Environmental and Earth Sciences Research Journal
Vol. 9, No. 2, June, 2022, pp. 57-62
Journal homepage: http://iieta.org/journals/eesrj

The Law of Endogenous Pollution Release from Reservoirs in Arid Regions

Feng Gao[1], Ying Qiao[2*]

[1] School of Civil Engineering, North Minzu University, Yinchuan 750021, China
[2] Mathematics and Information Science, North Minzu University, Yinchuan 750021, China

Corresponding Author Email: 2005045@nmu.edu.cn

https://doi.org/10.18280/eesrj.090206

Received: 3 April 2022
Accepted: 18 May 2022

Keywords:
Yazidang Reservoir, endogenous pollution, orthogonal experiment, nitrogen and phosphorus; release intensity

ABSTRACT

To maintain a healthy water eco-environment in the Yazidang Reservoir of the Ningxia Hui Autonomous Region of China, this study designed an indoor experiment to simulate the release of nitrogen and phosphorus and study the influencing factors in it. In the experiment, environmental factors of water temperature, pH, and dissolved oxygen (DO) were changed one by one to study the law of the release intensity of nitrogen and phosphorus, and the results revealed that: with the rise of temperature, the release amount of nitrogen and phosphorus increases significantly; the release intensity is the lowest under neutral condition and higher under acidic or alkaline conditions; under different DO levels, the change trend of nitrogen and phosphorus release is obvious, the release intensity increases significantly in anoxic environment, while in oxygen-rich environment, it decreases obviously. The research is very meaningful for the water pollution control of the Yazidang Reservoir and the eco-environment protection of inflow rivers, and the research findings attained in this paper could provide useful evidence for the water environment management and water ecology restoration of Yazidang Reservoir.

1. INTRODUCTION

Reservoirs are a type of artificial systems for regulating, storing, and managing water resources, they are an effective way to rationally develop and utilize the water resources. Reservoirs are semi-closed systems, water usually stays in reservoirs for a long time, which can cause disturbance to the circulation of nutrients. The large amount of nutrients such as nitrogen and phosphorus in the water body can accelerate the growth and reproduction of algae and plankton, resulting in water eutrophication and other water quality issues. The pollution of water body in reservoirs can be divided into endogenous pollution and exogenous pollution, wherein atmospheric deposition, waste water discharge, and soil erosion are main conditions that can lead to exogenous pollution, while the deposition of overlying pollutants is the main cause of endogenous pollution. Both endogenous and exogenous pollution can affect water quality for a long period. In recent years, China has begun to pay attention to water quality and safety issues, exogenous pollution has been or is being effectively controlled, and now endogenous pollution has become the main type of water pollution of reservoirs. Lake reservoir sediments are usually important storage places for nutrients such as nitrogen and phosphorus, and these two are the main pollutants of the endogenous pollution in lake reservoirs. According to the survey data of lake reservoirs, under the condition that the nutrients entering the lake reservoirs have reduced or been completely retained, the release of nutrients such as nitrogen and phosphorus in sediments will aggravate water pollution. Therefore, it's particularly meaningful to discuss topics such as reservoir sediments and nitrogen and phosphorus pollution of overlying water, and explore ways and measures to control and prevent nitrogen and phosphorus pollution in reservoirs.

World field scholars have studied many lakes and reservoirs around the globe, such as the shallow lakes in Denmark [1] and the Lake Pontchartrain in the United States [2]. In China, scholars have also investigated a few lakes and reservoirs, including the Lake Baiyangdian in Hebei province [3], the Yinfu Reservoir in Shandong [4], the Cuihu Lake [5] and Dianchi Lake [6] in Yunnan, the Tangyu Reservoir in Xi'an, and the Chanzhi reservoir in Qingdao [7, 8]. Results of these studies all suggested that the nitrogen and phosphorus pollutants in the sediments of lakes and reservoirs have a great impact on water quality, and the migration and transformation of nitrogen and phosphorus nutrients in sediments and overlying water layer are affected by multiple environmental factors such as water temperature, pH, and DO [9, 10]. The form, release completion time, release amount, and release speed of nitrogen and phosphorus are all random [11, 12]. Fan et al. [13] took Taihu Lake as subject to study the variation law of the release amount of nitrogen and phosphorus of sediment-water interface and discovered that it is positively related with temperature change. Fu et al. [14] took the Three Gorges Reservoir as the research object and concluded that the release amount of nitrogen from sediments decreases with the increase of pH value. Kim et al. [15] measured the release speed of phosphorus by controlling the content of DO, and the results revealed that the release speed is within the range of 2.85-5.71 $mg/(m^2 \cdot d)$ in oxygen-rich environment and within the range of 1.43-14.29 $mg/(m^2 \cdot d)$ in anoxic environment. Luo et al. [16] compared the release amount of nitrogen under different pH conditions, and concluded that the nitrogen release decreases with the increase of pH. The research of scholars Al-Harbi and Uddin [17] showed that anoxic environment promotes the release of phosphorus, while oxygen-rich environment inhibits phosphorus release. Moreover, domestic scholars have also studied the form and distribution of nutrients in lake reservoirs, the release of nutrients at the interface of sediment and overlying water, and the environmental factors [18-20], but the laws of the release of nitrogen, phosphorus, and other nutrients under different environmental factors of overlying water need to be studied further.

