The adsorption efficiency of nitrogen and phosphorus by in-situ remediation of modified sediment composite material
Zhaoliang Zhu, Jiale Zou, Qi Li, Hao Zhou and Mengmeng Liu

ABSTRACT
Dredged sediment can occupy a large amount of land area, resulting in waste of land resources, and high disposal costs. In response to the problem, this work calcinates and modifies the sediment and compounds it with the modified water purification plant sludge, zeolite powder, and bentonite. This is used as a covering material to inhibit the release of nitrogen (N) and phosphorus (P) in the sediment. The results showed that sediment modified composite material covering effectively reduces the release of nitrogen (N) and phosphorus (P) in the sediment, especially the release of P. When the thickness of the covering layer is 3 cm, the reduction rate of total N, NH₄⁺-N, and total P in the overlying water by the modified composite material of sediment is 61.58, 79.59, and 70.34%, respectively. It can be seen that the covering material has a significant effect on the control of the release of N and P in the sediment. Additionally, the reduction of nutrients in the overlying water can overcome the negative effects of temperature rise in controlling the release of N and P in the sediment.

Key words | landscape lake, nitrogen, phosphorus, release law, sediment

HIGHLIGHTS
• The material can inhibit the release of N and P pollution, and allow the reuse of waste.
• The N and P adsorption effects of modified sediment prepared at different calcination temperatures and times were studied to provide theoretical basis for sediment repair.
• Comparative analysis of the effect of covering materials on controlling the release of N and P provided a reference for solving the river sediment pollution.

INTRODUCTION
Eutrophication of lakes is one of the water pollution problems occurring all over the world (Huisman et al. 2018), mainly due to the excessive accumulation of nitrogen (N) and phosphorus (P) (Morgane et al. 2018). The external N and P pollutant loads include point source and non-point source pollution (Sutton & Bleeker 2013; Gilbert & Astrid Burford 2017). However, under the condition that the external source input is controlled, the internal N and P release of sediment becomes the dominant factors in eutrophicated water body (Nürnberg et al. 2012; Hui et al. 2017). In recent years, the problem of lake water eutrophication caused by the release of sediment pollutants has attracted more and more attention from scholars, such as and in Baiyangdian (Zhu et al. 2019b), Taihu Lake (Hu et al. 2010; Chunyan et al. 2019; Tingfeng et al. 2019), Dianchi Lake (Zhihao et al. 2019), Erhai Lake (Si-ru et al. 2020), West Lake (Hui et al. 2016), etc. The high N and P loads in the sediment not only aggravated the eutrophication of the lakes, but also delayed the self-repair process of the lake (Jepesen et al. 2005; Hui et al. 2016). Urban landscape lakes are shallow-water lakes. Due to their obvious wind-induced flow characteristics, intense material and energy exchange, and
the blurring of the boundary layer in the vertical space, the impact of sediment on the water quality of the lake is intensified (Spears et al. 2008; Bormans et al. 2016). At present, most of the landscape lakes are man-made lakes. The overflow water is directly connected to the municipal drainage pipe network, lacking long-term stable water replenishment, and the lake water cannot maintain good fluidity, resulting in the continuous accumulation of N, P, and other nutrients. When the input of external N and P decreases, only the release of the original internal pollutants can still make the water body in a eutrophication state (Geurts et al. 2011). Therefore, it is necessary to control the release of N, P, and other pollutants in the sediment to the overlying water to prevent pollution of the surface water environment (Pei et al. 2018).

In response to these problems, this article takes a landscape lake in Jinan as an example. The effects of the N and P content of lake sediments and environmental conditions on the release of N and P from the sediments were analyzed, and the effects of modified sediments and modified sediments mixed with zeolite powder and bentonite on controlling the release of N and P were investigated. Through research, we can further understand the migration and transformation of N and P in sediment and overlying water in theory, which can provide a scientific basis for the treatment of urban eutrophic water bodies and also technical support for the application of covering materials in actual eutrophic water.

