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Monitoring and control of algal growth in the Shuangxikou Reservoir and drinking water source for possible management measures

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ABSTRACT

Harmful algae, particularly cyanobacterial blooms, are global environmental problems that threaten the safety of drinking water supplies, worldwide. This phenomenon has also occurred in the Shuangxikou and the drinking water source, in recent years, especially during seasonal changes. The study aimed at identifying the potential content of algal contamination and how it can be controlled in the Shuangxikou Reservoir with remote sensing technology and field observations. Results revealed very low concentrations of N and P in drinking water that might result in algal blooms under high temperatures in summer. Remote sensing monitoring demonstrated its effectiveness in controlling algal growth in a large water source. It is a cost-effective technology that can be used to investigate the cyanobacterial growth trends. After obtaining the map of cyanobacterial growth and distribution, special ecofriendly ships and floating sodium percarbonate could be used to control algae in areas with high algal occurrence. In this way, the algal content can be controlled safely within a certain range throughout the year. This study, therefore, recommend a combination of remote sensing monitoring and these special ecofriendly ships and floating sodium percarbonate as possible management measures for the control of algal blooms in reservoirs and large drinking water sources.

Keywords: Drinking water source; Cyanobacterial management; Satellite warning system; Floating sodium percarbonate

1. Introduction

"Blooms", a rapid increase in the population of cyanobacteria in water bodies have become global environmental problems [1], for they can pose a serious threat to aquatic life and public health, and produce toxins that harm fish, birds, and other aquatic animals and can also cause skin irritation, nausea, and vomiting in humans who come into contact with affected water [2–4]. So, it has become important for scholars to research the growth trends of algae and the causes of "bloom" formation and to seek algae control solutions. In healthy water ecosystems, the population and quantity of organisms are in relatively balanced states, but when eutrophication occurs in water, some organisms that are suited to grow under high nitrogen and phosphorus conditions [5], such as cyanobacteria, become the dominant

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species, while the number of other organisms decreases sharply, thus destroying the original food chain in the water. Cyanobacterial species can cause hypoxia and anoxia and produce cyanotoxins, including microcystins [6,7], which causes a decline in biodiversity in the water and damages the ecological functions of lakes.

The main reason for cyanobacterial blooms is the over-enrichment of water bodies with nutrients such as phosphorus and nitrogen [8–10]. These nutrients come from various sources, including agricultural runoff, wastewater discharge, and urbanization. The excess nutrients create an environment where cyanobacteria can thrive and reproduce rapidly, leading to a bloom [11]. Higher temperatures and changes in water chemistry can also contribute to the growth of cyanobacteria [12,13]. Climate change can exacerbate the problem by leading to warmer temperatures and altered rainfall patterns, which can increase nutrient loading and promote cyanobacterial growth [14,15]. Overall, human activities are the main cause of cyanobacterial blooms, and reducing nutrient inputs into water bodies is the key to preventing them [16].

To address cyanobacterial blooms, it is necessary to reduce nutrient inputs into water bodies. Previous studies [17] have shown that many algae removal measures are performed for cyanobacterial treatment. Physical removal of cyanobacterial blooms can also be done by using various methods such as skimming, filtering, and dredging [18,19]. Chemical treatments, such as the use of copper sulfate, can be effective in controlling cyanobacterial blooms, but care must be taken to avoid harming other aquatic organisms [20,21]. Biological control methods, such as the introduction of natural predators or competition, can also be used to reduce cyanobacterial populations [22]. Overall, preventing cyanobacterial blooms requires a combination of measures, including reducing nutrient inputs, monitoring water quality, and implementing appropriate management strategies. While plankton biomass is a large part of the food chain in water ecosystems, the survival of all higher aquatic organisms ultimately depends on the presence of algae [23,24]. Therefore, the quantity of algae needs to be accurately controlled rather than completely eliminated in the water because it is of great significance to restore the water ecosystem and control water eutrophication.

The Shuangxikou Reservoir, a new drinking water source, was built in 2011. In November, it supplied raw water to the local urban area and its surrounding areas, providing 33.7 million meters of high-quality raw water. Since the water head site was put into operation, it has played a good role in drinking water supply, combined with flood control, farmland irrigation and other comprehensive utilization. The reservoir under study had no artificial fish and no other large organisms, not even aquatic plants, only zooplankton and benthos. But in recent years, there is a trend of eutrophication in reservoir, and algal blooms occur from time to time, especially during the seasons change (alternation). The objective of this paper is to discuss and identify the potential content of cyanobacterial contamination and how it can be controlled in drinking water sources. Algal blooms in the Shuangxikou Reservoir, mainly composed of cyanobacteria, green algae and Bacillariophyta, are one of the main pollutants in the Shuangxikou Reservoir in summer. We believe that the analysis and treatment of algae in water sources is helpful for improving the protection level of drinking water sources over the long term and for exploring efficient, environmentally friendly and advanced algae prevention and emergency control technologies that are in accordance with the characteristics of the Shuangxikou Reservoir.

