

# Four kinds of capping materials for controlling phosphorus and nitrogen release from contaminated sediment using a static simulation experiment

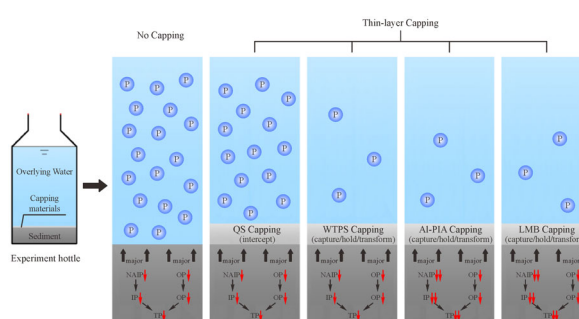
Zhenming Zhou (✉), Canyang Lin, Shuwen Li, Shupo Liu, Fei Li, Baoling Yuan

College of Civil Engineering, Huaqiao University, Xiamen 361021, China

## HIGHLIGHTS

- Lanthanum modified bentonite (LMB) can effectively absorb phosphorus (P).
- Water treatment plant sludge (WTPS) capping is effective for controlling P release.
- Aluminum-based P-inactivation agent (Al-PIA) is an efficient P control material.
- The P adsorbed by WTPS and Al-PIA is mainly in the form of NAIP.

## GRAPHIC ABSTRACT



## ARTICLE INFO

### Article history:

Received 25 December 2020

Revised 14 April 2021

Accepted 13 May 2021

Available online 28 June 2021

### Keywords:

Sediment

Eutrophication

Thin-layer capping

Phosphorus

Nitrogen

Aluminum-based P-inactivation agent

## ABSTRACT

We determined the effects of quartz sand (QS), water treatment plant sludge (WTPS), aluminum-based P-inactivation agent (Al-PIA), and lanthanum-modified bentonite (LMB) thin-layer capping on controlling phosphorus and nitrogen release from the sediment, using a static simulation experiment. The sediment in the experiment was sampled from Yundang Lagoon (Xiamen, Fujian Province, China), which is a eutrophic waterbody. The total phosphorus (TP), ammonium nitrogen ( $\text{NH}_4^+-\text{N}$ ), and total organic carbon (TOC) levels in the overlying water were measured at regular intervals, and the changes of different P forms in WTPS, Al-PIA, and sediment of each system were analyzed before and after the test. The average TP reduction rates of LMB, Al-PIA, WTPS, and QS were 94.82, 92.14, 86.88, and 10.68%, respectively, when the release strength of sediment TP was 2.26–9.19  $\text{mg}/(\text{m}^2 \cdot \text{d})$  and the capping strength of the materials was 2  $\text{kg}/\text{m}^2$ . Thin-layer capping of LMB, WTPS, and Al-PIA could effectively control P release from the sediment ( $P < 0.05$ ). However, thin-layer capping of LMB, Al-PIA, and QS did not significantly reduce the release of ammonium N and organic matter ( $P > 0.05$ ). Based on our results, LMB, Al-PIA, and WTPS thin-layer capping promoted the migration and transformation of easily released P in sediment. The P adsorbed by WTPS and Al-PIA mainly occurred in the form of NAIP.

© Higher Education Press 2021

## 1 Introduction

Eutrophication is a global environmental problem and pervasive in many lakes, coastal areas, and rivers around the world (Tu et al., 2019). With the rapid development of industrialization and urbanization, eutrophication ubiquitously poses a threat to drinking water supplies in China (He et al., 2021; Huang et al., 2014; Wang et al., 2019).

Sediment nutrients, especially nitrogen (N) and phosphorus (P), significantly contribute to water eutrophication (Cai et al., 2020; Pan G et al., 2012; Wu et al., 2019a). The release of N and P from lake sediment generates “internal loading,” which accelerates eutrophication and delays the recovery of damaged ecosystems, regardless of the reduction of “external loading” (Powers et al., 2014; Wu et al., 2019b). For example, Yundang Lagoon (Xiamen, China) has been eutrophicated for many years, and the local government has successively carried out a series of measures, such as sewage interception, silt removal, and ecological revetment construction, to deal with this

✉ Corresponding author  
E-mail: zhenming@hqu.edu.cn

problem. Although the water quality and ecological environment of Yundang Lagoon have improved to a certain degree, the N and P levels remain high, leading to serious water pollution (Ye et al., 2014). This problem is attributed to the continuous release of N and P from the contaminated sediment in Yundang Lagoon to the overlying water column. In this sense, reducing the release of N and P from the sediment can effectively control water eutrophication.

At present, dredging and capping are the two main measures to control the release of endogenous phosphorus (Yin et al., 2019). Due to the low cost, low hazard potential, and extensive adaptability, capping has recently attracted increased attention (Ichihara and Nishio, 2013; Zhan et al., 2019). In terms of capping technology, the selection of the capping materials is important for the performance and efficiency of pollutant control. The currently used capping materials can be divided into four categories (i.e., natural materials, synthetic materials, modified materials, and industrial by-products) (Douglas et al., 2016). Lanthanum-modified materials have received considerable attention, and lanthanum-modified bentonite (LMB) is widely used in Europe, the United States, and other regions (Waajen et al., 2016; Ding et al., 2018).

Water treatment plant sludge (WTPS) is a by-product formed by the adsorption of iron or aluminum salt flocculants during water purification (Ippolito et al., 2011; Okuda et al., 2014); it is rich in amorphous aluminum iron salt and has good sorption properties for phosphorus (Li et al., 2013; Wang et al., 2013). Wang and Pei et al (2011) reported that the maximum adsorptive capacity of WTPS could reach 45 mg/g, estimated via the Langmuir isotherm model. According to Wang et al. (2013), WTPS is an ideal material for controlling phosphorus pollution in lakes by laboratory simulation experiments. However, WTPS has the risk of releasing ammonium nitrogen and organic matter into the waterbodies, causing secondary pollution (Ichihara and Nishio, 2013). To deal with this problem, an aluminum-based P-inactivation agent (Al-PIA) has been developed (Liu et al., 2019), which was obtained by calcining WTPS and solved the problem of releasing ammonium nitrogen and organic matter from WTPS to waterbodies.