MATERIALS AND METHODS

Sediment sample collection and treatment

The sediment samples were collected in September 2018. According to the water inlet and outlet of the landscape lake and the type of plant distribution, a total of three sampling points were selected, labeled #1, #2, #3. The characteristics of each sampling point are as follows: #1 was located at the inlet, where the water body is disturbed greatly and the nutrient content is high; #2 was located next to the reeds, and has a superimposed dam, with high DO; #3 water body has poor fluidity. The distribution is shown in Figure 1. Using a columnar mud picker to collect sediment samples, a surface layer of 0–10 cm sediment was taken three times at each sampling point. The sand, garbage, plant residues, and other foreign objects were removed, and the samples were mixed evenly and put in a sealed bag. Samples were sent to the laboratory within 4 h, stored at 4 °C, and protected from light for testing.

The water sample is 0–50 cm of overlying water at each sampling point. After collecting using the water collector, the measurement was carried out on the same day. The samples were collected three times a month, and three sets of samples were taken each time.

Material modification

By studying the adsorption effect of NH₄⁺–N and total phosphorus (TP) by the sediment and the water purification plant sludge at different calcination temperatures, the optimal calcination modification conditions were determined, and the combination ratio with zeolite and bentonite was carried out to achieve composite optimization of materials for controlling the release of internal N and P in sediment.

Material

Modified sediment

The sediment samples were air-dried, ground, and crushed, passed through a 100-mesh sieve, and calcined at 250 °C, 400 °C, 550 °C, 700 °C, and 850 °C for 3 h to prepare sediment modified materials.

Water purification plant sludge

The water purification plant sludge was taken from a water purification plant in Jinan City. After air-drying, it was ground and crushed, passed through a 100-mesh sieve, and calcined at 250 °C, 400 °C, 550 °C, 700 °C, and 850 °C for 3 h to prepare water purification plant sludge modified materials.
Zeolite powder, bentonite

The particle size of the zeolite powder used in the experiment was less than 0.15 mm, the specific surface area was 500–800 m²/g, the density was 23 g/cm³, the SiO₂ content was 65%, and the purity of bentonite is analytical reagent, which is a secondary product, with high main component content, high purity, and low interference impurities, suitable for industrial analysis and chemical experiments.

Sediment modified test

The changes in the adsorption capacity of NH₄⁺-N and TP by the modified sediment under different calcination temperature conditions are shown in Figure 2.

It can be seen from Figure 2 that when the calcination temperature is 550 °C, the adsorption capacity of modified sediment for NH₄⁺-N is the largest; when the calcination temperature is less than 550 °C, most of the organic matter in the sediment is burned away as the calcination temperature rises, resulting in an increase in pore structure and an increase in specific surface area, which is conducive to the adsorption of NH₄⁺-N by the modified sediment. When the calcination temperature is higher than 550 °C, the adsorption capacity of NH₄⁺-N by the modified sediment decreases as the temperature rises. At this time, the residual organic matter and minerals in the sediment are decomposed at high temperature, the pores increase, and the specific surface area decreases, resulting in the weakening of the adsorption of NH₄⁺-N.

In summary, it can be determined that the optimal calcination temperature of modified sediment for N and P adsorption is 550 °C.

Water purification plant sludge modified test

The changes in the adsorption of NH₄⁺-N and TP by modified water purification plant sludge under different calcination temperature conditions are shown in Figure 3.

It can be seen from Figure 4 that when the calcination temperature is 400 °C, the adsorption capacity of NH₄⁺-N by the modified water purification plant sludge reaches the maximum. When the calcination temperature increased from 250 °C to 400 °C, the adsorption capacity of the
sample to NH$_4^+$-N increased significantly. This is mainly due to the large amount of organic matter in the water purification plant sludge being burned out in the temperature range, which increases the specific surface area of the sample, which is beneficial to the NH$_4^+$-N adsorption reaction. When the temperature is higher than 400 °C, as the temperature rises, the adsorption capacity of NH$_4^+$-N by the sample shows a downward trend. The reason for this phenomenon is related to the amorphous aluminum(Al)–iron (Fe) content in the sample (Sun et al. 2013). After the temperature rises, the amorphous Al–Fe form in the sample transforms into a crystalline state, and the Al–Fe crystals inhibits the adsorption capacity of NH$_4^+$-N.

