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Environmental dynamics of nitrogen and phosphorus release from river sediments of arid areas

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Abstract: Human activities lead to the accumulation of a large amount of nitrogen and phosphorus in sediments in rivers. Simultaneously, nitrogen and phosphorus can be affected by environment and re-enter the upper water body, causing secondary pollution of the river water. In this study, laboratory simulation experiments were conducted initially to investigate the release of nitrogen and phosphorus from river sediments in Urumqi City and the surrounding areas in Xinjiang Uygur Autonomous Region of China and determine the factors that influence their release. The results of this study showed significant short-term differences in nitrogen and phosphorus release characteristics from sediments at different sampling points. The proposed secondary kinetics model (i.e., pseudo-second-order kinetics model) better fitted the release process of sediment nitrogen and phosphorus. The release of nitrogen and phosphorus from sediments is a complex process driven by multiple factors, therefore, we tested the influence of three factors (pH, temperature, and disturbance intensity) on the release of nitrogen and phosphorus from sediments in this study. The most amount of nitrate nitrogen (NO_3^--N) was released under neutral conditions, while the most significant release of ammonia nitrogen (NH_4^+-N) occurred under acidic and alkaline conditions. The release of nitrite nitrogen (NO_2^--N) was less affected by pH. The dissolved total phosphorus (DTP) released significantly in the alkaline water environment, while the release of dissolved organic phosphorus (DOP) was more significant in acidic water. The release amount of soluble reactive phosphorus (SRP) increased with an increase in pH. The sediments released nitrogen and phosphorus at higher temperatures, particularly NH_4^+-N, NO_3^--N, and SRP. The highest amount of DOP was released at 15.0°C. An increase in disturbance intensity exacerbated the release of nitrogen and phosphorus from sediments. NH_4^+-N, DTP, and SRP levels increased linearly with the intensity of disturbance, while NO_3^--N and NO_2^--N were more stable. This study provides valuable information for protecting and restoring the water environment in arid areas and has significant practical reference value.

Keywords: sediment; nitrogen and phosphorus; environmental dynamics; pseudo-second-order kinetics model; dissolved organic phosphorus (DOP); Urumqi City

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1 Introduction

The release of nitrogen and phosphorus from sediments represents an essential ecological process at the sediment-water interface, which plays a crucial role in maintaining the balance and functions

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of aquatic ecosystems. However, anthropogenic nitrogen and phosphorus inputs into the biosphere have been increasing globally since the late 1980s (Wu et al., 2022). Excessive nitrogen and phosphorus may accumulate in the sediments of rivers and lakes. The nitrogen and phosphorus in sediments can become new pollution sources for the overlying water bodies due to external disturbances and adversely affect water quality, biodiversity, and human health (Peñuelas and Sardans, 2022). This effect is concerning in water-scarce arid areas and has received attention from environmental management authorities.

Nitrogen and phosphorus in sediments mainly exist in the form of organic nitrogen and inorganic phosphorus. They are primarily released into the overlying water through diffusion (Cheng et al., 2019) and resuspension (Liu et al., 2020). Many researchers have investigated the environmental factors influencing the release of nitrogen and phosphorus from lake sediments, including sediment characteristics, physicochemical properties of overlying water, biological activities, water level fluctuations, and physical disturbances. For example, sediment properties such as chemical composition and grain size affect the speciation and mobility of nitrogen and phosphorus (Li et al., 2022). The physicochemical properties of overlying water, such as nutrient concentrations and organic matter content, influence the chemical equilibrium of nitrogen and phosphorus in sediments. Biological processes, particularly microbial and plant activities, can strongly influence the cycling and release of nitrogen and phosphorus. Fluctuations in the water level and physical disturbances, such as changes in flow velocity and mechanical disturbances, can alter sediment structure, thus affecting the release of nitrogen and phosphorus (House and Denison, 2000; Jiang et al., 2008; Rippey et al., 2021; Zhao et al., 2021; Li et al., 2022). Dissolved oxygen content, pH of water, and temperature are key factors affecting the release of nitrogen and phosphorus from sediments. Low dissolved oxygen levels, deviation of pH from neutral, and higher temperatures increase the release of nitrogen and phosphorus from sediments, further exacerbating eutrophication in water bodies. Therefore, while implementing water environment management and restoration strategies, the comprehensive effects of these factors need to be considered as they determine the characteristics of the release of nitrogen and phosphorus from sediments.

The unique geographical and climatic characteristics of an area need to be considered while assessing the nitrogen and phosphorus release characteristics in river sediments. In Northwest China, Urumqi City in Xinjiang Uygur Autonomous Region has an arid and semi-arid climate. Due to the significant temperature difference between day and night, the release of nitrogen and phosphorus from river sediments is strongly affected. James and Barko (2004) and Jiang et al. (2008) showed that the relationship between temperature and the release of phosphorus from sediments is not linear due to factors such as biological activity and diffusion rate. The effects of temperature on lakes and rivers vary due to differences in sediment characteristics (Lovley and Phillips, 1986; Jensen and Andersen, 1992; Jiang et al., 2008; Anthony and Lewis Jr., 2012; Hunting and Kampfraath, 2013; Small et al., 2014; Wu et al., 2014), necessitating case-specific examination. Moreover, the pH in the water bodies of Xinjiang Uygur Autonomous Region often deviates from neutral, which may be related to the unique geological background and soil types of this region. Additionally, due to the water scarcity in arid areas, water bodies are primarily replenished due to the melting of glaciers in the mountains, leading to significant seasonal variations. Water bodies in arid areas may experience more frequent anthropogenic disturbances compared to those in humid areas, including water level regulation, water use management, and agricultural activities. Disturbances in water bodies can cause the resuspension of surface particles in sediments, thereby promoting the release of phosphorus from sediments (He et al., 2022). These factors, acting together on sediments, may result in nitrogen and phosphorus release characteristics in the arid areas of Xinjiang Uygur Autonomous Region that are different from those found in other regions. Therefore, studying the release of nitrogen and phosphorus from sediments in the arid areas of Xinjiang Uygur Autonomous Region can help understand the extent of eutrophication in local water bodies. Such information can provide valuable insights for water environment management in arid areas.