In this study, the effects of WTPS and Al-PIA as thin-layer capping materials to control the release of N and P from sediment were investigated using static simulative laboratory experiments. The other two commonly used adsorbent materials, LMB and quartz sand (QS), were tested for comparison. The concentration changes of total phosphorus (TP), ammonium nitrogen ( $\text{NH}_4^+\text{-N}$ ), and total organic carbon (TOC) in the overlying water were investigated. At the beginning and the end of the experiment, the concentrations of different forms of phosphorus, ammonium nitrogen, and organic matter in WTPS, Al-PIA, and sediment of each system were determined, and the transfer pathways of different P

forms were analyzed. Our results can provide a theoretical basis and technical support for the application of Al-PIA in controlling the release of nutrients from sediment and reducing water eutrophication.

## 2 Materials and methods

### 2.1 Experimental materials

#### 2.1.1 Sediment sampling

The sediment was sampled from the surface sediment of Yundang Lagoon (Xiamen, Fujian Province, China). A Peterson grab dredger was used for sediment collection to a depth of 20 cm. The collected sediment was mixed evenly and passed through 16 meshes (aperture 1 mm) of steel sieve, homogenized, and kept at 4°C until analysis. The overlying water used in the experiment was tap water.

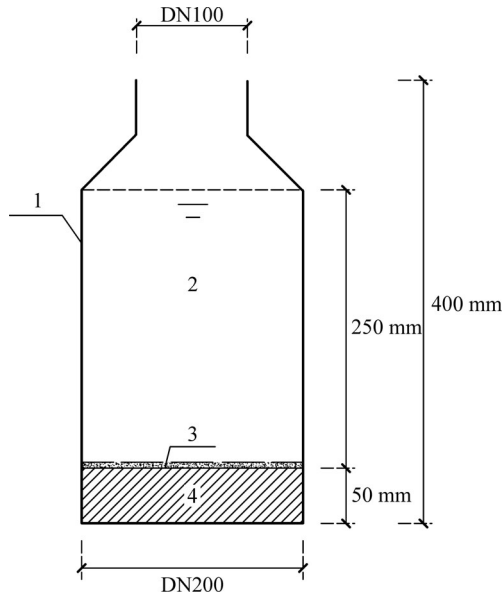
#### 2.1.2 Capping materials

The QS was purchased from China Lianyungang Xinhai Quartz Products Co., Ltd, rinsed thrice with tap water, and dried before use. The LMB was obtained from Taiwan Datang Xingye Co., Ltd., China.

The WTPS used in this experiment was obtained from waterworks station in Xiamen (Fujian Province, China), and the coagulant used in the plant was polymeric aluminum ferric chloride sulfate (PAFCS). The Al-PIA was obtained by calcining WTPS. The detailed preparation, mineral composition, and elemental composition of WTPS and Al-PIA are described in Zhou et al. (2018). The particle size of all capping materials was 1–2 mm.

### 2.2 Experimental procedures

The experiment lasted 118 days (d); Fig. 1 shows a scheme of the experimental set-up. The experimental device was a glass bottle with a 10-L volume and a 100-mm diameter. In total, there were 15 glass bottles, which were divided into five groups, and each group had three parallel samples. The five groups were numbered 1–5#, and the conditions of each group were as follows: (1) 1# was the control system without capping material; (2) 2# was the QS thin-layer capping system; (3) 3# was the WTPS thin-layer capping system; (4) 4# was the Al-PIA thin-layer capping system; (5) 5# was the LMB thin-layer capping system. The sediment weight in each bottle was 2.61 kg, at a thickness of 5 cm. The dose rate at 2 kg/m<sup>2</sup> of different capping materials was spread evenly on the sediment in the four thin-layer capping systems; the capping layer was approximately 2 mm. The selection of the dose rate and the capping layer thickness were based on a previous study (Li et al., 2019). The volume of the overlying water was 9 L, at a height of 25 cm.



**Fig. 1** Schematic of the experimental glass bottle. ① Glass bottle; ② Overlying water; ③ Capping materials; ④ Sediment.

During the experiment, the glass bottles were not sealed, and the dissolved oxygen (DO) concentration of the overlying water column was not controlled. Water temperature, pH, DO, and oxidation-reduction potential (ORP) were measured at a depth of 10 cm of the overlying water in each system every few days. The TP,  $\text{NH}_4^+\text{-N}$ , and TOC levels in the overlying water were measured at regular intervals. Tap water was supplemented to the original calibration line.

Surface sediment, WTPS, and Al-PIA samples were collected after the experiment. The sediment was mixed evenly, placed into a refrigerator for 2–3 h, and then dried in a freeze dryer. After that, the sediment was milled and passed through 100-mesh nylon sieves for detection. The collected WTPS and Al-PIA samples were rinsed thrice with tap water to remove impurities. Subsequently, WTPS

and Al-PIA samples were washed thrice with ultra-pure water and dried in an electric oven at  $105^\circ\text{C}$  for 6 h. Finally, the dried Al-PIA was milled and passed through a 100-mesh nylon sieve for analysis.

### 2.3 Chemical analysis

The solution pH was measured by using a Rex multi-parameter pH meter (DZS-708A, Shanghai Precision Instrument Co., Ltd., China). Water temperature and DO level were measured using a portable dissolved oxygen analyzer (HACH, HQ30d). The ORP was determined using a portable single parameter ORP meter (SX712, Shanghai Three-letter Instrument Co., Ltd., China). The concentrations of  $\text{NH}_4^+\text{-N}$  and TP in the overlying water were analyzed within 2 h according to the standard method (Ministry of environmental protection of China, 2002). The TOC concentration was measured using a TOC analyzer (V CPN, Shimadzu, Japan).