In the range of 250–700 °C, with the increase of calcination temperature, the adsorption capacity of TP by modified water purification plant sludge gradually increases. This is mainly because high-temperature calcination removes free water and bound water in the water purification plant sludge, as well as other easily pyrolyzed substances such as organic matter, so that more pores are formed inside the material, which is beneficial to the adsorption of TP (Wu et al. 2014). In addition, elements such as Fe and Al can be combined with P. Calcination leads to an increase in the weight percentage of Fe and Al in the modified water purification plant sludge per unit mass, thus increasing the adsorption capacity of the modified material to TP; when the temperature is higher than 700 °C, the adsorption capacity of the modified material on TP is greatly reduced. On the one hand, this is due to the high temperature that dehydroxylates the aluminum hydroxide (Al(OH)$_3$) inside the material. On the other hand, the high temperature causes the crystallization of amorphous substances such as Fe and Al inside the material (Tantawy 2015; Gu et al. 2019). Under the synergistic effect of these two aspects, the adsorption sites of the modified water purification plant sludge are gradually reduced, and so the adsorption capacity of TP is reduced.

In summary, it can be determined that the optimal calcination temperature for N and P adsorption by modified water purification plant sludge is 400 °C.

**Zeolite powder and bentonite test**

The adsorption effect of zeolite powder and bentonite on N and P is shown in Figure 4. It can be seen from Figure 5 that zeolite powder and bentonite have a certain adsorption effect on NH$_4^+$-N and TP. This is mainly due to their large specific surface area, that is, the pores and pore structure volume inside the zeolite powder crystal account for more than 50% of the total volume of the crystal. It could also be due to ion exchange adsorption. Zeolite is a hydrated aluminosilicate crystal compound. With a framework composed of silicon (Si)–oxygen (O) tetrahedrons, when part of the Si in the framework is replaced by Al and the charge is unbalanced, exchangeable cations will be adsorbed for compensation (Zhu et al. 2019a). At the same time, the negatively charged cations adsorbed by the mineral crystals in the bentonite can be exchanged with the cations in the solution. These two materials can also solve the cost problem at large-scale use.
Matching test

The adsorption capacity of NH\textsubscript{4}\textsuperscript{+}-N and TP was used as the evaluation index to obtain the best ratio of modified sediment, based on four factors: modified water purification plant sludge, zeolite powder, and bentonite. The orthogonal experiment table of L\textsubscript{9}(3\textsuperscript{4}) is listed in Table 1.

Orthogonal experiments were used to explore the adsorption capacity of NH\textsubscript{4}\textsuperscript{+}-N and TP by different ratios of composite materials. The results and analysis are shown in Table 2.

According to the analysis in Table 2, No. 5 has the highest adsorption capacity for NH\textsubscript{4}\textsuperscript{+}-N, which is 0.584 mg/g, and No. 9 has the highest adsorption capacity for TP, which is 0.412 mg/g. The larger the R, the greater the influence of the level changes of the factors listed on the test results. From the calculation results, the order of the composite material ratio affecting the NH\textsubscript{4}\textsuperscript{+}-N adsorption effect is from large to small: C (zeolite powder) > B (modified water purification plant sludge) > A (modified sediment) > D (bentonite); the order of the influence on the adsorption effect of TP is from large to small: D (bentonite) > A (modified sediment) > B (modified water purification plant sludge) > C (zeolite powder).

In this experiment, the test index is the adsorption rate of NH\textsubscript{4}\textsuperscript{+}-N and TP. The higher the adsorption rate, the better the effect. From the trend diagram of different levels of various factors (Figure 5) and the results of the L\textsubscript{9}(3\textsuperscript{4}) orthogonal design test (Table 2), the level corresponding to the maximum value of \(k_i\) for each factor was selected, where \(k_i\) represents the sum of the corresponding test results when the level number in any column is \(i\).