In this study, the kinetic characteristics and influence of different environmental factors on the short-term release of nitrogen and phosphorus from sediments in arid areas were investigated. The primary release characteristics of sedimentary nitrogen and phosphorus were investigated through laboratory simulation experiments, and kinetics models were constructed for fitting analysis. Additionally, the effects of pH, temperature, and disturbance intensity on the release of sedimentary nitrogen and phosphorus were examined. Investigating the process of release of nitrogen and phosphorus from sediments and their influencing factors can provide deeper insights into the speciation and release characteristics of nitrogen and phosphorus from sediments, offering a theoretical framework and technical support for the protection and restoration of rivers, lakes, and other water bodies in arid areas.

2 Materials and methods

2.1 Study area

Urumqi City, Xinjiang Uygur Autonomous Region, Chinais located in the arid Northwest China of Eurasian continent; specifically, it is located on the northern slope of the Tianshan Mountains and the south margin of the Junggar Basin. The daily temperature difference in Urumqi City varies greatly, with the maximum daily temperature difference of 20.0°C. In 2020, the annual average temperature was 8.7°C and the annual precipitation was only 199.6 mm. The river flowing through the city mainly receives its water from the melting of ice and snow from the Tianshan Mountains and the discharge of water from the surroundings. Therefore, the environmental migration of nitrogen and phosphorus in river sediments is influenced by local climate and human activities. The Shuimogou and Toutunhe rivers are the principal waterways that flow through Urumqi City, maintaining a consistent flow throughout the year. The Shuimogou River is situated in the eastern suburb of Urumqi City and flows through Shuimogou District and Midong District, Urumqi City and Wujiaqu City, among other areas, before discharging into Dongdao Haizi after merging with the Bayi Reservoir. The river's total length is 27.2 km, and it is the primary source of water for irrigation of agriculture and part of the water is used for drinking and landscape greening along the eastern suburb. The Toutunhe River has its source on the northern slopes of the Haga Mountains, situated in the central region of the Tianshan Mountains. It is a mountain stream river, with a total length of 190.0 km. Currently, the upper reaches of the Toutunhe River are closed the Changji Tingzhou Ecological Green Valley for ecological landscaping purposes. The downstream volume is supplemented by reclaimed water discharged from the Changji No. 2 Wastewater Treatment Plant. A total of 15 pre-sampling sites were established on the two rivers previously mentioned. Following field surveys and measurements, three sites exhibiting the slowest flow and lowest sediment exposure to external influences were selected as the sampling sites for this study (Fig. 1). The river flows from S1 to S3, and the physicochemical properties at the three sites are presented in Table 1. The pre-study demonstrated the most pronounced spatial variations in nitrogen and phosphorus concentrations between the three sampling sites, with S2 and S3 having the highest concentrations among the 15 pre-sampling sites, which may be attributed to the influence of surrounding residential discharges (Su et al., 2023).

River sediment samples were collected in May 2022 using a Petersen grab sampler (Fig. 1). We collected three samples from each sampling site, and then combined the three samples into one and utilized as representative sample for that specific sampling site. After removing rocks, plant roots, and other debris, the samples were transported to the laboratory in clean polythene bags and stored in a refrigerator at 4.0°C for analysis. A portion of the fresh sediment samples were used for analyzing the physicochemical properties (Table 1). All samples were analyzed for pH using YSI ProPlus (Xylem Inc., Yellow Springs, Ohio, USA). The water content in the sediment was measured by the weight loss method after drying at 105.0°C for 24 h, and organic matter was determined by heating the dried sediment at 550.0°C for 4 h (Yin et al., 2017). The metal oxides Fe_2O_3, Al_2O_3, and CaO were determined using Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES) after HNO_3-$HClO_4$-HF digestion. Another portion of the sediment samples were air-dried, ground, and sieved through a 0.15 mm mesh for simulation experiments.

