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Relationship Between Algal Bloom and Phosphorus in Water Environment in Zhushan Bay, Taihu Lake

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Abstract Algal bloom in eutrophication water, which can cause various risks, are closely related to phosphorus concentration of water environment, especially endogenous phosphorus. In this study, the relationship between algal bloom and phosphorus in water environment was investigated by collecting water and sediment in three different time in 2019 in Zhushan Bay, Taihu Lake. The result showed that algal bloom occurred during 27 June to 28 September in 2019. A large amount of phosphorus in overlying water was absorbed at the initial stage of algal bloom and sediment played as "source" to supplement AAP for bloom forming, which was mainly NAIP. Large phosphorus released at the decay period of algal bloom was largely OP and adsorbed by sediment, which played as "sink" of phosphorus. Moreover, the main phosphorus form of TP in the sediments of Zhushan Bay was IP, in which main component was NAIP. The main component of AAP was NAIP that phosphorus combined with iron, aluminum, and other metals. Furthermore, phosphate-solubilizing micro-organisms in the sediments of Zhushan Bay were mainly *Alcaligenes*, which could release phosphorus in sediment into overlying water to supplement phosphorus source required for algae bloom outbreak. The results of this study showed that endogenous phosphorus played an important role in the outbreak of algal blooms, and the control of endogenous phosphorus should be the key step of algal bloom control.

Keywords Endogenous phosphorus · Phosphorus components · Phosphate-solubilizing microorganism · Algal bloom

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1 Introduction

Lake is one kind of water body usually with wide water area and long exchange period, which is different from rivers and oceans. In the early stages of eutrophication, contaminants discharged into lake can be accumulated in large quantities by sediments, which slow the process of eutrophication (Gunnars & Blomqvist, 1997). However, nutrients in sediments can be released to overlying water under certain conditions, such as hydrodynamic disturbances and changes in redox environment (Yang et al., 2017). Thus, even when exogenous nutrients are well reduced or controlled, the endogenous nutrients accumulated in sediment could release into water and maintain the degree of eutrophication for a certain period of time, delaying the process of eutrophication recovery in lakes (Qiu et al., 2022; Wauer et al., 2005). This is the reason, although controlling exogenous nutrients has been highly valued, there are many lakes worldwide currently in a state of eutrophication even hyper eutrophication (Paerl & Paul, 2012), which has serious harm to lake ecosystem.

Algal blooms are a recurring phenomenon in many eutrophication aquatic environments worldwide (Huisman et al., 2018; Plaas & Paerl, 2021; Wang et al., 2020a), which can cause serious harm to water quality, aquatic ecology, and human life and health. In recent years, multiple safety incidents caused by algal blooms have been reported. In Brazil, more than 100 people died of renal failure in 1996 due to the exposure of algal toxins (Azevedo et al., 2002). There was a large range of cyanobacterial blooms occurred in Taihu Lake in 2007, which releasing algal toxins and causing 2 million people in Wuxi to be unable to supply water normally within one week (Chen et al., 2008; Qin et al., 2010). Researchers have studied the relationship between water eutrophication and algal blooms. Phosphorus, as an essential element for the life of algae, plays an important role in the process of biological nucleic acid synthesis and energy transfer (Hecky & Kilham, 1988). There were studies demonstrated that phosphorus plays an important role in controlling lake eutrophication and algal bloom control (Dang et al., 2018; Schindler et al., 2016). With the improvement of various wastewater discharge standards, the exogenous phosphorus of eutrophication lake has been well controlled. However, sediment acts as phosphorus "source" can release phosphorus to overlying water, which contributed to more and more important role on algal blooms. Some studies showed that the endogenous phosphorus released from sediments in some lakes could account for 60–80% of total phosphorus in water (Dugopolski et al., 2008; Penn et al., 1995). In addition, the decay of algal cells at the end of blooms could release phosphorus to the lake environment, forming a phosphorus cycle in water environment. Therefore, it is important to evaluate the potential of endogenous phosphorus release and utilization.

The availability of phosphorus depends on its fractions (Lu et al., 2020), leading the knowledge of total phosphorus content is not always sufficient to estimate its risk (Soliman et al., 2017). Thus, it is necessary to determine the fractions and bioavailability of endogenous phosphorus in sediment (Lu et al., 2016). The Standards Measurements and Testing (SMT) protocol issued by the European Commission in 2001 has been widely used due to its simple operation, easy repetition, and assessment of the source of phosphorus (Huang et al., 2015; Long et al., 2023; Qiu et al., 2022; Wang et al., 2020b). Long et al. reported that inorganic phosphorus (IP) in a shallow lake (Baiyangdian lake) was the dominant form of phosphorus, and the average of NaOH-P concentration was 237 mg/kg occupied 31% of IP (Long et al., 2023). On the other hand, the bioavailable phosphorus levels in lake sediments may be simply considered by quantifying the levels of readily desorbable phosphorus (RDP), water soluble phosphorus (WSP), algal available phosphorus (AAP), or $NaHCO_3$ extractable phosphorus (Olsen-P), which were frequently used in the determination of phosphorus bioavailability in sediments (Soliman et al., 2017; Younis et al., 2022; Zhou et al., 2001).