It can be seen from Figure 5 that, without considering the influence of interaction, the optimal solution for NH\textsubscript{4}\textsuperscript{+}-N adsorption is A1B2C3D3, and the optimal solution for TP adsorption is A1B2C3D1. Based on comprehensive considerations, the optimal plan is initially determined as A1B2C3D1, that is, the best quality ratio of covering material is modified sediment: modified water purification plant sludge: zeolite powder: bentonite = 1:2:3:1.

In summary, the modified sediment calcined at 550 °C: modified water purification plant sludge calcined at 400 °C: zeolite powder: bentonite was mixed in a mass ratio of 1:2:3:1 to prepare composite material.

### Table 1 | Orthogonal test table

<table>
<thead>
<tr>
<th>Number</th>
<th>Modified sediment</th>
<th>Modified water purification plant sludge</th>
<th>Zeolite powder</th>
<th>Bentonite</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<tr>
<td>9</td>
<td>3</td>
<td>3</td>
<td>2</td>
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</tr>
</tbody>
</table>

### Table 2 | L\textsubscript{9}(3\textsuperscript{4}) orthogonal test results

<table>
<thead>
<tr>
<th>Number</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>NH\textsubscript{4}\textsuperscript{+}-N (mg/g)</th>
<th>TP (mg/g)</th>
</tr>
</thead>
<tbody>
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<td>Orthogonal test</td>
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<td>0.044</td>
</tr>
<tr>
<td></td>
<td>5</td>
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<td>2</td>
<td>3</td>
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</tr>
<tr>
<td></td>
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<td>1</td>
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<td>3</td>
<td>3</td>
<td>2</td>
<td>0.357</td>
<td>0.412</td>
</tr>
</tbody>
</table>

\(k_1\), \(k_2\), \(k_3\), \(R\) represent the average of the corresponding test results when the level number in any column is \(1, 2, 3, \) or \(R\).
Coverage control experiment

A 1-cm layer and a 3-cm layer were used to cover the top of the sediment in the plexiglass cylinder (Figure 6); the test was carried out in the dark at 25 ± 1 °C. In the experiment, 30 mL of overlying water samples were collected every day for a total of 15 days. After collecting 20 mL of water sample (15 cm above the sediment–water interface) with a syringe, an equal volume of deionized water was added to maintain the total volume of the overlying water (Jiaqing et al. 2017; Jun et al. 2018).

RESULTS AND DISCUSSION

Physical and chemical properties of sediment

The sediments at the sampling points #1, #2 and #3 of the landscape lake are mostly dark brown and black. The physical and chemical properties of the sediments at different sampling points are shown in Table 3.

| pH | #1 | 6.74 | #2 | 6.86 | #3 | 6.83 |
| MC (%) | 64.51 | 73.05 | 66.4 |
| LOI (%) | 9.91 | 10.38 | 10.11 |
| NH₄⁺ (mg/kg) | 53.0513 | 126.38 | 103.22 |
| TN (mg/kg) | 6883.92 | 7261.39 | 5964.36 |
| TP (mg/kg) | 331.45 | 327.21 | 323.81 |

TN and TP are important indicators for analyzing sediment pollution. It can be seen from Table 4 that the average value of TN in the surface sediment of the landscape lake is 6.703 mg/g, the average value of TP is 0.327 mg/g, the average value of NH₄⁺-N is 0.094 mg/g, and the average value of organic matter is 10.133%. According to the U.S. Environmental Protection Agency’s (2019) guidelines for the classification of sediments of Great Lakes ports, the content of TN, TP, and organic matter in the sediments of the landscape lake belongs to the heavy pollution level. As a landscape lake, the N and P pollution in the sediments tends to increase rapidly, mainly due to the raw water containing high N and P content, and the sediment accumulating pollutants. The content of N and P rises rapidly in a short period of time, and because the water depth of the landscape lake is relatively shallow, there are more aquatic plants. This results in a large amount of plant humus sinking into the water body and sediment. The biological siltation promotion effect is obvious, and so the content of N and P in the sediment increases.