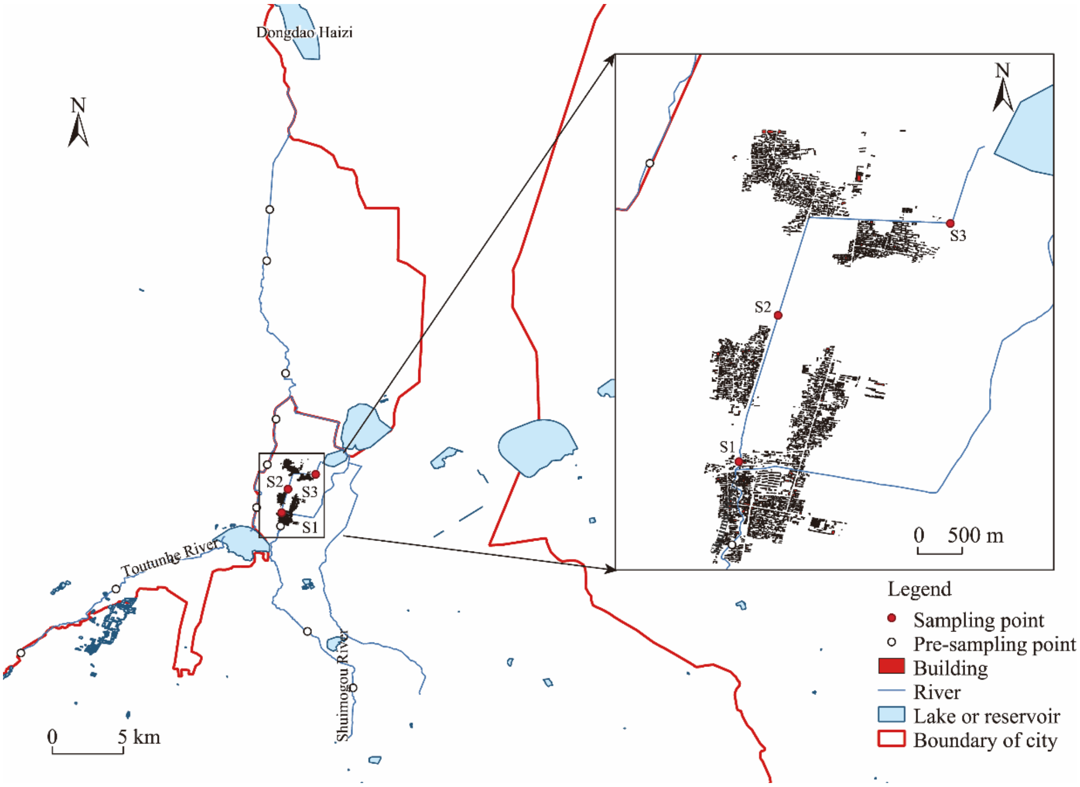

Fig. 1 A schematic illustration of the locations of sampling sites in Urumqi City

Table 1 Physicochemical properties of sediments from the three selected sampling sites

Sediment property	Sampling site		
	S1	S2	S3
Coordinate	44º08′46″N, 87º35′19″E	44º10′02″N, 87º35′40″E	44º10′48″N, 87º37′09″E
pH	7.71	7.71	7.76
Water content (%)	55.00	38.48	40.88
Organic matter (%)	8.52	8.27	5.78
Fe_2O_3 (%)	5.97	5.90	5.67
Al_2O_3 (%)	15.73	12.23	13.19
CaO (%)	7.45	3.10	1.49
Total nitrogen (mg/kg)	3084.62	3539.30	2709.39
Total phosphorus (mg/kg)	1135.64	1729.53	1803.16

2.2 Experimental design and measurement methods

2.2.1 Release dynamics of nitrogen and phosphorus from sediments

The nitrogen found in sediments can be divided into inorganic and organic nitrogen. Organic nitrogen needs to be converted into inorganic nitrogen by microorganisms before it can be utilized by aquatic organisms; inorganic nitrogen mainly includes ammonium nitrogen (NH_4^+-N), nitrate nitrogen (NO_3^--N), and nitrite nitrogen (NO_2^--N). Most studies on phosphorus release focused on soluble reactive phosphorus (SRP) (James and Barko, 2004; Jin et al., 2006; Zhang et al., 2014; Yin et al., 2017), while studies on the release of dissolved organic phosphorus (DOP) are lacking. The DOP in lake ecosystems is an important source of phosphorus for aquatic organisms, and DOP is calculated as the difference between dissolved total phosphorus (DTP) and SRP.

Each sediment sample was thoroughly blended and meticulously weighed into eight equal portions (each 0.50 g in weight), with each portion corresponding to a specific time point, and then, placed in a 50 mL centrifuge tube, followed by the addition of 30 mL of 0.02 mol/L KCl solution. Next, the tubes were placed in a constant temperature shaker and shaken at 25.0°C and 150 r/min. Samples were collected at intervals of 5, 15, 30, 60, 90, 120, 180, and 300 min and 8 samples were finally obtained. The samples were centrifuged (5000 r/min, 15 min) and filtered through a 0.45 μm filtration membrane and the concentrations of NH_4^+-N, NO_3^--N, NO_2^--N, DTP, SRP, and DOP in the supernatant were measured.

NH_4^+-N, NO_3^--N, and NO_2^--N were detected by Nessler's reagent spectrophotometry (UV8000, Shanghai Metash Instruments Co. Ltd., Shanghai, China), ultraviolet spectrophotometric screening method, and N-(1-radical)-ethidene diamine ($C_{10}H_7NHC_2H_4NH_2{\cdot}2HCl$) spectrophotometry, respectively (Han et al., 2022). The concentration of DTP was determined by the potassium persulfate ($K_2S_2O_8$) digestion-molybdenum antimony spectrophotometric method, while the concentration of SRP was evaluated by the molybdenum blue colorimetric method (Kong et al., 2020; Liu et al., 2022). The release time and the corresponding quantity of nitrogen and phosphorus released were substituted into the kinetic equations to calculate the kinetic parameters and plot the kinetic curves. All samples were analyzed in triplicate, and the data were presented as mean values.

Pseudo-first-order kinetic equation:

$$\ln\left(Q_e - Q_t\right) = \ln Q_e - k_1 t\,, \tag{1}$$

and pseudo-second-order kinetic equation:

$$\frac{t}{Q_t} = \frac{1}{k_2 Q_e^2} + \frac{t}{Q_e}\,, \tag{2}$$

where Q_e is the amount of phosphorus released or adsorbed at equilibrium (mg/kg); Q_t is the amount of phosphorus released or adsorbed at time t (mg/kg); and k_1 and k_2 are the rate constants for pseudo-first-order and pseudo-second-order adsorption, respectively.

2.2.2 Effects of pH on nitrogen and phosphorus release

The average pH of the sediment in Dongdao Haizi (tailwater channel of Toutunhe River and Shuimogou River) was found to be 9.60, 7.30, and 9.50 during the dry, normal, and wet seasons, respectively (Song, 2017). In another study, the results of a sediment sampling survey showed that the lowest pH of the sediment was 6.83 and the highest was 8.16 (Su et al., 2023). Therefore, in this study, the experiment was designed with three pH values (5.00, 7.00, and 9.00) to determine the effect of pH on the release of nitrogen and phosphorus from sediments.