There are many studies focused on the content, composition of phosphorus in sediment. Qiu et al. studied that the IP level in Daye Lake was higher than OP and accounted for about 49–63% of TP. And the contents of TP, IP, Ca-P, and Fe/Al-P in the western part of Daye Lake were significantly higher than those in other lake areas (Qiu et al., 2022). Long et al. found that the TP content tended to be higher in the surface layer and gradually declined with depth, which was related to the intense human activities and rapid industrial (Long et al., 2023). However, most of previous studies focused on the phosphorus components or availability of sediment at one certain sampling time. Few studies combined the fractions of phosphorus and bioavailability to analyze the relationship between algal bloom and phosphorus in water environment.

Taihu Lake, as the third largest freshwater lake in China, has outbroke algal blooms in successive years since the 1980s (Duan et al., 2009; Xu et al., 2015). The exogenous phosphorus of Taihu Lake has been well controlled in recent years (Qin et al., 2006, 2010), while the blooms have as yet shown no sign of decline (Zhu et al., 2013). Zhushan Bay of Taihu Lake, as the area with serious algal blooms, was chosen to explore the relationship between algal blooms and phosphorus in the water environment, especially endogenous phosphorus. In this study, we collected water and sediment samples in Zhushan Bay of Taihu

Lake in June, September, and December in 2019. The physical and chemical properties of water body and sediment were measured. The endogenous phosphorus forms in sediment were determined. In addition, phosphate-solubilizing microorganism can convert organic phosphorus into inorganic phosphorus, which could be utilized by algae. The microbial community composition in sediment was further investigated and analyzed. Furthermore, the relationship between algal bloom and phosphorus distribution in water environment in Zhushan Bay was explored. The results of this study could provide a theoretical basis for controlling endogenous phosphorus sources to achieve the control of algal bloom in eutrophic lakes.

2 Materials and Methods

2.1 Sampling Sites

The three sampling points selected in this study were point A (31° 27′ 47.27″ N, 120° 03′ 20.22″ E), point B (31° 26′ 12.94″ N, 120° 03′ 07.88″ E), and point C (31° 24′ 53.21″ N, 120° 02′ 32.21″ E) located in Zhushan Bay, Taihu Lake (Fig. 1). The water samples and sediments from the three sampling points were sampled on 27 June, 26 September, and 28 December in 2019.

2.2 Experimental Design

The water samples were taken at 30 cm depth using a conventional water sampler. The pH, temperature, and transparency of the water bodies were measured at sampling sites. The surface sediments were sampled using a grab dredger. The sampled water and sediments were stirred, placed in an ice bag environment, and then taken back to the laboratory for further analysis. The soluble reactive phosphate (SRP) concentration of water samples was determined using the molybdenum blue colorimetric method at the wavelength of 700 nm. The algae density of water samples was measured with an automatic algae counter. In brief, the water sample was first shake up; then, 1 mL of that was mixture with 10 μL Lugol's iodine solution for 5 min. Finally, the algae density was determined using Countstar® BioMarine, ALIT Life Science, China. The water content and porosity of sediment were measured by gravimetric and calculated by formula (1) and (2). The organic matter content in sediment was approximately reflected by loss on ignition (LOI) which calculated by formula (3).

$$W = \frac{m_1 - m_2}{m_1} \times 100\% \quad (1)$$

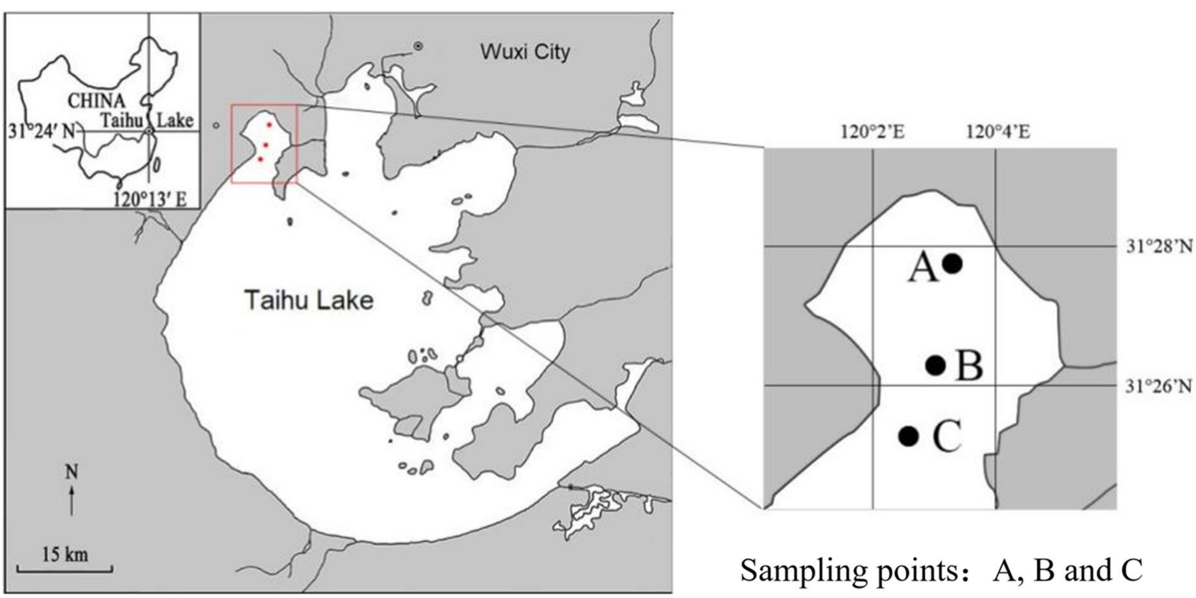

Fig. 1 The distribution of sampling points in Zhushan Bay of Taihu Lake

$$P = \frac{m_1 - m_2}{m_1 - m_2 + \frac{m_2}{2.5}} \times 100\% \quad (2)$$

$$LOI = \frac{m_2 - m_3}{m_2} \times 100\% \quad (3)$$

where *W* represents water content of sediment (%); *P* represents porosity of sediment (%); *LOI* represents organic matter content in sediment; m_1 is fresh weight of sediment (g); m_2 is dried weight of sediment (g); and m_3 is weight of sediment after calcination at 550 °C for 2 h.