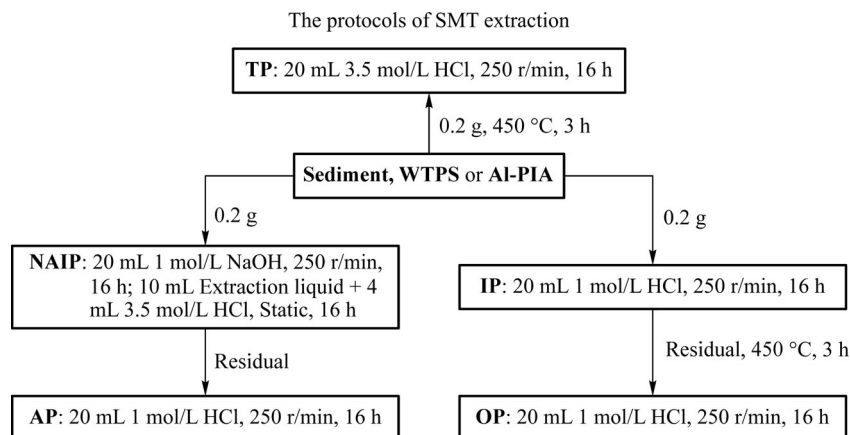
The contents of different P forms in sediment, WTPS, and Al-PIA were determined by the Standard Measurement and Testing (SMT) method, including total phosphorus (TP), inorganic phosphorus (IP), organic phosphorus (OP), non-apatite inorganic phosphorus (NAIP), and apatite phosphorus (AP) ( $\text{TP} = \text{OP} + \text{IP}$ ,  $\text{IP} = \text{NAIP} + \text{AP}$ ) (Ruban et al., 1999); Fig. 2 shows the extraction procedures (Zhou et al., 2018).

### 2.4 Data analysis

The release strength of sediment contaminants was calculated according to Eq. (1):

$$R_n = (V \times (C_n - C_0) + \sum_{i=1}^n V_i \times (C_i - C_0)) / (S \times t), \quad (1)$$

where  $R_n$  ( $\text{mg}/(\text{m}^2 \cdot \text{d})$ ) is the release intensity of sediment pollutants at the time of the  $n$  sampling,  $n$  is the total number of samples,  $V$  (L) is the overlying water volume in



**Fig. 2** The protocols of SMT extraction.

the glass bottle,  $C_n$  (mg/L) is the mass concentration of contaminants in the overlying water at the time of the  $n$ th sampling,  $C_0$  (mg/L) is the mass concentration of the initial pollutant,  $i$  is the number of samples,  $V_i$  (L) is the water volume of the  $i$ th sampling time,  $C_i$  (mg/L) is the quality concentration of pollutants of the  $i$ th sampling,  $S$  ( $m^2$ ) is the bottom mud-water interface area of the wide-mouth glass bottle, and  $t$  (d) is the release time of the pollutant.

The reduction efficiency for  $NH_4^+$ -N, TP, and TOC of the overlying water was calculated using Eq. (2):

$$P = (C_{NC_i} - C_{C_i}) / C_{NC_i} \times 100\%, \quad (2)$$

where  $P$  is the percent reduction efficiency of  $NH_4^+$ -N, TP, and TOC of the overlying water, and  $C_{C_i}$  (mg/L) and  $C_{NC_i}$  (mg/L) are the  $NH_4^+$ -N, TP, and TOC concentrations of the overlying water from the four thin-layer capping systems and the control system, respectively;  $i$  is the number of samplings.

We used variance analysis to analyze the difference of pollutant reduction effect among the thin-layer capping systems and the control system, applying Origin 8.5. Significance was assumed at  $p < 0.05$ .

### 3 Results and discussion

#### 3.1 Performance of TP controlling

During the experiments, the temperature, DO concentration, ORP, and pH of the overlying water at a depth of 10 cm ranged from 26.7 to 32.0°C, 1.92–7.58 mg/L, 12–254 Vm, and 6.8–8.8, respectively. To examine the performance of capping materials on the control of phosphorus release from the sediment, the changes in TP concentra-

tions of the overlying water in each system were measured (Fig. 3).

The release intensity of TP from the sediment of Yundang Lagoon was 2.26–9.19  $mg/(m^2 \cdot d)$ , with an average release intensity of 7.42  $mg/(m^2 \cdot d)$  in the control system. Compared with the control system, the reductive efficiency for TP increased at different degrees in the presence of capping materials. The removal rates for TP by LMB, Al-PIA, WTPS, and QS were 94.82, 92.14, 86.88, and 10.68%, respectively. Variance analysis showed that the reductive effects for TP by LMB, Al-PIA, and WTPS were significantly different from that of the control system ( $P < 0.05$ ), but similar to that of the QS system ( $P > 0.05$ ). The TP concentrations in the overlying water of the WTPS system, the Al-PIA system, and the LMB system were relatively low, mainly because the P in the sediment was fixed in the capping materials when passing through the capping layer and was therefore not transferred to the overlying water from the sediment. The Al-PIA and WTPS systems could effectively immobilize P and control the release of P from sediment due to their abundant amorphous iron-aluminum salts, large specific surface area, and positive charge (Li et al., 2013; Wang et al., 2013). Consequently, P could easily be fixed in the material via ligand (ion) exchange, surface precipitation, or complexation (Ippolito et al., 2003; Yang et al., 2006). Compared with WTPS thin-layer capping, Al-PIA thin-layer capping was more effective in controlling the release of P from sediment, which was attributed to the proportion of elements in the material. According to a previous study (Liu et al., 2019), compared with WTPS, the weight percentages of Al and Fe in Al-PIA slightly increased by 2.3 and 0.54%, respectively. This is due to the reduction of