First, 0.50 g of dried sediment samples were placed in a centrifuge tube, and 30 mL of 0.02 mol/L KCl was added (the pH of the solution was adjusted to 5.00, 7.00, and 9.00 with 0.10 mol/L HCl and NaOH solution), and the tube was placed in a constant temperature shaker and shaken at 25.0°C and 150 r/min. Samples were collected at intervals of 5, 15, 30, 60, 90, 120, 180, and 300 min and 8 samples were finally obtained. The samples were centrifuged (5000 r/min, 15 min) and filtered through a 0.45 μm filtration membrane and the concentrations of NH_4^+-N, NO_3^--N, NO_2^--N, DTP, SRP, and DOP in the supernatant were measured.

2.2.3 Effects of temperature on nitrogen and phosphorus release

The average water temperatures of Dongdao Haizi were 4.1°C, 14.5°C, and 32.4°C during the dry, normal, and wet seasons, respectively (Song, 2017). During the wet season, the river water temperature in the desert reached 45.0°C, indicating that the water temperature was very high. Accordingly, it was estimated that the upstream river water temperature during the wet season should be around 25.0°C. Therefore, three different temperature treatments (5.0°C, 15.0°C, and 25.0°C) were designed to investigate the effect of temperature on the release of nitrogen and phosphorus from sediments.

Dried sediment samples (0.50 g) were placed in a centrifuge tube, and 30 mL of 0.02 mol/L KCl solution was added (the pH of the solution was adjusted to 7.00 with 0.10 mol/L HCl and NaOH solution). The tube was placed in a constant temperature shaker and shaken at 150 r/min; the temperature was set at 5.0°C, 15.0°C, and 25.0°C. Samples were collected at intervals of 5, 15, 30, 60, 90, 120, 180, and 300 min and 8 samples were finally obtained. The samples were centrifuged (5000 r/min, 15 min) and filtered through a 0.45 μm filtration membrane and the concentrations of NH_4^+-N, NO_3^--N, NO_2^--N, DTP, SRP, and DOP in the supernatant were measured.

2.2.4 Effects of disturbance intensity on nitrogen and phosphorus release

First, 0.50 g of dried sediment samples were placed in a centrifuge tube, and 30 mL of 0.02 mol/L KCl solution was added (the pH of the solution was adjusted to 7.00 with 0.10 mol/L HCl and NaOH solution). The tube was placed in a constant temperature shaker and shaken at 25.0°C with different shaking speeds (50, 150, and 250 r/min). Samples were collected at 5, 15, 30, 60, 90, 120, 180, and 300 min and centrifuged at 5000 r/min for 15 min. The supernatant obtained was passed through a membrane filter (0.45 μm). Finally, the concentrations of NH_4^+-N, NO_3^--N, NO_2^--N, DTP, SRP, and DOP in the supernatant were measured.

2.3 Data analysis

All treatments and data from all tests were independently repeated three times, and the average value was used to determine the results. The data were analyzed using Microsoft Excel (Microsoft Corporation, Redmond, Washington, USA) to obtain the mean and standard deviation. Subsequently, the Origin 2021 software (OriginLab, Northampton, Massachusetts, USA) was used to fit the nitrogen and phosphorus release from sediments with pseudo-first-order and pseudo-second-order kinetics models and plot the data. The most appropriate kinetic simulation was determined by comparing the R^2 values (Liu et al., 2022). Bar plots were constructed using GraphPad Prime 10 (GraphPad Software, Boston, Massachusetts, USA), and multiple comparisons were performed with Bonferroni correction to determine the significance of differences within groups.

3 Results and discussion

3.1 Characterization of nitrogen and phosphorus release from sediments

The short-term release characteristics of nutrients from sediments in 300 min are shown in Fig. 2. The release process can be divided into three stages: rapid-release, slow-release, and equilibrium stages. In NH_4^+-N and NO_3^--N release processes, rapid release mainly occurred within the first 15 min, ranging from 47.74 to 72.75 and 13.72 to 36.18 mg/kg, respectively (Fig. 2a and b). Among these, the lowest amount of NH_4^+-N and the highest amount of NO_3^--N were released in S2, while the amount of NH_4^+-N released was almost same for the sampling sites S1 and S3; however, the amount of NO_3^--N released was higher in S1 than in S3.

The short-term release characteristics of NO_2^--N from sediments differed significantly among the different sampling points. The rate of NO_2^--N released in S2 and S3 sampling sites showed a trend from fast to slow (Fig. 2c). The amount of NO_2^--N released in S3 was higher than that released at S2 before 60 min, but the amount of NO_2^--N released in S3 entered the equilibrium stage after 60 min, while NO_2^--N continued to be released in S2. Additionally, for S1, the rate of NO_2^--N released from sediment increased within 300 min, and thus, it could not be fitted with kinetic equations. The rapid release of NH_4^+-N and NO_3^--N indicated active biogeochemical cycling of nitrogen in sediments. This occurred probably due to the strong mineralization of organic matter in sediments and the combined effects of nitrification and denitrification (Liu et al., 2020). The differences in nitrogen release may be related to factors such as the organic matter content, microbial activity, and environmental conditions of sediments (Li et al., 2022).

The amount of DTP and SRP released increased with an increase in contact time (Fig. 2d and e). The release amount increased rapidly within 15 min of initiation, reaching 9.39 to 17.85 and 7.62 to 14.36 mg/kg, respectively. Then, the rate of release slowed down and almost reached equilibrium after 180 min. The release of DTP and SRP showed a consistent trend in different sampling sites, and the release amounts of DTP and SRP were S2>S3>S1.