2.3 Determination of Phosphorus Components in Sediment

The fresh sediment samples were pretreated by freeze-drying, grinding through 100-mesh sieve. Then, the content of total phosphorus (TP) and various forms of phosphorus in sediment was determined by standard measurement test (SMT) method formed by European Standard Testing Organization (Ruban et al., 2001). SMT method can determine TP in sediments. Non-apatite inorganic phosphorus (NAIP), apatite phosphorus (AP), inorganic phosphorus (IP), and organic phosphorus (OP) can also be obtained through distribution extraction. Among these phosphorus forms, NAIP is mainly phosphorus bound with oxides or hydroxides of Fe, Al, and Mn, and AP is mainly phosphorus bound with Ca. Four kinds of bioavailable phosphorus (BAP) in sediments were further determined, which were water-soluble phosphorus (WSP), readily desorbable phosphorus (RDP), $NaHCO_3$ extractable phosphorus (Olsen-P), and algae available phosphorus (AAP). The test methods were shown in Fig. 2. In detail, (I) 1.0 g fresh sediment mixed with 100 mL deionized water, shaken at 220 r min^{-1} for 2 h. (II) Weigh 2.0 g fresh sediment mixed with 50 mL 0.01 mol L^{-1} $CaCl_2$, shaken at 220 r min^{-1} for 1 h. (III) Weigh 2.5 g fresh sediment mixed with 50 mL pH = 8.5 0.5 mol L^{-1} $NaHCO_3$, shaken at 220 r min^{-1} for 0.5 h. (IV) 0.8 g fresh sediment mixed with 200 mL 0.1 mol L^{-1} NaOH, shaken at 220 r min^{-1} for 4 h. The mixture of (I), (II), (III), and (IV) steps was centrifuged at 10,000 r min^{-1} for 20 min. The phosphorus concentration of the above extracting solution was WSP, RDP, Olsen-P, and AAP, respectively.

2.4 Analysis of the Microbial Community in Sediment

The fresh surface sediment was mixed evenly, transferred to a sterile centrifuge tube, then centrifuged at 10,000 r min^{-1} for 10 min to remove pore water and stored at − 80 °C before further analysis. The total DNA in sediment was extracted using E.Z.N.A. Soil DNA Kit (Omega, D5625-01, USA). The V3-V4 areas of 16S rRNA was amplified by ABI GeneAmp® 9700 PCR instrument with 338F (5′-ACTCCTACGGGAGGCAGCAG-3′) and 806R (5′-GGACTACHVGGGTWTCTAAT-3′) primers. Sequencing was conducted on the MiSeq PE300 platform of Illumina, and microbial community data was analyzed on the Meiji BioCloud platform (https://cloud.majorbio.com).

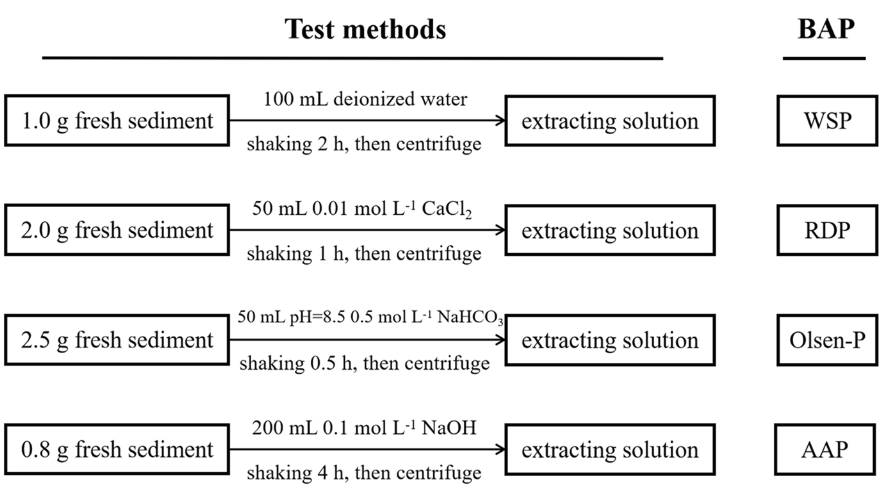

Fig. 2 Test methods for four kinds of bioavailable phosphorus

3 Results and Discussion

3.1 Water Physicochemical Properties

The temperature, pH, transparency, and SRP concentration that were used as water quality parameters were detected (Wong, et al., 2020). The results of these items and algae density of the water bodies at three sampling times were shown in Table 1. The ambient temperature is relatively high on 27 June, and the water temperature of the three sampling points was 27.3–27.4 °C. The water temperature decreased to about 20 °C and 10 °C on 26 September and 28 December, respectively. Similarly, the pH and transparency also showed a gradually decreasing trend over time. The pH at sampling point A on 27 June was high to 9.45, which was significantly higher than the weak alkalinity of normal lake water. The pH of three sampling points reduced to weak alkalinity on 28 December. On the contrary, the SRP concentration of water gradually increased from June (0.012–0.017 mg L^{-1}) to December (0.069–0.082 mg L^{-1}).