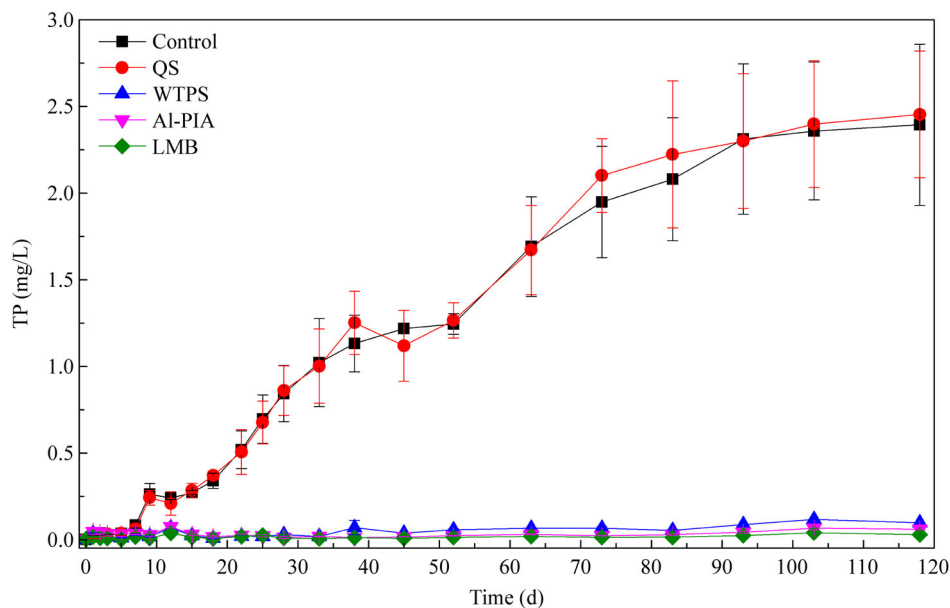


Fig. 3 Changes of TP concentrations of overlying water in the five systems.

N and organic matter during calcination at 400°C, whereas the boiling point of Al and Fe is higher than 400°C, which means that these elements retain in Al-PIA during the calcination process (Zhou et al., 2018). The increase in the proportion of Al<sup>3+</sup> and Fe<sup>3+</sup> after calcination is conducive to the increase of P absorption, because these metal ions can form strong precipitation complexes with P (Hauduc et al., 2015).

The control mechanism of P in LMB is focused on the formation of highly insoluble lanthanum phosphate complexes by lanthanum ions and phosphates (Haghseresh et al., 2009), and P would precipitate with lanthanum ions and be fixed in LMB while migrating through the sediment and capping layer. In this experiment, the average P control effects of the Al-PIA system and the WTSP system were only 2.72 and 7.94% lower than that of the LMB system, respectively, indicating that WTSP and its modified materials can effectively control P levels.

### 3.2 Performance of NH<sub>4</sub><sup>+</sup>-N control

To further assess the performance of the capping materials in the control of NH<sub>4</sub><sup>+</sup>-N fluxes, the changes in the NH<sub>4</sub><sup>+</sup>-N concentrations of the overlying water in each system were investigated (Fig. 4).

The NH<sub>4</sub><sup>+</sup>-N release from sediment was 6.62–232.68 mg/(m<sup>2</sup>·d) in the control system, with an average calculated level of 90.84 mg/(m<sup>2</sup>·d). From 0 to 28 d, the NH<sub>4</sub><sup>+</sup>-N level in the overlying water increased, caused by the large difference in the concentration of NH<sub>4</sub><sup>+</sup>-N between the overlying water and the sediment, facilitating the release of NH<sub>4</sub><sup>+</sup>-N from the sediment to the overlying water column. After 28 d, the NH<sub>4</sub><sup>+</sup>-N level gradually

decreased because the transformation of NH<sub>4</sub><sup>+</sup>-N was the dominant process. Compared with the control system, the average reduction rates for NH<sub>4</sub><sup>+</sup>-N in Al-PIA and LMB systems were 20.32 and 11.51%, respectively. The concentrations of NH<sub>4</sub><sup>+</sup>-N in the overlying water of the Al-PIA system and the LMB system were 3.35 and 4.71 mg/L, respectively, at 28 d, which was lower than in the control system (8.97 mg/L). This indicates that the Al-PIA and the LMB system had a certain effect on the release of NH<sub>4</sub><sup>+</sup>-N from the sediment via physical interception and adsorption of the capping layer, slowing down the material exchange between the sediment and the overlying water (Li et al., 2019).

The average removal rate of NH<sub>4</sub><sup>+</sup>-N in the WTSP system was –19.24% compared with the control system, implying that the WTSP system could not control the release of NH<sub>4</sub><sup>+</sup>-N from the sediment and also released a certain amount of NH<sub>4</sub><sup>+</sup>-N to the overlying water. This result was consistent with the findings of a previous study by Ichihara and Nishio (2013). As shown in Table 1, the content of ammonium N in WTSP was 156.86 mg/kg before the experiment and decreased by 110.70 mg/kg after the experiment. This leads us to infer that ammonium N in WTSP will be released into the waterbody, thus causing secondary pollution. However, compared with WTSP, the ammonium N content in Al-PIA slightly decreased by 99.44 mg/kg, which was attributed to the complex combustion oxidation reaction during the calcination process, leading to the gaseous release of carbohydrates and nitrogenous compounds (Zhou et al., 2018; Liu et al., 2019). Overall, the Al-PIA modified by WTSP calcination could solve the problem of releasing NH<sub>4</sub><sup>+</sup>-N from sediment.

