Environmental Science and Pollution Research (2022) 29:16427–16435
https://doi.org/10.1007/s11356-021-16981-x

RESEARCH ARTICLE

Three kinds of active thin-layer capping materials for reducing the phosphorus load in eutrophic water body: comparison in dynamic experiment

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Received: 27 June 2021 / Accepted: 6 October 2021 / Published online: 14 October 2021

Abstract

In this article, dynamic simulation experiments have studied the effects of three capping materials, quartz sand (QS), aluminum-based phosphorus-locking agent (Al-PIA), and lanthanum-modified bentonite (LMB) in reducing phosphorus load in eutrophic water bodies. The changes of various forms of phosphorus in Al-PIA and sediment before and after the test were analyzed, and the mechanism of phosphorus migration and transformation in different capping systems was described. The dynamic simulation test lasted 95 days. The results showed that when the initial concentration of total phosphorus (TP) was 3.55 mg/L, the capping strength was 2 kg/m^2 and the hydraulic retention time of water circulation was 0.5 days, indicating that the average reduction rates of TP by LMB, Al-PIA and QS systems were 74.66%, 69.54%, and 3.64%, respectively, compared with the control system. The analysis of variance showed that there were significant differences ($P < 0.05$) in the TP concentration of the overlying water between the LMB, Al-PIA capping system, and the control system. Lanthanum ions in LMB can fix phosphorus. Al-PIA reduces the phosphorus concentration in water by means of ion exchange, adsorption, complexation, etc. LMB and Al-PIA promoted the migration of phosphorus in sediment. Among them, the phosphorus fixed by Al-PIA was mainly in the form of non-apatite inorganic phosphorus (NAIP) in inorganic phosphorus (IP), which can be seen; Al-PIA can effectively reduce the phosphorus load of eutrophic water.

Keywords Eutrophic water · Sediment · Dynamic simulation · Al-PIA, Thin-layer capping · Phosphorus

Introduction

Eutrophication of river was considered to be one of the most serious problems in the world, and it has attracted much attention from researchers around the world (Le Moal et al. 2019; Tu et al. 2019; Wang et al. 2019). In freshwater ecosystems, phosphorus plays an important role in controlling primary productivity. It is usually considered as an important nutrient limiting factor and a major factor leading to eutrophication of the water body (Wu et al. 2019a, b). Phosphorus in lakes comes from two sources, external and internal sources. As the internal source of phosphorus in lakes, sediment continuously releases phosphorus to the water body, and its impact is particularly prominent (Wu et al., 2019a, b). Therefore, under the condition of effective control of exogenous phosphorus, reducing the release of phosphorus from sediment in lakes is one of the effective methods to control eutrophication of lakes.

At present, the main ways to reduce the release of phosphorus from sediment are dredging and capping (Spears et al. 2014; Yin et al. 2019). The capping method has attracted much attention from scholars from all over the world because of its advantages of small disturbance to the sediment, less potential harm to the environment, and suitability for a variety of inorganic and organic sediment (Fan et al. 2017; Huang et al. 2013; Zhou et al. 2016). The capping material is the core part of the in situ capping technology. And it has developed from traditional inert capping materials such as sand, gravel, and clean soil to current active capping materials such as natural zeolite or biological zeolite or physicochemically modified zeolite (Fan et al. 2017; Zhan et al. 2020), synthetic material Fe–Mn binary oxide (FMBO) (Lu et al. 2014), lanthanum-modified

Responsible Editor: Philippe Garrigues

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bentonite (LMB) (Ding et al. 2018; Waajen et al. 2016), and lanthanum-modified water purification plant sludge (Wang et al. 2018). It is worth mentioning that the LMB has formed industrialization because of its good phosphorus adsorption effect and has been widely used in engineering in European and American countries (Ding et al. 2018; Waajen et al. 2016). However, the mineralization formed by lanthanum adsorption of phosphorus is difficult to desorb, which is not conducive to the recovery of phosphorus resources (Rui et al. 2017). Zeolite has a significant adsorption effect on ammonia nitrogen in water and is often used in actual water projects (Zhou et al. 2016). But it can reduce the phosphorus concentration in water, so the application range of this material is limited. Fe-Al-modified zeolite (Zhan et al. 2020) and FMBO (Lu et al. 2014) can reduce the phosphorus concentration of the overlying water. However, due to its complicated preparation process, it is currently difficult to produce and apply on a large scale.