By comparing the physicochemical properties of Zhushan Bay water in June, September, and December, it could be seen that the water temperature and pH on 27 June were higher than that on September and December, while the SRP concentrations were lower on 27 June. The study of Wang et al. found that the optimal temperature range for algal bloom was 24–30 °C (Wang et al., 2008). Meanwhile, the growth of algae could lead the increase of pH (López-Archilla et al., 2004; Xu et al., 2010) and absorb a large amount of phosphorus (Cao et al., 2016; Xu et al., 2010). These results suggested that it was the initial stage of algal bloom around 27 June 2019, in which algae proliferated in the lower water body, but no large-scale bloom had been formed on the surface. In this stage, algae cells adsorbed large amount of phosphorus to supplement their growth and caused pH of water increasing. Moreover, Yu et al. found that there would be 3–4 times cyanobacterial blooms in Shazhu water source area within a year, mainly in the middle of July, August, and early September (Yu et al., 2010). In addition, combined with the trend of temperature, pH, and SRP concentration, it may be the late stage of algae bloom and dormant period of algae on 26 September and 28 December 2019, in which algae cells decayed and released acid substances and intracellular phosphorus, leading the pH decrease and SRP concentration increase (Huisman et al., 2018). The algae densities of point A were higher on 27 June and 26 September than that on point B and C, and the contrary trend was showed on transparency. These results may due to the prevailing southeasterly wind in summer and autumn in Zhushan Bay of Taihu Lake, which caused algae to gather in the bay (Zhang, 2019).

3.2 Sediment Physicochemical Properties

Physicochemical properties of sediment are closely related to the adsorption and release of phosphorus, dissolved organic carbon (DOC), ammonium-nitrogen

Table 1 Physicochemical properties of Zhushan Bay water in Taihu Lake

Physicochemical properties	Sampling time	Point A	Point B	Point C
Temperature (°C)	27 June	27.3	27.4	27.3
	26 September	20.4	20.3	20.3
	28 December	9.8	9.8	9.8
pH	27 June	9.45	9.08	8.83
	26 September	7.97	8.33	8.36
	28 December	7.82	7.98	7.99
Transparency (cm)	27 June	30.5	52.1	64.4
	26 September	25.2	48.5	32.7
	28 December	19.5	32.5	39.0
SRP concentration (mg L^{-1})	27 June	0.013	0.017	0.012
	26 September	0.042	0.059	0.016
	28 December	0.070	0.082	0.069
Algae density (cells mL^{-1})	27 June	646,000	356,000	572,000
	26 September	934,000	312,000	473,000
	28 December	320,000	367,500	352,400

(NH_4-N), and nitrate-nitrogen (NO_3-N) (Howard & Howard, 1990; Schreckinger et al., 2022). The results of water content, porosity, and organic matter content in sediment were shown in Fig. 3. The water content and porosity of sediments at three sampling times ranged from 57.63 to 66.96% and 77.27 to 83.52%, respectively (Figs. 3a and b). The porosity of sediment is related to the size of sediment particles, which can represent the diffusion capacity of pollutants in sediment. The diffusivity of sediment is positively correlated with porosity (Zhang, 2019). The porosity of point B was slightly higher than that of point A and C, indicating that the pollutant diffusion capacity of sediment at point B was slightly stronger than that of sampling points A and C. This result further explained that the SRP concentration in water at point B was higher than that at points A and C.

The degradation of P-containing organic matter in sediment is one of the sources of endogenous phosphorus (Liu et al., 2023). The order of organic matter content in sediment on 27 June, 26 September, and 28 December was A > C > B, B > C > A, and B > A > C, respectively. In addition, the correlation analysis was further carried out to determine the relationship between organic matter and porosity. The result showed the correlation coefficients between organic matter and porosity in this study were 0.581. The sediment diffusion capacity of point B was higher, leading the organic matter content of point B on 27 June was the lowest (4.31%). The organic matter content in sediment of points B and C on 26 September was higher than that on 27 June, which may due to the bloom could promote the diffusion of organic matter from deeper sediment to surface sediment. In contrast, the organic matter of point A on 26 September was lower than that of 27 June, which may owe to the algal bloom at point A was more severe, boosting the release of organic matter from surface sediment into the water column. Furthermore, the relatively high organic matter concentration of point A, B, and C