2. Materials and methods

2.1. Study site

The Shuangxikou Reservoir (29.925702°N; 121.333651°E, Fig. 1) is in the mountainous area of Yuyao City, Zhejiang Province, China. The reservoir has a surface area of 1.6 km^2, a maximum depth of 45.3 m, a mean depth of 35.2 m, and a volume of 2.87×10^8 m^3. It was built in 2011 to provide drinking water, agricultural irrigation, and flood control for the Dayin River area and to generate power for Yuyao City. The main inflow originates in the southeast. A water purification plant is located in the northeast of the reservoir, and drinking water is continually taken from a 20 m depth and delivered to the purification plant through a tunnel.

2.2. Field sampling

A field survey was performed at sites 1–7 of the Shuangxikou Reservoir (Fig. 1) from March 2021 to November 2021 in the stagnant zone (St.1), outlet (St.2), lake center A1 (St.3), lake center A2 (St.4), entrance B1 (St.5), mixed flow zone (St.6), and entrance B2 (St.7). Water was sampled from depths of 0.5, 5, 10, and 20 m, the bottom (1 m above the bottom sediment), between Sts. 1–7 using a water sampler (Gaodun, China) and multiparameter water quality monitor (YSI EXO, USA).

2.3. Laboratory sample analysis

The pH value and temperature were measured immediately by a YSI Professional Plus Instrument (Pro Plus, USA). Chemical oxygen demand (COD) was determined with a COD rapid online monitor (YHCA-100A, made in China).

The total phosphorus in the samples was determined with the ammonium molybdate spectrophotometric method using 50 g/L ammonium molybdate to digest the water sample, with a 0.01 mg/L detection limit. Total nitrogen was determined using a UV spectrophotometric method after digestion with a 40 g/L alkaline potassium persulfate solution, with a 0.05 mg/L detection limit. The adsorption levels of the spectrophotometer is 200~900 nm.

The NO_3^- and NO_2^- concentrations in the samples were determined with an ion-chromatograph (Dionex ICS-2000) using isocratic 15-min elution with a 22 mM KOH eluent at 30°C at a flow rate of 1 mL/min. The detection limits were 0.08 and 0.04 mg/L for NO_3^- and NO_2^-, respectively. Blanks and standards were run regularly between samples.

The chlorophyll concentration of phytoplankton was determined using a chlorophyll fluorescence system (PHYTO-PAM-II, Germany).

2.4. Experiment to control algae

Using an ecofriendly ship: A special ship, 9 m long and 3 m wide, was used to stir and mix the treated water

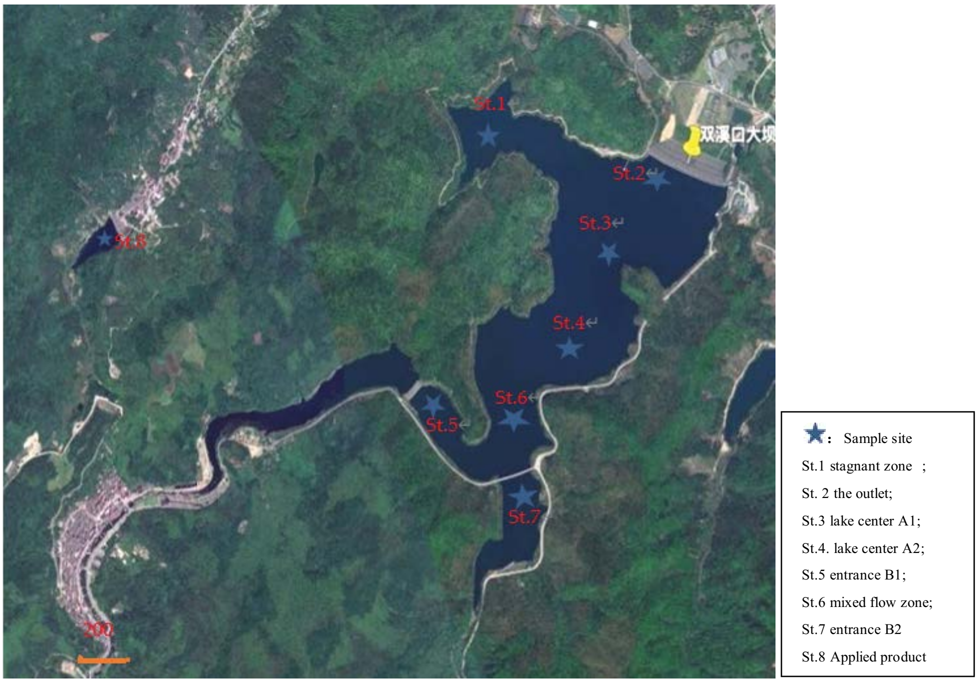

Fig. 1. Study area in the Shuangxikou Reservoir, China, with sample sites (St.1 stagnant zone; St.2 outlet; St.3 lake center A1; St.4 lake center A2; St.5 entrance B1; St.6 mixed flow zone; St.7 entrance B2) from March 2021 to November 2021.

in a vertical direction from the end of Mar. to Nov. 2021 in the stagnant zone of the Shuangxikou Reservoir (St.1). The ship processing time was 4 h in the morning and 4 h in the afternoon.