Water treatment plant sludge (WTPS) is a by-product formed by the iron or aluminum salt flocculant adsorbing pollutants in the water purification process of the water purification plant (Ippolito et al. 2011; Okuda et al. 2014). And it contains abundant amorphous aluminum iron salt and has a good adsorption effect on phosphorus (Li et al. 2013; Wang et al. 2013a, b, c). In 2011, it has been reported that WTPS has a good phosphorus removal effect (Wang and Pei 2011). But it will release a large amount of ammonia nitrogen to the water (Liu et al. 2018a, b), so it is not suitable for direct use. In order to solve this problem, Zhou's research group calcined and modified the WTPS to prepare an efficient phosphorus removal product: aluminum-based P-inactivation agent (Al-PIA). Research has shown that (Liu et al. 2018a, b) Al-PIA (formerly known as calcined water treatment plant sludge) not only has a good adsorption effect on phosphorus but also basically does not release ammonia nitrogen to water. Another article by the author mentioned the influence of pH on the phosphorus removal effect of Al-PIA (Zhou et al. 2018), and the results showed that the Al-PIA adsorbs phosphorus in water relatively stably when the pH is in the range of 3–10. But when the pH reaches 11, there is a risk of releasing phosphorus into the water. Al-PIA also has a good effect on controlling the release of phosphorus from sediment (Li et al. 2019). Some scholars have studied the effect of secondary capping on the release of phosphorus in sediment controlled by Al-PIA (Zhu et al. 2021) and found that as the thickness of the secondary capping layer increases, the effect of Al-PIA on the release of phosphorus in sediment decreases. When the thickness of the secondary capping reaches 15 mm thick, the phosphorus removal capacity of the Al-PIA is only 32.11%. However, most of the phosphorus removal experiments of Al-PIA are static simulation studies, and dynamic simulation experiments are rarely reported.

Therefore, this paper takes the polluted sediment of landscape water as the research object and studies three materials quartz sand (QS), Al-PIA, and LMB with thin-layer capping on controlling the release of phosphorus from sediment through dynamic simulation experiments in the laboratory. During the test, the changes in the concentration of TP in the overlying water were investigated, the changes of various forms of phosphorus in Al-PIA and the sediment before and after the test were analyzed, and the mechanism of phosphorus migration and transformation during the repair process of Al-PIA thin-layer capping was explained. The research results can provide theoretical basis and technical support for the practical application of Al-PIA thin-layer capping to control the release of phosphorus from sediment.

Materials and methods

Experimental materials

The overlying water and sediment used in the experiment were taken from the landscape lake of a college in Fujian. The sediment were passed through a 16 mesh (1 mm aperture) steel sieve and mixed well for the experiment. The QS used in the experiment is ordinary quartz sand. The Al-PIA used in the experiment is the material obtained by calcining and modifying the sludge of the water purification plant. The specific steps are as follows: the dehydrated sludge taken from a water purification plant in Xiamen is naturally air-dried, and it is put into a muffle furnace calcining at 400 °C for 2.5 h when moisture content is about 10 ~ 13%, obtaining the experimental material of 1–2 mm through crushing and sieving. The detailed Al-PIA preparation parameters follow Liu et al. (2018a, b), and the specific change of physical and chemical properties of the sludge before and after calcination modification is in Zhou et al. (2018). The detailed Al-PIA preparation parameters and the specific change of physical and chemical properties of the sludge before and after calcination modification are in the reference. The LMB used in the experiment was developed by the Australian Industrial Research Association and provided by China Taiwan Datang Industrial Co. Ltd.

Experimental device and method

Experimental device

The experimental devices are plexiglass tank and peristaltic pump, as shown in Fig. 1. The size of the plexiglass tank is 60 cm long × 30 cm wide × 40 cm high, and the effective volume was 72L. The peristaltic pump was purchased from Lange Constant Flow Pump Co., Ltd.; the model is BT100-2 J (DG15-28); the number of channels is 2. The