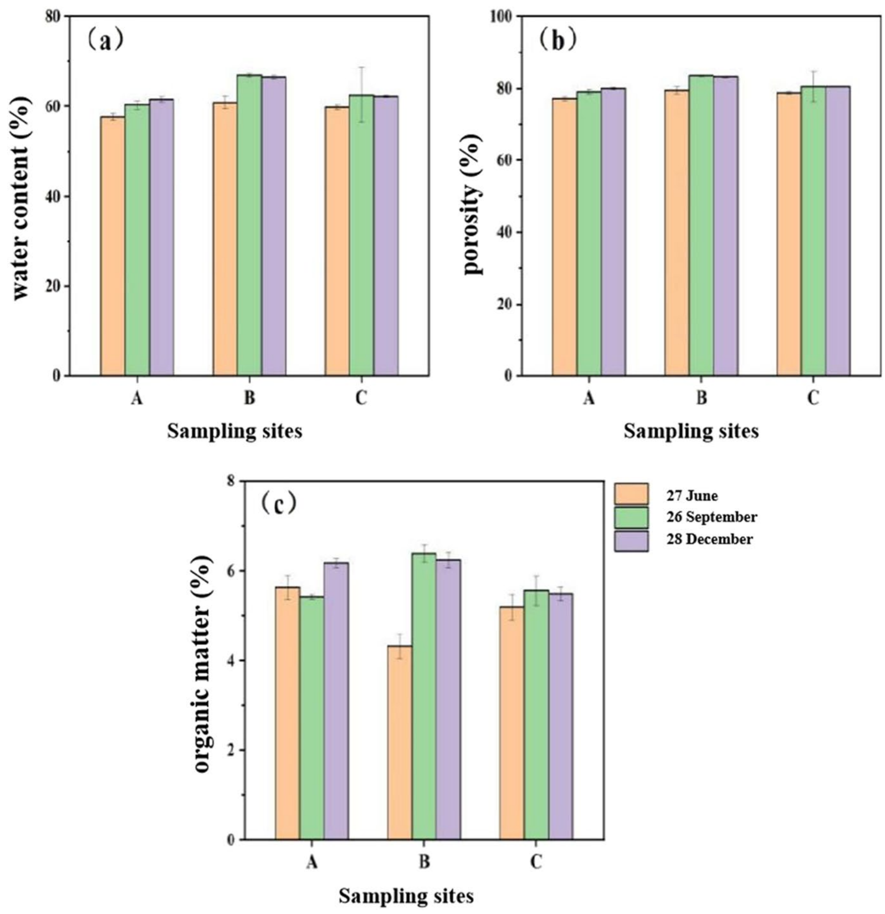

Fig. 3 The change of water content (**a**), porosity (**b**), and organic matter (**c**) in sediment

on 28 December that was larger than that of 27 June could be explained that algae cell apoptosis, settlement, and accumulation on the surface sediment after bloom.

3.3 Phosphorus Forms Distribution and Bioavailable Phosphorus in Sediment

It could be seen from Fig. 4 that the TP concentrations of sediments on 27 June were lower, especially at points B and C. The TP concentrations of points B and C were increased from 886.7 mg kg^{-1} and 757.9 mg kg^{-1} (on 27 June) to 1167.6 mg kg^{-1} and 1021.3 mg kg^{-1} (on 28 December), respectively. This result may be due to the decay and settlement of a large amount of dead algae, which would possibly increase TP in surface sediment (Zhu et al., 2013). Yin et al. determined that TP in surface sediment of Zhushan Bay could be ordered as Oct. > Jan. > Aug. > Apr., and the higher TP in Oct. was attributed to the deposition of algae (Yin et al., 2023). This result was also consistent with the finding of Zhang Weizhen's research, which showed cyanobacteria decomposition could cause the increase of TP concentration in the sediment surface (Zhang, 2019). Further analysis of phosphorus forms showed that IP and OP accounted for 71.1–88.1% and 13.6–20.9% in TP, respectively. The IP form in sediment obviously changed, in which the NAIP content changed greatly. The IP concentration of points A, B, and C in sediment on 27 June was 1214.5 mg kg^{-1}, 781.3 mg kg^{-1}, and 658.4 mg kg^{-1}, respectively, which increased to 1226.2 mg kg^{-1}, 1009.6 mg kg^{-1}, and 781.3 mg kg^{-1} on 28 December, respectively. These observations indicated that the phosphorus of Fe/Al-P forms was significantly affected by algal bloom, which may be the main phosphorus form used by algae bloom. Furthermore, sediment may have a high diffusion and adsorption capacity. The content of OP in points A, B, and C sediments increased from 146.3–228.2 mg kg^{-1} on 27 June to 200.1–279.8 mg kg^{-1} on 28 December, which may be caused by the deposition of algae cells and other biological organisms into the sediments.

The results of four kinds of bioavailable phosphorus were shown in Fig. 5. WSP is relatively easy to release into water, mainly orthophosphate. The range of sediment WSP content in the three sampling sites was 1.77–5.57 mg kg^{-1}, which was close to the results of Wang Q. et al. on the sediment WSP