Samples characterization

In order to understand the morphology of the modified sediment and composite materials, scanning electron microscopy (SEM) was used to characterize the samples. The results are shown in Figure 7. We found that the modified sediment had rough surface, loose structure, and blurred particle boundary due to the high-temperature calcination. It also presented an irregular and amorphous shape, with many fine particles and inconspicuous holes in the structure. The surface of the composite material had a relatively regular porous structure, which made the specific surface area of the material increase significantly. The microporous crystal structure of zeolite powder and bentonite increases the porosity of the modified sediment and also provides a wider place for the adsorption of composite materials and the adhesion of pollutants, which is beneficial to increase its adsorption capacity.

The energy dispersive X-ray spectroscopy (EDS) analysis results of the modified sediment and composite materials are shown in Figure 8. It can be seen from the

<table>
<thead>
<tr>
<th>Sample</th>
<th>SBET/ m² g⁻¹</th>
<th>SMicro/ m² g⁻¹</th>
<th>Sextem/ m² g⁻¹</th>
<th>Vtotal/ cm³ g⁻¹</th>
<th>Vmicro/ cm³ g⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modified sediment</td>
<td>12.016</td>
<td>4.424</td>
<td>7.592</td>
<td>0.0197</td>
<td>0.002354</td>
</tr>
<tr>
<td>Composite material</td>
<td>37.332</td>
<td>6.931</td>
<td>30.402</td>
<td>0.0775</td>
<td>0.003563</td>
</tr>
</tbody>
</table>
EDS results that the main elements of the modified sediment are O and Ca. In the composite material, the peaks of Si and Al elements are significantly enhanced, while O and Ca are slightly weakened. The reason for the analysis is that the main components of zeolite powder and bentonite are silica (SiO₂) and aluminum oxide (Al₂O₃). Due to the increase of Si and Al, the proportion of O and Ca is relatively decreased. In addition, zeolite powder, bentonite, and water purification plant sludge all contain trace metal elements, which makes the peaks of metal ions such as Fe and Mg in the composite material also slightly increase.

The increase in the composition of these elements is conducive to improving the adsorption capacity of the modified sediment for pollutants.

Figure 9 shows that there is a difference in material composition and content between the modified composite material and the modified bottom sludge. Both mineral components of the two materials includes quartz (SiO₂), muscovite (K₁₃₂₆₂₆₁₂₁₀₂(OH)₂), calcite (calcium carbonate, CaCO₃), and albite (Na₂O·Al₂O₃·6SiO₂), of which the CaCO₃ diffraction peak is the strongest and is the mineral component with the highest content in the
two materials. However, the content of calcite is significantly reduced after the modified sediment is compounded. The main analysis is that some metal elements react with CaCO$_3$ to produce a new mineral component dolomite (CaMg(CO$_3$)$_2$). The crystal structure of dolomite and the active sites of Ca$^{2+}$ and Mg$^{2+}$ help to enhance the adsorption and ion exchange of pollutants by the covering material.

