *in-situ* sediment resuspension

Jiao Fang[a,b], Yande Li[d], Ming Su[a,f,*], Tengxin Cao[a,f], Xufeng Sun[c], Yufan Ai[a,f], Jinyi Qin[e], Jianwei Yu[a,f], Min Yang[a,f,*]

[a] *State Key Laboratory of Environmental Aquatic Chemistry, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, P.O. Box 2871, Beijing, 100085,*

[b] *School of Environment and Spatial Informatics, China University of Mining and Technology, Xuzhou, 221116,*

[c] *Zhejiang Weicheng Huanbao Co. Ltd., Yunxiu North Road 1200, Huzhou, 313200,*

[d] *Management Station of Shuangxikou Reservoir, Reservoir Management Service Center of Yuyao, Ningbo, 315423,*

[e] *School of Civil Engineering, Chang'an University, Xi'an, 710054,*

[f] *University of Chinese Academy of Sciences, Beijing, 100049,*

Abstract

Mitigating harmful cyanobacterial blooms is a global challenge, particularly crucial for safeguarding source water. Given the limitations of current technologies for application in drinking water reservoirs, we propose an innovative strategy based on *in-situ* sediment resuspension (SR). This method's effectiveness in cyanobacterial control and its potential impacts on water quality were assessed through laboratory culture experiments and further validated via field applications in five drinking water reservoirs. The results revealed that SR could significantly mitigate cyanobacterial growth, evidenced by the treated sets (removal rate: 3.82×10^6 cells L^{-1} d^{-1}) compared to the control set (growth rate: 2.22×10^7 cells L^{-1} d^{-1}) according to the laboratory experiments. The underlying mechanisms identified included underwater light reduction (2.38× increase in extinction coefficient) and flocculation and entrainment of cells by resuspended particles (30% reduction per operation). Additional contributions were noted in the reduction of bioavailable phosphate and remediation of anaerobic sediment characterized by increased redox potential. This facilitated the oxidation of iron, which in turn promoted the co-precipitation of phosphate (removal rate: 46 μg L^{-1} d^{-1}) and inhibited its release from the sediment. The SR operation, devoid of importing extra substances, represents a safe and economical technology for controlling

harmful cyanobacteria in drinking water reservoirs.

Keywords: Sediment resuspension, Harmful cyanobacterial control, Underwater light availability, Floccuation, Phosphate, Drinking water reservoir

[1] State Key Laboratory of Environmental Aquatic Chemistry, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences

[2] School of Environment and Spatial Informatics, China University of Mining and Technology

[3] Zhejiang Weicheng Huanbao Co. Ltd.

[4] Management Station of Shuangxikou Reservoir, Reservoir Management Service Center of Yuyao

[5] School of Civil Engineering, Chang'an University

[6] University of Chinese Academy of Sciences

[*] Correspondence: Ming Su <mingsu@rcees.ac.cn>, Min Yang <yangmin@rcees.ac.cn>

1. Introduction

Cyanobacterial blooms significantly deteriorate water quality (Qin et al., 2012; Huisman et al., 2018) and pose a critical threat to drinking water safety (Agrawal and Gopal, 2012; Cheung et al., 2013). The excessive photosynthesis by surface cyanobacteria depletes carbon dioxide, leading to increased pH value in source water (Cao et al., 2016). This further diminishes the effectiveness of coagulation and flocculation processes in drinking water plants (DWPs) (Naceradska et al., 2019). Blooms of microcystin-producing *Microcystis* are recognized as a serious global public health issue (de Figueiredo et al., 2004) because cyanotoxins can threaten the survival of aquatic organisms (Acuña et al., 2012), wildlife, livestock (Davis et al., 2009; Dittmann et al., 2013), and human health (de Figueiredo et al., 2004). Moreover, filamentous cyanobacteria are the main source of off-flavor issues in drinking water systems and have become a major concern (Bruchet et al., 2019) as the primary signal of drinking-water integrity (Watson, 2004). Even though they exist at a low abundance, hardly forming algal blooms, the invisible growth of

*Corresponding author
Email addresses: mingsu@rcees.ac.cn (Ming Su), yangmin@rcees.ac.cn (Min Yang)

filamentous cyanobacteria beneath the water surface often extensively causes musty odor problems in drinking water systems (Van Der Ploeg et al., 1995; Wang and Li, 2015; Li et al., 2016; Chia et al., 2018; Su et al., 2019). Therefore, the prevention and control of harmful cyanobacteria in source water are preferred approaches prior to water treatment processes across various aspects (Chorus and McKeown, 2021; Su et al., 2021; WHO, 2015).

Controlling harmful cyanobacteria in source water presents an enduring challenge, despite the availability of various methods capable of technically killing cells and inhibiting bloom formation. Proposed approaches encompass chemical (algaecides, flocculants, surfactants, etc.), physical (skimmer removal, perimeter skirt isolation, ultrasound, etc.), and biological (grazing, algicidal bacteria/viruses, enzymes, etc.) methods, as extensively documented (Kim, 2006). However, these methods often encounter limitations, including negative ecological impacts, high costs, and poor maneuverability in natural environments.

Key factors such as temperature, nutrients, and light intensity primarily influence surface blooms. Phosphorus has been widely recognized as a limiting factor for cyanobacterial blooms (Cao et al., 2016), while nitrogen (in forms such as nitrate, ammonia) is essential for nitrogen fixation by cyanobacteria, leading to the production of microcystins (Chaffin et al., 2018). Consequently, nutrient reduction strategies, such as non-point nutrient control and endogenous nutrient locking, have been extensively implemented. However, reducing nutrients alone is deemed insufficient for many lakes (Paerl et al., 2014), especially considering the persistent occurrence of water quality issues related to harmful cyanobacteria in drinking water reservoirs (Su et al., 2015; He et al., 2016). The availability of underwater light has been emphasized as a crucial factor influencing phytoplankton community succession, as highlighted in the 15th Workshop of the International Association for Phytoplankton Taxonomy and Ecology (Zohary et al., 2010). Case studies like those in Miyun Reservoir have demonstrated the succession from surface-dwelling *Microcystis* to subsurface-dwelling *Planktothrix* driven by changes in underwater light conditions (Su et al., 2019). Another case study in QCS Reservoir illustrated that the filamentous strain *Planktothrix* was replaced by another filamentous strain, *Pseudanabaena*,

due to declines in light intensity (Su et al., 2022).

A noteworthy non-chemical strategy involves the use of flocculant clay, which efficiently scavenges particles, including algal cells, from the water column, by depositing them into bottom sediments (Beaulieu et al., 2005). To enhance the performance of flocculation performance, various coagulants have been integrated, including inorganic flocculants such as poly-aluminum chloride (PAC, (Sengco et al., 2001; Pierce et al., 2004; Lürling and van Oosterhout, 2013; Lu et al., 2016)), aluminum sulfate (AS, (Boyd, 1979)), iron (III) chloride (PIX; (Waajen et al., 2016)), as well as organic flocculants like chitosan (Zou et al., 2006; Li and Pan, 2015; Lürling et al., 2017), sophorolipid (Lee et al., 2008; Sun et al., 2004), and synthetic materials such as coal fly ash (Yuan et al., 2016), moringa oleifera coagulant (Li and Pan, 2013), and larch tannin (Wang et al., 2013). Currently, UNESCO and APEC recommend modified clay technology for mitigating harmful algal blooms in coastal waters to safeguard marine products (Anderson et al., 2001). However, concerns about the introduction of new chemicals or exotic organisms may restrict its application in source water, potentially raising public apprehensions about drinking water safety.

A significant amount of dissolved and reduced iron is present in the sediment especially under strongly reductive conditions (Murray and Hesterberg, 2006; Hammond et al., 2023). The iron can be easily oxidized upon entering the overlying water (Munger et al., 2016; Santana-Casiano et al., 2006; Millero et al., 1987; Yang et al., 2023). Subsequently, in (weakly) alkaline raw water, iron can react with carbonate(CO_3^{2-}), bicarbonate(HCO_3^-) and hydroxide ions(OH^-), to form precipitates of iron oxide/hydroxide (Santana-Casiano et al., 2006; King, 1998; Schroeder and Young, 1996). Therefore, we hypothesized that local sediment could act as a natural flocculants, potentially replacing modified clay for controlling cyanobacteria. Besides, sediment resuspension can significantly increase the surface water turbidity, thereby reducing underwater light intensity and inhibiting the growth of harmful cyanobacteria. This effects has been verified by the real case in Miyun Reservoir (Su et al., 2017) and QCS Reservoir (Su et al., 2022). Consequently, the effectiveness of algal mitigation and potential risk of water quality problems should be investigated and evaluated.

On this basis, we propose a new strategy for cyanobacterial control through the resuspension of local sediment in source water. This strategy is based on the hypothesis that the combined effects of cell flocculation and/or entrainment, along with reduced underwater light availability due to increased turbidity, can effectively mitigate cyanobacterial growth. A simulation system was designed to evaluate the cyanobacterial control effect and the potential impact on water quality of sediment resuspension (SR) technology, and the causal mechanism was revealed according to the comprehensive monitoring of cell density, underwater light intensity, nutrients (dissolved phosphorus, nitrogen, and organic carbon), dissolved iron, and sediment oxidation-reduction potential (ORP) etc. Further, field applications of SR operation were performed in five drinking water reservoirs to validate its effectiveness. By introducing and assessing this innovative SR approach, this study provides a new approach for harmful cyanobacterial control in drinking water reservoir, without using exotic chemicals or organisms.