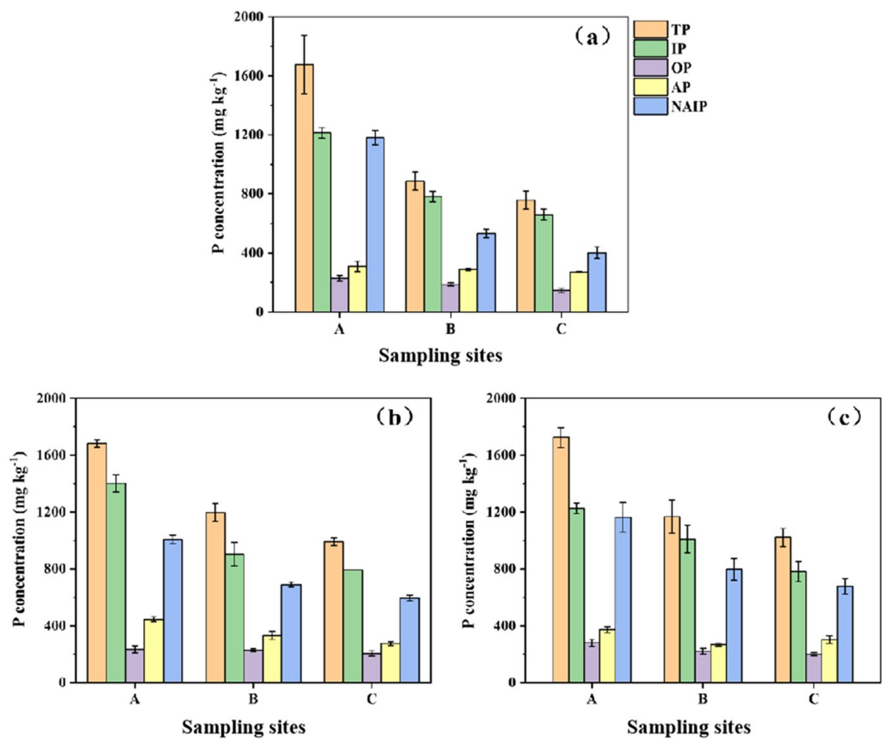

Fig. 4 Distribution of phosphorus forms in sediment of three sampling sites in June (**a**), September (**b**), and December (**c**)

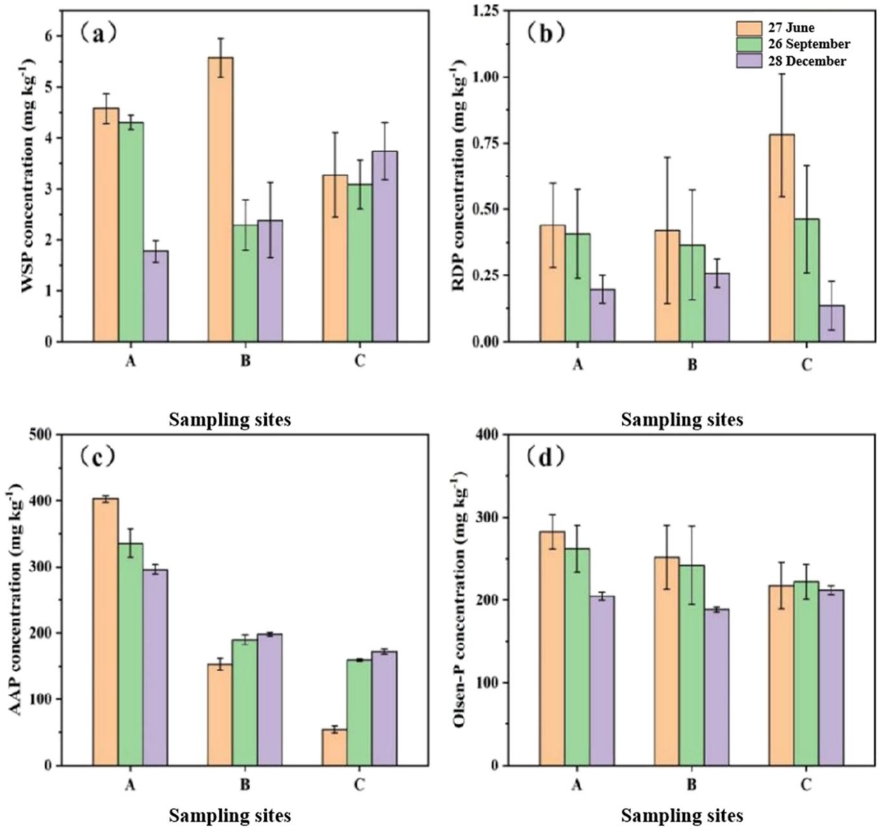

Fig. 5 Bioavailable phosphorus concentrations of sediment in three sampling sites, which **a** is WSP, **b** is RDP, **c** is AAP, and **d** is Olsen-P

content (1.87–7.52 mg kg^{-1}) in Taihu Lake (Wang et al., 2006). The WSP of sediment in September was lower than that in June, which may because sediment as the "source" of phosphorus releasing WSP into water. RDP is a phosphorus form that is adsorbed on the sediment surface and easy to be desorbed and released. When the phosphorus concentration in water decreases, RDP can be rapidly released to supplement the phosphorus concentration in the water. The RDP contents of sampling points A, B, and C in June were 0.44, 0.42, and 0.78 mg kg^{-1}, respectively, which was consistent with the result of RDP contents (0.34 and 0.75 mg kg^{-1}) in Zhushan Bay sediments reported by Xu W.L. et al. in July 2010 (Xu et al., 2011) The RDP of sediments at the three sampling points decreased gradually from June to December. This may be due to the adsorption capacity of phosphorus on sediment was related with pH that higher pH was beneficial for phosphate adsorption (Xue et al., 2009). Combined with the result of pH, the decrease of RDP in different time may due to the decline of pH, which resulted in the reduce of RDP. AAP is the available phosphorus of algae extracted by alkali, and AAP concentration of Zhushan Bay sediments was 54.21–402.76 mg kg^{-1}. The AAP content of point A sediment at different sampling times was higher, which was about 1.72–7.43 times that of points B and C. This result indicated point A had great potential to release AAP, which could provide much more phosphorus to support algal cells growth and lead to the algal density on June 27 and September 26 at point A was much higher than that of point B and C. Olsen-P is an important indicator of soil nutrients. The soil is at a higher nutrient level, when the Olsen-P content of soil is higher than 46 mg kg^{-1}. The Olsen-P content in the three points ranged from 188.43 to 282.43 mg kg^{-1}. The high Olsen-P concentration in sampling sites was mainly was due to the history of external pollution from man-made pollution source around Zhushan Bay, leading to the high nutrient level of the sediment in Zhushan Bay, which may be the potential phosphorus resource for algal bloom utilization. Xu et al. also concluded that the Olsen-P content of the sediment in Zhushan Bay was higher than that in other areas of Taihu Lake (Xu et al., 2011).