Floating sodium percarbonate: At St.8, a pond with the same water quality as the reservoir, a shallow water area with a depth of 1.0~1.3 m and an area of approximately 250 m^2 was used, and the floating sodium percarbonate product was applied at 1.0 kg/ha in the morning of 10:30 on 20 July 2021.

3. Results

3.1. Growth of algae monitored by satellite

A comprehensive understanding of the status of chlorophyll A in water and algae growth at different times via satellite imagery with a Case 2 Regional Coast Color (C2RCC) algorithm provides a favorable basis for economic and efficient algae control. The increase in chlorophyll A in the Shuangxikou Reservoir was interpreted by satellite images from February to November 2021. Fig. 2 shows that the amount of chlorophyll A fluctuated in the water throughout the year. The algae accumulated in the water, and small amounts of cyanobacterial scum were observed around the lake in March. As the temperature increased in April, the algal cells proliferated in the water and formed a scum visible to the naked eye on the surface. Then, phytoplankton growth increased markedly in May, June and August, and the maximum value was observed in May. Comparisons of the satellite monitoring values with laboratory measurement values showed that the growth of algae in the water had essentially the same trend. Moreover, from the map of satellite images, the growth points in algae were mainly concentrated in front of the dam and downstream of the reservoir. Therefore, the satellite monitoring map provided a clear cyanobacterial growth distribution and was very useful in identifying the growth trends of algae and the locations of algae, thus providing suitable times and locations for the large-scale algae treatment of the water body. This is an economical and beneficial control measure for cyanobacterial control over a large scale.

3.2. Seasonal variations in nutrients in the reservoir

The satellite monitoring in Fig. 2 shows that the highest levels of algae occurred in May, and the data from May 2021 were selectively analyzed. The water quality was generally good in the reservoir water source (Table 1), and most of the monitoring parameters, including pH, COD, ammonia, total N and total P, had relatively low levels in the water.

In addition, the content of total nitrogen was between 1.1 and 1.5 mg/L, which was in a range that matched the water quality Class IV standards, which defined the water quality Class IV with a total nitrogen content between 1.0 and 1.5 mg (Environmental Quality Standards for Surface Water, GB3838-2002, China). Among Sts. 1~St.7, the levels of the monitored parameters were higher at St.5 and St.7 than at the other sites, which indicated that there were some pollutants in the effluent to the reservoir.

The contents of nutrients such as ammonia, nitrogen and total nitrogen varied over a small range throughout the year (Figs. 3 and 4), and their concentrations across the vertical distribution of the deep water were close to those in the surface water. Fig. 3 shows the contents of NH_4^+, NO_3^- and total nitrogen, which were detected to determine the relationship between cyanobacterial blooms and water quality