2. Methods and materials

2.1. Mechanical experiments in three customized simulators

Sediment resuspension (SR) operation was conducted in three custom-built cylindrical simulators (height: 150 cm, diameter: 20 cm), each filled with sterilized reservoir water (height: 120 cm, approx. 40 L) and sediment (thickness: 20 cm, approx. 6.5 L), as illustrated in Fig. 1A). A stock culture solution of *Microcystis aeruginosa* (FACHB-905) was obtained from the Freshwater Algae Culture Collection in the Institute of Hydrobiology, Chinese Academy of Science. Approximately 6 L of high-density *Microcystis aeruginosa* cells (1×10^9 cells L^{-1}) were cultivated in BG11 medium at 25°C with the light intensity of 40 μmol m^{-2} s^{-1} under a 12h/12h light/dark cycle. The *Microcystis* suspensions were evenly distributed into the three simulators, forming an initial cell density of $(5.13 \pm 0.90) \times 10^7$ cells L^{-1} in each, to simulate subsequent cyanobacterial blooms. Sediment was regularly resuspended and sprayed on the water surface using pumps with a flow rate of 25 mL min^{-1} in two of simulators, designated as treated set (LE1, LE2). No SR operation was performed in the third simulator, designated as untreated control set (LC). All simulators were placed in a dark and thermostatic chamber (25 ± 1 °C). According to the field monitoring of

underwater light intensity (daily mean: ~9000 lux), the commonly-used fluorescent lamps (30 W, 9000 lux) were selected to imitate the natural sunlight. The lamps were fixed on the top of each simulator (0.10 m above the water surface) as the unique light source and operated from 7:00 to 19:00. Additionally, three temperature and light data loggers (HOBO Pendant 64K, UA-002-64) were positioned within the water column at different depths (0.10 m, 0.50 m, 1.00 m). Water temperature and underwater light intensities were recorded every 10 minutes throughout the whole experiment.

According to a preliminary field test (Fig. S3A), the SR operation was periodically conducted in LE1 and LE2 for two minutes every 2 hours from 7:00 to 19:00 over the first 10 days (Stage SR-ON). SR operations were halted in the LE simulator after day 10 (SR-OFF stage) aiming to check whether cyanobacteria bloom would reoccur. Sampling and monitoring were performed until day 40 (except between day 21–30 due to COVID-19 constraints) when evidences were enough for this study. More details on the SR operation and sampling procedure were summarized in Fig. S1.

Water samples (approximately 60 mL) were collected from each depth (0.10 m, 0.50 m, 1.00 m below the water surface) before the first SR operation (6:50) every day during Stage SR-ON (day 1-10) and every two days during Stage SR-OFF (day 11-20, 31-40). Surface sediment samples (approximately 50 mL) were collected using disposable syringe equipped with a hose every two days. The abundance of *Microcystis* in the water samples, as well as water quality indicators including dissolved nutrients concentration and dissolved iron in both water samples and sediment samples were measured.

Furthermore, *Microcystis* cell densities were quantified to evaluate the cyanobacterial removal efficiency of a single SR operation in LE1 and LE2. Water samples (5 mL) were collected from five depths (0.10 m, 0.25 m, 0.50 m, 0.75 m, and 1.00 m) at 0 min, 30 min, 60 min, 90 min, 120 min. This experiment was repeated across three independent SR cycles.

2.2. Field applications in five drinking water reservoirs

Shipborne sediment resuspension equipment was developed and assembled on diesel boats shown in Fig. S2 and Table S1. Surface sediment (0-20 cm) is dredged and sprayed to water surface with the efficacy (η, kg h^{-1}) of approximately 21600 kg h^{-1}, creating an initial sediment concentration (c, kg m^2) of 4.32 kg m^2 in the water column (ω, 2.5 m width) by setting the boat speed (v) of 2 km h^{-1} (Eq. 1).

$$c = \frac{\eta}{1000\omega v} \tag{1}$$

The degree of working frequency (ζ, d^{-1}) at a special site can be determined by the working hours per day (h), the number of equipped boats (n) and the surface area of working zone (S, m^2), as described in Eq. 2.

$$\zeta = \frac{nv\omega\tau}{10^7 S} \tag{2}$$

The SR intensity (Φ, kg m^{-2} d^{-1}) can be determined by c and ζ, according to Eq. 3.

$$\Phi = \zeta c \tag{3}$$

Field applications were conducted in five drinking water reservoirs in Zhejiang Province, China (Fig. 1B). These reservoirs have been impacted by harmful algal blooms in recent years (Table S1).

Long-term SR operations were conducted in Siminghu Reservoir (SMH, 29°56'57.43"N, 121°3'0.52"E, Fig. S2A) and Shuangxikou Reservoir (SXK, 29°55'50.29"N, 121°19'53.03"E, Fig. S2B) from April to October between 2017 and 2023, with the aim of preventing algal blooms. Before 2022, SR operations were implemented across most areas of both reservoirs. A risk zone (approximately 25 ha) was identified in SMH Reservoir according to historical monitoring

data. In 2023, two specific sites were selected to compare the algal control effect and evaluate the efficiency of SR technology. SR operations were conducted for 10 hours daily between 7:00 and 17:00 using a boat around FE (29°56'56.65"N, 121°3'1.47"E, 12 ha). No SR operations were performed around FC (29°56'35.71"N, 121°3'17.35"E), which served as the untreated control site. The water depths at both sites are around 10.5 m. Similarly, SR operations were conducted around FE (29°55'38.39"N, 121°20'2.86"E, 6.4 ha) within the identified risk zone (18 ha) of SXK Reservoir, with FC (29°55'59.66"N, 121°19'44.59"E) serving as the control site. The water depths at both sites are around 28.7 m.

Short-term SR operations (10–14 days, 10 hours per day) were conducted in Nanjiang Reservoir (NJ, 29°6'6.85"N, 120°26'3.66"E, Fig. S2C), Changxi Reservoir (CX, 30°4'31.84"N, 121°26'0.10"E, Fig. S2D), and Human Reservoir (HM, 28°22'8.63"N, 121°25'18.49"E, Fig. S2E), aiming to control cyanobacterial blooms. The designated risk zones in these reservoirs encompass areas of 26.5 ha, 3.8 ha, and 12 ha, respectively. Two boats were employed for both CX and NJ Reservoirs, and three boats for HM Reservoir. The more details of SR operations and investigation status were shown in Table S1 and further explained in the captions of Fig. S12, Fig. S13 and Fig. S14. SR operations were specifically conducted around FE sites in each reservoir, which cover areas of approximately 14.3 ha, 1.3 ha, and 4.1 ha respectively. FC sites were designated as the untreated control sets. The water depths of FE and FC sites are around 7.8 m in NJ Reservoir, 4.0 m in CX Reservoir, and 6.4 m in HM Reservoir.

Systematic investigations were performed during the SR operation periods in the five reservoirs. Water temperature and underwater light intensity were recorded every 30 minutes using six temperature/light data loggers (HOBO Pendant 64K UA-002-64) at different depths (0.50 m, 1.00 m, 1.50 m, 2.00 m, 2.50 m, 3.00 m) in each reservoir throughout the investigation period. Specifically, these data loggers were deployed in two long-term reservoirs during April to October in 2023, and in three short-term reservoirs during their 10–14 days' SR operation. Physico-chemical parameters, including pH, redox potential (ORP), salinity, conductivity, turbidity, and chlorophyll-*a* (Chl-*a*), were recorded using a multi-water quality parameter instrument

(YSI 6600V2, US) during each sampling session. Water samples (1 L) were collected by a Kemmerer water sampler from all sites at three depths (CX Reservoir: 0.5 m, 2.0 m, and 4.0 m; others: 0.5 m, 3.0 m, and 6.0 m). Sediment samples (approximately 1 L) were collected with an Ekman dredge and rapidly transferred into airtight containers to avoid oxidation. Sampling occurred biweekly in SMH and SXK Reservoirs to evaluate the effects of long-term SR operations, while water samples were collected daily during each 10–14 day short-term SR operation in the other three reservoirs (Table S1).

In addition, turbidity and Chl-*a* were monitored to assess the maintenance of turbidity and the algal removal efficiency of a single SR operation during field application in SXK Reservoir. Turbidity were monitored *in-situ* from six depths (0.2 m, 1.0 m, 2.0 m, 4.0 m, 6.0 m) at 0 min, 5 min, 15min, 30 min, 45 min, 60 min, 80 min 100 min, and 120 min using multi-water quality parameter (YSI 6600V2, US) instrument. Concurrently, Chl-*a* were monitored using a chlorophyll analyzer (BBE, Germany) from the same depth at 0 min, 30 min, 60 min, 90min and 120 min. Three independent SR cycles were repeated in the tests. (Fig. S3A and Fig. S16).

2.3. Phytoplankton identification and quantification

Field water subsamples (500 mL) for cell enumeration were preserved with 5% Lugol's iodine (Sherr and Sherr, 1993) and left to settle for 48 hours, then pre-concentrated 20× and kept in the dark until cell counting. While water samples (5 mL) from simulators were used for *Microcystis* cell counting without pre-concentration. Genus or species level of phytoplankton community was identified according to Komárek and Anagnostidis (1998), Komarek et al. (2014) and Bellinger and Sigee (2015). Phytoplankton were identified and enumerated using an upright microscope (Olympus BX53, Japan) following the protocol established by Martinez et al. (1975). The filamentous cyanobacteria abundances were quantified based on the length of each filament and the mean cell length of each strain. The number of cells in colony species such as *Microcystis* sp. was estimated based on colony volume and mean cell number per volume. The mean cell morphological characteristics including cell length, cell volume etc. were determined according to >50 filaments/colonies of each strain using a in-house developed cell counting tool

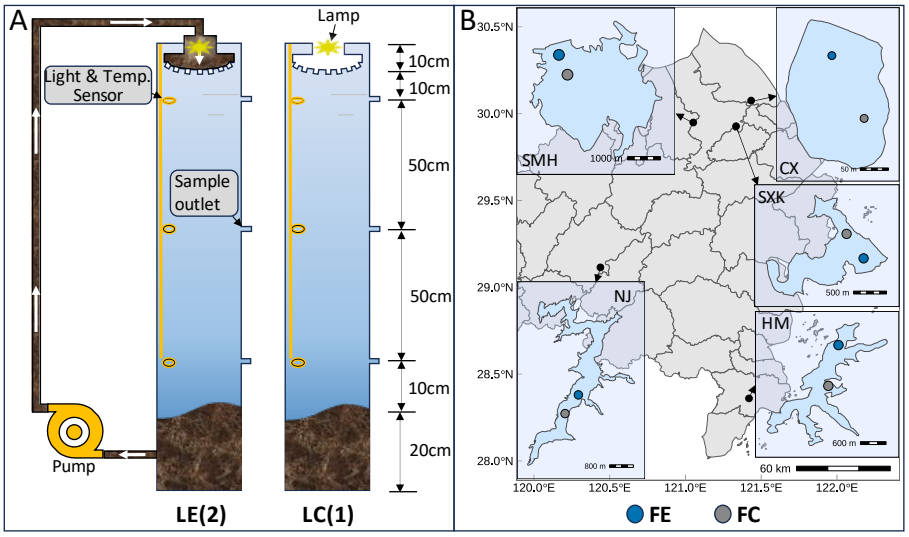

Fig. 1The figure illustrates the laboratory simulators (A) and five drinking water reservoirs (B) where Sediment Resuspension (SR) technology was implemented. Two simulators were assembled with pump to perform SR, and one simulator without SR. Long-term SR operations were conducted in SMH Reservoir and SXK Reservoir to prevent cyanobacterial bloom occurrences, while short-term SR operations were carried out in HM Reservoir, NJ Reservoir, and CX Reservoir. The designation 'LC' and 'FC' indicates simulators or sites without SR operations, serving as untreated controls, whereas 'LE' and 'FE' denotes simulators or sites where SR operations were conducted.