Correlation analysis results of BAP and various forms of phosphorus in sediments were shown in Table 2. The correlation coefficients between TP and IP, OP, NAIP and AAP in sediments were 0.963, 0.863, 0.976, and 0.946, respectively, which indicated that they had significant correlation. The correlation coefficients between IP and NAIP, AAP were 0.917 and 0.915, respectively, and the correlation coefficient between AAP and NAIP was 0.952. These results showed there was strong correlation between TP, IP, NAIP, and AAP. Besides, IP and NAIP occupied large proportion of TP and IP, respectively, which indicated that IP was the main component of TP, and NAIP was the main component of IP in sediments of Zhushan Bay. AAP was highly significantly related to NAIP. Based on the lower content of AAP compared to NAIP, it could indicate that the main component of AAP was NAIP, which was mainly the phosphorus combined with iron, aluminum, and other metals, namely Fe/Al-P. This was consistent with the result in Caoxin's study that the main component of AAP in Dianchi Lake sediments was NAIP (Cao, 2017). Depending on the results of phosphorus fractions and bioavailability in sediment and their correlation, it could be concluded that at the outbroke stage of algal bloom, the Fe/Al-P forms were released into overlying water and used by algae, while OP and IP would be adsorbed on sediment during the deposits of dead algae and decay of algae after the bloom.

3.4 Distribution Characteristics of Microbial Communities in Sediments

The microbial community abundances and structures of sediment in three sampling points at three sampling times were detected via 16S rRNA sequence analysis in this study. The number of operational taxonomic units (OTUs) at a 97% similarity threshold of microbial communities of 9 sediments was shown in Table 3. It can be seen that the microbial richness of sediment at the three sampling points on 27 June and 26 September was higher (> 45,000) than that on 28 December (< 25,000). This may be due to the high temperature in summer and autumn, which was suitable for the growth and reproduction of microorganisms. And the temperature in winter was low in which microbial activity and quantity was low lead to less abundance of microbial communities. The results of alpha diversity of sediment samples and rarefaction curve of Shannon index on OTU level were shown in supplementary (Table S1 and Fig. S1). The results indicated that there were differences in microbial diversity among 9 sediments, and the sequencing data in sediments were large enough to reflect the vast majority of microbial diversity information in samples.

Percent of community abundance on phylum level in 9 sediment samples were shown in Fig. 6. The dominant bacteria in sediments were *Proteobacteria*, range from 35.7 to 67.1%. Bacteria with higher abundance next were *Chloroflexi*, *Acidobacter*, and *Nitrospira*, respectively. The proportion of *cyanobacteria* bacteria on 27 June in point A, B, and C was 0.25%, 0.14%, and 0.20%, respectively, which was 0.69%, 0.30%, 0.41% and 0.50%, 1.67%, 7.92% on 26 September and 28 December, respectively. It can be seen that from June to December, the abundance of *cyanobacteria* in the sediments of the three sampling points in Zhushan Bay showed an overall increasing trend. This result indicated that the *cyanobacteria* in the sediments appear to float up in the early stage of the bloom outbreak, and the *cyanobacteria* abundance in

Table 2 Correlation analysis of TP and BAP and various forms of phosphorus in sediment

	TP	IP	AP	NAIP	OP	WSP	RDP	AAP	Olsen-P
TP	1	0.963**	0.747*	0.976**	0.863**	−0.125	−0.388	0.946**	0.354
IP		1	0.796*	0.917**	0.793*	−0.035	−0.329	0.915**	0.361
AP			1	0.607	0.622	−0.011	−0.246	0.618	0.346
NAIP				1	0.857**	−0.121	−0.462	0.952**	0.292
OP					1	−0.410	−0.675*	0.753*	0.021
WSP						1	0.246	0.124	0.693*
RDP							1	−0.367	0.286
AAP								1	0.538
Olsen-P									1

**$P < 0.01$: extremely significant correlation; *$P < 0.05$: significant correlation.

Table 3 OTU sequences number of microbial communities in sampling sites at different time

Sampling time	Point A	Point B	Point C
27 June	55,583	54,964	49,604
26 September	45,546	53,160	49,687
28 December	20,885	24,267	24,610

the sediments was low. After the bloom, the *cyanobacteria* decayed and disposed to sediments, which made the abundance of *cyanobacteria* increase.

Venn diagram of microorganisms in sediments at different sampling times according to family classification level was shown in Fig. S2. The number of unique families in June, September, and December was 22, 4, and 5, respectively. Among them, *Azambacteria* was the unique microbial family in June. There were 22 microbial families in June and September but did not exist in December, including *Bacillales* and *Enterobacteriaceae*. Phosphate-solubilizing microorganisms existed in the above three families. These results showed that the number of families containing phosphate-solubilizing microorganisms in the sediment increased in June and September, which could improve the release of endogenous phosphorus to a certain extent.