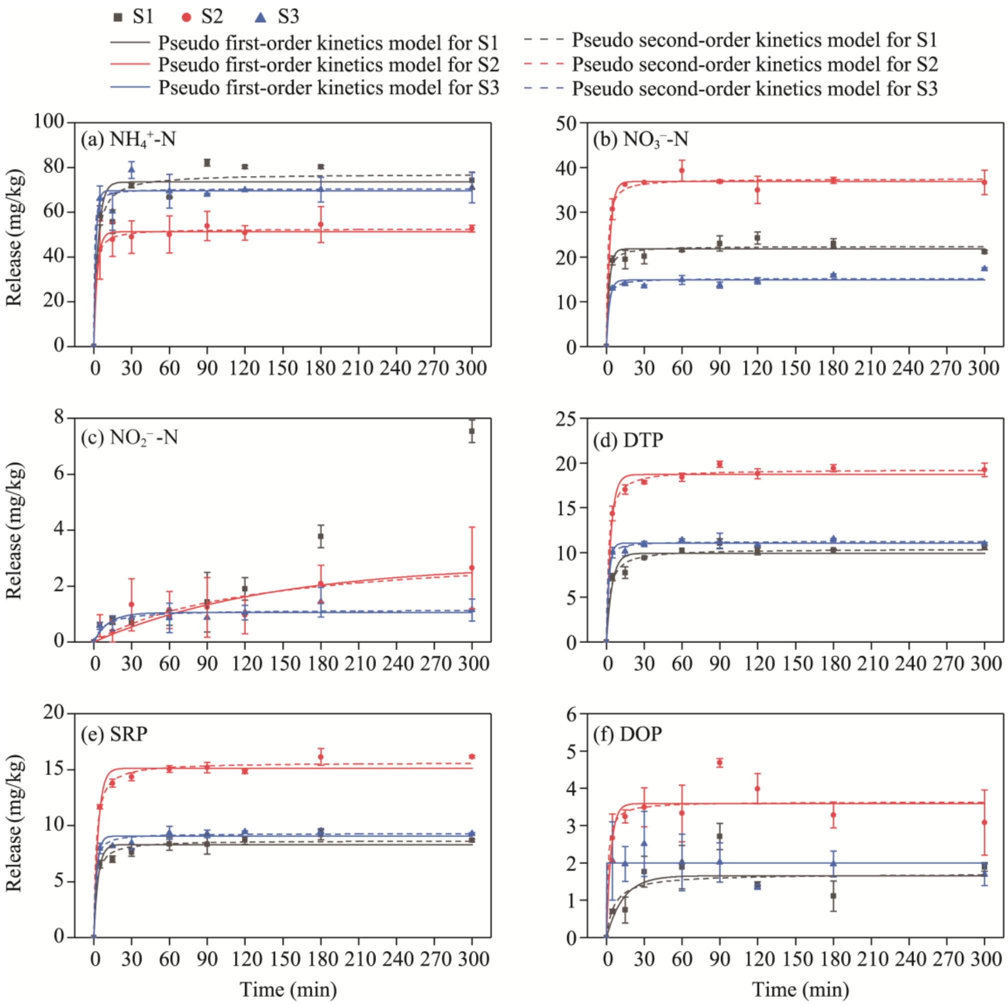

Fig. 2 Release kinetic fitting curves of NH_4^+-N (a), NO_3^--N (b), NO_2^--N (c), DTP (d), SRP (e), and DOP (f) in sediments from different sampling sites. NH_4^+-N, ammonia nitrogen; NO_3^--N, nitrate nitrogen; NO_2^--N, nitrite nitrogen; DTP, total dissolved phosphorus; SRP, soluble reactive phosphorus; DOP, dissolved organic phosphorus.

The release trend of DOP was the same as that of DTP and SRP, but the release characteristics of DOP differed among the sampling sites (Fig. 2f). The kinetic fitting curves showed that as the contact time increased, the amount of DOP released increased rapidly in S1 (within 30 min) and S2 (within 15 min); finally, the amount released slowed down and almost reached equilibrium after 30 min.

The differences in the release trend of phosphorus in different sampling sites were mainly due to the differences in DOP (Fig. 2). Previous study showed that the organic phosphorus content in sediments followed the order S2>S3>S1, and the main organic phosphorus form was HCl-OP in S2 and S3 (Su et al., 2023). The release of organic phosphorus from sediments was mainly influenced by the morphology of organophosphorus and the mineralization of organophosphorus (Lü et al., 2016). The effect of the morphology of organophosphorus refers to the conversion of DOP into reactive organophosphorus in water bodies (Kong et al., 2020), whereas, the mineralization of organophosphorus converts it into inorganic phosphorus under the mineralization effects of microorganisms (Joshi et al., 2015); inorganic phosphorus is then released into the water body. Additionally, Liu et al. (2022) showed that changes in the humification and aromaticity of dissolved organic matter (DOM) may also affect the release rate and pattern of DOPs. Changes in the functional groups, such as hydroxyl, carboxyl, and carbonyl groups on the phenyl rings of the hydrophobic DOM in sediments, can influence the release of phosphorus from sediments (Liu et al., 2022).

The kinetics model fitting parameters are shown in Table 2. The coefficient of determination (R^2) of the fitted model was used to evaluate the degree of fit between the model and the actual data (Liu et al., 2022). In this study, except for the release of NO_2^--N in S1, which did not follow kinetic characteristics, and thus, could not be fitted, the lowest R^2 for the pseudo-first-order kinetics model was 0.63, and the lowest R^2 for the pseudo-second-order kinetics model was 0.59. However, in most cases, the pseudo-second-order kinetics model had higher R^2 values, which indicated that it was a more accurate and better fit to the actual data.