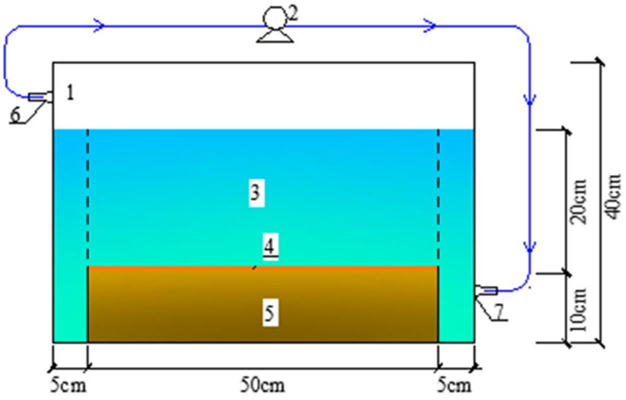


Fig. 1 Schematic of the experimental device. (1) Plexiglass tanks; (2) peristaltic pump; (3) overlying water; (4) capping materials; (5) sediment; (6) water outlet; (7) water inlet

maximum flow rate of a single channel is 75 mL/min, and it is suitable for silicone hoses with an inner diameter of 3 mm and a wall thickness of 1 mm.

Dynamic experimental method

There were 8 plexiglass tanks in the experiment, divided into 4 groups, 2 parallel samples in each group, numbered 1 ~ 4#. 1# is the control system, without capping materials; 2# is the QS capping system; 3# is the Al-PIA capping system; 4# is the LMB capping system. The weight of the sediment in each plexiglass tank is about 15.6 kg (the thickness is about 10 cm); the volume of the overlying water is about 34.2L (the water depth is about 20 cm). And the lake water was slowly added to the tank along the tank wall through a plastic hose using the principle of siphon. The capping strength of the capping material is 2 kg/m^2. The hydraulic residence time is 0.5 days.

The experiment was conducted indoors and lasted 95 days. During the experiment, the plexiglass slot was open (do not control the dissolved oxygen (DO) concentration of the overlying water). Water temperature, pH, DO, and oxidation–reduction potential (ORP) at the depth of 10 cm in each system were measured regularly every day. Regularly, 50 mL water samples were collected for the total phosphorus (TP) detection. After sampling, the tap water (50 mL) was replenished into the system.

The dynamic simulation experiment was divided into two stages. The first stage was from the beginning of the experiment to the TP concentration in the overlying water of the Al-PIA capping system reaching the class III criteria of surface water in China ($P < 0.2$ mg/L), which lasted for 44 days; the second stage was the subsequent monitoring of TP concentration changes in the overlying water, which lasted for 51 days. After each stage of the experiment, the content of 5 forms of phosphorus in the capping material in the Al-PIA capping system and the sediment in each capping system was measured. In a previously published paper (Liu et al. 2018a, b), the author described the collection method and pretreatment procedures of Al-PIA and sediment.

Chemical analysis

Water temperature and DO were measured by portable DO meter (HACH, HQ30d type); pH was measured by portable pH meter (Shanghai Ohaus Instrument Co., Ltd., STARTER3100 type); ORP was measured by portable single-parameter ORP meter (Shanghai Sanxin Instrument Co., Ltd. Company, SX712); the concentrations of TP in overlying water were analyzed according to the standard method (State Environmental Protection Administration (SEPA) of China, 2002).

The SMT method (Ruban et al. 1999) was used to determine the content of different forms of phosphorus in the sediment, including TP (total phosphorus), IP (inorganic phosphorus), OP (organic phosphorus), NAIP (non-apatite inorganic phosphorus), and AP (calcium phosphorus) mainly. The analysis process is shown in Fig. 2.

Data analysis

The pollutant reduction rate P in the overlying water is calculated by *Eq. (1)*:

$$P = \frac{C_{\mathrm{NCi}} - C_{\mathrm{Ci}}}{C_{\mathrm{NCi}}} \times 100\% \tag{1}$$

In the formula, C_{Ci} is the pollutant concentration in the overlying water of the capping system of ith time sampling (mg/L); C_{NCi} is the pollutant concentration in the overlying water of the control system of ith time sampling (mg/L); and i is the number of samplings.