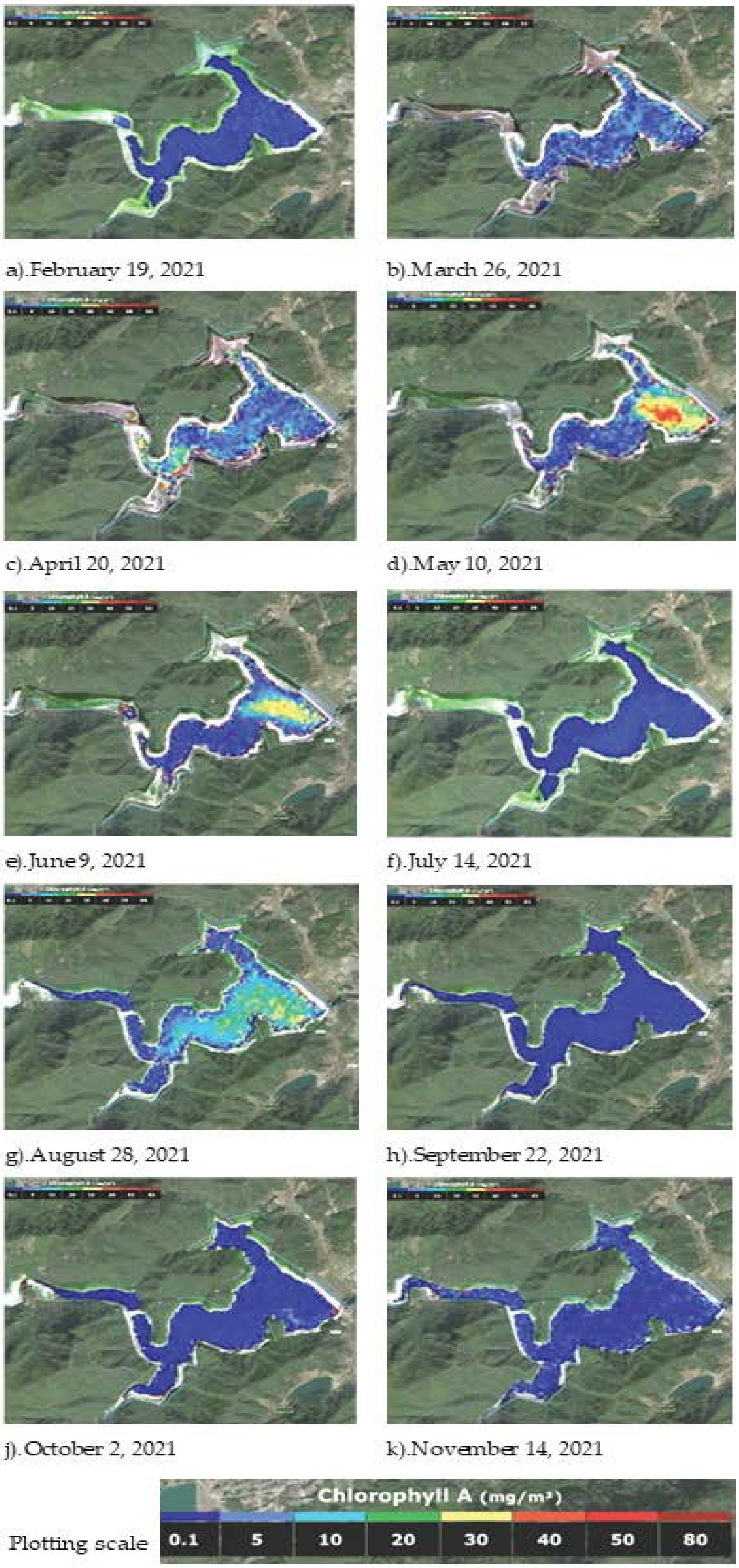

Fig. 2. Image of algal growth by satellite monitoring in the Shuangxikou Reservoir from February to November 2021. The different colors in the plotting scale represent different chlorophyll contents.

Table 1
Nutrient content in the deep reservoir water (20 m) in May 2021

Station ID	Temp. (°C)	pH	COD (mg/L)	Ammonia (mg/L)	Total N (mg/L)	Total P (mg/L)
St.1	15.3	7.34	8.4	0.258	1.28	0.043
St.2	15.7	7.35	9.1	0.295	1.33	0.045
St.3	15.5	7.37	8.0	0.291	1.32	0.039
St.4	15.8	7.32	8.4	0.278	1.32	0.038
St.5	15.5	7.35	8.3	0.299	1.32	0.043
St.6	15.2	7.29	8.3	0.264	1.37	0.038
St.7	15.0	7.34	8.8	0.289	1.36	0.041

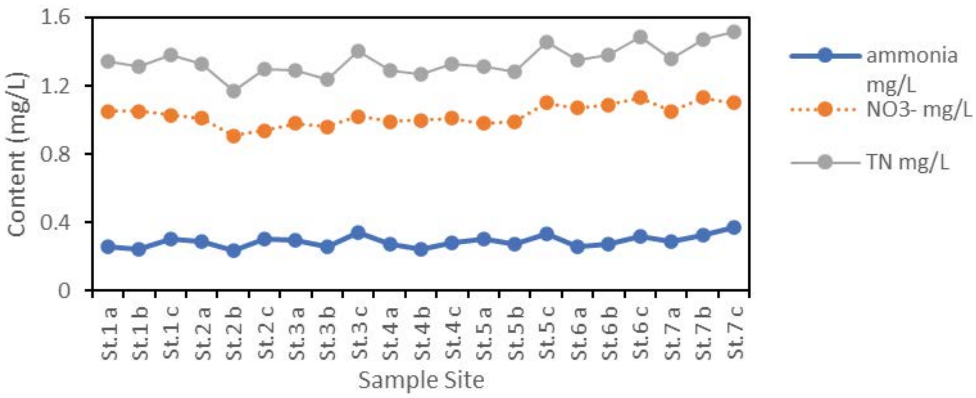

Fig. 3. Contents of ammonia, NO_3^- and total nitrogen at Sts. 1~7 at different depths (a) 0.5 m, (b) 10 m, and (c) 20 m in May 2021.