Table 2 Parameters of fitting kinetics models for the release of nitrogen and phosphorus from sediments in different sampling sites

Parameter	Sampling site	Pseudo-first-order kinetics model			Pseudo-second-order kinetics model		
		Q_e (mg/kg)	k_1	R^2	Q_e (mg/kg)	k_2	R^2
NH_4^+-N	S1	73.52	0.28	0.89	77.16	0.01	0.93
	S2	51.28	0.36	0.98	52.57	0.02	0.99
	S3	69.65	0.59	0.95	70.49	0.03	0.96
NO_3^--N	S1	21.83	0.42	0.95	22.40	0.04	0.97
	S2	36.86	0.36	0.99	37.47	0.03	0.99
	S3	14.85	0.41	0.94	15.23	0.06	0.95
NO_2^--N	S1	\	\	\	\	\	\
	S2	2.82	0.01	0.71	3.38	0.00	0.73
	S3	1.05	0.09	0.75	1.16	0.10	0.83
DTP	S1	10.06	0.21	0.93	10.57	0.03	0.97
	S2	18.72	0.28	0.98	19.37	0.03	1.00
	S3	10.99	0.48	0.99	11.17	0.13	0.99
SRP	S1	8.31	0.29	0.95	8.67	0.06	0.98
	S2	15.12	0.29	0.98	15.65	0.04	0.99
	S3	9.07	0.41	0.97	9.30	0.10	0.99
DOP	S1	1.82	0.06	0.63	1.93	0.06	0.59
	S2	3.60	0.26	0.84	3.72	0.14	0.85
	S3	1.95	11.45	0.79	1.95	5.20×10^{44}	0.79

Note: The "\" in the table indicates a failure of fit, and the rest of the data in this table are from Origin nonlinear curve fitting. Q_e represents the amount of phosphorus released or adsorbed at equilibrium; k_1 represents the rate constant for pseudo-first-order adsorption; and k_2 represents the rate constant for pseudo-second-order adsorption. DTP, total dissolved phosphorus; SRP, soluble reactive phosphorus; DOP, dissolved organic phosphorus.

3.2 Release of nitrogen and phosphorus from sediments under different pH conditions

The amounts of different nitrogen forms released from sediments under different pH conditions is shown in Figure 3a. The amount of NH_4^+-N released was different under different pH conditions. Among them, the amount of NH_4^+-N released was the highest at pH of 5.00, followed by pH of 9.00 and 7.00, respectively. Thus, acidic conditions promoted the release of NH_4^+-N from sediments, which occurred probably because in water, under acidic conditions, H^+ can inhibit the activity of nitrifying bacteria in surface sediments, thus suppressing the conversion of ammonium to nitrate and promoting the release of accumulated ammonium into the overlying water (Zhang et al., 2014). The ammonium ions in the sediment colloids were exchanged with hydrogen ions (present in high concentrations) in water, thus promoting the release of a large number of ammonium ions from sediments and facilitating the release of ammonia nitrogen (Liang et al., 2010). In alkaline water environments, excess OH^- ions can convert NH_4^+ to NH_3, and NH_3 can easily escape from the water body, reducing the concentration of NH_4^+-N in the water under alkaline conditions. However, this process results in a greater difference in ammonium ion concentration between the sediment and the water than that would be observed in a neutral water environment. This difference in concentration facilitates the release of NH_4^+-N in sediments.

The amount of different phosphorus forms released from sediments under different pH conditions is shown in Fig.ure 3b. The amount of DTP released was not significantly different in treatments between pH of 5.00 and 7.00, but it increased significantly in the alkaline water environment at pH of 9.00. The amount of SRP released increased with an increase in pH, and the amount of SRP released differed significantly among the three pH conditions. In contrast, the amount of DOP released decreased as the pH increased, and no significant difference was found between treatments at pH of 7.00 and 9.00. This effect of pH on phosphorus release mainly manifests as the binding of phosphorus with metal elements (such as iron, aluminum, and calcium) (Kim et al., 2003). In acidic water environments, metal ions such as iron, aluminum, and calcium in sediments can dissolve in large amounts, and these metal elements can adsorb phosphates, thus promoting the release of phosphates from sediment (Temporetti et al., 2019). However, excessive H^+ in acidic water can also lead to the protonation of surface functional groups in sediment, thus enhancing the electrostatic adsorption of phosphates (Gong et al., 2020), which can partly weaken the release of phosphates. Under alkaline conditions, the main form of phosphorus present is HPO_4^{2-}, and the release of phosphorus from sediments is mainly achieved through ion exchange, where OH^- exchanges with the phosphate anions, thus enhancing the dissolution of phosphates and promoting the release of phosphorus into the overlying water. High pH favors the release of NaOH-P, while low pH favors the release of HCl-P (Jin et al., 2004). As the pH of overlying water and sediments increases, the ability of iron and aluminum compounds to bind phosphorus decreases, mainly because OH^- ions replace orthophosphate in the coordination exchange reaction (Jin et al., 2006).

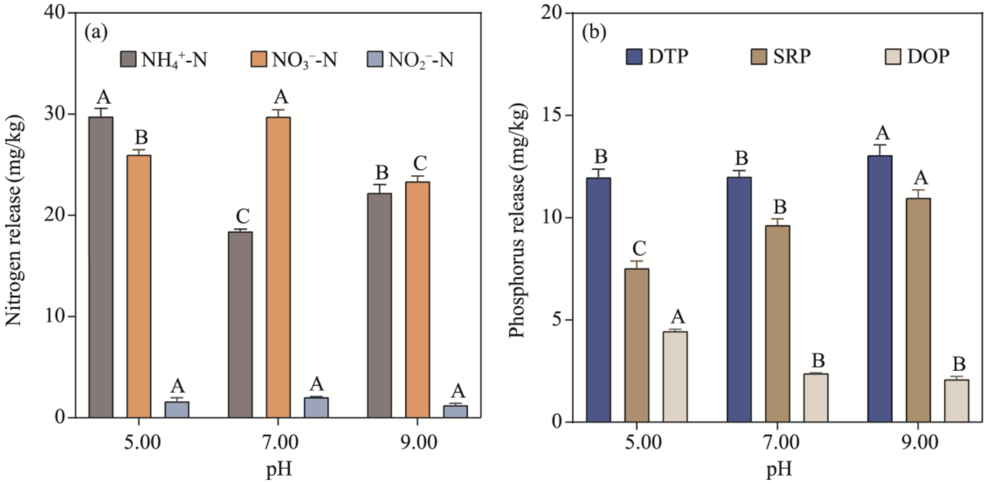

Fig. 3 Release of different forms of nitrogen (a) and phosphorus (b) from sediments under different pH conditions. Different capital letters indicate significant differences at $P<0.05$ level.