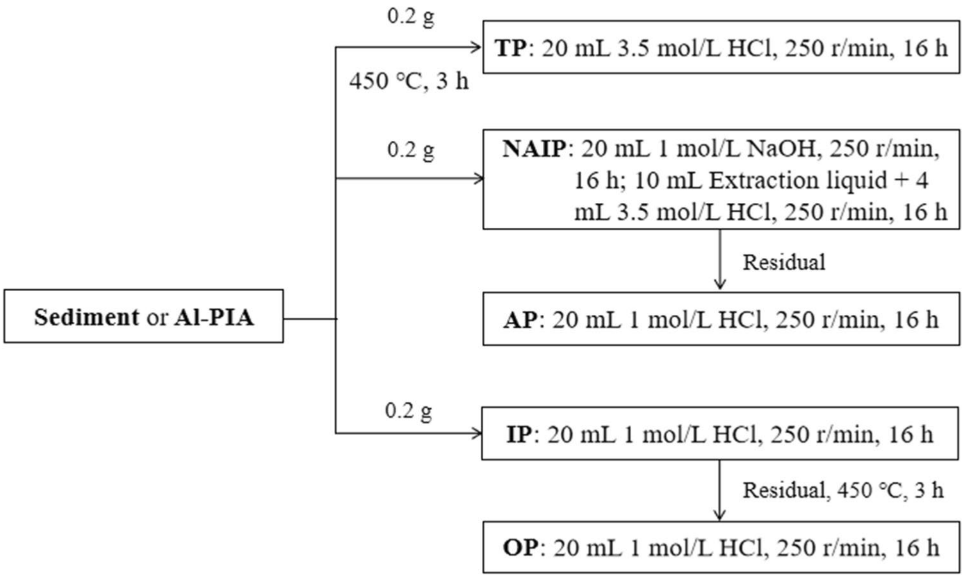
Origin8.5 variance analysis is used to study the difference of phosphorus reduction effect between the control system and the capping system.

Results and discussion

The effects of the three capping materials in reducing TP concentration in the overlying water

The dynamic simulation test lasted for 95 days. The temperature of the overlying water in each system varied from 15.6 to 22.3 °C, the pH varied from 6.94 to 7.69, the DO varied from 1.39 to 8.54 mg/L, and the ORP varied from 143 to 335 mV; the specific data were shown in Fig. 3. During the test, the change of TP concentration in the overlying water of each system was shown in Fig. 4.

Fig. 2 The protocols of SMT extraction



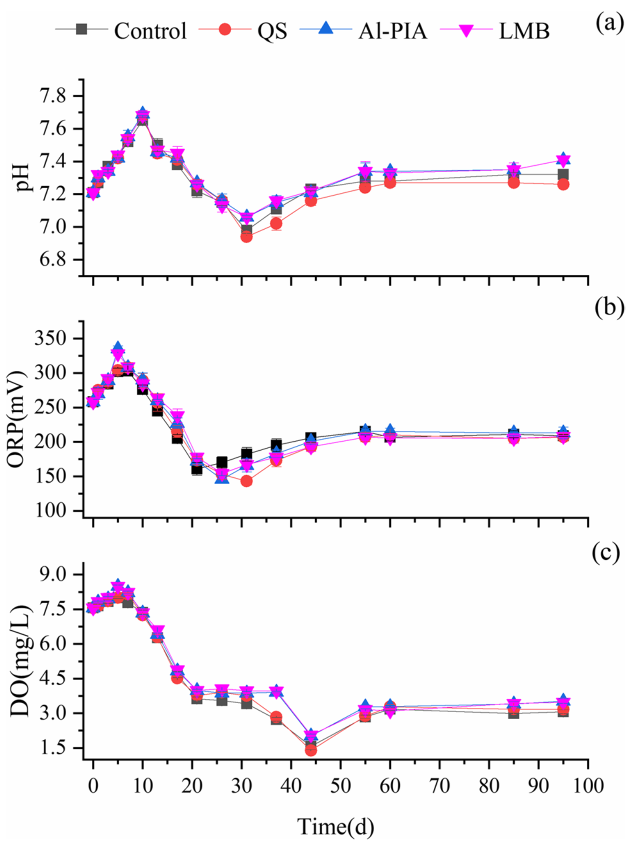


Fig. 3 Changes of **a** pH, **b** ORP, and **c** DO concentration, in the four systems