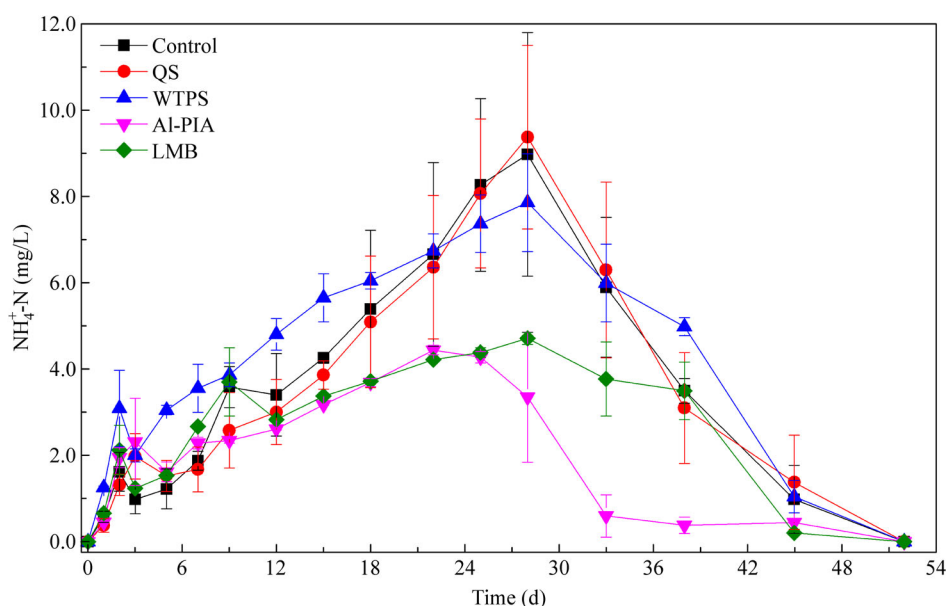


Fig. 4 Changes of NH<sub>4</sub><sup>+</sup>-N concentrations of overlying water in the five systems.

**Table 1** Changes of various forms of ammonium nitrogen and organic matter content in WTSP and Al-PIA before and after tests

Sample		Ammonium nitrogen content (mg/kg)	Organic matter content (mg/kg)
WTSP	Before reaction	156.86±1.08	163.69±0.24
	After reaction	46.16±0.22	91.64±2.51
Al-PIA	Before reaction	57.42±0.86	38.32±0.08
	After reaction	38.90±0.65	35.94±0.47

### 3.3 Performance of TOC control

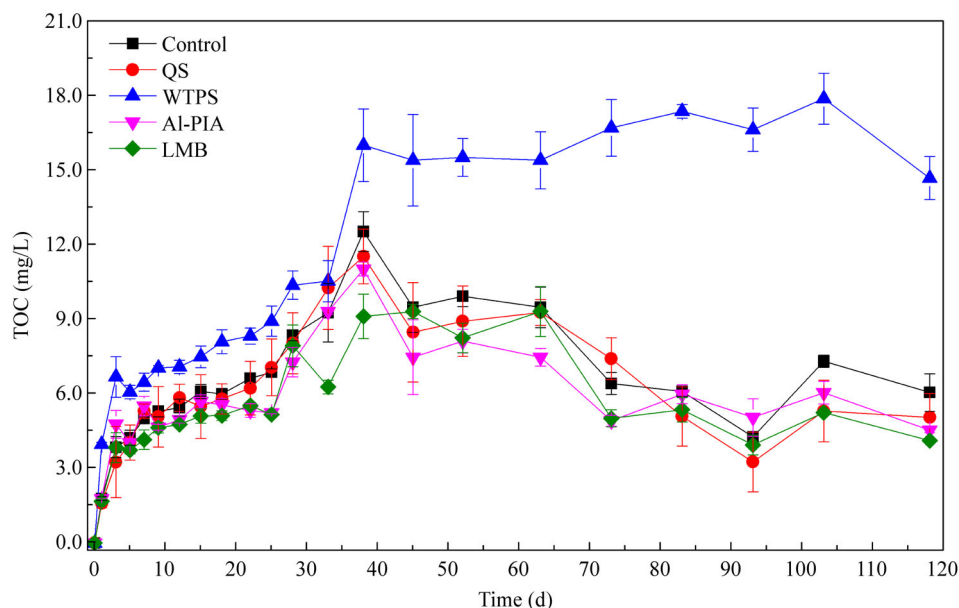
The changes in TOC concentrations in the overlying water of each system are shown in Fig. 5. The release intensity range for TOC from sediment was 13.28–370.03 mg/(m<sup>2</sup>·d), and the average release intensity was 105.13 mg/(m<sup>2</sup>·d) in the control system. The average TOC reduction rates of LMB, Al-PIA, WTSP, and QS systems were 14.34, 7.94, –73.94, and 6.21%, respectively, indicating that the physical interception of Al-PIA, LMB, and QS thin-layer capping slowed down the release of organic matter from sediment. However, WTSP thin-layer capping could not control the release of TOC from sediment, also releasing a certain amount of organic matter into the waterbody, which mainly attributed to the high content of organic matter (Table 1) in WTSP and thus resulted in a high risk of organic matter release. This result was in agreement with the findings of Liu et al. (2019). Overall, secondary pollution (i.e., the release of organic matter into the water) could only be caused by the WTSP system.

### 3.4 Analysis of various forms of phosphorus in sediment

To explore the differences of the transformation of P, N,

and organic matter among the overlying water, the capping materials, and the sediment, the contents of various forms of the above indicators in the sediment were examined (Fig. 6).