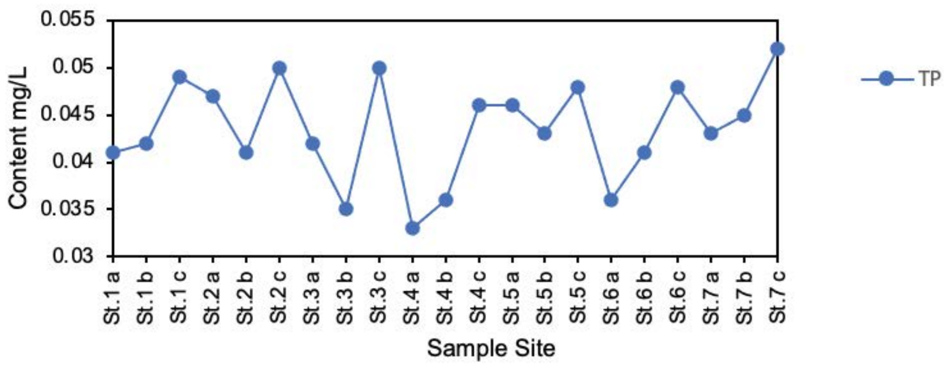

Fig. 4. Content of total P at Sts. 1~7 at different depths (a) 0.5 m, (b) 10 m, and (c) 20 m in May 2021.

at Sts. 1~7 at different depths (*a* = 0.5 m, *b* = 10 m, *c* = 20 m) in May 2021. The results showed that the content of total nitrogen was above 1.2 mg/L but was lower than 1.6 mg/L from the surface to the bottom, while the content of NH_4^+ ranged from 0.2 to 0.3 mg/L in the surface water among the 7 monitoring sites. The vertical distribution of ammonia nitrogen, total P and total N in the water shows that their concentrations were higher in the deep (20 m) water than in the surface (0.5 m) water.

It is generally believed that when the phosphorus content in water is above 0.02 mg/L, eutrophication pollution and algal blooms occur. The content of total phosphorus ranged from 0.02 to 0.05 mg/L in the surface water among the 7 monitoring sites (Fig. 4), which means there is enough phosphorus in the water for algae to grow. Moreover, the phosphorus concentration in the bottom water was higher than that in the surface water, indicating that a large amount of phosphorus is deposited in the sediment.

3.3. Phytoplankton concentration changes in reservoirs under seasonal variation

The algae content at 0.5 m depth from March to November 2021 was analyzed in the Shuangxikou Reservoir. Fig. 5 shows that the relatively high peak value for total algae appeared in late April to early May, mid-June, mid-July, mid-August, late September and early October. In terms of the algae population, from April to May, Bacillariophyta was the dominant algal species, and cyanobacteria were dominated throughout June; then, Bacillariophyta dominated and peaked in July, August and September. Chlorophyta, Bacillariophyta, and Cryptomonas are common algae in water, but they do not typically exhibit outbreaks like cyanobacteria, so they are less harmful to the water environment (though they can sometimes cause problems by blocking smaller pipes). In addition, they do not produce toxins, and they are the food of fish and play an important role in fish growth and reproduction. In contrast, cyanobacteria can produce phytotoxins that destroy other species of algae, and they multiply when nutrients are abundant, and sunlight supports their growth. Some studies [25] have shown that the main species of phytoplankton are Bacillariophyta when the temperature is below 25°C in the water and that cyanobacteria dominate when the water temperature is above 25°C, but the results of this study are inconsistent with the literature. The temperature reached 25°C in July and August (Fig. 6), and the algae that exhibited relatively large abundances were Bacillariophyta rather than cyanobacteria.

3.4. Possible algal control measures for the water source

Ecofriendly algae control ship for algae control. High algal growth rates affect water quality and require economic and reliable measures to control algal growth. An experiment was carried out in the reservoir using ecofriendly technology. The technical principle used involved the deployment of a suction pipe to stir the bottom water of the reservoir, and then the mixture of silt and water was collected and sprayed onto the surface. When the uniform mixture was sprayed onto the water surface, the water transparency decreased over a short period of time, and the intensity of algal photosynthesis was inhibited. In addition, due to spraying, aeration and stirring, the dissolved oxygen content of the water was directly increased, and the growth of algae was inhibited over the short term.

Ecological algal control boat system exchanged the water up and down and produced disturbance, which destroyed the quiet and gentle hydraulic conditions for the cyanobacteria. It had a good inhibitory effect on the growth of cyanobacteria. Water mixing and circulation promoted the homogenization of water temperature, dissolved oxygen, pH, and of nutrients. This homogenization helped other algae competed with cyanobacteria for growth. Through reoxygenation in the water, ecological algal control ship system improved the decomposition and digestion function of aerobic microorganisms, resulting in the reduction of nutrient salt content in water, then inhibited the nutrient conditions required for algae growth. In addition, the vertical

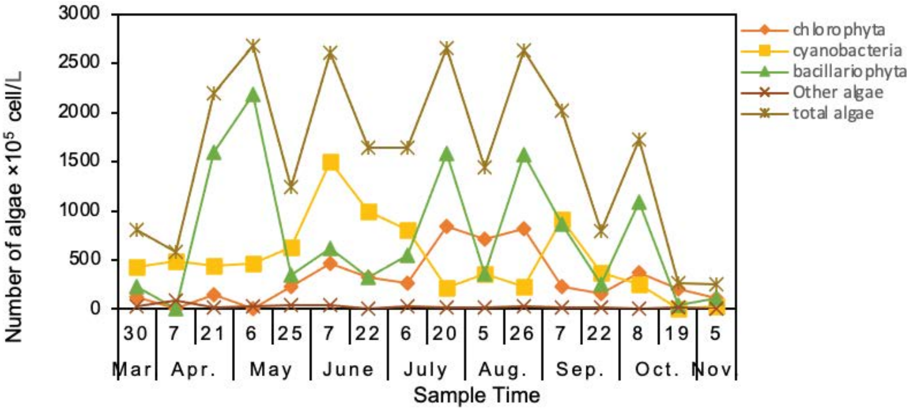

Fig. 5. Kinetic curves of phytoplankton in the St.2 surface water (0.5 m); samples were taken twice a month from April to October and once in March and November 2021.