Analyzing the pollution process and release law of nutrients in reservoir sediments and overlying water lays a theoretical foundation for the treatment of endogenous pollution. This study employed field survey, laboratory simulation, theoretical analysis, and other methods to study our target, the Yazidang Reservoir. In the experiment, the law of the release of nitrogen and phosphorus at the interface of sediment-overlying water was studied by controlling three environmental factors, temperature, pH, and DO; and the pollution load of the sediments was estimated. The research findings of this paper provided useful evidence for the water environment management and water ecology restoration of Yazidang Reservoir.

2. EXPERIMENT AND METHOD

In view of the actual water pollution conditions of Yadidang Reservoir, sampling points at the tail position of the reservoir were selected to perform the nitrogen-phosphorus release simulation experiment. Grab-style sampler was used for sampling, and the samples were placed into polyethylene buckets and brought back to the laboratory for the nitrogen-phosphorus release experiment. At the same time, water sampler was used to take water samples of overlying water from the same position for the sediment release experiment.

2.1 Devices

Devices used in the experiment include: PMMA cylinder (inner diameter 100 mm, height 350 mm), constant-temperature water bath, air inlet pipe, and sampling pipe. The devices are shown in Figure 1. The accessories used in the devices were purchased and assembled in the lab.

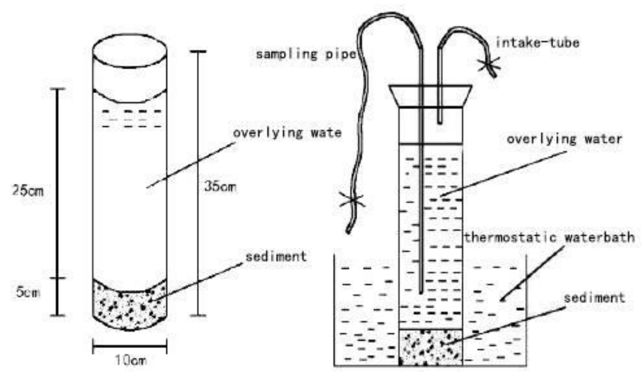

Figure 1. Devices of the sediment release experiment

2.2 Simulation scheme of nitrogen-phosphorus release of sediments

The simulation experiment was started on June 9, 2018 and ended on June 13, 2018, the duration was 120 hours. Environmental influencing factors include water temperature (T), pH value, and dissolved oxygen (DO). By respectively controlling and changing T, pH, and DO in the designed reactor, the release of total nitrogen (TN) and total phosphorus (TP) was simulated, and changes in the quality of the overlying water were monitored. All devices were placed in the dark environment.

Situations of the three influencing factors are:

(1) T adjustment: the pH value in the simulation reactor was controlled at 7; DO was 8 mg/L; T was set to four levels: 15°C, 20°C, 25°C, and 30°C.

(2) pH adjustment: the temperature of the simulation reactor was controlled at 20°C; DO was 8 mg/L; NaOH and HCI solutions were used to control the pH of overlying water at four levels of 5, 7, 9, and 10.

(3) DO control: the temperature of the simulation reactor was controlled at 20°C; pH was 7; DO was adjusted by filling nitrogen and oxygen into the reactor, the DO content was controlled at four levels: 2 mg/L, 6 mg/L, 8 mg/L, and 10 mg/L.

Parallel experiment was performed twice, and the average values of the experimental results were taken as the measurement results.