(CCT v1.4, https://drwater.rcees.ac.cn, in Chinese).

2.4. Laboratory detection and analysis

Water samples (approximately 50 mL) were collected to assess water quality indicators for both laboratory simulators and field reservoirs. After filtration through a 0.45 µm poly ether sulfone (PES) membrane, the water sample was used to determine dissolved substances in the water. Dissolved organic carbon (DOC) of filtered sample (15 mL) was analyzed according to the National Standard Methods of China by TOC Analyzer (TOC-L CPH, Shi- 170 madzu, Japan). It should be noted separately that DOC were not investigated in SMH and SXK Reservoirs. Total dissolved nitrogen (TDN) and total dissolved phosphate (TDP) were determined using a 20 mL filtered water sample with a Continuous Flow Analyzer (SAN ++, Skalar Analytical B.V). Filtered water sample (10 mL) after acidified with 1% w/w nitric acid was used to determine the total dissolved iron and manganese using ICP-MS (Thermo Fisher Scientific Co., Ltd). Here, iron and manganese monitoring was only conducted in NJ Reservoir (short-term SR) and in the long-term

operational (SMH and SXK) reservoirs.

Sediment ORP in laboratory experiment was measured using an ORP tester (STORP2, OHAUS, America) within 5 minutes after sediment collection in a tube. In field application, Sediment ORP was measured using a Soil ORP Meter (TR-901, Leici, China) promptly within 5 minutes after sediment collection.

2.5. Data analysis

The extinction coefficient (k) was determined according to a logarithmic-linear model between underwater light intensity (I) and water depth (z) at different depths, following the Beer-Lambert Law (Eq. 4).

$$I_z = I_0 e^{-kz} \tag{4}$$

where I_0 represents light intensity at the surface and I_z represents light intensity at depth z.

The relative change in extinction coefficient (ρ) in a special time of the SR cycle (120 min) during SR operation was represented by Eq. 5.

$$\rho = \frac{\overline{k_{LE}(t)}}{\overline{k_{LC}}} \tag{5}$$

where t is the time differences relative to each SR operation.

The removal rate of algal cells by SR (ρ_C) is determined by the ratio of median cell densities between the SR treated group (FE) and the untreated control group (FC).

Considering that the decrease in dissolved phosphorus is mainly contributed by SR removal and biosynthesis of cell growth, the removal rate of SR (ρ_{SR}) is estimated by the difference between the total dissolved phosphorus decrease (Δc_{DP}) and cellular phosphorus increase (Δc_{CP}), as defined by (Eq. 6).

$$\rho_{SR} = \frac{-\Delta c_{DP} - \Delta c_{CP}}{\Delta t} \quad (6)$$

Here, cell-bound phosphorus (c_{CP}) was defined by Eq. 7.

$$c_{CP} = N \times \overline{CCP} \quad (7)$$

where N denotes the cell density, and $\overline{CCP}$ denotes the mean cellular phosphorus content. The value of $\overline{CCP} = 1.86 \times 10^{-7}$ μg cell^{-1} was used based upon a study on the composition of phosphorus in single typical cyanobacteria cells (Blanco et al., 2013).

All statistical analyses and illustrations were performed with the **vegan** and **tidyverse** packages (Dixon, 2003; Wickham et al., 2019) using R 4.0 (R Core Team, 2021). Median values were used in all box plots, and the interquartile range (IQR) was used to describe the increase of sediment ORP. More specifically, the box plot displays statistical quantiles, including the median, the 25th and 75th percentiles. The box itself represents the interquartile range (IQR), with whiskers extending to 1.5 times the IQR from the quartiles. Outliers are depicted as individual points beyond the whiskers. Mean (± standard error) values were used to describe all other variables in the main text, as well as for all plots featuring error bars. *p*-values < 0.05 were regarded as statistically significant.

3. Results

3.1. Evaluation of algae control effect and water quality changes for SR operation in laboratory simulators

A significant reduction in *Microcystis* abundance was observed in laboratory experiment sets (LEs, LE1 and LE2) during Stage SR-ON (day 1–10, *p*-values < 0.0001, Fig. 2A). By day 10, the cell density decreased to 1.34 × 10^8 cells L^{-1} and 1.49 × 10^7 cells L^{-1} and 1.10 × 10^7 cells L^{-1}, with removal rates of 3.39 × 10^6 cell L^{-1} d^{-1} and 4.25 × 10^6 cell L^{-1} d^{-1} for LE1 and LE2, respectively.

In contrast, the cell density of the laboratory control set (LC) significantly increased (*p*-value = 0.0000) at a rate of 2.22×10^7 cell L^{-1} d^{-1} (Fig. 2A).

A significant decrease in TDP concentration was observed for both LEs and LC, although they followed different trajectories starting from the same initial TDP concentrations (181 ± 20 μg L^{-1}). Remarkable declines began on day 4 and concluded on day 8, resulting in a TDP concentration of (7.97 ± 8.56 μg L^{-1}) for LC. Conversely, the decrease for LEs started on day 1 and ended on day 5,reaching a minimum TDP concentration of 8.24 ± 9.32 μg L^{-1}. Meanwhile, the total intracellular phosphorus concentration of *Microcystis* in LEs decreased from 88.36 ± 16.31μg L^{-1} to 27.55 ± 7.33μg L^{-1} (Fig. 2B).

Furthermore, TDN concentration exhibited significant decreases in both LEs and LC (Fig. S4, *p*-values < 0.0001) during Stage SR-ON. The differences in TDN between LEs and LC were also significant (Fig. S5A, *p*-value = 0.0116). Dissolved organic carbon (DOC) concentrations were 6.16 ± 2.26 mg L^{-1} (LC) and 7.35 ± 5.24 mg L^{-1} (LEs) in the laboratory simulation, respectively. No significant differences in DOC (Fig. S5B, *p*-value = 0.2379) concentrations were observed between LEs and LC.

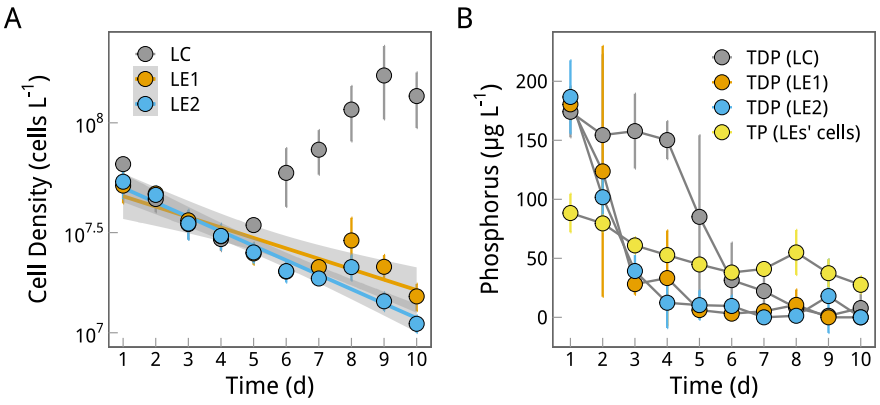

Fig. 2The dynamics of *Microcystis* cell density (A) and phosphorus concentration (B) in laboratory simulators, comprising two simulators with Sediment Resuspension (SR) operations (designated as LE1 and LE2), and one simulator without SR serving as an untreated control (LC). Additionally, panel B illustrates the phosphorus content within the cell.

3.2. *Improvement of sediment properties by SR in laboratory simulators*

During 10-days SR operation, the oxidation-reduction potential (ORP) of the surface sediment in the LEs (-246.50 ± 52.95 mV) was higher than that in the LC (-288.67 ± 32.22 mV), although the difference was not statistically significant (Fig. 3A, *p*-value = 0.0946). Oxide films were observed on the surface sediment layers in LEs (Fig. S6). A significant decrease in dissolved iron concentration (Fig. 3B, *p*-value = 0.0052) in the overlying water was noted after 10-day SR operation in the LEs compared to the LC (Fig. 3B). In addition, the TDP concentrations in the overlying water column of the LEs were significantly lower than those in the LC , even after the cessation of the SR operation (Fig. 3C, *p*-value = 0.0003). This phenomenon was linked to a lower phosphorus increase rate (Fig. S8) in the LEs (1.55 μg L^{-1} d^{-1}, R^2 = 0.53, *p*-value = 0.007) than that in LC(4.29 μg L^{-1} d^{-1}, R^2 = 0.92, *p*-value = 0.0027).