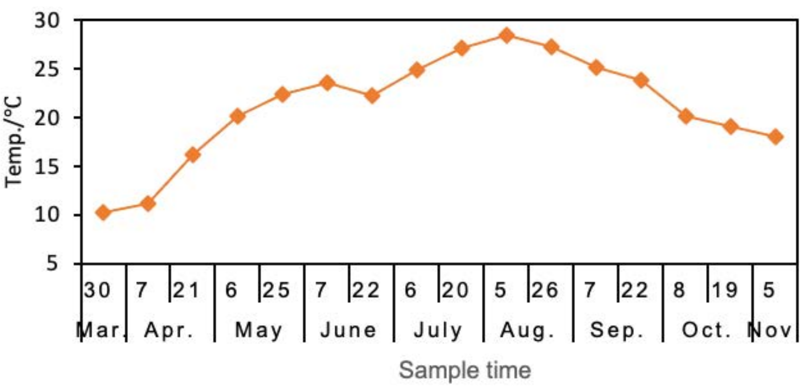

Fig. 6. Temperature in the St.2 surface water (0.5 m); samples were taken twice a month from April to October and once in March and November 2021.

circulation generated by the ecological algal control boat system reduced the time of algae especially cyanobacteria, in the light layer, and inhibited the propagation and growth of harmful algae. The competitive advantage of cyanobacteria was suppressed by the strong growth of beneficial algae such as diatoms and green algae.

The experiment lasted for 8 months, from the end of Mar. to Nov. 2021. The growth of algae was controlled by temperature. Once the temperature was 25°C or higher during the high-temperature season, the growth rate of cyanobacteria gradually increased. The temperature in July and August was substantially high, which supported the growth of cyanobacteria, but according to the monitoring data (Figs. 4 and 6), the dominant algae in the Shuangxikou Reservoir was still Bacillariophyta rather than cyanobacteria, which may have been related to the use of the ecofriendly ships in the reservoir. Compared with the growth trend of algae at St.1 of the reservoir in 2019, 2020 and 2021 (Fig. 7), the total amount of algae in 2021 was lower than that in 2020 and in 2019 during the same time period, indicating that the use of ecofriendly ships was conducive to reducing algal blooms.

3.5. Floating sodium percarbonate to control algae

Floating sodium percarbonate is an environmentally friendly product, non-toxic, to other aquatic organisms, and can be used to control cyanobacteria [26]. Floating sodium percarbonate, commonly known as solid hydrogen peroxide, a strong oxidant, is an addition compound of hydrogen peroxide and sodium carbonate with a nanoscale inert biodegradable polymer. Hydrogen peroxide is not convenient to store, transport, or apply because it is a liquid. Therefore, the use of sodium percarbonate as the carrier of hydrogen peroxide is safer, more convenient and cheaper. Sodium percarbonate has the advantages of being nontoxic, tasteless and pollution-free. The active ingredient in killing cyanobacterial cells is hydrogen peroxide, one of the products of the chemical reaction that occurs when sodium percarbonate meets water. When sodium percarbonate meets water, it quickly produces hydrogen peroxide, and it is unstable and produces oxygen and water. The other final product of the reaction is sodium carbonate, commonly known as soda, which is harmless to the environment and human body. Therefore, it can be seen that the decomposition products of sodium percarbonate are water, oxygen and sodium carbonate, all of which are substances produced by nature. They do not accumulate in the environment and will not cause secondary harm or environmental harm (Fig. 8). The introduction of sodium carbonate into the water environment in the absence of a buffering system resulted in a slight increase in pH. However, due to the buffering capacity of large bodies of water, the pH changes were almost undetectable.

The effect of floating sodium percarbonate on cyanobacteria was very obvious. After 24 h of floating sodium percarbonate application, the algae on the water surface decreased significantly. The Secchi depth improved, and aquatic animals, such as fish and water spiders, were free to move on the surface water, and no dead aquatic organisms were found (Fig. 9). The chlorophyll of surface water decreased significantly at 6 h, 12 h, and 18 h after the application of sodium percarbonate (Fig. 10).