2.3 Test monitoring

Raw water samples were taken as initial samples, at time moments 12h, 24h, 48h, 60h, 72h, 84h, 96h, 108h, and 120h, samples were taken from the glass cylinder through the sampling pipe, 120 mL of the sample was taken each time, meanwhile the raw water samples taken from the same sampling point was used to supplement till the desired level, and the environmental conditions were kept the same during the experiment. Water quality measurement items include: total nitrogen (TN), ammonia nitrogen, and total phosphorus (TP). The adopted methods referred to the *Water and Wastewater Monitoring and Analysis Methods* issued by the State Environmental Protection Administration.

3. RESULTS AND DISCUSSION

3.1 Impact of different environmental conditions on TP release of sediments

To figure out the impact of pH on the TP release of sediments, in the experiment, under pH values of 5, 7, 9, and 10, the release intensity of TP of overlying water was measured, and the results are shown in Figure 2.

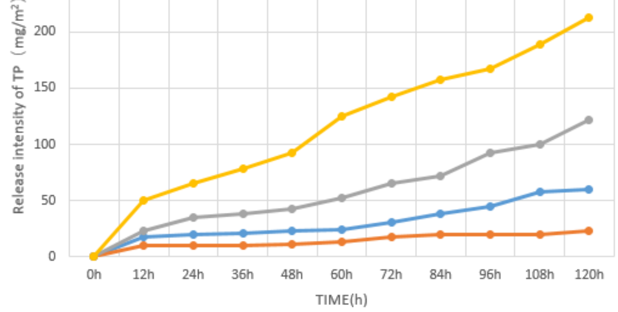

Figure 2. Release intensity of TP under different pH conditions

According to Figure 2, in the alkaline environment, the release intensity of TP is high; at 120h, the release intensity of TP under pH=10 and pH=9 was accumulated to 213.2 mg/m^2 and 121.32 mg/m^2, respectively, this is because under alkaline conditions, the OH^- ions in the water exchange with H_2PO^{4-} ions in other bound phosphorus, and the release intensity of phosphorus is increased. When pH=5, namely in the acidic environment, the release intensity of TP was relatively high, at 120h, the release intensity of TP was accumulated to 60.31 mg/m^2, this is because under acidic conditions, on the one hand, H^+ can dissolute some bound phosphorus, thereby increasing the H_2PO^{4-} in the water; on the other hand, the microorganisms can degrade the organic matters, and the released CO_2 dissolves bound phosphorus, thereby releasing phosphate, resulting in an increase in the amount of phosphorus released. In the neutral environment, namely when pH=7, the release intensity of TP was the lowest, at 120h, the release intensity of TP was accumulated to 22.87 mg/m^2, this is because under neutral conditions, Al^{3+} in water will be hydrolyzed to form colloidal $Al(OH)_3$ with a large specific surface area, which can adsorb HPO_4^{2-} and H_2PO^{4-} in water, resulting in the lowest release intensity of phosphorus.

Overall speaking, the TP release intensity of sediments is higher in the acidic or alkaline environment than that in the neutral environment. In a strong alkali environment (pH=10) during the experiment period, the phosphorus release speed of sediments was respectively 3.54 and 9.32 times of that in the strong acid environment (pH=5) and in the neutral environment.

3.2 Impact of DO on phosphorus release of sediments

Under four DO level conditions of 10 mg/L, 8 mg/L, 6 mg/L, and 2 mg/L, the TP concentration in the overlying water was measured, as shown in Figure 3.