The result of N$_2$ adsorption–desorption isotherm is shown in Figure 10. According to the classification of the International Union of Pure and Applied Chemistry, the adsorption–desorption isotherm of the two samples belong to type IV isotherms. The curve a in Figure 10 has a weak H3 type hysteresis loop, indicating that there is a small part of intercrystalline mesopores in the modified sediment. The N$_2$ adsorption in the low pressure zone ($P/P_o \leq 0.1$) is low, indicating that the microporous structure in the modified sediment is almost zero. In the high pressure zone ($P/P_o \approx 1.0$), the rapid increase in the amount of N$_2$ adsorption reflects the rich macroporous structure of the modified sediment material. This conclusion is consistent with the results of SEM (Figure 7). The H3 type hysteresis loop is more obvious in curve (b) of Figure 10, indicating that there are a lot of mesoporous structures in the sediment modified composite material. The N$_2$ adsorption in the low pressure zone ($P/P_o \leq 0.1$) increases rapidly and then tends to be flat, because the micropores of the material are quickly filled with N$_2$. In addition, it can be seen that the N$_2$ adsorption in the high pressure zone ($P/P_o \approx 1.0$) is linear. The rise indicates that the material has a strong external surface adsorption, which is caused by the combined effect of nano-size effect and particle agglomeration. At the same time, the hysteresis loop of the sediment modified composite material ($P/P_o \approx 0.4$) appeared later than that of the modified sediment ($P/P_o \approx 0.45$), indicating that the mesoporous distribution range of the sediment modified composite material was larger than that of the modified sediment.

It can be seen from Table 4 that the $S_{BET}$ and $V_{micro}$ of the modified sediment composite material are 37.332 m$^2$/g and 0.0036 cm$^3$/g, respectively. They are much higher than the modified sediment (12.016 m$^2$/g and 0.0024 cm$^3$/g), mainly due to the addition of zeolite powder and bentonite introducing a large number of micropores. The $S_{Micro}$ of the sediment modified composite material calculated by the t-plot method is 6.931 m$^2$/g, which is higher than that of the modified sediment (4.424 m$^2$/g), indicating that the composite material has excellent particle dispersion performance.

The control of N and P release by composite material

The influence of the thickness of the overburden on the release of N and P from the sediment is shown in Figures 11 and 12.

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Figure 9 | The X-ray diffraction spectra: (a) modified sediment; (b) composite material.

Figure 10 | N$_2$ adsorption–desorption isotherm.
Figure 11 | The influence of the thickness of the overburden on controlling the release of N and P from the sediment: (a) the influence of thickness on TN concentration; (b) the influence of thickness on NH$_4^+$-N concentration; (c) the influence of thickness on TP concentration.

Figure 12 | Inhibition rate of overburden thickness on N and P release from sediment: (a) the influence of thickness on TN concentration; (b) the influence of thickness on NH$_4^+$-N concentration; (c) the influence of thickness on TP concentration.
In all test groups, the concentrations of TN and NH$_4^+$-N in the overlying water showed a trend of first increasing and then decreasing and finally stabilizing. As the thickness of the overburden increases, it takes a shorter amount of time for the nutrient concentration in the water to reach a dynamic stable state. In the first 3 days, the TN and NH$_4^+$-N concentrations in the 1-cm coverage group decreased to 3.89 and 0.632 mg/L, respectively. The TN and NH$_4^+$-N concentrations in the 3-cm coverage group decreased to 2.35 and 0.258 mg/L, respectively. This obvious concentration drop is mainly caused by the adsorption characteristics of the covering material. Over the next few days, it can be observed that the composite material has a good inhibitory effect on the release of TN, NH$_4^+$-N, and TP in the sediment. The concentration of N and P does not increase significantly, and the covering layer has a positive effect on TP to provide the highest retention efficiency. This is because the material contains metal ions such as Fe and Al which can fix P in the overlying water and sediment, and can effectively inhibit the eutrophication of the water body caused by the excessive P concentration.

Under certain background factors, when the thickness of the cover layer is 1 cm, the concentrations of TN, NH$_4^+$-N, and TP in the overlying water on the 15th day are 6.58, 0.78, and 0.08 mg/L, respectively. The coverage inhibition rates are 40.10, 48.85, and 52.20%, respectively. When the cover layer thickness is 3 cm, the concentrations of TN, NH$_4^+$-N, and TP are 4.22, 0.317, and 0.035 mg/L, respectively. The coverage inhibition rate is 61.58, 79.59, 70.34%. A thick covering layer has a good effect on controlling the release of N and P from the sediment, mainly because it strengthens the mechanical blocking effect and prevents the sediment from re-suspending. The comparison of N and P nutrient salt concentrations in the overlying water under different covering layer thicknesses shows that the covering layer thickness is the main factor affecting the covering effect, and the thicker the covering layer, the better the covering effect.