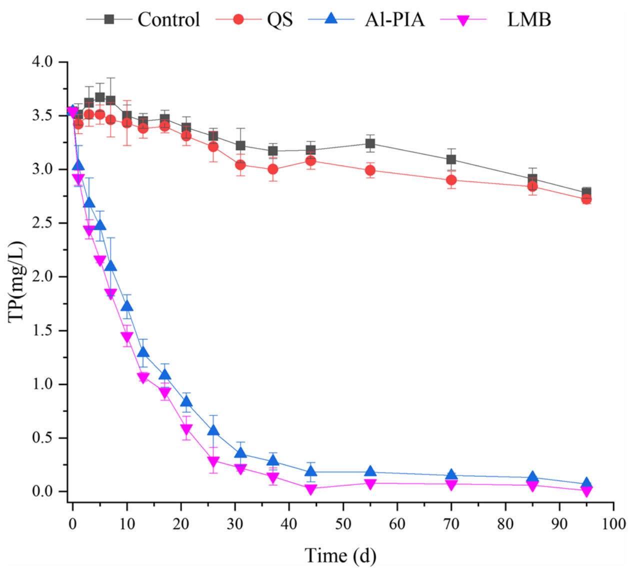


Fig. 4 Changes of TP concentrations of overlying water in the four systems

Figure 4 demonstrated that (1) in the control system, the TP concentration in the overlying water increased first and then gradually decreased under the condition of water flow. The reason possibly was the flow of water increased the DO of the overlying water and the average level of DO was 3.09 mg/L. Sufficient DO accelerates the mineralization of organic matter and mineralizes the stable organophosphate in the sediment into easily released inorganic phosphorus. That leads to the increase in the TP concentration of the overlying water (Huang et al. 2014). Another probable reason was that the DO may change the valence state of the overlying water iron salt. That leads the ferric salt and phosphorus to form iron and phosphorus particles and precipitating in the surface sediment (Liu et al. 2018a, b). And research has shown that (Wang et al. 2015) under the alternate action of the aerobic-anaerobic environment on the surface of the sediment, the mutual transformation of Fe^{2+}, Fe^{3+}, and iron oxides is promoted. And it promotes the transformation of phosphorus forms in sediment. In addition, the DO may change the oxidation–reduction potential and pH of the surface of the sediment and affect the species or quantity of certain microorganism. These changes may help surface sediment to adsorb TP in the overlying water (Wang et al. 2013a, b, c). In summary, it can be seen that flowing water bodies can enhance the self-purification ability of water bodies (Wu et al. 2014). (2) When the capping strength is 2 kg/m^2, compared with the control system, the average reduction rate of TP by LMB, Al-PIA, and QS capping systems was 74.66%, 69.54%, and 3.64%, respectively. The LMB and Al-PIA capping systems make the TP concentration in the overlying water reach the class V criteria of surface water ($P<0.4$ mg/L) on the 26th day and 31st day, respectively. And these systems can also guarantee the lower phosphorus concentration of the overlying water in the later stage. The TP concentration of the overlying water in the control system and the QS capping system was still greater than 2.5 mg/L on the 95th day. And the water quality was still maintained at the inferior class V criteria of surface water. The analysis of variance showed that LMB and Al-PIA capping system with the control system have significant differences in reducing TP effect ($P<0.05$), while QS capping system has no significant difference ($P>0.05$). To conclude, LMB and Al-PIA can effectively reduce the phosphorus concentration in the overlying water (Copetti et al. 2016; Liu et al. 2018a, b). It can enhance the self-purification ability of water bodies and accelerate the restoration of eutrophic water bodies. The reason is that the lanthanum ions in LMB can fix phosphorus (Dithmer et al. 2015), thereby reducing the phosphorus concentration in the water. Al-PIA maintains a low concentration of phosphorus in water through ion exchange, surface precipitation, and complexation (Lin et al. 2016). In this dynamic simulation test, the average phosphorus control effect of Al-PIA under the same capping intensity is only 5.12% lower than that of LMB. So Al-PIA can also effectively control phosphorus when covered in a certain strength of flowing water.

Changes of various forms of phosphorus in the sediment of each system before and after the test

The test lasted for 95 days. After the test, the changes of various forms of phosphorus in the sediment before and after are shown in Table 1.

Table 1 showed that during the first stage of the dynamic simulation test which lasted for 44 days, (1) compared with before the test, the TP, IP, NAIP, and AP in the sediment increased significantly after the test. It showed that the phosphorus in the overlying water of each system flows into the sediment and mainly converts into NAIP, AP, and a small amount of OP. The reason may be that the concentration of phosphorus in the overlying water was large. And the circulation of water increases the DO concentration of the overlying water. The higher DO concentration changes the microenvironment of some sediment, such as the oxidation–reduction potential, pH, and the valence of certain metal ions. These changes were beneficial to sediment fixation for phosphorus (Wang et al. 2013a, b, c). (2) The average content of TP, IP, OP, NAIP, and AP in the sediment of the QS capping system of inert materials was the largest. The reason may be that the QS capping reduces the contact area between the sediment and the overlying water. This leads to a reduction in the area of surface sediment that is reformed by the same level of DO, but the transformation effect may be better. Therefore, the phosphorus fixation capacity of the transformed sediment was stronger than that of the control system. (3) The contents of TP, IP, NAIP, and AP in the sediment of the Al-PIA and LMB capping systems were all lower than those of the control system. It showed that Al-PIA and LMB can intercept part of the phosphorus that enters the sediment and cooperate with the sediment to quickly reduce the phosphorus concentration