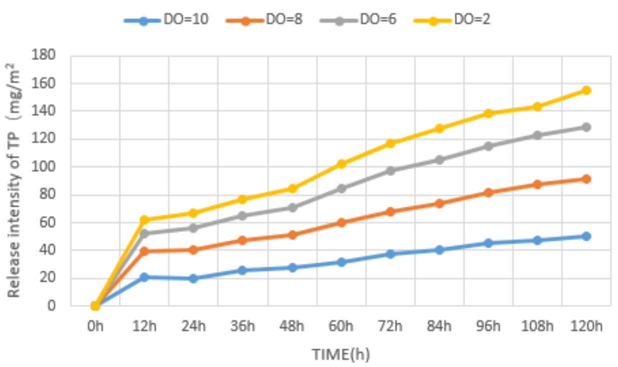

Figure 3. Phosphorus release intensity under different DO conditions

According to the figure, the release intensity of TP reaches the highest level in an anoxic environment when DO=2, then with the increase of DO, the release intensity decreases gradually, and reaches the lowest level in oxygen-rich environment. The main reason is that DO can affect the changes of redox potential of the sediments; if DO decreases, redox potential will decrease accordingly, the $Fe(OH)_3$ precipitates and Fe^{3+} ions in water are easily reduced to Fe^{2+}, the phosphorus adsorbed by $Fe(OH)_3$ is released, which will increase the phosphorus release intensity of the sediments. With the increase of DO, redox potential of the overlying water increases as well, that is, the Fe^{2+} ions are oxidized to Fe^{3+}, forming $Fe(OH)_3$ precipitates which can adsorb phosphorus in water; at the same time, Fe^{3+} combines with PO_4^{3-} to form precipitates, thereby reducing the release of phosphorus of the sediments. In general, the average TP release intensity of sediments decreases with the increase of DO. In the anoxic environment (DO=2) during the experiment period, the phosphorus release speed of sediments was respectively 1.89 and 1.34 times of that in the oxygen-rich environment (DO=10 and DO=8).

3.3 Impact of temperature on TP release of sediments

At four different temperature levels of 15°C, 20°C, 25°C, and 30°C, the TP concentration in the overlying water was measured, as shown in Figure 4.

According to the figure, at T=30°C, the release intensity of TP reaches the highest, and at T=15°C, it reaches the lowest, the possible reason for this is that temperature rise can promote the activity of microorganisms and benthic organisms in the sediments, enhance their resistance to biological interference and the ability of oxidative decomposition, which leads to an increase in the oxygen consumption intensity of the overlying water body, thereby accelerating the phosphorus release of sediments. Overall, the TP release intensity of sediments increases with temperature rise. During the experiment period, the phosphorus release speed of sediments at T=30 ℃ was respectively 3.29 and 3.52 times of that at T = 20 °C and T = 15 °C.

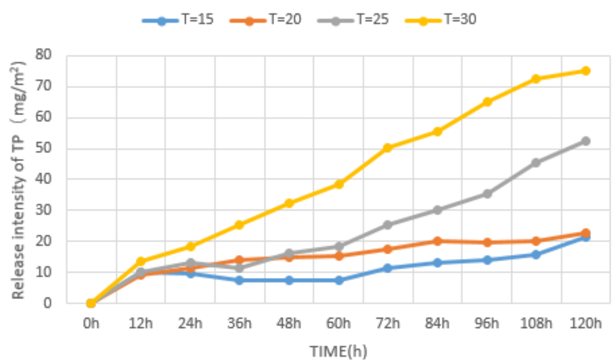

Figure 4. TP release intensity under different temperature conditions

3.4 Impact of environmental factors on the nitrogen release of sediments

3.4.1 Impact of pH on nitrogen release of sediments

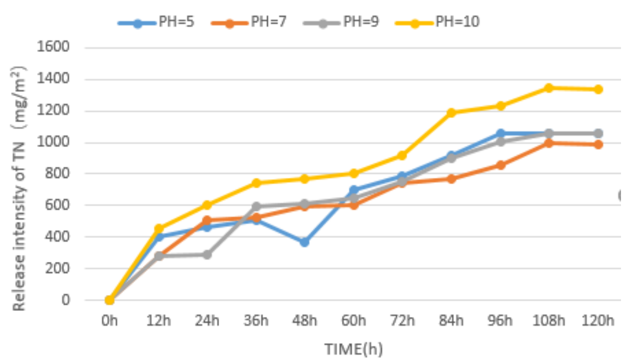

Figure 5. TN and TP release intensity under different pH conditions

The changes of nitrogen content under four pH conditions of 5, 7, 9, and 10 are shown in Figure 5.