According to relevant research, there were more than 20 genera of bacteria with phosphorus dissolving ability (Kour et al., 2021; Prescott et al., 1997). Sediment bacteria were further classification and screening at the genus level, and the changes of OTU abundance of phosphate-solubilizing microorganisms in sediment are shown in Table 4. The variation trend of OTU abundance of different phosphate-solubilizing microorganisms in the sediments of Zhushan Bay of Taihu Lake was different with time. The main phosphate-solubilizing microorganisms at sampling points A, B, and C at different sampling times was *Alcaligenes*. Among them, the OUT abundance of *Alcaligenes* and *Bacillus* was higher on 27 June and 26 September than that on 28 December. A decreasing trend from June to December was showed on the OUT abundance of *Thiobacillus*. There was research showed that the type and quantity of phosphate-solubilizing microorganisms were related to the physical and chemical properties of sediment or soil, such as organic matter content, soil temperature, and other factors (Lin et al., 2017). The increase of phosphate-solubilizing microorganism abundance in sediments may due to the warmer temperature in June and September stimulate the activity of microorganism. Phosphate-solubilizing microorganisms could mineralize organic phosphorus in sediment, complex phosphorus with metal ions (such as Al and Fe) to form soluble phosphate, which enhanced the decomposition of the OP into IP (Behera et al., 2014; Li et al., 2012). The similar result was found in the study of Ding et al. that the Fe/Al (hydr)oxide-adsorbed P in sediments was the dominant source for P desorption (Ding et al., 2023). These results indicated that

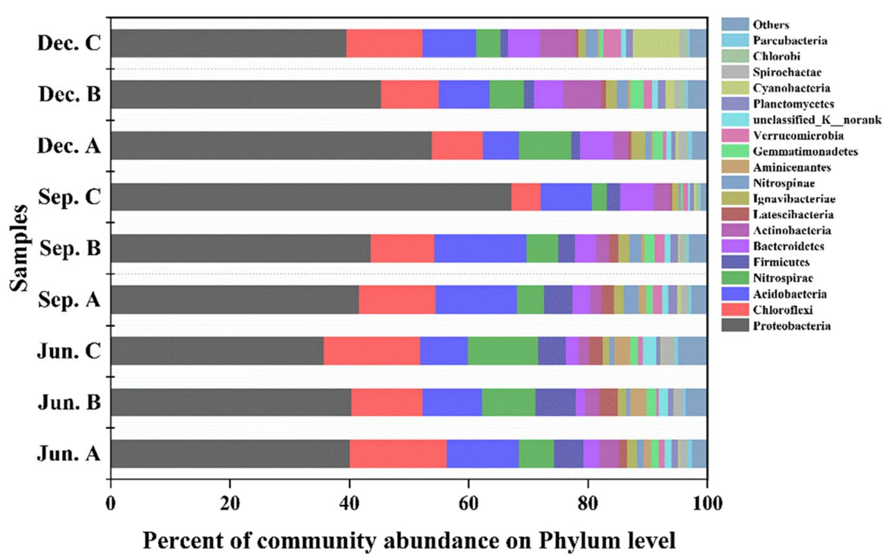

Fig. 6 Percent of community abundance on Phylum level in surface sediment

Table 4 The abundance of phosphate-solubilizing microorganisms on OTU level in surface sediment

Phosphate-solubilizing microorganisms	27 June			26 September			28 December		
	A	B	C	A	B	C	A	B	C
Alcaligenes	1105	2107	1021	889	1557	3734	375	518	564
Thiobacillus	128	209	90	127	75	27	111	36	19
Pseudomonas	82	21	113	88	69	7	146	117	40
Flavobacterium	63	23	46	33	60	32	19	34	86
Escherichia	2	0	1	25	0	0	0	0	0
Bacillus	34	25	107	130	242	74	21	21	17

sediment acted as the "source" of phosphorus in June and September to supplement the phosphorus needed for the algae bloom.

4 Conclusion

The water and sediment samples in Zhushan Bay, Taihu Lake, were sampled at three sampling sites on 27 June, 26 September, and 28 December. The results indicated that TP concentration in Zhushan Bay sediment was very high, ranged from 757.9 to 1724.6 mg kg^{-1}, which was due to the history accumulation of external phosphorus pollution. The main component of TP was IP, and NAIP was the main component of IP. Moreover, the contents of bioavailable phosphorus (WSP, AAP, RDP, and Olsen-P) in sediments of Zhushan Bay varied considerably. The rank order of four bioavailable phosphorus was AAP > Olsen-P > WSP > RDP. The result of correlation analysis showed that strong correlation (0.915) between NAIP and AAP, which indicated that AAP was highly significantly related to NAIP, indicating AAP was mainly the phosphorus combined with iron, aluminum, and other metals. The Fe/Al-P form in sediment was released into overlying water and used by algae during the outbreake stage of algal bloom, while OP and IP would be adsorbed on sediment during the deposits of dead algae and decay of algae after the bloom. Furthermore, phosphate-solubilizing microorganisms in the sediments of Zhushan Bay were mainly *Alcaligenes*, which could release phosphorus in sediment into overlying water to supplement phosphorus source required for algal bloom. Consequently, the best way to obtain algal bloom control is to hinder the phosphorus cycling in water environment, especially for the release of endogenous phosphorus into overlying water.

For future research, the impact of endogenous phosphorus load and algae bloom outbreak can be studied through controllable laboratory conditions. Explore the threshold of endogenous phosphorus load for algal bloom, which can provide clear goals for endogenous phosphorus control. As the bioavailability of different phosphorus components is various, phosphorus components and bioavailability should be considered when exploring endogenous phosphorus limitations.

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Data Availability The authors declare that the data supporting the findings of this study are available within the paper and its Supplementary Information files. Should any raw data files be needed in another format they are available from the corresponding author upon reasonable request. Source data are provided with this paper.

Declarations

Conflict of Interest The authors declare no competing interests.

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