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RESEARCH ARTICLE

Combining hydrogen peroxide addition with sunlight regulation to control algal blooms

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Abstract The concentration, light conditions during treatment, and the number of hydrogen peroxide (H_2O_2) additions as well as the H_2O_2 treatment combined with subsequent shading to control algal blooms were studied in the field (Lake Dianchi, China). The cyanobacterial stress and injury due to H_2O_2 were dose dependent, and the control effectiveness and degradation of H_2O_2 were better and faster under full light than under shading. However, H_2O_2 was only able to control a bloom for a short time, so it may have promoted the recovery of algae and allowed the biomass to rebound due to the growth of eukaryotic algae. A second addition of H_2O_2 at the same dose had no obvious effect on algal control in the short term, suggesting that a higher concentration or a delayed addition should be considered, but these alternative strategies are not recommended so that the integrity of the aquatic ecosystem is maintained and algal growth is not promoted. Moreover, shading (85%) after H_2O_2 addition significantly reduced the algal biomass during the enclosure test, no restoration was observed for nearly a month, and the proportion of eukaryotic algae declined. It can be inferred that algal blooms can be controlled by applying a high degree of shading after treatment with H_2O_2.

Keywords Phytoplankton · Hydrogen peroxide (H_2O_2) · Shading · Maximum quantum yield of PSII (F_v/F_m) · Lake Dianchi

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Introduction

The occurrence of algal blooms in freshwaters such as lakes, reservoirs, and ponds has been recognized as a serious environmental problem. Several options exist for controlling algal blooms (He et al. 2016, Paerl & Otten 2013), of which the addition of hydrogen peroxide (H_2O_2) is strongly oxidizing. The impacts of H_2O_2 on algae mainly include decreasing metabolic activity (Chen et al. 2016, Mikula et al. 2012), destroying pigment synthesis (Chen et al. 2016, Qian et al. 2010) and membrane integrity (Fan et al. 2014, Mikula et al. 2012, Qian et al. 2010), inhibiting photosynthetic activity and genes expression (Bouchard & Purdie 2011, Qian et al. 2010), altering circadian rhythms (Qian et al. 2012), and inducing apoptotic-like cell death (Ding et al. 2012). Hydrogen peroxide will also decrease the toxins in algal cells (Qian et al. 2010) and remove toxins from raw water (Barrington et al. 2013) by increasing the toxin oxidation rate over the release rate (Fan et al. 2014). Therefore, H_2O_2 has commonly been used to control algal blooms, although it can be produced in raw water under natural conditions (Cooper & Zika 1983).

Different H_2O_2 tolerances exist among algal species (Barrington & Ghadouani 2008, Drábková et al. 2007a, Drábková et al. 2007b, Matthijs et al. 2012, Weenink et al. 2015), and the stress and injury to algae due to H_2O_2 is dose dependent (Chen et al. 2016, Ding et al. 2012, Drábková et al.

2007a, Drábková et al. 2007b). However, aquatic ecosystems contain assemblages of bacteria, phytoplankton, zooplankton, and other organisms, and excessive H_2O_2 concentrations are harmful to zooplankton (Burson et al. 2014, Reichwaldt et al. 2012). Meanwhile, the rate of H_2O_2 decomposition depends on the algal species present (Drábková et al. 2007a) and is proportional to the irradiance (Drábková et al. 2007a, Mikula et al. 2012), and fast decomposition rates have been recorded in both the laboratory (Drábková et al. 2007a) and natural water (Matthijs et al. 2012). Thus, the appropriate H_2O_2 dose and application conditions needed to control algal blooms must be determined in practice. However, the time scales of laboratory studies on the effects of H_2O_2 on algae have generally been on the order of hours (Barrington & Ghadouani 2008, Drábková et al. 2007b), and field studies have often focused on the selective suppression of cyanobacteria and the removal of cyanotoxins (Barrington et al. 2013, Matthijs et al. 2012). Additionally, research on the effects of the number of H_2O_2 addition is lacking.

According to our experiment results, the duration of the impact of H_2O_2 on algae is short, so the algal F_v/F_m and biomass will likely rebound. Therefore, the application of H_2O_2 should be combined with other control methods, e.g., light intensity (Drábková et al. 2007a), pH (Kuzirian et al. 2001), flocculation and sedimentation (Wang et al. 2012), for better results. Light shading has occasionally been used to control phytoplankton in raw water (Chen et al. 2009, Zhou et al. 2014) and because the inhibition of phytoplankton by H_2O_2 is proportional to the irradiance (Drábková et al. 2007a, Mikula et al. 2012), H_2O_2 treatment was combined with subsequent shading in this study.

Therefore, the concentration, light conditions during treatment and the number of H_2O_2 additions used to control algal blooms were studied via outdoor microcosm experiments, and the combined method (i.e., shading after H_2O_2 treatment) was investigated through an enclosure test in Lake Dianchi.