As seen in Fig. 6, the initial concentrations of TP, IP, OP, NAIP, and AP in the sediment layer before the experiment were 1,022.12, 794.91, 194.76, 435.85, and 346.35 mg/kg, respectively. Among them, IP and NAIP accounted for 77.77 and 42.64% of TP. This indicates that P in sediment mainly occurs in the form of NAIP, which means that the risk of P release from the sediment was greater (Li et al., 2019). The levels of TP, IP, OP, and NAIP decreased in the control sediment, whereas the AP concentration increased to a certain degree, indicating that P in the sediment not only migrates to the overlying water column but is also transformed into the more stable form (AP). In particular, the amount of migratory P in the sediment was higher than that of transformative P, which attributed to the difference in the P concentration between the overlying water and the sediment. Compared with the background value, the migration and transformation values of TP in control, QS, WTSP, Al-PIA, and LMB sediment were 92.49, 102.49, 169.57, 246.65, and 262.06 mg/kg, respectively. Based on our results, LMB, Al-PIA, and WTSP thin-layer capping promoted the migration and transformation of easily released P in sediment, whereas QS thin-layer capping had little effect. Moreover, WTSP, Al-PIA, and LMB sediment decreased TP by 77.08, 154.16, and 169.57 mg/kg, IP by 58.59, 122.82, and 156.22 mg/kg, NAIP by 35.97, 115.10, and 122.30 mg/kg, AP by 10.28, 12.58, and 20.55 mg/kg, and OP by –10.28, 2.57, and 2.57 mg/kg, respectively. We could show that LMB, Al-PIA, and WTSP thin-layer capping contributed to the migration and transformation of NAIP from inorganic P, facilitating the

**Fig. 5** Changes of TOC concentrations of overlying water in the five systems.

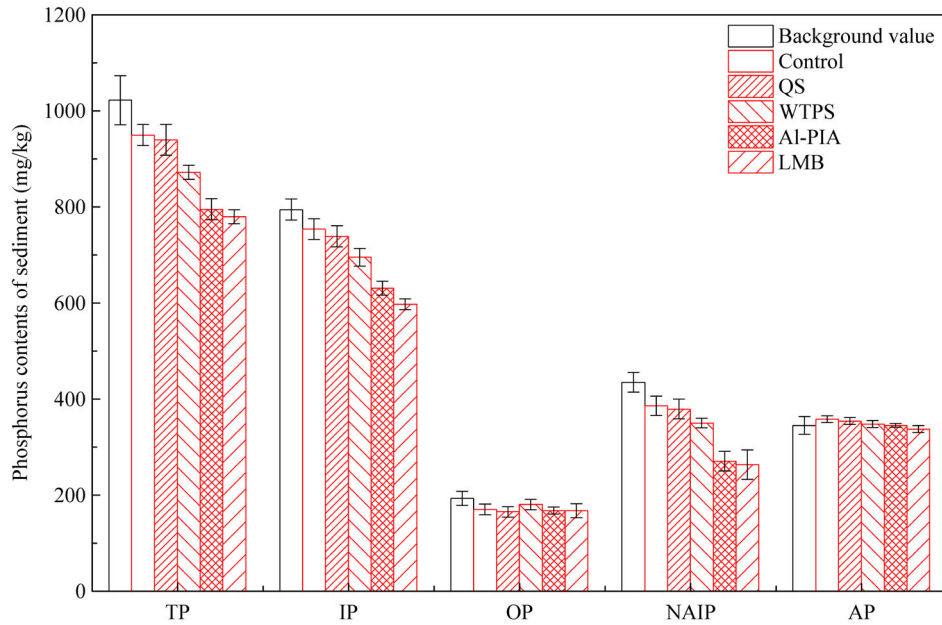


Fig. 6 Changes of various forms of phosphorus content in the WTPS and Al-PIA.

formation of more stable P (Li et al., 2019; Liu et al., 2019). Most likely, this is because these three active materials had a strong ability to immobilize P, changing the migratory and transformative direction of easily released P in sediment and inhibiting the release of fixed P (Wang and Jiang, 2016).

### 3.5 Analysis of various forms of phosphorus in WTPS and Al-PIA

To explore the transformation of P between WTPS and Al-

PIA materials, the variation in different P forms in WTPS and Al-PIA before and after the test were measured (Fig. 7).

At the start of the experiment, NAIP in Al-PIA increased by 748.16 mg/kg and OP in Al-PIA decreased by 539.54 mg/kg compared with WTPS, most likely because the conversion from OP to NAIP in WTPS during the calcination process. The concentrations of TP and IP increased throughout the simulation experiment. The increase in the TP content of WTPS and Al-PIA was caused by IP. Moreover, NAIP most significantly con-

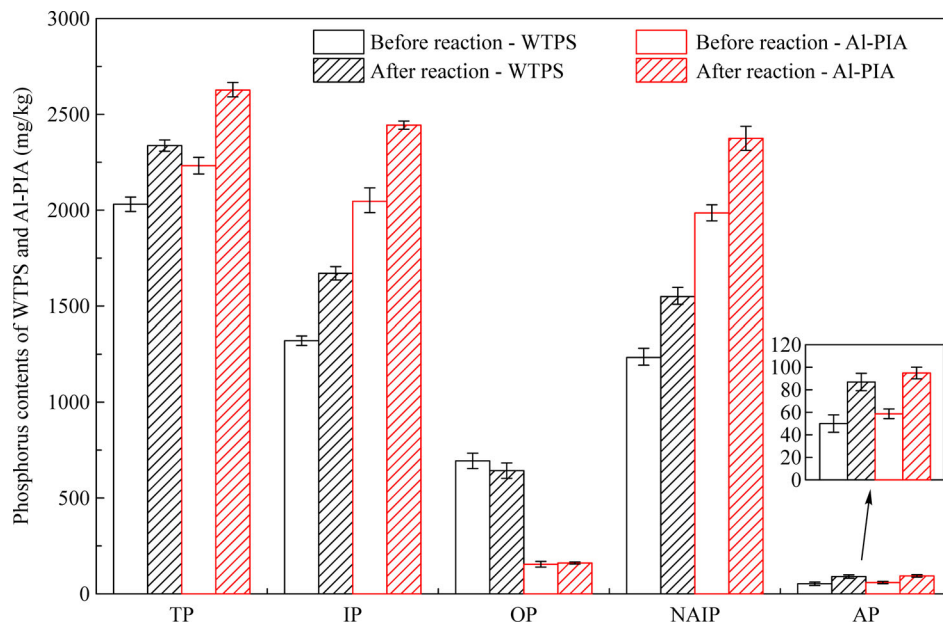


Fig. 7 Changes of phosphorus content of sediment in different systems.