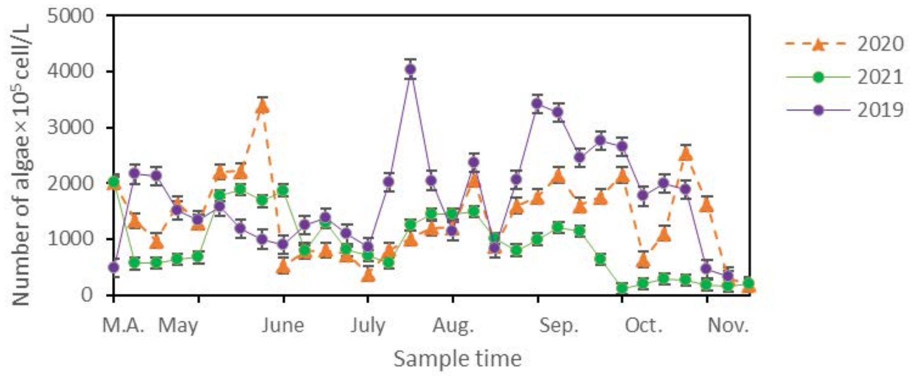

Fig. 7. Growth trend of algae in 2 m deep water at St.1 from March to November in 2019 2020 and 2021.

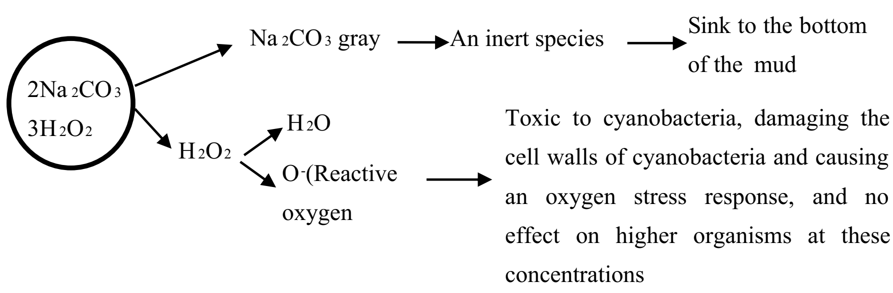

Fig. 8. Action mechanism and environmental tendency of floating sodium percarbonate.

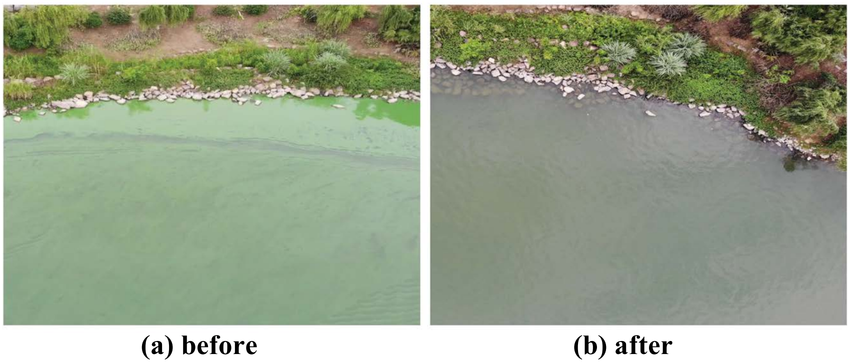

Fig. 9. Surface water in the pond before (a) and after (b) 24 h of application of 1.0 kg/ha floating sodium percarbonate.

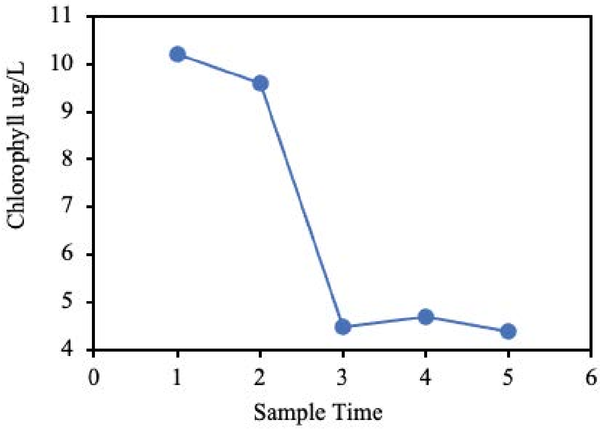

Fig. 10. Variation trend of chlorophyll content in the pond surface water at different times; samples were taken at 6-h intervals after application of 1.0 kg/ha floating sodium percarbonate.

4. Discussion

Satellite images can be very useful for identifying the growth trend and location of algae, and these images provide a suitable time and location of algae treatment for large-scale water bodies. According to satellite images, algae existed in the Shuangxikou Reservoir year-round, the chlorophyll A content in the water was very high in April, May, June and August, and the growth area was mainly concentrated in front of the dam. The dominant algae were Bacillariophyta in 2021, not cyanobacteria. Under normal temperatures, cyanobacteria are restricted by the growth of other algal species, so large-scale outbreaks are not possible. However, during the high-temperature season, cyanobacteria gradually attained a growth speed advantage when the water temperature exceeded 25°C. Nonetheless, the dominant algae in the Shuangxikou Reservoir were Bacillariophyta in July, August and September, although these months represented the high-temperature seasons. This result may be related to the use of ecofriendly algae control ships in the reservoir, which reduced the temperature of the surface water.