Materials and methods

Site description

Lake Dianchi (24° 30′ N–25° 02′ N, 102° 36′ E–102° 47′ E), a freshwater lake, is located downstream and southwest of Kunming City in Yunnan Province, southwestern China. The regional climate is subtropical (humid monsoon climate) with an annual mean temperature of approximately 14.5 °C, an annual precipitation of approximately 797–1007 mm, 227 frost-free days, 2470 sunshine hours per year, and a mean wind speed of approximately 2.5 m/s (Sheng et al. 2012, Yang et al. 2010). The mean water depth of the lake is 4.4 m, with a total water surface area of approximately 309 km^2 when the water level is at 1887.4 m. Due to rapid economic development and the intensive use of water resources, the water in the lake has become more severely polluted and eutrophic since the 1980s (Yang et al. 2010), experiencing extensive cyanobacterial blooms (Li et al. 2007, Zhou et al. 2016).

Concentration of H_2O_2 and light conditions during addition

Algae and water samples were taken from Lake Dianchi (Fig. 1), and the dominant algae was *Microcystis* spp. First, the concentration of H_2O_2 and the light conditions during addition were investigated outdoors. In this test, water samples were aliquoted into 24 beakers (each beaker had a volume of 500 mL and contained a 500-mL water sample), which were randomly divided into two groups that either received full sunlight or were shaded by black perforated nets (85% shading rate). The H_2O_2 was diluted immediately before being added to the beakers to reach final concentrations of 1, 2, 4, 6, and 8 mg/L; beakers without H_2O_2 were used as controls (0 mg/L) that also either received full sunlight or were shaded. Hydrogen peroxide was added at 10:30 on 16 October 2013, and the test lasted 48 h. The initial concentration of chlorophyll *a* (chl.*a*) was 553 μg/L, and each treatment was tested in duplicate. During the test, the photosynthetically active radiation (PAR), air temperature, F_v/F_m, and chl.*a* were determined.

Number of H_2O_2 additions

Water samples (dominated by *Microcystis* spp.) from Lake Dianchi (Fig. 1) were aliquoted into 12 blue plastic barrels (each barrel had a volume of 100 L and contained a 90-L water sample) that were assigned to six treatments in duplicate as follows: a control group (no H_2O_2 addition), 2 mg/L H_2O_2 added once, 2 mg/L H_2O_2 added twice, 4 mg/L H_2O_2 added once, 4 mg/L H_2O_2 added twice, and 8 mg/L H_2O_2 added once. Hydrogen peroxide was first added (day 0) at 12:00 on 31 December 2013 and then added a second time (day 7) at 12:00 on 7 January 2014. The experiment lasted 12 days, and the initial chl.*a* concentration was 172 μg/L. During the trial, the H_2O_2 concentration was determined every day after the two additions until it had completely decayed. Additionally, the PAR at 8:00, 13:00, and 18:00 and the F_v/F_m value were determined every day, and the water temperature (WT), dissolved oxygen (DO), electrical conductivity (EC), salinity (Sal), oxidation-reduction potential (ORP), pH, and chl.*a* concentrations were determined every 2 days. The concentrations of chlorophyll *b* (chl.*b*) and chlorophyll *c* (chl.*c*) were determined every 6 days. The total nitrogen (TN), total phosphorus (TP), total dissolved nitrogen (TDN), and total dissolved phosphorus (TDP) were