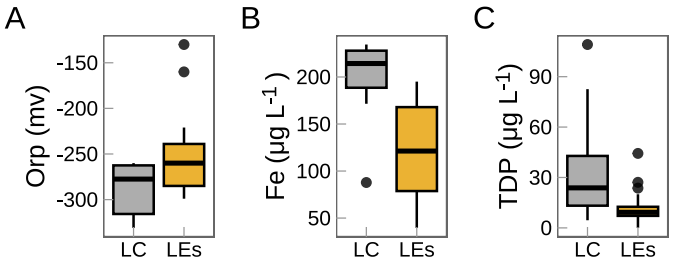

Fig. 3The comparison of Oxidation-Reduction Potential (ORP) in the surface-resuspended sediment (A) and dissolved iron concentration in the overlying water (B) among laboratory simulators over the initial 10 days. This includes two simulators with Sediment Resuspension (SR) operations (LE1, LE2) and one without SR serving as an untreated control (LC) were shown. Additionally, panel C illustrates the comparison of dissolved phosphorus concentration in the overlying water between LC and LEs after the cessation of SR operations from day 11 onwards (day 11–20 and day 31–40).

3.3. *Field applications in five drinking water reservoirs*

All five reservoirs exhibited significantly lower phytoplankton cell densities at the FEs where *in-situ* SR operations were performed compared to the untreated control group (FC, *p*-value < 0.0001). Specifically, in SMH Reservoir with one boat operating SR at a frequency of approximately 0.63 d^{-1}, phytoplankton abundance showed a reduction from 1.63 × 10^8 cell L^{-1} (median, FC) to 0.59 × 10^8 cell L^{-1} (median, FE), achieving a removal rate of 64% (Fig. 4A, Fig. S9). Similarly, in SXK Reservoir, a removal rate of 46% was achieved with a working frequency of 1.17 d^{-1},

as part of long-term operation aimed at preventing cyanobacterial blooms (Fig. 4A, Fig. S10). In terms of short-term SR operations, three boats were utilized in HM Reservoir and two boats were served in both CX and NJ Reservoirs, resulting in the removal rates of 60%, 88%, and 66% respectively (Fig. 4B, Fig. S12–Fig. S14). Overall, the removal rates exhibited a positive correlation with SR intensity, although it was not significant (p-value = 0.1123, Fig. 4D). Besides, the occurrence of surface blooms were noticeably relieved following several days of SR operation in CX Reservoir (Fig. 4D).

After long term SR operation, the sediment ORP exhibited a significant increase from -156 mv (IQR: 28.75 mv) to 4 mv (IQR: 91.125 mv), and the TDP concentrations of reservoir water exhibited a significant decrease from 100 μg L^{-1} (IQR: 65 μg L^{-1}) to 30 μg L^{-1} (IQR: 20 μg L^{-1}) (Fig. 4C). No significant differences in sediment ORP and the TDP were observed between FC and FE in short-term SR operation.

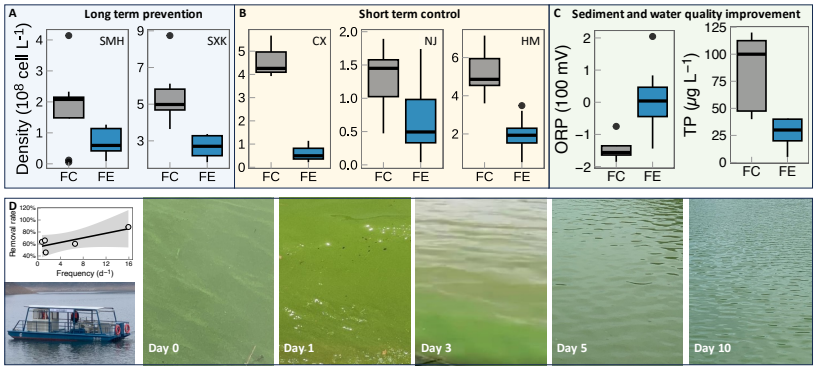

Fig. 4The comparison of observed total phytoplankton cell densities between sites with Sediment Resuspension (SR) operations (FE) and those without (FC) was conducted across five drinking water reservoirs. Long-term SR technology was implemented in SMH and SXK Reservoirs to evaluate its effectiveness in preventing cyanobacterial growth (A), while the CX, NJ, and HM Reservoirs underwent short-term evaluation for cyanobacterial bloom control (B). Panel C illustrates the comparison of Oxidation-Reduction Potential (ORP) of reservoir sediment and total phosphorus concentration of reservoir water, assessing the effect of long-term SR on sediment and water quality. Furthermore, panel D depicts the relationship between cell removal rate and SR working intensity, accompanied by several images that document the changes in the water surface of the CX Reservoir following SR operations from day 0 to day 10. Notably, a severe *Microcystis* bloom in the CX Reservoir provided a vivid visual representation of the changes in the water bodies.

4. Discussion

4.1. The effect of SR operation on light intensity and algal cell sedimentation

Cyanobacterial blooms and associated drinking water safety issues are common in source waters globally. However, controlling algal blooms in source water reservoirs is complicated by the potential introduction of additional water quality risks. Despite the development of various technologies, such as algaecides, flocculants, surfactants, ultrasound, etc., their widespread application in source water reservoirs is severely constrained. In response to this challenge, we have developed and implemented several "green" technologies tailored for source water reservoirs, leveraging the ecological characteristics of harmful cyanobacteria. For instance, water level regulation was implemented in Miyun Reservoir (Su et al., 2017) and turbidity regulation was conducted in QCS Reservoir (Su et al., 2023) to exploit the sensitivity of MIB-producers to underwater light conditions. Additionally, hydraulic regulation has been used to control harmful cyanobacteria with short growth rates, preventing their proliferation through relatively short hydraulic retention times (Lu et al., 2022, 2023). However, the application of these technologies is often constrained by specific prerequisites, such as an insufficient inflow rate. In contrast, the sediment resuspension (SR) technique developed in this study offers a more broadly applicable solution. The SR operation demonstrated substantial algal control effects in the laboratory simulations (Fig. 2A, Fig. S7) and in five drinking water reservoirs (Fig. 4), indicating its effectiveness in managing harmful algal blooms. Furthermore, concerns regarding nutrient release from resuspended sediments into the water column, a highly debated issue, have also been addressed. A key advantage of this approach is the use of local sediment without the need for additional materials or modifications, distinguishing it from other clay-based methods (Zou et al., 2006; Pan et al., 2006).

Systematic monitoring of the laboratory simulation system has revealed key causal mechanisms influenced by sediment resuspension (SR) operations. Notably, underwater light intensity has been identified as a primary factor influenced by SR. During the first 10 minutes of SR operations, the extinction coefficient experienced significant increases with the effects lasting for at

least 2 hours per operation (Fig. 5A, Fig. S3B). Similar patterns of turbidity variation have also been observed in *in situ* practices (Fig. S3A). Specifically, the values of extinction coefficient for the treated set (LEs and FE) were significantly higher compared to the untreated sets (LC and FC) (Fig. 5B). Consequently, the substantial reduction in underwater light intensity due to SR operations plays a crucial role in inhibiting cyanobacterial growth.

The effect of light intensity on the growth of various cyanobacteria (e.g. *Planktothrix* sp. (Jia et al., 2019), *Pseudanabaena* sp. (Wang and Li, 2015; Cao et al., 2023), *Microcystis* (Chaffin et al., 2018), *Planktothricoides* (Lu et al., 2022), *Phormidium* sp. (Li et al., 2012) and so on (Fig. S15) have been extensively studied. These studies suggest that underwater light regulation is an effective method (Su et al., 2017), as demonstrated and validated for *Planktothrix* sp. in Miyun Reservoir (Jia et al., 2019) and QCS Reservoir (Su et al., 2023). Therefore, underwater light reduction resulting from SR operation probably a major factor that restricts the cyanobacterial growth.

In addition to light regulation, SR operation increases the abundance of sinking particles, which envelop cyanobacterial cells, facilitating their co-precipitation and removal from the water surface. This process occurs at a rate of 831 cells mL^{-1} min^{-1} for LE (Fig. 5C), as observed shortly after SR operations. Field application corroborate this mechanism, with FE showing a descent rate of 0.319 μg mL^{-1} min^{-1} for Chl-*a* (Fig. S16). Furthermore, algal cells have the ability to flocculate with sediment particles. During SR, suspended sediment particles collide with algal cells, and the positively charged areas of the particle surface attract the negatively charged algal cells, facilitating their sedimentation. Algal cells tend to adhere to the surfaces of positively charged limestone and iron (III) oxide-hydroxide coatings (Liu et al., 2021). Additionally, particles with larger specific surface areas, higher concentrations, suitable particle sizes, and positive Zeta potentials are more prone to adsorbing algal cells. This multifaceted approach highlights the effectiveness of SR operation in controlling cyanobacterial growth through mechanisms such as light reduction and sediment-assisted removal.

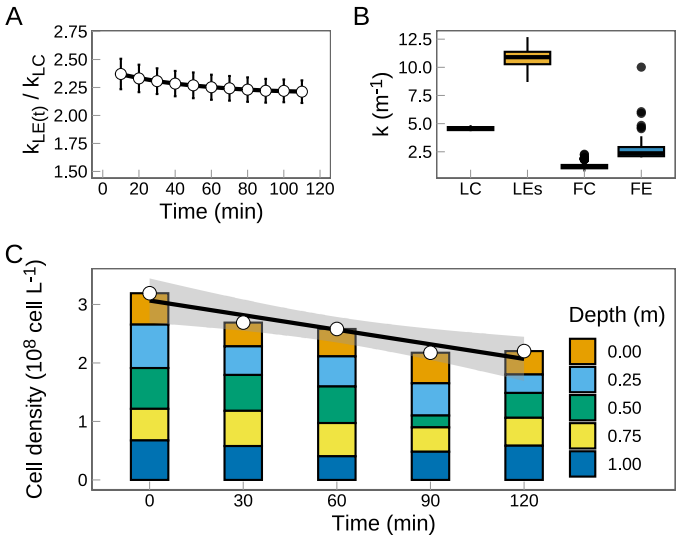

Fig. 5The effects of SR operations on algal control, comparing various parameters between SR-operated sites and untreated control sets. (A) The ratio of the extinction coefficient of SR-operated sites to untreated control sets during the 10-day SR operation cycle (k_{LEs}/k_{LC}, calculation details in Section 2.5); (B) Comparison of the extinction coefficient between SR-operated sites (LEs, FE) and untreated control sets (LC, FC) in laboratory simulators (10 days of SR ON stage, n = 720) and in the NJ reservoir (n = 468); (C) The cell density during the SR operation cycle in an independent experiment (n = 3) as described in Section 2.1.