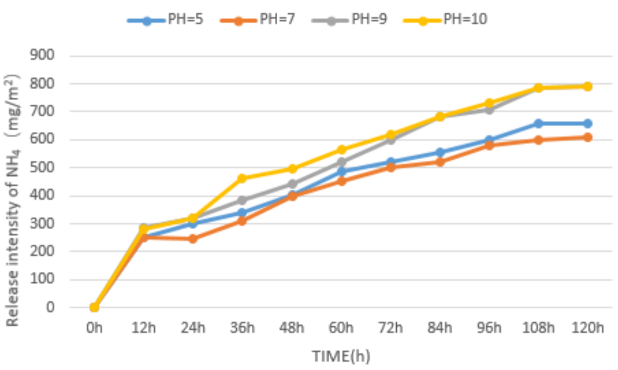

Figure 6. Release intensity of ammonia nitrogen under different pH conditions

In acidic or alkaline environment, the release intensity of ammonia nitrogen of the sediments is higher than that in the neutral environment. During the experiment period, the release speed of ammonia nitrogen of the sediments under strong alkali and strong acid conditions (pH=10 and pH=5) was respectively 1.35 and 1.09 times of that under the neutral condition (pH=7.0). The release intensity of ammonia nitrogen reached the highest when pH=10, this is because in the alkaline environment, NH^{4+} combines with OH^- to produce ammonia gas, which will reduce the concentration of NH^{4+} in water. Under the condition of increased concentration gradient, the NH^{4+} in sediments diffuses to the overlying water, and the release intensity of ammonia nitrogen increases. The release intensity of ammonia nitrogen was also relatively high in the acidic environment (pH=5), this is because under acidic conditions, H^+ and NH^{4+} in the water would compete for adsorption positions on the colloid. With the decrease of pH, the release amount of NH^{4+} would increase, and the release intensity of ammonia nitrogen of the sediments will be higher; when pH increases and becomes neutral, the exchange amount of NH^{4+} will decline, and the release intensity of ammonia nitrogen decreases as well (Figure 6).

The reaction mechanism is:

$$NH_4^+ + OH^- \leftrightarrow NH_3 + H_2O \rightarrow NH_3$$

The TN release of sediments is similar to the release of ammonia nitrogen, the TN release intensity of sediments in acidic or alkaline environment is higher than that in the neutral environment. During the experiment period, the TN release intensity of sediments under strong alkali and strong acid conditions (pH=10 and pH=5) was respectively 1.34 and 1.15 times of that under neutral condition (pH=7.0).

3.4.2 Impact of DO on nitrogen release of sediments

Under the conditions of four DO levels of 10 mg/L, 8 mg/L, 6 mg/L, and 2 mg/L, the release intensity of ammonia nitrogen and TP is shown in Figures 7 and 8.

The release intensity of ammonia nitrogen of the sediments decreases with the increase of DO in the overlying water. During the experiment period, the release intensity of ammonia nitrogen was higher in anoxic environment (DO=2), and its value was 1.35 times of that in oxygen-rich environment (DO=8). Under oxygen-rich conditions, the redox potential of sediments and overlying water is higher, which can promote the conversion of matters of various forms; nitrobacteria can convert ammonia nitrogen into nitrate nitrogen, which offsets the release of ammonia nitrogen to a certain extent, thereby reducing the release intensity of ammonia nitrogen. Under anoxic conditions, the release of ammonia nitrogen is more obvious, this is because when DO content decreases to an anoxic level, the nitrification effect of microorganisms will be weakened, and meanwhile it will promote the release of ammonia nitrogen from sediments and move to the overlaying water, thereby increasing the release intensity of ammonia nitrogen. The TN release of the sediments is similar to the release of ammonia nitrogen, the higher the DO level, the lower the release intensity of ammonia nitrogen. During the experiment period, the release intensity of ammonia nitrogen under anoxic conditions (DO=2) was 1.35 and 1.46 times of that under oxygen-rich conditions (DO=6 and DO=8).