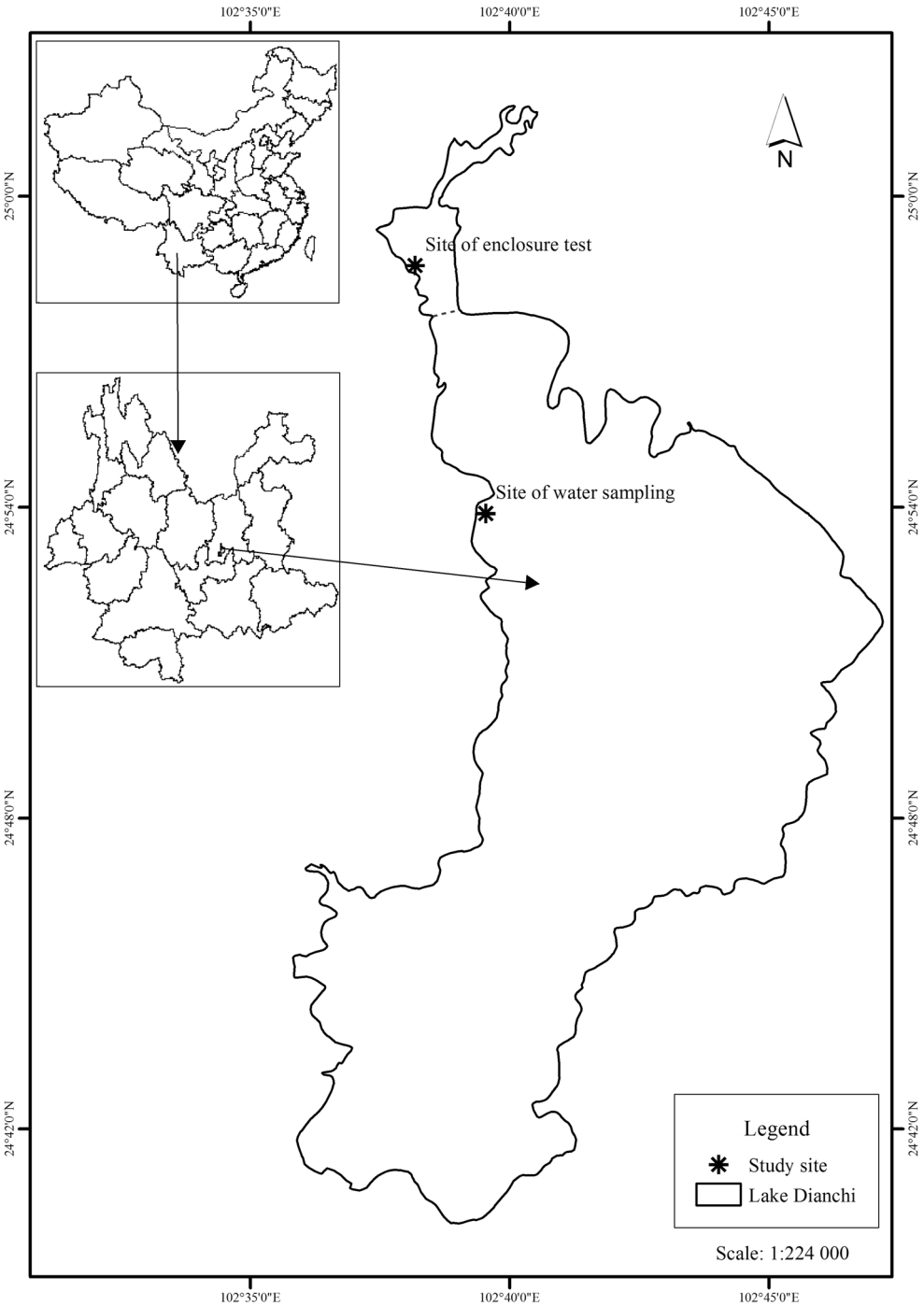

Fig. 1 Location of Lake Dianchi and the study sites

determined on the 0th, 7th, and 12th days, and the concentration of dissolved organic carbon (DOC) was determined 30 h after the second H_2O_2 addition.

Shading after H_2O_2 addition

Four enclosures (2 m × 2 m × 1.8 m each) that were open to the air at the top and closed by sediment at the bottom were built in Lake Dianchi (Fig. 1) using geotextiles. Before the experiment, all enclosures were placed under the water for 2 months, and the water in the enclosures was mixed together using a pump on 1 March 2014. Because an excessive dose of H_2O_2 would have a harmful impact on zooplankton (Kuzirian et al. 2001, Reichwaldt et al. 2012), a final concentration of 4 mg/L of H_2O_2 was selected based on Shan (2014) and our above study. Hydrogen peroxide was added to each enclosure at 11:30 on 2 March 2014 (day 0). On 5 March 2014 (day 3), two treatments were established and tested in duplicate: one

receiving full sunlight and another shaded by covering the enclosures with black perforated nets (85% shading rate). During the test, the water transparency (SD), WT, DO, EC, Sal, pH, and ORP were determined before enclosures were artificially disturbed; and water samples were collected from a depth of 0.5 m to determine the H_2O_2 concentration, as well as the TN, TP, TDN, TDP, chl.*a*, chl.*b*, and chl.*c* concentrations. To improve the experimental design, an analogous enclosure without H_2O_2 or shading was selected as a control in this study according to Zhou et al. (2015). Initially, cyanophytes and chlorophytes were the dominant groups in the five enclosures, but other eukaryotic algae, especially bacillariophytes, were also found.

Sample analysis

The PAR was measured using a Quantum light meter (Spectrum Technologies Inc., USA), and the SD was measured using a Secchi disk. The WT, DO, EC, Sal, pH, and ORP were monitored using a Professional Plus handheld multiparameter meter (Yellow Springs Instruments, USA). The DOC was measured using a TOC/TNb analyzer (Elementar, Germany), and the samples were filtered through a 0.22-μm micro PES membrane (Membrana GmbH, Germany) before this analysis. The H_2O_2 concentration was determined according to Drábková et al. (2007a), and the samples were also filtered through a 0.22-μm membrane before analysis. The TN, TP, TDN and TDP were analyzed according to *The Standard Methods for Observation and Analysis of Lake Eutrophication* (Jin & Tu 1990). The chl.*a*, chl.*b*, and chl.*c* concentrations were determined according to standard methods using 90% (*v*/*v*) acetone (Mitchell & Kiefer 1984), and the relative content of chl.*b* + *c* was the ratio of the concentrations of chl.*b* and chl.*c* to that of chl.*a*. The concentration of chl.*a* was indicative of the total algal biomass, and the relative content of chl.*b* + *c* was indicative of the relative proportion of non-cyanophytes (eukaryotic algae) and was based on the pigment composition of the algae (Lee 2008) as well as the dominant algae during the experiment (Zhou et al. 2015). The F_v/F_m value was determined via multiwavelength pulse-amplitude-modulated fluorometry (Water-PAM, Heinz Walz GmbH, Germany); approximately 3 mL of a water sample was placed in the dark for 10 min prior to analysis.