4.2. The effect of SR operation on dissolved phosphorus removal

Since the dynamics of TDP were different between laboratory SR sets (LEs) and the untreated control set (LC) (Fig. 2B), we conducted an analysis to understand the underlying causal mechanisms. During the SR operation period, the TDP concentration in LC exhibited a significant negative correlation with Chl *a* (R^2 = 0.8335; *p*-value < 0.0001, Fig. 6A), suggesting that the decrease in dissolved phosphorus between day 4 and day 8 (Fig. 2B) was likely due to the consumption by cell growth in LC. In contrast, the linear decrease of phosphorus with the rate of 46 μg L^{-1} d^{-1} was observed in LEs (Fig. 6C), closely following the SR operation from day 1 to day 5, resulting in very low concentrations (Fig. 2B). The distinct phosphorus dynamics between LEs and LC strongly supports the effectiveness of resuspended particles in removing dissolved phosphorus, with dissolved iron probably playing an important role, as evidenced by the significant correlation between dissolved iron and TDP in LEs (R^2 = 0.8309, *p*-value < 0.0001, Fig. 6D). This findings aligns with several clay-based algal control studies (Lürling and Faassen, 2012; Noyma et al., 2016; Heinrich et al., 2021; Cavalcante et al., 2021).

Co-precipitation and oxidation processes within sediments may also contribute to the decline of dissolved phosphorus, as suggested by a field study (You et al., 2007). Colloid-sized particles formed during the SR operation can bind chemicals (Jiang et al., 2017), affecting their mobility and transportation (Qin et al., 2004; Giles et al., 2015; Eltohamy et al., 2023). The coupling of phosphorus with dispersed iron nanoparticles in lakes may alter the bioavailability of phosphorus to phytoplankton (Moorleghem et al., 2013). A field study (Saeed et al., 2018) indicated that the increase of colloid-sized particles during SR operation may decrease phosphorus bioavailability. Additionally, cyanobacterial blooms are often associated with summer stratification in deep reservoirs, where anoxic hypolimnion enhances the reductive dissolution of Fe colloids and phosphorus desorption from sediment (Saeed et al., 2018), especially above the sediment-water interface (Giles et al., 2015). The SR operation can disrupt this stratification by mixing the top warm water with the cold sediment/water, promoting the oxidation of Fe(II) (Miao et al., 2006), co-precipitation of Fe(III) and phosphorus, and/or phosphorus adsorption onto Fe hydroxide colloids. This leads to iron and phosphorus sedimentation and uniformly low dissolved iron and

phosphorus concentrations throughout the water column.

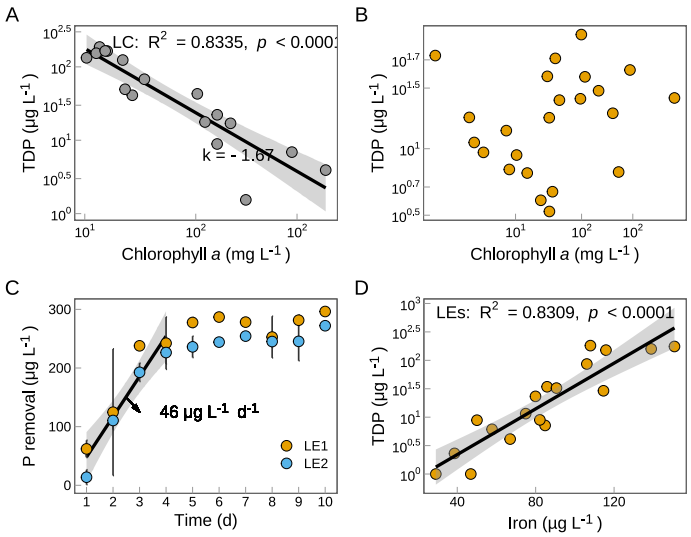

Fig. 6In the laboratory simulator where no SR operation was conducted (LC), a significant correlation between Chl-*a* and total dissolved phosphorus was observed ($R^2 = 0.834$, *p*-value < 0.0001, A). In contrast, no correlation was obtained in SR-operated simulators (LEs), where cell growth was greatly inhibited (B). Phosphorus removal was rapid during the initial 4 days of SR operation in LEs, with a removal rate of 46 µg L^{-1} d^{-1} (C), and the decrease exhibited a significant correlation with dissolved iron ($R^2 = 0.831$, *p*-value < 0.0001).

4.3. SR operation for cyanobacterial control: a promising technology

Based on the laboratory test and field applications, we have developed a conceptual mechanism as illustrated in Fig. 7, although some processes have not been verified in the present study. We deduced that several mechanisms were responsible for the harmful cyanobacterial control and sediment improvement. 1) Significantly reduction of underwater light intensity due to sediment resuspension is probably the primary factor inhibiting and controlling cyanobacterial bloom, especially for the long-term cyanobacterial management. 2) sediment resuspension generates a large amount of particle precipitation. These particles can absorb and flocculate/entrain cyanobacterial cells. The resulting co-precipitation confines the cells within the sediment, thereby inhibiting their growth due to a lack of underwater light and/or the collapse of gas vesicles, especially if the reservoir is sufficiently deep (Abeynayaka et al., 2017). 3) SR operation can introduce dissolved oxygen into resuspended particles, significantly enhancing the

redox potential of sediment. It plays a remarkable role in oxidizing dissolved iron into particulate Fe (III), which, in turn, can reduce the soluble phosphorus concentration via adsorption (Zeng et al., 2004). Besides, the sediment will be covered by "oxidized particle layer", which helps inhibit the release of phosphate and iron. 4) SR operation could be conducive to break the stratification, which may inhibit the cyanobacterial growth (Visser et al., 2016).

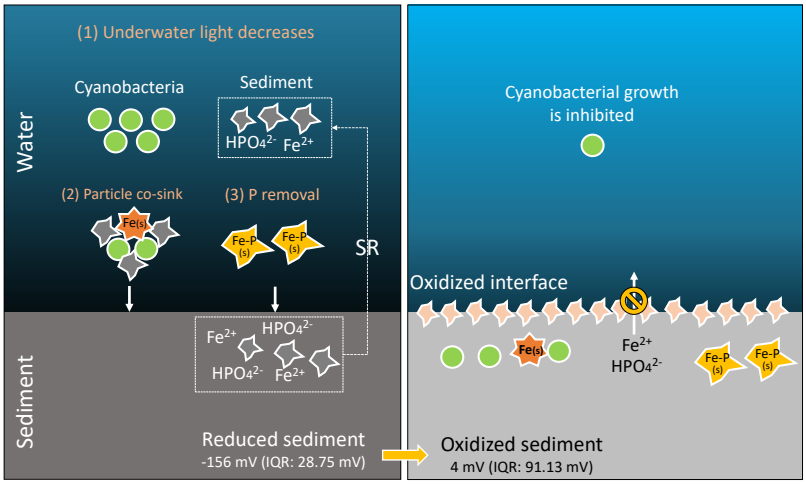

Fig. 7Mechanical sketch illustrating the operation of Sediment Resuspension (SR) and its effects on algal control, phosphorus removal, and sediment quality improvement.

As a novel technology, SR operation offers a sustainable solution for controlling cyanobacteria without the need to introduce additional substances. This makes it a safe and cost-effective alternative to methods such as clay application (Park et al., 2013; Gallardo-Rodríguez et al., 2018). A particularly significant concern is the potential excessive release of iron and manganese from the sediment, as their accumulation could adversely impact water quality (Munger et al., 2016; Zhou et al., 2022; Chen et al., 2015). Consequently, the concentrations of iron (Fig. S17) and manganese (Fig. S18) during SR operation in field applications have been investigated. No significant difference in iron concentration (Fig. S17A, *p*-value = 0.2891; Fig. S17B, *p*-value = 0.2898) was found between FE and FC across three reservoirs. Additionally, higher concentrations of manganese were not observed (Fig. S18A, *p*-value = 0.4392; Fig. S18B, *p*-value = 0.0031) in FE. Nevertheless, continuous research is imperative to refine and broaden our understanding of SR

operation and its contribution to sustainable cyanobacterial control. Several aspects necessitate further elucidation, including application scenarios, limitations, and the succession of the benthic ecosystem.

5. Conclusion

This study proposes a new technology based on *in-situ* sediment resuspension (SR) for cyanobacterial control. Results from laboratory simulators revealed that significant cyanobacterial removal is resulted from the reduction of underwater light and the flocculation and/or entrainment of cyanobacterial cells contributed by resuspended particles. Meanwhile, phosphorus can be rapidly removed from the water attributed by the iron-bind particles. Moreover, The long-term sediment resuspension significantly improved sediment quality, with the oxidized surface sediment inhibiting the release of phosphate, iron, and other elements. As SR technology does not require the addition of external substances, it presents a safe and economical technology for managing harmful cyanobacteria in drinking water reservoirs.

6. Acknowledgement

This work received financial support from the following sources, National Natural Science Foundation of China (Grant Numbers: 52030002), China Key Research and Development Program (Grant Number: 2022YFC3203603) and Youth Innovation Promotion Association CAS.

References

Abeynayaka, H.D.L., Asaeda, T., Kaneko, Y., 2017. Buoyancy limitation of filamentous cyanobacteria under prolonged pressure due to the gas vesicles collapse. Environmental Management 60, 293–303. URL: https://doi.org/10.1007/s00267-017-0875-7, doi:10.1007/s00267-017-0875-7.