In order to study the effect of temperature on in-situ coverage and control of N and P release from sediments, four reactors were set up for each indicator, and were divided into coverage groups and uncovered groups. They were placed at 5°C and 20°C, respectively, and the covered group used 3 cm of sediment. The composite material was laid flat on the surface of the bottom sediment.

The release curves of TN, NH$_4^+$-N, and TP of the sediment of the covered group and the uncovered group at different temperatures are shown in Figure 13. At the beginning of the test, the TN, NH$_4^+$-N, and TP of the uncovered group increased rapidly, and the temperature was lower than at the bottom. The release of N and P from the sediment has a greater impact, and the higher temperature, the
greater release. In addition, the content of TN, NH$_4$-N, and TP in the covering group decreased to a certain extent due to the effect of the modified composite material on the adsorption of N and P in the overlying water.

At 5 °C, the concentrations of TN, NH$_4$-N, and TP in the overlying water of the uncovered group were 9.745, 1.101, and 0.096 mg/L, respectively. The concentrations of the covered group were 2.99, 0.231, and 0.044 mg/L, respectively. After equilibrium, the concentrations of TN, NH$_4$-N, and TP decreased by 69.32, 79.02, and 54.17%, respectively. At 20 °C, the concentrations of TN, NH$_4$-N, and TP in the overlying water of the uncovered group on the 15th day were 10.846, 1.589, and 0.118 mg/L, respectively. The concentrations of the coverage group were 4.22, 0.317, and 0.058 mg/L, respectively. After equilibrium, the concentrations of TN, NH$_4$-N, and TP decreased by 61.09, 80.05, and 50.85%.

After the in-situ covering control, the release of N and P in the sediment had a good control effect. The performance of the covering group under different temperature conditions is not much different, indicating that the covering layer can effectively play its role at 5 °C and room temperature. Adsorption and barrier function can effectively overcome the negative impact of temperature increase on the release of N and P from the sediment.

CONCLUSIONS

(1) Based on the results of single-factor adsorption experiments, orthogonal experiments were carried out on the combination of zeolite power, bentonite, calcined modified sediment, and water purification plant sludge. The optimal solution was determined to be modified sediment: modified water purification plant sludge: zeolite powder: bentonite = 1:2:3:1, and the combined material has good removal efficiency for N and P nutrients.

(2) The sediment modified composite material covering effectively reduces the release of N and P nutrients in the sediment, especially the release of P. When the thickness of the covering layer was 3 cm, the concentrations of TN, NH$_4$-N, and TP were 4.22, 0.317, and 0.035 mg/L, respectively. The coverage inhibition rate was 61.58, 79.59, and 70.34%, respectively. It can be seen that the covering material has a significant effect on controlling the release of N and P in the sediment and reducing the nutrients in the overlying water. The greater the thickness of the covering layer, the better the covering effect. Considering the cost and the impact on the living environment of benthic organisms, it is recommended to use a 3-cm thick cover layer as the endogenous N and P pollution remediation material.

(3) Simulation tests under different temperature conditions show that temperature increase will increase the release of N and P in the sediment. The composite material has a good adsorption and control effect on N and P. In addition, it can overcome the negative effects of temperature rise.

(4) This experiment optimized the adsorption capacity of the sediment by calcining and modifying it with other covering materials. The physical and chemical properties of the covering material before and after the modification were analyzed, and the effect of the composite material to control the release of N and P in the sediment and the temperature influencing factors were investigated. The results of this study can be used as a reference for the next stage of protection and management of eutrophic water bodies.

AUTHOR CONTRIBUTIONS

All authors of this article – Zhaoliang Zhu, Jiale Zou, Qi Li, Hao Zhou, Mengmeng Liu – contributed to the content. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

No conflict of interest.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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