3.3 Release of nitrogen and phosphorus from sediments at different temperatures

The amount of NO_3^--N released was greater than that of NH_4^+-N released; the amount of NO_2^--N released was the lowest at different temperatures (Fig. 4a). As the temperature increased, the amounts of NO_3^--N and NO_2^--N released increased. The amount of NH_4^+-N released at 25.0°C was higher than those released at 5.0°C and 15.0°C, but the amount of NH_4^+-N released at 15.0°C was only half of that released at 5.0°C. Typically, high temperatures promote the release of NH_4^+-N from sediments; in contrast, low temperatures inhibit its release (Jäntti and Hietanen, 2012). However, the results shown in this study were slightly different. An increase in the temperature can increase the activity of organisms in sediments, thereby accelerating the mineralization of organic nitrogen into soluble inorganic nitrogen at the sediment-water interface. Moreover, under aerobic conditions, ammonium ions can be converted to nitrate ions through nitrification (Zhang et al., 2014). However, under low-temperature conditions with limited dissolved oxygen, nitrate can be reduced to ammonium through microbial heterotrophic denitrification (Søndergaard et al., 1999). In this study, the amounts of NO_3^--N and NH_4^+-N released increased with the increase in the temperature, and a significant difference was found between treatments at different temperatures, but no difference was recorded in the amount of NO_2^--N released between temperatures. These results indicated that in arid areas of Xinjiang Uygur Autonomous Region, compared to lower temperatures at night, higher temperatures during the day may increase the amounts of NO_3^--N and NH_4^+-N released from sediments.

The amount of DTP released was more significant than the amount of SRP released, and the release of DOP was the lowest at different temperatures (Fig. 4b). As the temperature increased, the amounts of DTP and SRP released also increased accordingly. The amount of SRP released differed significantly under the three temperature treatments, while the amount of DTP released was not significantly different between 15.0°C and 25.0°C. The amount of DOP released at 15.0°C was significantly higher than that released at 25.0°C. This occurred probably because increasing the temperature increased the solubility of the products of various insoluble compounds and led to the release of phosphorus (Coffman and Kildsig, 1996). Additionally, increasing the temperature decreased the phosphorus adsorption capacity of sediments, increased the biological and microbial activity in sediments, and promoted biological disturbance and mineralization, thereby releasing organically bound phosphorus (Lovley and Phillips, 1986; Jensen and Andersen, 1992; Cornelissen et al., 1997; Katsev et al., 2006; Wu et al., 2008; Hunting and Kampfraath, 2013; Small et al., 2014). The dissolved oxygen concentration in the overlying water decreases due to microbial consumption, reducing the redox potential. The transition from Fe^{3+} to Fe^{2+} is enhanced, releasing Fe-P from sediments (Holdren and Armstrong, 1980; Jensen and Andersen, 1992; Kosten et al., 2012). Furthermore, from the perspective of free diffusion, increasing the temperature increased the activity of ions in the water, thus increasing the diffusion rate and the flux of phosphorus from sediments to the water body (Jiang et al., 2008; Anthony and Lewis Jr., 2012).

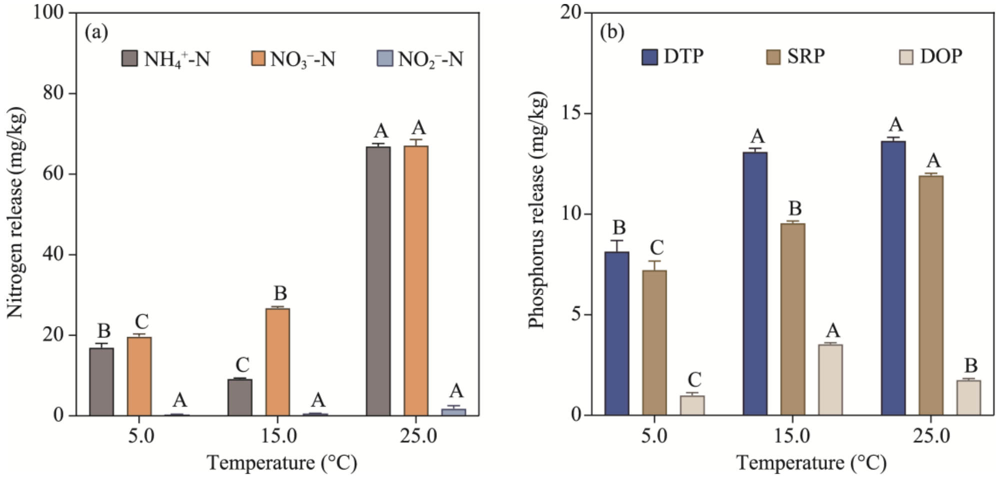

Fig. 4 Release of different forms of nitrogen (a) and phosphorus (b) from sediments at different temperatures. Different capital letters indicate significant differences at $P<0.05$ level.