tributed to the increased IP concentration, accounting for 90.59 and 91.94% of the IP for WTPS and Al-PIA, respectively. This implies that WTPS and Al-PIA mainly fixed NAIP in IP, and Al-PIA exhibited a higher performance than WTPS in immobilizing P, which is in accordance with the study of Hou et al. (2018). This can be explained by the enhanced amorphous iron and aluminum salt levels and by the active sites in Al-PIA during calcination (Zhou et al., 2018). Moreover, AP in WTPS and Al-PIA was increased by 37.00 and 35.97 mg/kg, respectively. Liu et al. (2019) reported that the mass fraction of calcium in WTPS and Al-PIA was 0.10 and 0.11% respectively, indicating that WTPS and Al-PIA could also form calcium P under certain conditions. Furthermore, the P adsorption capacity of Al-PIA in this experiment was 0.43 mg/g; this low efficiency was mainly attributed to the low P concentration applied in the overlying water of the Al-PIA thin-layer capping system (below 0.2 mg/L), consequently suppressing the P adsorption capacity of Al-PIA materials (Li et al., 2019). Therefore, to obtain a good P removal, the concentration of P and the coverage strength of Al-PIA should be taken into account.

### 3.6 Evaluation of the four capping materials

As a traditional in situ capping material, QS is inexpensive and readily available, but its thin-layer capping cannot effectively control the release of pollutants from sediment. Thick-layer capping can reduce the capacity of the waterbody and affect the function of flood control and drainage. In contrast, LMB is a widely used P-locking agent and can rapidly reduce the P concentration in water. However, because of its high cost and the formation of stable  $\text{LaPO}_4$ , LMB does not support the recovery and reuse of P resources. The large-scale use of LMB may lead to the depletion of P resources (Lüring et al., 2016).

The WTPS is a by-product (Okuda et al., 2014) produced during water purification. It has a wide range of sources, as well as abundant amorphous iron and aluminum salts. Although it effectively adsorbs P (Li et al., 2013; Wang et al., 2013), the direct application of WTPS poses a threat to the waterbody (e.g., the release of ammonium N and organic matter). Regarding Al-PIA prepared with WTPS resource, it has several advantages, such as low cost, large-scale applications, a great P adsorption potential, and a low risk of ammonium N and organic matter release (Liu et al., 2019). Our results show that the average P reduction rate of Al-PIA was only 2.68% lower than that of LMB when the coverage strength was 2 kg/m<sup>2</sup>, implying that Al-PIA is a promising P removal material.

## 4 Conclusions

In our study, LMB, WTPS, and Al-PIA could effectively

control the release of P from sediment, in contrast to QS. However, LMB, Al-PIA, and QS showed no significant reduction in ammonium N and organic matter released from the sediment. The WTPS not only increased ammonium N and organic matter, but also released ammonium N and organic matter into the water. The LMB, Al-PIA, and WTPS systems efficiently immobilized P, changing the migratory and transformative pathway of P easily released from sediment and inhibiting the release of fixed P. In summary, WTPS and its modified materials could efficiently control P release from sediment, making them promising tools in water purification.

**Acknowledgements** This work was supported by the National Natural Science Fund of China (Grant No. 51878300), the Natural Science Foundation of Fujian Province of China (Grant No. 2019J01052) and Project of production, study and research of colleges and universities of Xiamen City (Grant No. 3502Z20203044).

## References

- Cai O, Xiong Y, Yang H, Liu J, Wang H (2020). Phosphorus transformation under the influence of aluminum, organic carbon, and dissolved oxygen at the water-sediment interface: A simulative study. *Frontiers of Environmental Science & Engineering*, 14(3): 12
- Ding S M, Sun Q, Chen X, Liu Q, Wang D, Lin J, Zhang C S, Tsang D C W (2018). Synergistic adsorption of phosphorus by iron in lanthanum modified bentonite (Phoslock®): New insight into sediment phosphorus immobilization. *Water Research*, 134: 32–43
- Douglas G B, Hamilton D P, Robb M S, Pan G, Spears B M, Lurling M (2016). Guiding principles for the development and application of solid-phase phosphorus adsorbents for freshwater ecosystems. *Aquatic Ecology*, 50(3): 385–405
- Haghsheresht F, Wang S B, Do D D (2009). A novel lanthanum-modified bentonite, Phoslock, for phosphate removal from wastewaters. *Applied Clay Science*, 46(4): 369–375
- Hauduc H, Takács I, Smith S, Szabo A, Murthy S, Daigger G T, Spérandio M (2015). A dynamic physicochemical model for chemical phosphorus removal. *Water Research*, 73: 157–170
- He H, Yu Q, Lai C, Zhang C, Liu M, Huang B, Pu H, Pan X (2021). The treatment of black-odorous water using tower bipolar electro-flocculation including the removal of phosphorus, turbidity, sulfion, and oxygen enrichment. *Frontiers of Environmental Science & Engineering*, 15(2): 18
- Hou Q J, Meng P P, Pei H Y, Hu W R, Chen Y (2018). Phosphorus adsorption characteristics of alum sludge: Adsorption capacity and the forms of phosphorus retained in alum sludge. *Materials Letters*, 229: 31–35
- Huang C C, Wang X L, Yang H, Li Y M, Wang Y H, Chen X, Xu L J (2014). Satellite data regarding the eutrophication response to human activities in the plateau lake Dianchi in China from 1974 to 2009. *Science of the Total Environment*, 485–486: 1–11
- Ichihara M, Nishio T (2013). Suppression of phosphorus release from sediments using water clarifier sludge as capping material. *Environmental Technology*, 34(15): 2291–2299