Statistical analysis

Statistical analysis was conducted with IBM SPSS Statistics software (version 22.0) and included nonparametric tests for two independent samples (Mann-Whitney *U*) or nonparametric tests for k independent samples (Kruskal-Wallis H) to identify the sources of the detected variation as well as multivariate analysis of variance. In all cases, comparisons that showed a P value < 0.05 were considered significant.

Results

Concentration of H_2O_2 and light conditions during addition

During the beaker test conducted outdoors, the air temperature ranged from 14 to 20 °C; the first day was cloudy while the other days were sunny, and the maximum PAR intensity value was approximately 2000 μE/(m^2 s). As shown in Fig. 2a, the F_v/F_m values of the algae all decreased within the first 0.5 h, and the values under full light were significantly lower than those under shade when the added concentration of H_2O_2 was greater than or equal to 2 mg/L. Under full light, the F_v/F_m value of the algae decreased to approximately 0.113 within 1 h at 2 mg/L H_2O_2 and to approximately 0.063 within 1 h, which did not restore within 24 h, at an H_2O_2 concentration greater than or equal to 4 mg/L. Under shading, the F_v/F_m value of the algae decreased to 0.15 or less after 4 h, with no further significant decline, at 6 mg/L H_2O_2 and to 0.1 or less at 8 mg/L H_2O_2. The results of the multivariate analysis of variance demonstrated that the F_v/F_m value of the algae was affected by the H_2O_2 concentration and light intensity ($P < 0.01$). Figure 2b shows the relative chl.*a* concentration during the experiment; after 48 h under full light, the algal biomass decreased to 34.3, 9.6 and 0.88% of that of the control group at H_2O_2 concentrations of 4, 6, and 8 mg/L, respectively. Under shading, the algal biomass of the groups treated with H_2O_2 was not less than 70% of that of the control group after 48 h.

Number of H_2O_2 additions

During the test, the mean PAR intensity at 13:00 was 1462 ± 405 μE/(m^2 s) and was less than 1400 μE/(m^2 s) in only 1 day (January 12, 2014). The residual H_2O_2 concentration gradually decreased to the natural level over time with decay time of 30, 78, and 102 h for the first additions of 2, 4, and 8 mg/L H_2O_2, respectively (Fig. 3a). After the second additions, the residual H_2O_2 concentration was reduced to low levels within 30 h (Fig. 3b). There were no significant differences in the DOC concentrations between the groups receiving one or two additions of 2 and 4 mg/L H_2O_2 at 30 h after the second addition. Furthermore, the F_v/F_m values of the algae treated with H_2O_2 first decreased and then began to gradually increase after recovery. The recovery time was inversely proportional to the added concentration, while the degree of decline and rebound were directly proportional to the added concentration (Fig. 4a), which similarly varied with the relative chl.*a* concentration

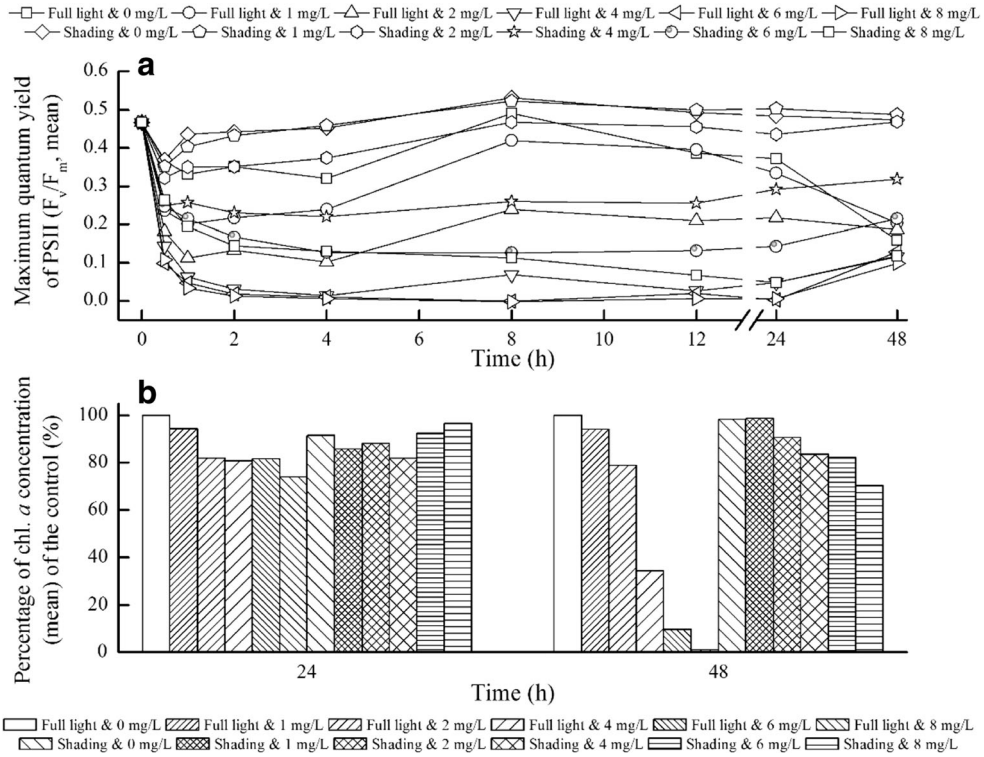

Fig. 2 Variation in the maximum quantum yield of PSII (F_v/F_m, **a**) and the relative chl.*a* concentration (compared to that in the control, **b**) in the outdoor beaker test