3.4 Release of nitrogen and phosphorus from sediments under different disturbance intensities

The disturbance intensity significantly affected the amount of NH_4^+-N released (Fig. 5a). As the disturbance intensity increased, the amount of NH_4^+-N released also increased accordingly, which was similar to the findings of Wang et al. (2008). The results of controlled experiments showed that due to the lower amount of dissolved oxygen in the water of the non-interference treatment group, the amount of NH_4^+-N released decreased. Additionally, continuous interference increased the amount of dissolved oxygen in water, resulting in a higher rate of release of NH_4^+-N than the rate of release recorded in the non-interference treatment group (Xu et al., 2023). Therefore, the results obtained in this study may have occurred because an increase in dissolved oxygen levels in the water under hydrodynamic disturbance enhances the proliferation and activity of nitrifying bacteria (Pauer and Auer, 2000), thus promoting the nitrification of NH_4^+-N (Jäntti and Hietanen, 2012; Zhang et al., 2014). However, a high-speed disturbance may lead to the saturation of dissolved oxygen levels in the water (Peng et al., 2021). The amount of NO_3^--N released did not change significantly under different disturbance intensities, except for a significant difference in the amount of NO_3^--N released found between 50 and 150 r/min. The differences under other disturbance intensities were relatively small, and the amount of NO_3^--N released at 150 r/min was slightly higher than that at 250 r/min. The effect of disturbance intensity on the release of NO_2^--N was relatively small, and no significant difference was recorded in the amount of NO_2^--N released under the three disturbance intensity conditions. A study showed that hydrodynamic disturbance can promote the short-term release of NO_2^--N from sediments because, under high-speed disturbance (200 r/min), the high dissolved oxygen in the overlying water is favorable for nitrifying bacteria to convert NO_2^--N into NO_3^--N (Peng et al., 2021). The findings of that study matched the results of this study. This occurred probably because the NO_2^--N content in sediments was low, and thus, the amount released was not significant. Additionally, the long-term aerobic environment under hydrodynamic disturbance is not suitable for denitrification (Reddy et al., 1984), which may lead to the depletion of NO_2^--N at the sediment-water interface (Peng et al., 2021).

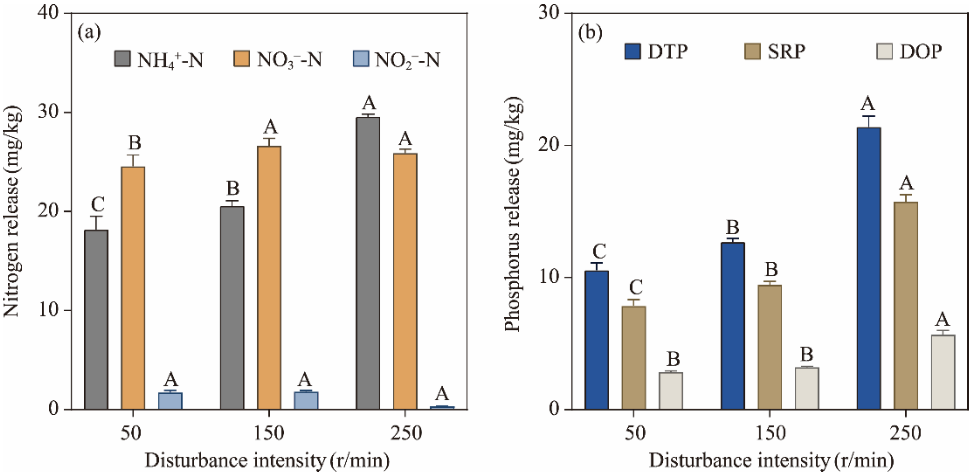

Fig. 5 Release of different forms of nitrogen (a) and phosphorus (b) from sediments under different disturbance intensities. Different capital letters indicate significant differences at $P<0.05$ level.

The amounts of DTP, SRP, and DOP released increased with an increase in disturbance intensity, especially the release amounts at 250 r/min were significantly higher than those at 150 and 50 r/min, indicating that the disturbance significantly affected the release of nitrogen and phosphorus from sediments. Generally, phosphate release in water is positively correlated with the disturbance rate (Holdren and Armstrong, 1980). This might occur because water disturbance causes the resuspension of surficial sediments, increases the contact area between particles and water, and also accelerates the diffusion of phosphorus in the interstitial water of sediments, thus promoting the rapid release of phosphorus from sediments to the overlying water body (Holdren and Armstrong, 1980; Li and Huang, 2010; Xu et al., 2018). Additionally, a study showed that moderate hydrodynamic disturbance promoted the release of nitrogen and phosphorus nutrients from the lake sediments of Taihu Lake, China, thus worsening the eutrophication of the lake (Huang et al., 2016). When the disturbance intensity was 25, 50, and 100 r/min, the release rates of total phosphorus and total nitrogen increased by 36.2%, 41.7%, and 127.6%, respectively, compared to static conditions, which confirmed the significant effect of disturbance on the release of phosphorus and nitrogen from sediments (Jiang et al., 2010).

4 Conclusions

In this study, laboratory simulation experiments were conducted to initially investigate the process of nitrogen and phosphorus release from river sediments in Urumqi City and the surrounding areas located in an arid area of Northwest China and determine their influencing factors. The release of nitrogen and phosphorus from sediments is a complex multifactor interaction-driven process.

The release characteristics of nitrogen and phosphorus from sediments differed significantly in different sampling sites, and pseudo-second-order kinetics models were found to better fit the release process of nitrogen and phosphorus from sediments. The ambient pH significantly affected nitrogen release from sediments. Significantly greater levels of NH_4^+-N were released in acidic and alkaline environments than in neutral environments. The release of NO_3^--N was the highest at pH of 7.00; however, the pH did not significantly affect the release of NO_2^--N. Increasing the temperature and disturbance intensity in water significantly promoted the release of nitrogen and phosphorus from sediments, especially the release of NH_4^+-N, NO_3^--N, DTP, and SRP. To summarize, pH, temperature, and disturbance intensity strongly affected the release of nitrogen and phosphorus from sediments.

Overall, a comprehensive understanding of the release of nitrogen and phosphorus from sediment requires the consideration of additional environmental factors and long-term monitoring and modeling experiments. These measures have important theoretical and practical implications for the conservation and restoration of water resources in arid areas.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author contributions

Conceptualization: SU Wenhao, ZHU Xinping, WANG Ling; Methodology: SU Wenhao, LEI Rongrong, LEI Li; Formal analysis: SU Wenhao, WU Chengcheng, SUN Xuanxuan; Writing - original draft preparation: SU Wenhao; Writing - review and editing: SU Wenhao, ZHU Xinping; Funding acquisition: WANG Ling; Resources: WANG Ling; Supervision: ZHU Xinping, WANG Ling. All authors approved the manuscript.

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