Table 1 Changes of different forms of phosphorus content in sediment before and after test

Materials	Time	Different forms of phosphorus content in sediment (mg/kg)				
		TP	IP	OP	NAIP	AP
Background value		2983.23 ± 14.42	2521.21 ± 7.21	431.44 ± 7.21	1674.38 ± 10.09	370.36 ± 1.08
Control	Day 44	3458.78 ± 22.04	2945.64 ± 43.60	442.59 ± 15.21	2208.49 ± 44.08	581.75 ± 29.25
	Day 95	3736.61 ± 127.67	3245.64 ± 87.36	412.35 ± 35.21	2315.22 ± 22.04	697.97 ± 29.23
QS	Day 44	3526.42 ± 29.07	3057.86 ± 58.14	467.96 ± 20.86	2254.40 ± 29.38	658.77 ± 14.54
	Day 95	3908.40 ± 87.20	3373.99 ± 58.14	438.84 ± 10.90	2320.42 ± 29.39	764.64 ± 14.53
Al-PIA	Day 44	3187.69 ± 43.60	2747.90 ± 21.53	472.58 ± 14.53	2042.65 ± 22.05	625.29 ± 7.27
	Day 95	3594.95 ± 87.20	3147.90 ± 43.60	429.85 ± 14.52	2190.55 ± 44.07	736.37 ± 7.26
LMB	Day 44	3068.69 ± 58.14	2653.83 ± 21.80	462.81 ± 20.86	1934.71 ± 44.08	614.85 ± 14.53
	Day 95	3399.36 ± 58.14	2993.75 ± 43.61	402.87 ± 10.09	2034.71 ± 44.10	733.81 ± 7.27

of the overlying water. The reason may be that Al-PIA and LMB have high-efficiency phosphorus adsorption capacity. And the imported phosphorus in the overlying water first passes through the active capping material and then contacts the sediment, resulting in that only a small part of the imported phosphorus can be fixed by the sediment (Wang et al. 2013a, b, c).

During the 51-day dynamic simulation test in the second stage, comparing the phosphorus content of the sediment on the 95th day with that on the 44th day, the contents of TP, IP, NAIP, and AP in the sediment of each capping system increased. The reason for the increase of phosphorus in the sediment of the control system and the QS capping system may be that the phosphorus in the overlying water continues to flow into the sediment, or it may be that the surface sediment modified by DO fixed the easy-release phosphorus that migrates within the sediment (Liu et al. 2018a, b). The sediment phosphorus in Al-PIA and LMB capping system increased which may be due to the migration and diffusion of phosphorus from the bottom of the sediment to the surface (S Ndergaard et al. 1996). The AP in sediment is relatively stable, and it is not easy to transform and migrate. The content of sediments in the mulching systems did not change much. NAIP is an unstable inorganic phosphorus, which is easily released under low redox potentials or high pH environments (Zhou et al. 2018). The NAIP content of Al-PIA and LMB capping system was lower than that of the control group. This shows that the phosphorus form of sediment in Al-PIA and LMB capping system is more stable. Research has shown that (Petterson 1998) the release of a small amount of phosphorus in the sediment will significantly increase the concentration of phosphorus in the water. When the external phosphorus in the receiving water body gradually decreases, the phosphorus accumulated in the sediment due to long-term input will be released with the environment. This may be due to concentration diffusion (Lei et al. 2018) or changes in the pH of the water body (Zhou et al. 2018). It then becomes the source of eutrophication of the water body.

Changes of various forms of phosphorus in Al-PIA before and after the test

The test lasted for 95 days. After the test, the changes in the phosphorus content of various forms in Al-PIA before and after are shown in Table 2.