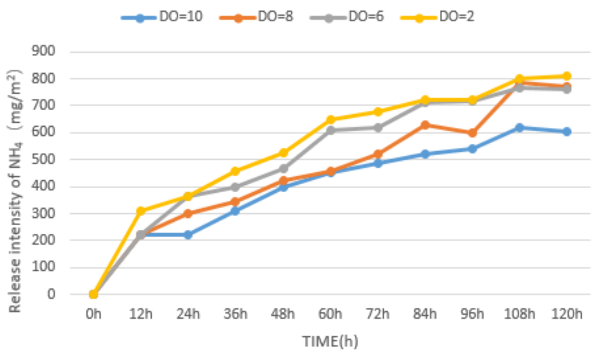

Figure 7. Release intensity of ammonia nitrogen under different DO conditions

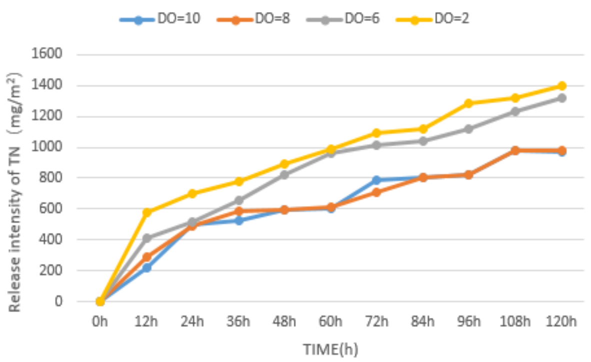

Figure 8. TN release intensity under different DO conditions

3.4.3 Impact of temperature on nitrogen release of sediments

Under four temperature conditions of 15°C, 20°C, 25°C, and 30°C, the release intensity of ammonia nitrogen and TN was measured, and the results are shown in Figures 9 and 10.

The release intensity of ammonia nitrogen of sediments is positively correlated with the temperature change of overlying water. As the temperature rises, the release intensity of ammonia nitrogen of sediments increases accordingly, and the release intensity of ammonia nitrogen at 30°C is 1.75 times of that at 15°C. According to the research conclusion of relevant papers, temperature rise can inhibit the adsorption effect of sediments for ammonia nitrogen, thereby increasing the release amount of ammonia nitrogen. Analysis of the experiment showed that, the features of ammonia nitrogen in the sediments at high temperature are high release intensity and weak adsorption; while at low temperature, the features are low release intensity and strong adsorption. The TN release of sediments is similar to the release of ammonia nitrogen. Experimental results showed that, the average TN release intensity increases with temperature rise, and the TN release intensity of sediments at 30°C is 1.65 times of that at 15°C. Analysis of the experiment revealed that, temperature rise can enhance the metabolic activity of microorganisms, promote the decomposition of organic nitrogen, and increase the release amount and release intensity of sediments and overlying water.

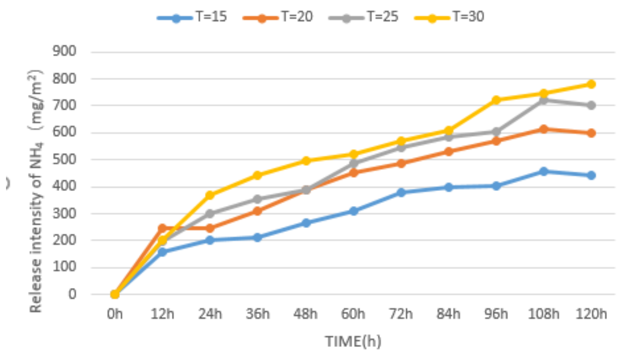

Figure 9. Release intensity of ammonia nitrogen under different temperature conditions

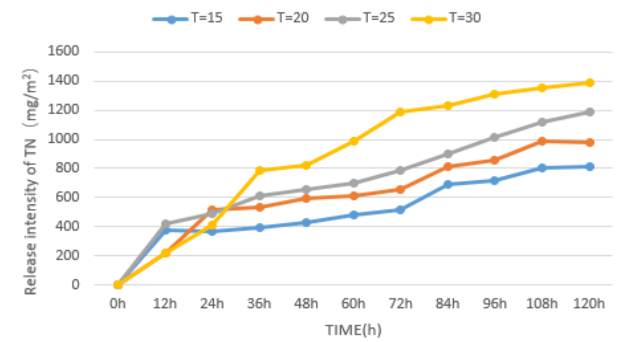

Figure 10. TN release intensity under different temperature conditions

4. CONCLUSION

Temperature, pH, and DO can affect the release of nitrogen and phosphorus nutrients of reservoir sediments. Changes in temperature would change the physical, chemical, and biological reaction conditions in the reservoir, and the release of nitrogen and phosphorus nutrients will increase significantly with temperature rise. The release intensity of nitrogen and phosphorus nutrients is the lowest in the neutral environment, and higher in the acidic or alkaline environment. Under the conditions of different DO levels, the change trend of the release of nitrogen and phosphorus nutrients is more significant. In anoxic environment, the release intensity of nitrogen and phosphorus is increased significantly, while in oxygen-rich environment, it decreases obviously.

ACKNOWLEDGEMENT

Ningxia Natural Science Foundation (Grant No.: 2021AAC03176 and 2021AAC03195); High Level Talent Introduction Fund Project, North Minzu University; Ningxia Key Research and Development Plan (Talent Introduction) (Grant No.: 2018BEB04039). The Construction Project of First-Class Disciplines in Ningxia Higher Education (NXYLXK2017B09).

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