Acuña, S., Baxa, D., Teh, S., 2012. Sublethal dietary effects of microcystin producing *Microcystis* on Threadfin Shad, Dorosoma Petenense. Toxicon 60, 1191–1202. URL: http://www.sciencedirect.com/science/article/pii/S0041010112007179, doi:10.1016/j.toxicon.2012.08.004.

Agrawal, A., Gopal, K., 2012. Toxic cyanobacteria in water and their public health consequences, in: Biomonitoring of Water and Waste Water. Springer India, pp. 135–147. URL: https://doi.org/10.1007/978-81-322-0864-8_13, doi:10.1007/978-81-322-0864-8_13.

Anderson, D.M., Andersen, P., Bricelj, V.M., Cullen, J.J., Rensel, J.J., 2001. Monitoring and management strategies for harmful algal blooms in coastal waters. Unesco Paris, France:.

Beaulieu, S.E., Sengco, M.R., Anderson, D.M., 2005. Using clay to control harmful algal blooms: deposition and resuspension of clay/algal flocs. Harmful Algae 4, 123–138. URL: https://doi.org/10.1016/j.hal.2003.12.008, doi:10.1016/j.hal.2003.12.008.

Bellinger, E., Sigee, D., 2015. Freshwater Algae: Identification, enumeration and use as bioindicators: Second edition. doi:10.1002/9781118917152.

Blanco, E.P., Karlsson, C., Pallon, J., Granéli, E., 2013. Composition of carbon, nitrogen and phosphorus in single cells of three filamentous cyanobacteria using nuclear microprobe and traditional techniques. Aquatic Microbial Ecology 71, 91–97. URL: https://doi.org/10.3354/ame01665, doi:10.3354/ame01665.

Boyd, C.E., 1979. Aluminum sulfate (alum) for precipitating clay turbidity from fish ponds. Transactions of the American Fisheries Society 108, 307–313. URL: https://doi.org/10.1577/1548-8659%281979%29108%3C307%3Aasafpc%3E2.0.co%3B2, doi:10.1577/1548-8659(1979)108<307:asafpc>2.0.co;2.

Bruchet, A., LIN, T., WATSON, S., DIETRICH, A., SUFFET, I., 2019. Taste and odour in source and drinking water: Causes, controls, and consequences.

Cao, T., Fang, J., Jia, Z., Zhu, Y., Su, M., Zhang, Q., Song, Y., Yu, J., Yang, M., 2023. Early warning of mib episode based on gene abundance and expression in drinking water reservoirs. Water Research 231, 119667. URL: https://www.sciencedirect.com/science/article/pii/S0043135423001021, doi:https://doi.org/10.1016/j.watres.2023.119667.

Cao, X., Wang, Y., He, J., Luo, X., Zheng, Z., 2016. Phosphorus mobility among sediments, water and cyanobacteria enhanced by cyanobacteria blooms in eutrophic lake dianchi. Environmental Pollution 219, 580–587. URL: https://doi.org/10.1016/j.envpol.2016.06.017, doi:10.1016/j.envpol.2016.06.017.

Cavalcante, H., Araújo, F., Becker, V., Lucena-Barbosa, J.E., 2021. Control of internal phosphorus loading using coagulants and clays in water and the sediment of a semiarid reservoir susceptible to resuspension. Hydrobiologia 849, 4059–4071. URL: http://dx.doi.org/10.1007/s10750-021-04737-0, doi:10.1007/s10750-021-04737-0.

Chaffin, J.D., Davis, T.W., Smith, D.J., Baer, M.M., Dick, G.J., 2018. Interactions between nitrogen form, loading rate, and light intensity on *Microcystis* and *Planktothrix* growth and microcystin production. Harmful Algae 73, 84–97. URL: http://www.sciencedirect.com/science/article/pii/s1568988318300210, doi:10.1016/j.hal.2018.02.001.

Chen, Y., Xiao, F., Liu, Y., Wang, D., Yang, M., Bai, H., Zhang, J., 2015. Occurance and control of manganese in a large scale water treatment plant. Frontiers of Environmental Science & Engineering 9, 66–72. URL: http://dx.doi.org/10.1007/s11783-014-0637-1, doi:10.1007/s11783-014-0637-1.

Cheung, M.Y., Liang, S., Lee, J., 2013. Toxin-producing cyanobacteria in freshwater: A review of the problems, impact on drinking water safety, and efforts for protecting public health. Journal of Microbiology 51, 1–10. URL: https://doi.org/10.1007/s12275-013-2549-3, doi:10.1007/s12275-013-2549-3.

Chia, M.A., Jankowiak, J.G., Kramer, B.J., Goleski, J.A., shuo Huang, I., Zimba, P.V., Bittencourt-oliveira, M.D.C., Gobler,

C.J., 2018. Succession and toxicity of *Microcystis* and *Anabaena* (*dolichospermum*) blooms are controlled by nutrient-dependent allelopathic interactions. Harmful Algae 74, 67–77. URL: http://www.sciencedirect.com/science/article/pii/s1568988318300295, doi:10.1016/j.hal.2018.03.002.

Chorus, I., McKeown, R.M., 2021. Assessing and managing cyanobacterial risks in water-use systems, in: Toxic Cyanobacteria in Water. CRC Press, pp. 401–432.

Davis, T.W., Berry, D.L., Boyer, G.L., Gobler, C.J., 2009. The effects of temperature and nutrients on the growth and dynamics of toxic and non-toxic strains of *Microcystis* during cyanobacteria blooms. Harmful Algae 8, 715–725. URL: http://www.sciencedirect.com/science/article/pii/s1568988309000390, doi:10.1016/j.hal.2009.02.004. this Issue Contains the Special Section on Strains.

Dittmann, E., Fewer, D.P., Neilan, B.A., 2013. Cyanobacterial toxins: Biosynthetic routes and evolutionary roots. Fems Microbiology Reviews 37, 23–43. URL: http://femsre.oxfordjournals.org/content/37/1/23, doi:10.1111/j.1574-6976.2012.12000.x, arXiv:http://femsre.oxfordjournals.org/content/37/1/23.full.pdf.

Dixon, P., 2003. VEGAN, a package of r functions for community ecology. Journal of Vegetation Science 14, 927–930. URL: https://doi.org/10.1111/j.1654-1103.2003.tb02228.x, doi:10.1111/j.1654-1103.2003.tb02228.x.

Eltohamy, K.M., Li, J., Gouda, M., Menezes-Blackburn, D., Milham, P.J., Khan, S., Li, F., Liu, C., Xu, J., Liang, X., 2023. Nano and fine colloids suspended in the soil solution regulate phosphorus desorption and lability in organic fertiliser-amended soils. Science of The Total Environment 858, 160195. URL: https://doi.org/10.1016/j.scitotenv.2022.160195, doi:10.1016/j.scitotenv.2022.160195.

de Figueiredo, D.R., Azeiteiro, U.M., Esteves, S.M., Gonçalves, F.J., Pereira, M.J., 2004. Microcystin-producing blooms—a serious global public health issue. Ecotoxicology and Environmental Safety 59, 151–163. URL: https://doi.org/10.1016/j.ecoenv.2004.04.006, doi:10.1016/j.ecoenv.2004.04.006.

Gallardo-Rodríguez, J.J., Astuya-Villalón, A., Llanos-Rivera, A., Avello-Fontalba, V., Ulloa-Jofré, V., 2018. A critical review on control methods for harmful algal blooms. Reviews in Aquaculture 11, 661–684. URL: https://doi.org/10.1111/raq.12251, doi:10.1111/raq.12251.

Giles, C.D., Isles, P.D.F., Manley, T., Xu, Y., Druschel, G.K., Schroth, A.W., 2015. The mobility of phosphorus, iron, and manganese through the sediment–water continuum of a shallow eutrophic freshwater lake under stratified and mixed water-column conditions. Biogeochemistry 127, 15–34. URL: https://doi.org/10.1007/s10533-015-0144-x, doi:10.1007/s10533-015-0144-x.

Hammond, N.W., Birgand, F., Carey, C.C., Bookout, B., Breef-Pilz, A., Schreiber, M.E., 2023. High-frequency sensor data capture short-term variability in fe and mn concentrations due to hypolimnetic oxygenation and seasonal dynamics in a drinking water reservoir. Water Research 240, 120084. URL: http://dx.doi.org/10.1016/j.watres.2023.120084, doi:10.1016/j.watres.2023.120084.

He, X., Liu, Y.L., Conklin, A., Westrick, J., Weavers, L.K., Dionysiou, D.D., Lenhart, J.J., Mouser, P.J., Szlag, D., Walker, H.W., 2016. Toxic cyanobacteria and drinking water: Impacts, detection, and treatment. Harmful Algae 54, 174–193. URL: https://doi.org/10.1016/j.hal.2016.01.001, doi:10.1016/j.hal.2016.01.001.

Heinrich, L., Rothe, M., Braun, B., Hupfer, M., 2021. Transformation of redox-sensitive to redox-stable iron-bound phosphorus in anoxic lake sediments under laboratory conditions. Water Research 189, 116609. URL: http://dx.doi.org/10.1016/j.watres.2020.116609, doi:10.1016/j.watres.2020.116609.

Huisman, J., Codd, G.A., Paerl, H.W., Ibelings, B.W., Verspagen, J.M.H., Visser, P.M., 2018. Cyanobacterial blooms. Nature Reviews Microbiology 16, 471–483. URL: https://doi.org/10.1038/s41579-018-0040-1, doi:10.1038/s41579-018-0040-1.

Jia, Z., Su, M., Liu, T., Guo, Q., Wang, Q., Burch, M., Yu, J., Yang, M., 2019. Light as a possible regulator of MIB-producing *Planktothrix* in source water reservoir, mechanism and *in-situ* verification. Harmful Algae 88, 101658. URL: http://www.sciencedirect.com/science/article/pii/s1568988319301313, doi:10.1016/j.hal.2019.101658.