Table 2 showed that compared with the background value before the test, the content of TP, IP, and NAIP in Al-PIA increased significantly ($P < 0.05$). The average content of TP in Al-PIA increased by 1317.60 mg/kg. The increase in NAIP content was 1167.75 mg/kg, accounting for 88.62% of the total increase. Obviously, the phosphorus fixed by Al-PIA was mainly in the form of NAIP in IP, and this result was consistent with some research results (Hou et al. 2018; Liu et al. 2019). The OP content in Al-PIA had a certain decrease. The reason may be that when Al-PIA exchanges ions (ligands) to fix phosphorus, some organic ligands may contain phosphorus. Another reason is, when under aerobic conditions, the organic matter in the Al-PIA located in the surface of the sediment was mineralized, resulting in the reduction of organic phosphorus (Huang et al. 2014).

In the overlying water with an initial TP concentration of 3.55 mg/L, the final phosphorus adsorption capacity of Al-PIA is 1.32 mg/g. (1) The first stage of the test lasted for 44 days. After the end of the test, the phosphorus concentration in the overlying water in the Al-PIA system was measured to be 0.18 mg/L, the concentration decreased by 3.37 mg/L, and the phosphorus adsorption capacity of Al-PIA was 0.39 mg/g. It showed that Al-PIA can quickly reduce the phosphorus concentration of the overlying water and the phosphorus absorbed by the material mainly comes from the overlying water. (2) The second stage of the test lasted for 51 days. The overlying water TP concentration in the Al-PIA system was measured to be 0.07 mg/L in the end, and the phosphorus adsorption capacity of the material was 0.93 mg/g. However, in the second stage of the test, the phosphorus concentration in the overlying water only decreased by 0.11 mg/L, indicating that the phosphorus adsorbed by Al-PIA mainly comes from the easy release of phosphorus from sediment. It showed that the thin layer of Al-PIA can not only quickly reduce the phosphorus concentration of the overlying water but also can effectively control the release of phosphorus from the sediment to the overlying water.

Table 2 Changes of different forms of phosphorus content in materials before and after test

Materials	Time	Different forms of phosphorus content in materials (mg/kg)				
		TP	IP	OP	NAIP	AP
Al-PIA	Background value	2460.34 ± 46.25	2342.16 ± 20.55	158.29 ± 5.14	2257.51 ± 43.16	50.16 ± 1.03
	Day 44	2849.14 ± 14.53	2724.54 ± 29.07	145.65 ± 5.27	2569.47 ± 14.53	52.73 ± 2.91
	Day 95	3777.94 ± 29.07	3644.34 ± 29.06	137.74 ± 2.66	3425.26 ± 58.77	56.58 ± 2.92

The migration and transformation of phosphorus in various systems

Based on the above discussion, the migration and transformation of phosphorus in three different capping systems and control systems were clarified and shown in Fig. 5.

In the control system and the QS capping system, due to the increase of DO in the flowing state of the water body, the ability of part of the surface sediment to fix phosphorus was improved, so that a small part of the phosphorus in the water was fixed by the sediment. The phosphorus concentration in the overlying water was reduced, while the bottom sludge was constantly fixing phosphorus, which indicated that part of the easily released phosphorus in the bottom sludge will diffuse to the overlying water. Therefore, the phosphorus in the overlying water and bottom mud in the control system and the QS capping system did not change much. Although the capping of QS hindered the exchange of overlying water and sediment, since the surface of QS was smooth and there were very few ligands, this physical barrier did not play any role.

In the LMB capping system, the lanthanum ions on the phosphorus-locking agent will capture and fix the phosphorus, generating two kinds of monazite (monazite, $LaPO_4$) and water-containing phosphate rare earth ore (rhabdophane, $LaPO_4 \cdot nH_2O$, $n \leq 3$) lanthanum and phosphorus minerals (Dithmer et al. 2015). The iron aluminum compounds, iron oxide (hydroxide) compounds, and manganese compounds in bentonite can fix phosphorus by means of ion exchange, adsorption, and complexation (Kaiserli et al. 2002; Lin et al. 2016). Therefore, the capping of LMB can reduce the TP concentration of the overlying water and reduce the phosphorus content of the sediment. Similarly, in the Al-PIA capping system, Al-PIA is rich in amorphous iron and aluminum salts, and the material has a large specific surface area and is generally positively charged. Therefore, the iron aluminum oxide, iron aluminum hydroxide, iron aluminum complex, and some metal ions (such as iron, aluminum, calcium, and magnesium ions) in Al-PIA can easily fix phosphorus in the material through ligand (ion) exchange, surface precipitation, or complexation (Al-Tahmazi et al. 2016, Makris et al. 2004, Yang et al. 2006). In this way, Al-PIA effectively controls the release of phosphorus from sediments to overlying water. However, the adsorption capacity of Al-PIA for phosphorus decreases under low redox potentials or high pH environments (Zhou et al. 2018). Moreover, when the pH value is equal to or higher than 11, Al-PIA might be at risk of releasing phosphorous into the water body (Zhou et al. 2018). However, the pH value of natural water bodies is rarely greater than 9, so this does not affect the application of Al-PIA in actual projects. And the overlying water and sediment in the Al-PIA and LMB capping systems form a large difference in phosphorus concentration, which leads to the easy release of phosphorus from the sediment and spreads to the overlying water (Lei et al. 2018). During this migration process, LMB and Al-PIA will fix a part of the sediment that was easy to release phosphorus, and the phosphorus-fixing capacity decreased in turn. The phosphorus easily released from sediment will first pass through the surface sediment modified by DO and then through the Al-PIA or LMB thin-layer capping and finally enter the overlying water. According to the analysis of the content of various forms of phosphorus in the test material Al-PIA, it also supported that this migration pathway was easy for releasing of phosphorus from sediment.