In the Shuangxikou Reservoir, many factors affect the growth of algae, and the main factors include temperature, biology and nutrient concentration. The existence of large amounts of phosphorus in water, that is, more than 0.02 mg/L, should be given sufficient attention. Temperature is another important factor affecting the growth of algae in this reservoir. The average depth of this reservoir is over 40 m, causing the temperature of the water body to be less than 25°C most of the time, and long-term monitoring results show that Chlorophyta and Bacillariophyta are the dominant algae. If water exchange can be enhanced, the retention time can be shortened, the size of the mixed water layer can be increased, and thermal stratification can be effectively prevented, which can destroy algal reproduction and living conditions, thus inhibiting algal growth in the water and reducing cyanobacterial blooms. Continued monitoring of relevant water quality factors in reservoirs is suggested to better manage water quality and provide technical support for the construction of beautiful lakes.

Two treatment options were present in the Shuangxikou Reservoir: the use of an ecofriendly algae control boat and the use of floating sodium percarbonate. The core of the treatment using the "ecofriendly algae control boat" involved extracting the water and sediment from the bottom of the reservoir and spraying a mixture of both onto the surface. This practice transfers nutrients from the sediment to the trophogenic surface layer and increases the turbidity to limit the growth of algae and cyanobacteria *via* light limitation. Such practices will not limit and overcome eutrophication and sustainably improve the water quality because pollutants are not removed from the water. However, the treatment can reduce the occurrence of cyanobacterial blooms. According to the approach, the biomass of plankton decreased significantly compared to previous years. In addition, the drinking water is taken from 26 m below the surface in the Shuangxikou Reservoir away from areas where the ecofriendly algae control boat work occurred, and thus, the effort and costs of drinking water production did not change. Therefore, the influence of the treatment is clearly visible, and this treatment is a physical approach that does not introduce new pollutants into the water, so it meets the requirements in this reservoir.

The use of floating sodium percarbonate is very easy, as it is spread into water by boat or unmanned aerial vehicles. The relevant mechanisms of floating sodium percarbonate are explained in Fig. 8. The floating sodium percarbonate makes the products float on the surface water to slowly release the active ingredient due to the coated nanofilm. The floating property allows the product to rely on the same natural forces (wind and current) to simulate the movement pattern of the cyanobacteria, that is, the product drifts with the cyanobacteria in the natural water body, ensuring sufficient contact between the slow-release active ingredient and the cyanobacteria for treatment purposes. After the sodium percarbonate meets water, it quickly produces hydrogen peroxide. The other final product of the reaction is sodium carbonate, commonly known as baking soda, which sinks to the bottom of the mud and is harmless to the environment and human body. Hydrogen peroxide is a strong oxidant and has the potential to kill microorganisms, but the experimental results showed it posed no harm to zooplankton. Instead, it added oxygen to the water and lowered ammonia levels. Practical engineering also showed that the product was effective in controlling algae in Setumo (South Africa) and Lake Minneola (Florida, USA). It is worth noting the water pH. Due to the buffering capacity of large bodies of water, pH changes were almost undetectable. Thus, sodium percarbonate is nontoxic, tasteless and pollution-free. The active ingredient involved in killing cyanobacterial cells is hydrogen peroxide, which is one of the products of the chemical reaction that occurs when sodium percarbonate mixes with water.

5. Conclusion

Satellite images showed that algae grew year-round in the Shuangxikou Reservoir, and the higher the temperature was, the higher the chlorophyll content in the water. According to the map of algae growth tendency, it was easy to determine where algae was growing in the reservoir, and targeted measures could be taken to control it. Laboratory testing was also conducted to accurately determine the species and content of algae when necessary. The results showed that Bacillariophyta was the main type of algae in 2021, while cyanobacteria were the dominant algae only in June. As a drinking water source, the main parameters exceeding the standard were total phosphorus and ammonia nitrogen. Relatively safe management measures could be used in water sources to control algae involving special ecofriendly ships and floating sodium percarbonate.

Author contributions

Conceptualization and methodology, A.L. Yan; investigation, Y.F. Chen; data curation, P. Dev.; writing—original draft preparation, A.L. Yan.; writing—review and editing, A.L. Yan.; visualization, D.H. Hu.; supervision, Y.T. Qi; project administration, N.Y. Li; software D. Xu. All authors have read and agreed to the published version of the manuscript.

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Institutional review board statement

Not applicable.

Informed consent statement

Informed consent was obtained from all subjects involved in the study.

Data availability statement

Please refer to the suggested Data Availability Statements in the section "MDPI Research Data Policies" at https://www.mdpi.com/ethics.

Conflicts of interest

The authors declare no conflicts of interest.

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