(Fig. 4b). Interestingly, similar trends in the variation of the F_v/F_m values and the relative chl.*a* concentration were observed between the groups with H_2O_2 added once or twice (Fig. 4a, b). The initial mean relative content of chl.*b* + *c* was 0.08; and the value after the first addition increased with the concentration of H_2O_2 (day 6), but the values were not obviously different between the groups with or without second addition (day 12, Fig. 4c). The physical-chemical parameters are shown in Table 1.

Shading after H_2O_2 addition

Generally, from the 5th day to 30th day, the mean relative chl.*a* concentration in the shaded group was significantly lower than that in the control group ($P < 0.05$), and the value in the full-light group was significantly higher than that in the control group ($P < 0.05$), as shown in Fig. 5a. After the 5th day, the mean relative chl.*b* + *c* content in the shaded group was significantly lower than that in the full-

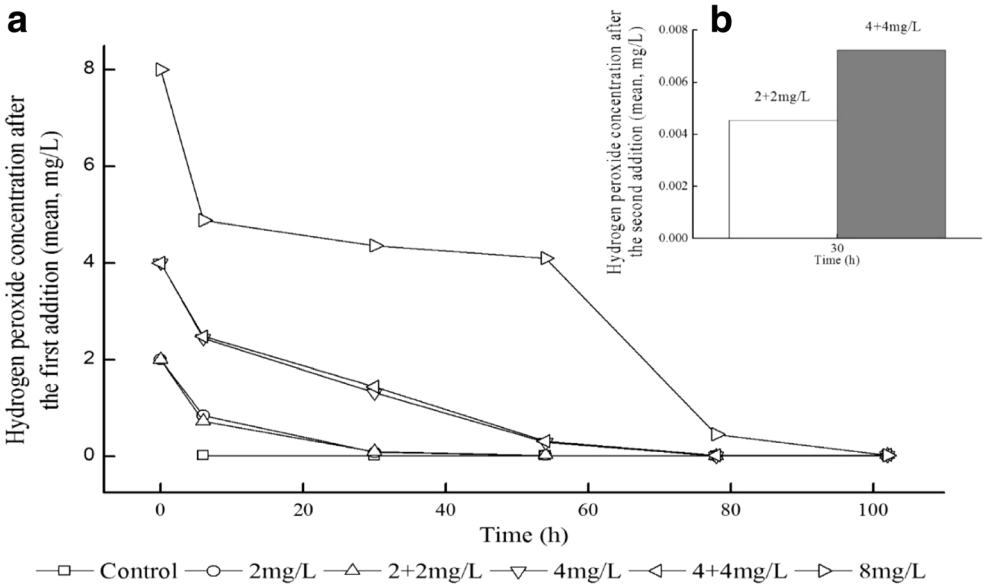

Fig. 3 Residual concentration of H_2O_2 after the first (**a**) and second (**b**) addition in the addition number test (conducted via blue plastic barrels outdoors)