- Ippolito J A, Barbarick K A, Elliott H A (2011). Drinking water treatment residuals: a review of recent uses. *Journal of Environmental Quality*, 40(1): 1–12
- Ippolito J A, Barbarick K A, Heil D M, Chandler J P, Redente E F (2003). Phosphorus retention mechanisms of a water treatment residual. *Journal of Environmental Quality*, 32(5): 1857–1864
- Li S W, Zhou Z M, Yang S M, Liu S P, Li F, Yuan B L (2019). The efficiency of controlling the phosphorus release from the sediment using calcined modified water purification plant sludge (C-WTPS). *Journal of Lake Science*, 31(4): 961–968
- Li Z F, Jiang N, Wu F F, Zhou Z (2013). Experimental investigation of phosphorus adsorption capacity of the waterworks sludges from five cities in China. *Ecological Engineering*, 53: 165–172
- Liu Q D, Zhou Z M, Zhang H Z, Fei L X, Xie B J, Li S W, Yuan B L (2019). Phosphorus removal characteristics of calcined water treatment plant sludge. *Environmental Chemistry*, 38(02): 325–333
- Lürling M, Mackay E, Reitzel K, Spears B M (2016). A critical perspective on geo-engineering for eutrophication management in lakes. *Water Research*, 97: 1–10
- Okuda T, Nishijima W, Sugimoto M, Saka N, Nakai S, Tanabe K, Ito J, Takenaka K, Okada M (2014). Removal of coagulant aluminum from water treatment residuals by acid. *Water Research*, 60: 75–81
- Pan G, Dai L C, Li L, He L C, Li H, Bi L, Gulati R D (2012). Reducing the recruitment of sedimented algae and nutrient release into the overlying water using modified soil/sand flocculation-capping in eutrophic lakes. *Environmental Science & Technology*, 46(9): 5077–5084
- Powers S M, Robertson D M, Stanley E H (2014). Effects of lakes and reservoirs on annual river nitrogen, phosphorus, and sediment export in agricultural and forested landscapes. *Hydrological Processes*, 28 (24): 5919–5937
- Ruban V, López-Sánchez J F, Pardo P, Rauret G, Muntau H, Quevauviller P (1999). Selection and evaluation of sequential extraction procedures for the determination of phosphorus forms in lake sediment. *Journal of Environmental Monitoring*, 1(1): 51–56
- Ministry of Environmental Protection of China (2002). *Determination Methods for Examination of Water and Wastewater*, 4th ed. Beijing: China Environmental Science Press (in Chinese)
- Tu L Y, Jarosch K A, Schneider T, Grosjean M (2019). Phosphorus fractions in sediments and their relevance for historical lake eutrophication in the Ponte Tresa Basin (Lake Lugano, Switzerland) since 1959. *Science of the Total Environment*, 685: 806–817
- Waajen G, Van Oosterhout F, Douglas G, Lürling M (2016). Management of eutrophication in Lake De Kuil (The Netherlands) using combined flocculant: Lanthanum modified bentonite treatment. *Water Research*, 97: 83–95
- Wang C H, Gao S J, Pei Y S, Zhao Y Q (2013). Use of drinking water treatment residuals to control the internal phosphorus loading from lake sediments: Laboratory scale investigation. *Chemical Engineering Journal*, 225: 93–99
- Wang C H, Jiang H L (2016). Chemicals used for in situ immobilization to reduce the internal phosphorus loading from lake sediments for eutrophication control. *Critical Reviews in Environmental Science and Technology*, 46(10): 947–997
- Wang C H, Pei Y S (2011). Characteristics of orthophosphate adsorption on ferric-alum residuals (FARs) from drinking water treatment plant. *Environmental Sciences*, 32(8): 2371–2377
- Wang J L, Fu Z S, Qiao H X, Liu F X (2019). Assessment of eutrophication and water quality in the estuarine area of Lake Wuli, Lake Taihu, China. *Science of the Total Environment*, 650: 1392–1402
- Wu T F, Qin B Q, Brookes J D, Yan W M, Ji X Y, Feng J (2019a). Spatial distribution of sediment nitrogen and phosphorus in Lake Taihu from a hydrodynamics-induced transport perspective. *Science of the Total Environment*, 650: 1554–1565
- Wu Z H, Wang S R, Ji N N (2019b). Phosphorus (P) release risk in lake sediment evaluated by DIFS model and sediment properties: A new sediment P release risk index (SPRRI). *Environmental Pollution*, 255: 113279
- Yang Y, Zhao Y Q, Babatunde A O, Wang L, Ren Y X, Han Y (2006). Characteristics and mechanisms of phosphate adsorption on dewatered alum sludge. *Separation and Purification Technology*, 51 (2): 193–200
- Ye G, Chou L M, Hu W (2014). The role of an integrated coastal management framework in the long-term restoration of Yundang Lagoon, Xiamen, China. *Journal of Environmental Planning and Management*, 57(11): 1704–1723
- Yin H B, Wang J F, Zhang R Y, Tang W Y (2019). Performance of physical and chemical methods in the co-reduction of internal phosphorus and nitrogen loading from the sediment of a black odorous river. *Science of the Total Environment*, 663: 68–77
- Zhan Y H, Yu Y, Lin J W, Wu X L, Wang Y, Zhao Y Y (2019). Simultaneous control of nitrogen and phosphorus release from sediments using iron-modified zeolite as capping and amendment materials. *Journal of Environmental Management*, 249: 109369
- Zhou Z M, Liu Q D, Li S W, Li F, Zou J, Liao X B, Yuan B L, Sun W J (2018). Characterizing the correlation between dephosphorization and solution pH in a calcined water treatment plant sludge. *Environmental Science and Pollution Research International*, 25 (19): 18510–18518