Jiang, X., Bol, R., Cade-Menun, B.J., Nischwitz, V., Willbold, S., Bauke, S.L., Vereecken, H., Amelung, W., Klumpp, E., 2017. Colloid-bound and dissolved phosphorus species in topsoil water extracts along a grassland transect from cambisol to stagnosol. Biogeosciences 14, 1153–1164. URL: https://doi.org/10.5194/bg-14-1153-2017, doi:10.5194/bg-14-1153-2017.

Kim, H.G., 2006. Mitigation and Controls of HABs. Springer Berlin Heidelberg, Berlin, Heidelberg. URL: https://doi.org/10.1007/978-3-540-32210-8_25, doi:10.1007/978-3-540-32210-8_25.

King, D.W., 1998. Role of carbonate speciation on the oxidation rate of fe(ii) in aquatic systems. Environmental Science & Technology 32, 2997–3003. URL: http://dx.doi.org/10.1021/es980206o, doi:10.1021/es980206o.

Komarek, J., Kastovsky, J., Mares, J., Johansen, J.R., 2014. Taxonomic classification of cyanoprokaryotes (cyanobacterial genera) 2014, using a polyphasic approach. Preslia 86, 295–335.

Komárek, J., Anagnostidis, K., 1998. Cyanoprokaryota 1. volume 19(1). Deu.

Lee, Y.J., Choi, J.K., Kim, E.K., Youn, S.H., Yang, E.J., 2008. Field experiments on mitigation of harmful algal blooms using a sophorolipid—yellow clay mixture and effects on marine plankton. Harmful Algae 7, 154–162. URL: https://doi.org/10.1016/j.hal.2007.06.004, doi:10.1016/j.hal.2007.06.004.

Li, H., Pan, G., 2015. Simultaneous removal of harmful algal blooms and microcystins using microorganism- and chitosan-modified local soil. Environmental Science & Technology 49, 6249–6256. URL: https://doi.org/10.1021/acs.est.5b00840, doi:10.1021/acs.est.5b00840.

Li, L., Pan, G., 2013. A universal method for flocculating harmful algal blooms in marine and fresh waters using modified sand. Environmental Science & Technology 47, 4555–4562. URL: https://doi.org/10.1021/es305234d, doi:10.1021/es305234d.

Li, X., Dreher, T.W., Li, R., 2016. An overview of diversity, occurrence, genetics and toxin production of bloom-forming dolichospermum (anabaena) species. Harmful Algae 54, 54–68. URL: http://www.sciencedirect.com/science/article/pii/s1568988315301050, doi:10.1016/j.hal.2015.10.015. global Expansion of Harmful Cyanobacterial Blooms: Diversity, Ecology, Causes, and Controls.

Li, Z., Hobson, P., An, W., Burch, M.D., House, J., Yang, M., 2012. Earthy odor compounds production and loss in three cyanobacterial cultures. Water Research 46, 5165–5173. URL: http://www.sciencedirect.com/science/article/pii/

s0043135412004046, doi:10.1016/j.watres.2012.06.008.

Liu, H., Yuan, P., Liu, D., Zhang, W., Tian, Q., Bu, H., Wei, Y., Xia, J., Wang, Y., Zhou, J., 2021. Insight into cyanobacterial preservation in shallow marine environments from experimental simulation of cyanobacteria-clay co-aggregation. Chemical Geology 577, 120285. URL: https://doi.org/10.1016/j.chemgeo.2021.120285, doi:10.1016/j.chemgeo.2021.120285.

Lu, G., Song, X., Yu, Z., Cao, X., 2016. Application of PAC-modified kaolin to mitigate prorocentrum donghaiense: effects on cell removal and phosphorus cycling in a laboratory setting. Journal of Applied Phycology 29, 917–928. URL: https://doi.org/10.1007/s10811-016-0992-3, doi:10.1007/s10811-016-0992-3.

Lu, J., Su, M., Su, Y., Fang, J., Burch, M., Cao, T., Wu, B., Yu, J., Yang, M., 2023. MIB-derived odor management based upon hydraulic regulation in small drinking water reservoirs: principle and application. Water Research 244, 120485. URL: https://www.sciencedirect.com/science/article/pii/S0043135423009259, doi:10.1016/j.watres.2023.120485.

Lu, J., Su, M., Su, Y., Wu, B., Cao, T., Fang, J., Yu, J., Zhang, H., Yang, M., 2022. Driving forces for the growth of mib-producing *Planktothricoides raciborskii* in a low-latitude reservoir. Water Research , 118670URL: https://www.sciencedirect.com/science/article/pii/S0043135422006236, doi:10.1016/j.watres.2022.118670.

Lürling, M., Faassen, E.J., 2012. Controlling toxic cyanobacteria: Effects of dredging and phosphorus-binding clay on cyanobacteria and microcystins. Water Research 46, 1447–1459. URL: https://doi.org/10.1016/j.watres.2011.11.008, doi:10.1016/j.watres.2011.11.008.

Lürling, M., Noyma, N.P., de Magalhães, L., Miranda, M., Mucci, M., van Oosterhout, F., Huszar, V.L., Marinho, M.M., 2017. Critical assessment of chitosan as coagulant to remove cyanobacteria. Harmful Algae 66, 1–12. URL: https://doi.org/10.1016/j.hal.2017.04.011, doi:10.1016/j.hal.2017.04.011.

Lürling, M., van Oosterhout, F., 2013. Controlling eutrophication by combined bloom precipitation and sediment phosphorus inactivation. Water Research 47, 6527–6537. URL: https://doi.org/10.1016/j.watres.2013.08.019, doi:10.1016/j.watres.2013.08.019.

Martinez, M., Chakroff, R., Pantastico, J., 1975. Note: direct phytoplankton counting techniques, using the haemacytometer. Philippine agriculturist .

Miao, S., DeLaune, R., Jugsujinda, A., 2006. Influence of sediment redox conditions on release/solubility of metals and nutrients in a louisiana mississippi river deltaic plain freshwater lake. Science of The Total Environment 371, 334–343. URL: https://doi.org/10.1016/j.scitotenv.2006.07.027, doi:10.1016/j.scitotenv.2006.07.027.

Millero, F.J., Sotolongo, S., Izaguirre, M., 1987. The oxidation kinetics of Fe(II) in seawater. Geochimica et Cosmochimica Acta 51, 793–801. URL: https://www.sciencedirect.com/science/article/pii/0016703787900937, doi:https://doi.org/10.1016/0016-7037(87)90093-7.

Moorleghem, C.V., Schutter, N.D., Smolders, E., Merckx, R., 2013. The bioavailability of colloidal and dissolved organic phosphorus to the alga pseudokirchneriella subcapitata in relation to analytical phosphorus measurements. Hydrobiologia 709, 41–53. URL: https://doi.org/10.1007/s10750-013-1442-8, doi:10.1007/s10750-013-1442-8.

Munger, Z.W., Carey, C.C., Gerling, A.B., Hamre, K.D., Doubek, J.P., Klepatzki, S.D., McClure, R.P., Schreiber, M.E., 2016.

Effectiveness of hypolimnetic oxygenation for preventing accumulation of fe and mn in a drinking water reservoir. Water Research 106, 1–14. URL: http://dx.doi.org/10.1016/j.watres.2016.09.038, doi:10.1016/j.watres.2016.09.038.

Murray, G.C., Hesterberg, D., 2006. Iron and phosphate dissolution during abiotic reduction of ferrihydrite-boehmite mixtures. Soil Science Society of America Journal 70, 1318–1327. URL: https://acsess.onlinelibrary.wiley.com/doi/abs/10.2136/sssaj2005.0292, doi:https://doi.org/10.2136/sssaj2005.0292. tex.eprint: https://acsess.onlinelibrary.wiley.com/doi/pdf/10.2136/sssaj2005.0292.

Naceradska, J., Pivokonska, L., Pivokonsky, M., 2019. On the importance of pH value in coagulation. Journal of Water Supply: Research and Technology-Aqua 68, 222–230. URL: https://doi.org/10.2166/aqua.2019.155, doi:10.2166/aqua.2019.155.

Noyma, N.P., de Magalhães, L., Furtado, L.L., Mucci, M., van Oosterhout, F., Huszar, V.L., Marinho, M.M., Lürling, M., 2016. Controlling cyanobacterial blooms through effective flocculation and sedimentation with combined use of flocculants and phosphorus adsorbing natural soil and modified clay. Water Research 97, 26–38. URL: https://doi.org/10.1016/j.watres.2015.11.057, doi:10.1016/j.watres.2015.11.057.

Paerl, H.W., Gardner, W.S., McCarthy, M.J., Peierls, B.L., Wilhelm, S.W., 2014. Algal blooms: Noteworthy nitrogen. Science 346, 175–175. URL: https://science.sciencemag.org/content/346/6206/175.1, doi:10.1126/science.346.6206.175-a.

Pan, G., Zhang, M.M., Chen, H., Zou, H., Yan, H., 2006. Removal of cyanobacterial blooms in taihu lake using local soils. i. equilibrium and kinetic screening on the flocculation of microcystis aeruginosa using commercially available clays and minerals. Environmental Pollution 141, 195–200. URL: https://doi.org/10.1016/j.envpol.2005.08.041, doi:10.1016/j.envpol.2005.08.041.

Park, T.G., Lim, W.A., Park, Y.T., Lee, C.K., Jeong, H.J., 2013. Economic impact, management and mitigation of red tides in korea. Harmful Algae 30, S131–S143. URL: https://doi.org/10.1016/j.hal.2013.10.012, doi:10.1016/j.hal.2013.10.012.

Pierce, R.H., Henry, M.S., Higham, C.J., Blum, P., Sengco, M.R., Anderson, D.M., 2004. Removal of harmful algal cells (karenia brevis) and toxins from seawater culture by clay flocculation. Harmful Algae 3, 141–148. URL: https://doi.org/10.1016/j.hal.2003.09.003, doi:10.1016/j.hal.2003.09.003.