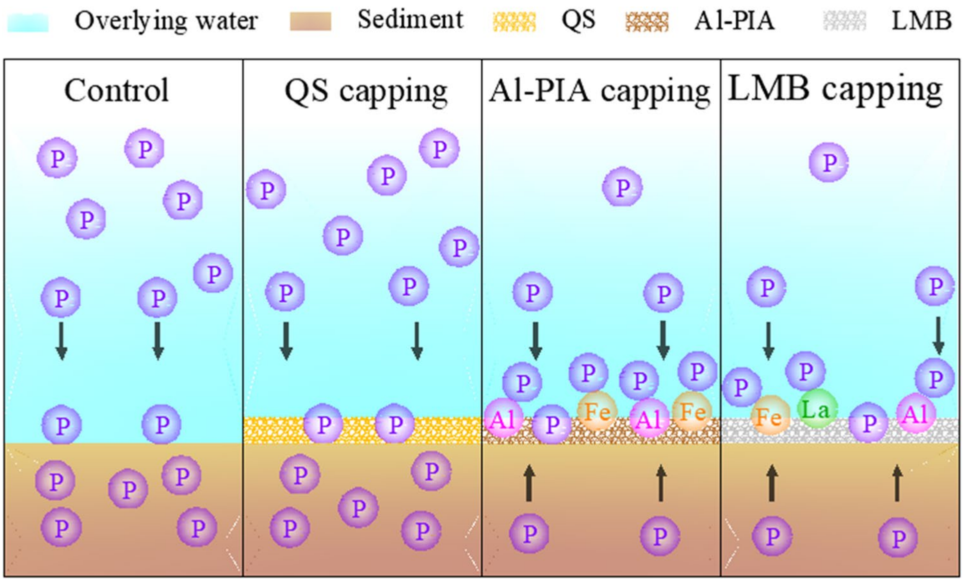


Fig. 5 Migration and transformation of phosphorus in different systems

Conclusions

Based on this study, three conclusions can be drawn as follows:

(1) When the initial concentration of TP is 3.55 mg/L, the capping strength is 2 kg/m^2, and the hydraulic retention time is 0.5 days. Compared with the control system, the LMB, Al-PIA, and QS capping systems have the average reduction rates of TP which are 74.66%, 69.54%, and 3.64%, respectively. It shows that both LMB and Al-PIA capping can effectively control the release of sediment phosphorus.

(2) The phosphorus fixed by Al-PIA is mainly the NAIP in the inorganic phosphorus, and the NAIP phosphorus in the material is more stable than the NAIP in the sediment.

(3) Phosphorus that is easily released from the sediment will migrate and be fixed in the capping materials LMB and Al-PIA. The high-efficiency phosphorus fixation capacity of LMB and Al-PIA may affect the migration and transformation of different forms of phosphorus in the sediment and make it difficult to release the fixed phosphorus.

Author contribution Zhenming Zhou received support from the funding. Zhenming Zhou conceived and designed the study. Yichao Wang and Shuwen Li performed eligibility screening and data extraction. Yichao Wang analyzed the data and performed the statistical analysis, as well as wrote the initial manuscript. Shupo Liu and Fei Li critically revised the manuscript.

Funding This work is 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 the Science and Technology Project Foundation of Xiamen City (Grant No. 3502Z20203044).

Availability of data and materials The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent for publication The participant has consented to the submission of the case report to the journal.

Competing interests The authors declare no competing interests.

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