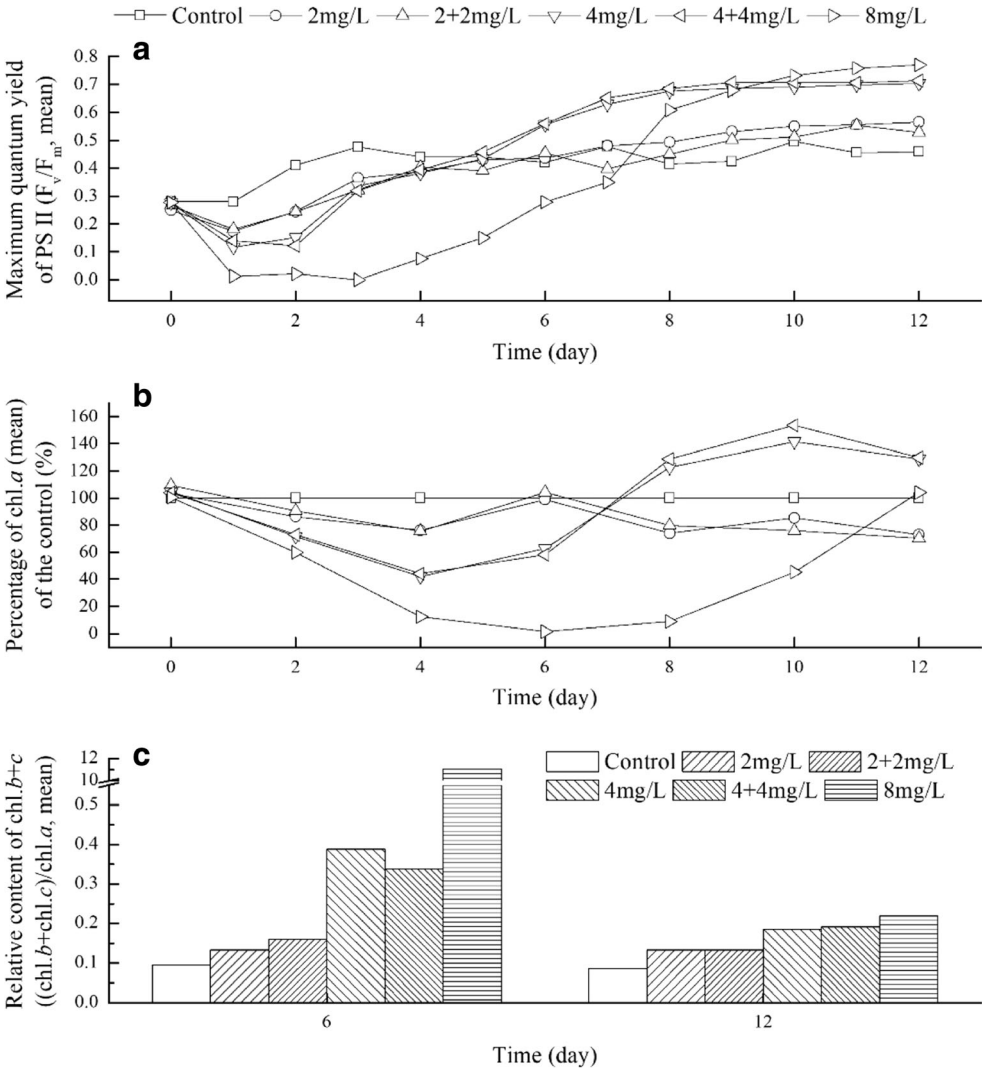

Fig. 4 Variation in the maximum quantum yield of PSII (F_v/F_m, **a**) and the relative chl.*a* concentration (compared to that in the control, **b**) and the relative content of chl.*b* + *c* (**c**) in the addition number test (conducted via blue plastic barrels outdoors)

Table 1 Physical-chemical parameters (mean ± SE) during the addition number test ($N = 14$)

Parameters	Control	2 mg/L	2 + 2 mg/L	4 mg/L	4 + 4 mg/L	8 mg/L
WT (°C)	18.0 ± 1.5	18.0 ± 1.4	17.9 ± 1.4	17.9 ± 1.4	17.8 ± 1.4	17.4 ± 1.3
DO (mg/L)*	7.67 ± 0.20	6.60 ± 0.30	6.47 ± 0.31	6.94 ± 0.40	6.92 ± 0.42	5.77 ± 0.50
EC (μs/cm)	542.4 ± 19.1	554.8 ± 19.8	553.5 ± 19.4	549.9 ± 19.8	548.2 ± 19.8	548.2 ± 19.0
Sal (ppt)	0.31 ± 0.00	0.31 ± 0.00	0.31 ± 0.01	0.31 ± 0.00	0.31 ± 0.00	0.31 ± 0.01
pH	9.11 ± 0.03	9.11 ± 0.02	9.09 ± 0.02	9.13 ± 0.06	9.12 ± 0.07	8.93 ± 0.06
ORP (mV)	− 5.7 ± 4.9	0.2 ± 5.5	2.2 ± 6.1	3.9 ± 6.1	5.2 ± 6.2	10.3 ± 6.8
TN (mg/L)	1.31 ± 0.38	1.39 ± 0.49	1.37 ± 0.50	1.30 ± 0.47	1.56 ± 0.47	1.40 ± 0.50
TP (mg/L)	0.09 ± 0.02	0.09 ± 0.01	0.09 ± 0.01	0.09 ± 0.01	0.09 ± 0.01	0.09 ± 0.01
TDN (mg/L)	0.67 ± 0.33	0.78 ± 0.33	0.67 ± 0.32	0.70 ± 0.29	0.65 ± 0.29	0.73 ± 0.38
TDP (mg/L)**	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	0.02 ± 0.00	0.02 ± 0.00	0.02 ± 0.00

WT, water temperature; *DO*, dissolved oxygen; *EC*, electrical conductivity; *Sal*, salinity; *ORP*, oxidation-reduction potential; *TN*, total nitrogen; *TP*, total phosphorus; *TDN*, total dissolved nitrogen; *TDP*, total dissolved phosphorus

* and ** denote significant differences (* ($P < 0.05$) and ** ($P < 0.01$))