Qin, B., Gao, G., Zhu, G., Zhang, Y., Song, Y., Tang, X., Xu, H., Deng, J., 2012. Lake eutrophication and its ecosystem response. Chinese Science Bulletin 58, 961–970. URL: https://doi.org/10.1007/s11434-012-5560-x, doi:10.1007/s11434-012-5560-x.

Qin, B., Hu, W., Gao, G., Luo, L., Zhang, J., 2004. Dynamics of sediment resuspension and the conceptual schema of nutrient release in the large shallow lake taihu, china. Chinese Science Bulletin 49, 54–64. URL: https://doi.org/10.1007/bf02901743, doi:10.1007/bf02901743.

R Core Team, 2021. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing. Vienna, Austria. URL: https://www.r-project.org/.

Saeed, H., Hartland, A., Lehto, N.J., Baalousha, M., Sikder, M., Sandwell, D., Mucalo, M., Hamilton, D.P., 2018. Regulation of phosphorus bioavailability by iron nanoparticles in a monomictic lake. Scientific Reports 8. URL: https://doi.org/10.1038/s41598-018-36103-x, doi:10.1038/s41598-018-36103-x.

Santana-Casiano, J., González-Dávila, M., Millero, F., 2006. The role of fe(ii) species on the oxidation of fe(ii) in natural waters in the presence of o2 and h2o2. Marine Chemistry 99, 70–82. URL: http://dx.doi.org/10.1016/j.marchem.2005.03.010, doi:10.1016/j.marchem.2005.03.010.

Schroeder, E.D., Young, T.M., 1996. Aquatic chemistry, third edition. Eos, Transactions American Geophysical Union 77, 284–284. URL: http://dx.doi.org/10.1029/96EO00205, doi:10.1029/96eo00205.

Sengco, M., Li, A., Tugend, K., Kulis, D., Anderson, D., 2001. Removal of red- and brown-tide cells using clay flocculation. i. laboratory culture experiments with gymnodinium breve and aureococcus anophagefferens. Marine Ecology Progress Series 210, 41–53. URL: https://doi.org/10.3354/meps210041, doi:10.3354/meps210041.

Sherr, E.B., Sherr, B.F., 1993. Preservation and storage of samples for enumeration of heterotrophic protists. Handbook of Methods in Aquatic Microbial Ecology. Lewis Publishers, Boca Raton , 207–212.

Su, M., Andersen, T., Burch, M., Jia, Z., An, W., Yu, J., Yang, M., 2019. Succession and interaction of surface and subsurface cyanobacterial blooms in oligotrophic/mesotrophic reservoirs: A case study in Miyun Reservoir. Science of the Total Environment 649, 1553–1562. URL: http://www.sciencedirect.com/science/article/pii/s0048969718332789, doi:J.scitotenv.2018.08.307.

Su, M., Jia, D., Yu, J., Vogt, R.D., Wang, J., An, W., Yang, M., 2017. Reducing production of taste and odor by deep-living cyanobacteria in drinking water reservoirs by regulation of water level. Science of the Total Environment 574, 1477–1483. URL: http://www.sciencedirect.com/science/article/pii/s0048969716318356, doi:10.1016/j.scitotenv.2016.08.134.

Su, M., Suruzzaman, M., Zhu, Y., Lu, J., Yu, J., Zhang, Y., Yang, M., 2021. Ecological niche and in-situ control of MIB producers in source water. Journal of Environmental Sciences 110, 119–128. URL: https://doi.org/10.1016/j.jes.2021.03.026, doi:10.1016/j.jes.2021.03.026.

Su, M., Yu, J., Zhang, J., Chen, H., An, W., Vogt, R.D., Andersen, T., Jia, D., Wang, J., Yang, M., 2015. MIB-producing cyanobacteria (*Planktothrix* sp.) in a drinking water reservoir: Distribution and odor producing potential. Water Research 68, 444–453. URL: http://www.sciencedirect.com/science/article/pii/s004313541400668x, doi:10.1016/j.watres.2014.09.038.

Su, M., Zhu, Y., Andersen, T., Wang, X., Yu, Z., Lu, J., Song, Y., Cao, T., Yu, J., Zhang, Y., Yang, M., 2022. Light-dominated selection shaping filamentous cyanobacterial assemblages drives odor problem in a drinking water reservoir. npj Clean Water 5, 37. URL: https://doi.org/10.1038/s41545-022-00181-2, doi:10.1038/s41545-022-00181-2.

Su, M., Zhu, Y., Burch, M., Lu, J., Cao, T., Ai, Y., Yu, J., Yang, M., 2023. Control of MIB-producing cyanobacteria based upon turbidity management in an estuary reservoir. Unpublished 0, 0–0.

Sun, X.X., Lee, Y.J., Choi, J.K., Kim, E.K., 2004. Synergistic effect of sophorolipid and loess combination in harmful algal blooms mitigation. Marine Pollution Bulletin 48, 863–872. URL: https://doi.org/10.1016/j.marpolbul.2003.11.002,

doi:10.1016/j.marpolbul.2003.11.002.

Van Der Ploeg, M., Dennis, M., De Regt, M., 1995. Biology of *Oscillatoria chalybea*, a 2-methylisoborneol producing blue-green alga of Mississippi Catfish Ponds. Water Science and Technology 31, 173–180. URL: https://www.sciencedirect.com/science/article/pii/027312239500473Z, doi:10.1016/0273-1223(95)00473-Z.

Visser, P.M., Ibelings, B.W., Bormans, M., Huisman, J., 2016. Artificial mixing to control cyanobacterial blooms: A review. Aquatic Ecology 50, 423–441. URL: https://doi.org/10.1007/s10452-015-9537-0, doi:10.1007/s10452-015-9537-0.

Waajen, G., van Oosterhout, F., Douglas, G., Lürling, M., 2016. Management of eutrophication in lake de kuil (the netherlands) using combined flocculant – lanthanum modified bentonite treatment. Water Research 97, 83–95. URL: https://doi.org/10.1016/j.watres.2015.11.034, doi:10.1016/j.watres.2015.11.034.

Wang, L., Liang, W., Yu, J., Liang, Z., Ruan, L., Zhang, Y., 2013. Flocculation of *Microcystis aeruginosa* using modified larch tannin. Environmental Science & Technology 47, 5771–5777. URL: https://doi.org/10.1021/es400793x, doi:10.1021/es400793x.

Wang, Z., Li, R., 2015. Effects of light and temperature on the odor production of 2-methylisoborneol-producing *Pseudanabaena* sp. and geosmin-producing *Anabaena ucrainica* (cyanobacteria). Biochemical Systematics and Ecology 58, 219–226. URL: http://www.sciencedirect.com/science/article/pii/s0305197814003378, doi:10.1016/j.bse.2014.12.013.

Watson, S.B., 2004. Aquatic taste and odor: A primary signal of drinking-water integrity. Journal of Toxicology and Environmental Health, Part A 67, 1779–1795. URL: https://doi.org/10.1080/15287390490492377, doi:10.1080/15287390490492377, arXiv:https://doi.org/10.1080/15287390490492377. pMID: 15371216.

WHO, W.H.O., 2015. Management of cyanobacteria in drinking-water supplies. Technical Report. World Health Organization. Geneva, Switzerland.

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, T., Miller, E., Bache, S., Müller, K., Ooms, J., Robinson, D., Seidel, D., Spinu, V., Takahashi, K., Vaughan, D., Wilke, C., Woo, K., Yutani, H., 2019. Welcome to the tidyverse. Journal of Open Source Software 4, 1686. URL: https://doi.org/10.21105/joss.01686, doi:10.21105/joss.01686.

Yang, B., Graham, N., Liu, P., Liu, M., Gregory, J., Yu, W., 2023. Atomic-level structural differences between fe(iii) co-precipitates generated by the addition of fe(iii) coagulants and by the oxidation of fe(ii) coagulants determine their coagulation behavior in phosphate and dom removal. Environmental Science & Technology 57, 12489−12500. URL: http://dx.doi.org/10.1021/acs.est.3c03463, doi:10.1021/acs.est.3c03463.

You, B., Zhong, J., Fan, C., Wang, T., Zhang, L., Ding, S., 2007. Effects of hydrodynamics processes on phosphorus fluxes from sediment in large, shallow taihu lake. Journal of Environmental Sciences 19, 1055–1060. URL: https://doi.org/10.1016/s1001-0742%2807%2960172-7, doi:10.1016/s1001-0742(07)60172-7.

Yuan, Y., Zhang, H., Pan, G., 2016. Flocculation of cyanobacterial cells using coal fly ash modified chitosan. Water Research 97, 11–18. URL: https://doi.org/10.1016/j.watres.2015.12.003, doi:10.1016/j.watres.2015.12.003.

Zeng, L., Li, X., Liu, J., 2004. Adsorptive removal of phosphate from aqueous solutions using iron oxide tailings. Water Research 38, 1318–1326. URL: https://doi.org/10.1016/j.watres.2003.12.009, doi:10.1016/j.watres.2003.12.009.

Zhou, X., Nakanishi, T., Echigo, S., Kosaka, K., Itoh, S., 2022. Effect of hydraulic conditions on manganese accumulation by physical and chemical pathways in chlorinated water distribution system: A preliminary laboratory study. Water Supply 22, 7576–7589. URL: http://dx.doi.org/10.2166/ws.2022.338, doi:10.2166/ws.2022.338.

Zohary, T., Padisák, J., Naselli-flores, L., 2010. Phytoplankton in the physical environment: Beyond nutrients, at the end, there is some light. Hydrobiologia 639, 261–269. URL: http://dx.doi.org/10.1007/s10750-009-0032-2, doi:10.1007/s10750-009-0032-2.

Zou, H., Pan, G., Chen, H., Yuan, X., 2006. Removal of cyanobacterial blooms in taihu lake using local soils II. effective removal of microcystis aeruginosa using local soils and sediments modified by chitosan. Environmental Pollution 141, 201–205. URL: https://doi.org/10.1016/j.envpol.2005.08.042, doi:10.1016/j.envpol.2005.08.042.