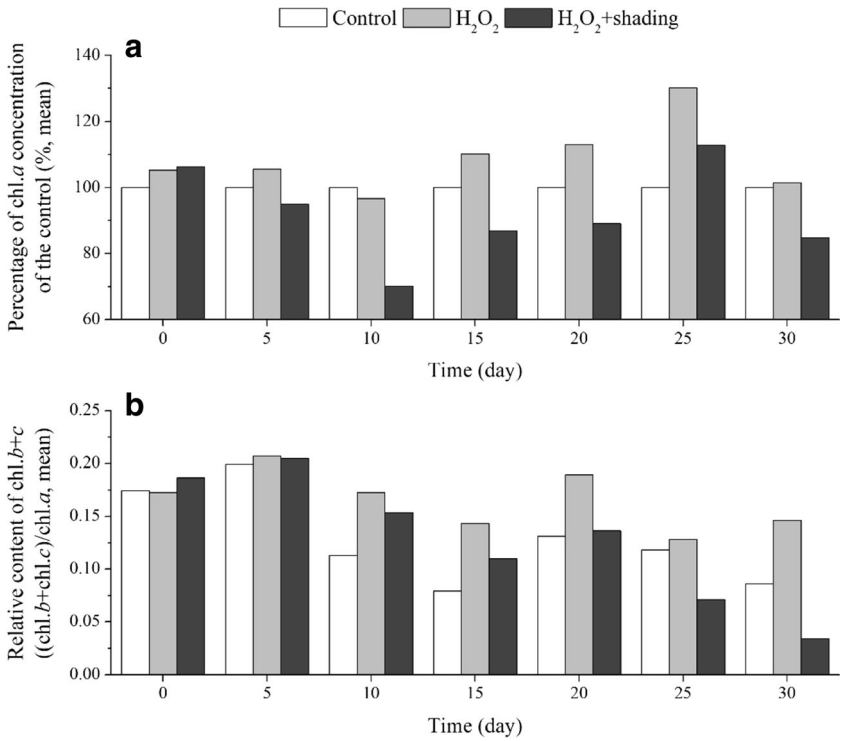

Fig. 5 The relative chl.*a* concentration (compared to that in the control, **a**) and the relative content of chl.*b* + *c* (chl.*b* + *c*/chl.*a*, **b**) in the enclosure test

light group ($P < 0.05$), and the value in the control group was moderate (Fig. 5b). Additionally, H_2O_2 decomposition was essentially completed within 30 h. The physical-chemical parameters are shown in Table 2.

Table 2 Physical-chemical parameters during the enclosure test

Parameters	Control		H_2O_2		H_2O_2 + shading	
	Mean ± SE	*N*	Mean ± SE	*N*	Mean ± SE	*N*
SD (cm)	47.9 ± 3.1	7	45.4 ± 1.7	14	52.6 ± 3.2	14
WT (°C)	16.2 ± 0.5	7	16.2 ± 0.3	14	16.0 ± 0.3	14
DO (mg/L)**	9.70 ± 1.25	7	10.39 ± 1.09	14	4.13 ± 0.48	14
EC (μs/cm)**	489.1 ± 3.8	7	533.5 ± 6.8	14	589.2 ± 7.4	14
Sal (ppt)**	0.29 ± 0.00	7	0.32 ± 0.01	14	0.35 ± 0.00	14
pH**	8.63 ± 0.14	7	8.72 ± 0.16	14	7.74 ± 0.14	14
ORP (mV)	−3.3 ± 26.4	7	−4.0 ± 21.8	14	−1.5 ± 24.2	14
TN (mg/L)	3.99 ± 0.24	6	3.79 ± 0.15	14	4.28 ± 0.13	14
TP (mg/L)**	0.17 ± 0.02	7	0.24 ± 0.01	14	0.23 ± 0.01	14
TDN (mg/L)**	2.84 ± 0.16	6	2.25 ± 0.14	14	3.14 ± 0.13	14
TDP (mg/L)	0.06 ± 0.01	7	0.07 ± 0.01	14	0.06 ± 0.00	14

SD, water transparency; *WT*, water temperature; *DO*, dissolved oxygen; *EC*, electrical conductivity; *Sal*, salinity; *ORP*, oxidation-reduction potential; *TN*, total nitrogen; *TP*, total phosphorus; *TDN*, total dissolved nitrogen; *TDP*, total dissolved phosphorus

**denotes significant differences ($P < 0.01$)

Discussion

With increasing H_2O_2, the relative chl.*a* concentration and the F_v/F_m value decreased, indicating that the effect of H_2O_2 on the algae was dose-dependent, and the relative chl.*a* concentration under full light was obviously lower than that under shading after 48 h, indicating that the effect was also irradiance-dependent. These results were also reported previously by others (Barrington et al. 2013, Drábková et al. 2007a, Mikula et al. 2012, Wang et al. 2015). Furthermore, Wang et al. (2012) also indicated that the lowest effective dose of H_2O_2 was 60 mg/L for 100 μg/L cyanobacterial chl.*a* (0.6 mg/μg chl.*a* for *Microcystis*-dominant field samples in the laboratory), and Barrington and Ghadouani (2008) suggested that the lowest effective dose was approximately 3.0 mg/μg phytoplankton chl.*a* (for field samples analyzed in the laboratory). In the present study (*Microcystis*-dominant field samples in an outdoor beaker test), the relative chl.*a* concentration significantly decreased to less than 35% of that in the control group after 48 h when the H_2O_2 dose was equal to or greater than 4 mg/L (0.007 mg/μg chl.*a*) under full light, which implied that the lowest effective dose was related to phytoplankton composition and environmental conditions.

The F_v/F_m value and the relative chl.*a* concentration (compared to that in the control) recovered in this study, similar to that observed in another single-algal species test with H_2O_2 treatment (Ding et al. 2012) and a multiple-algal species test with tryptamine treatment (Churro et al. 2010). In our opinion, this recovery might be related to the increasing proportion of

non-cyanophytes (due to the change in the relative content of chl.*b* + *c*) due to their higher H_2O_2 tolerance than cyanobacteria (Barrington & Ghadouani 2008, Chen et al. 2016, Drábková et al. 2007a, Drábková et al. 2007b, Matthijs et al. 2012). Therefore, to prevent further proliferation, the next step should be considered, but a second addition of H_2O_2 at the same dose did not significantly affect the potential photosynthetic activity or biomass of the algae, which might have been related to change in the phytoplankton composition as mentioned above. In addition, decomposing algae killed by the first H_2O_2 addition might release organic matter and ammonium, which would weaken the effect of the second addition (Liao & Gurol 1995), but the decay ratio of H_2O_2 after the second addition was also higher than that after the first addition. These results imply that the second H_2O_2 addition should be at a higher concentration, which may be harmful to certain organisms (e.g., zooplankton and macrofauna), and that the timing of the second addition should be postponed, which may be lead to continued algal growth and result in missing the best control period.

Combining another method (i.e., non-synchronized shading) with H_2O_2 addition was considered in our study. Shading has occasionally been used to control blooms in raw water (Chen et al. 2009, Zhou et al. 2014). However, a higher irradiance is needed when adding H_2O_2, so postponed shading was considered. Similar to the long-term results obtained in the dry season in Lake Dianchi (Zhou et al. 2016), our synchronized experiment revealed that a shading rate of 85% was beneficial for phytoplankton growth and increased the biomass in the lake by 13.4% (5.8~26.4%) in spring (Zhou et al. 2015). However, the same shading rate (85%) after H_2O_2 addition significantly inhibited algal growth for nearly a month, suggesting that the selected method (i.e., shading after H_2O_2 addition) can effectively control algal blooms and that a higher shading rate would be more effective (Zhou et al. 2015). Additionally, the addition of H_2O_2 at 4 mg/L did not effectively control the total biomass of the phytoplankton in the enclosure test, which might have resulted due to the dominant eukaryotic algae (Zhou et al. 2015). Moreover, the variation in the relative chl.*b* + *c* content implied that H_2O_2 mainly killed cyanobacteria in the enclosure test, so the difference in the relative chl.*b* + *c* content among the three treatment groups might be related to the different favorable light intensities of the cyanobacteria and eukaryotic algae (Coles & Jones 2000, Xu et al. 2012). The relative chl.*b* + *c* concentration in the single H_2O_2 treatment group was higher than that in the control group, implying that the addition of H_2O_2 increased the growth of eukaryotic algae. Although the subsequent shading would decrease the proportion of eukaryotic algae compared to that in the control group, it would also control the total biomass of the phytoplankton.

H_2O_2 has commonly been used to control algal blooms in raw water or wastewater (Barrington et al. 2011, Barrington et al. 2013, Burson et al. 2014, Matthijs et al. 2012), but according to the results of this study, a single treatment with H_2O_2 followed by a second addition in the short term is not recommended. However, applying H_2O_2 in combination with sunlight regulation could potentially be used to control phytoplankton blooms in certain areas, e.g., around water intake locations or small water bodies. First, the optimal H_2O_2 concentration for addition should be selected based on the effectiveness for killing algae and the harmfulness to other organisms, such as zooplankton and macrofauna, as well as the temporal-spatial heterogeneities of bloom degree and phytoplankton composition. Second, treatment with H_2O_2 under higher light intensity would be more effectively control algal blooms, and it could be combined with subsequent shading to prevent the algae from recovering or even rebounding. While it is not practical to shade the water surface of a lake like Dianchi, there are other ways to regulate light intensity that have potential applications in lakes as we discussed previously (Zhou et al. 2014).

Conclusion

Hydrogen peroxide acted as a powerful algicide that reduced algal (cyanobacterial) photosynthetic capacity and biomass in a dose- and irradiance-dependent manner. The duration of inhibition by H_2O_2 was short; a single addition of H_2O_2 resulted in algal recovery and a rebound in biomass, and a second addition at the same dose had no obvious further effect in the short term. Subsequent shading (85%) after H_2O_2 treatment effectively controlled algal blooms and the proportion of eukaryotic algae changed. Additionally, the lowest effective doses of H_2O_2 under different environmental conditions should be determined, and the timing of H_2O_2 treatment and subsequent shading should be optimized in the future.

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