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POLLUTION REMOVAL CAPACITIES OF AQUATIC PLANT SPECIES IN THE DATONG WETLAND PARK IN NORTH CHINA

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Highlights

- Provide new ideas for the construction of constructed wetlands in northern China.
- The water quality is purified through the triple synergy of base soil wetland plant microorganisms.
- Bioremediation is a new concept to restore environmental quality.
- Base soil, aquatic plants and microorganisms convert harmful substances in water into absorbable substances.

Abstract. The purification effect of a natural wetland landscape is often low when the focus is placed on the landscape effect. The effective combination of constructed wetland technology with landscape construction is challenging. Taking the Yuhe Wetland Park in Datong, Shanxi Province, China, as an example, the COD, phosphorus, and nitrogen removal capacities of aquatic plant species were determined, as well as the effects of the soil and the microbial communities. The highest COD and P removal capacity was observed for *Typha orientalis* Presl. which the purification rate reached 76.9% and 76.6%, and the highest N removal capacities were found for *Scirpus validus* Vahl., the rate of purification was 83.4%. Gram-negative bacteria were dominant.

Keywords: constructed wetland, wetland landscape, basal, aquatic plant, microorganism.

Introduction

Well-constructed wetland parks can considerably improve water quality, strengthen the purification capacity of natural wetlands, and provide valuable sites for various human uses (leisure, scientific education) (Yang et al., 2019; DiCenzo et al., 2019; Chen et al., 2018; Wang et al., 2020; Nuamah et al., 2020; Egea-Corbacho et al., 2021; Egbuikwem et al., 2020). As a typical biological water purification system, constructed wetlands have essential functions such as increasing the water quality, supplying groundwater, improving the microclimate, and increasing biodiversity.

In China, when constructing wetland landscapes, the landscape effect is often focused on, largely ignoring the base soil, plants and microorganisms, and the purification abilities of different plants regarding the chemical oxygen demand (COD), phosphorus (P), and nitrogen (N), which often leads to a low water quality (Mu'azu et al., 2020; Kumar et al., 2021; Oliveira et al., 2021; Yang et al., 2021).

Although constructed wetlands are widely used for water purification (Abbasi et al., 2021; Rodríguez-Varela et al., 2021; Çelekli & Şahin, 2021; Lee et al., 2021), landscape designers often lack the systematic understanding of the purification methods and the underlying mechanisms. In the last decade, because of the gradual complexity of water pollution sources, water purification in wetlands has become more challenging. Frequently, the pollutant tolerance limits of aquatic plants are ignored. When the concentration is above the threshold value that can be tolerated by a given plant species, purification is impeded (Gibson & Moyle, 2020). Generally, wetlands are formed according to the landscape features; because of the few technical standards and specifications, there is a lack of quality wetland ecosystem assessment, and real-case studies are scarce. In this sense, controlling the characteristics of the soil matrix and the growth characteristics of aquatic plants is of great significance for the improvement of constructed wetland landscapes.

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Datong City is located in Datong Basin in the north of Shanxi Province, with a high terrain, low rainfall, strong winds, and a coarse soil texture. As the annual rainfall is only 400 mm, wetland parks are crucial in this region Taking Datong Wetland Park in Shanxi Province as the research area, this paper investigates and analyzes the application of the constructed wetland technology from an ecological aspect. Combined with specific engineering examples, the effects of soil properties, substrate composition ratio, growth characteristics of aquatic plants, and dominant bacteria on water purification are investigated, and the most suitable purification scheme is determined. The research questions are as follows: 1) what is the optimal composition of base soil in constructed wetlands in Datong Yuhe? 2) which wetland has the highest COD, N, and P removal abilities? 3) which wetland has the most stable water purification capacity? The results of this study improve our understanding of the impacts of the base soil ratio and the joint activities of aquatic plants and microorganisms on water bodies, facilitating the development of wetland parks in northern China and promoting the integration of constructed wetland technology and the wetland landscape.

1. Materials and method

1.1. Study area

Datong is located in Shanxi Province in Central China (Figure 1). The average annual temperature in this area is 6.4 °C, with an annual precipitation of 400–500 mm. The climate is dry, cold and windy, with significant temperature differences.

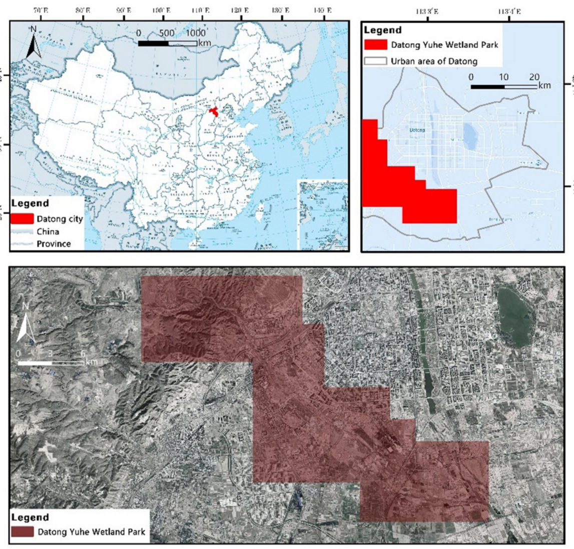

Figure 1. Geographical location of the study area

For this study, the Shilihe greenway and the Yuhe Wetland Park in Datong were used, located in the eastern part of the Eurasian continent and the northern part of Datong. The wetland park is located at the confluence of Shilihe and Yuhe in Datong. In the early stages of the implementation of the park, the following issues were identified: as the wetland park is located in the water land ecotone and vulnerable to flood, the central wetland area is subjected to rapid and seasonal inundation, severe river water pollution, exposed riverbeds, serious water and soil loss, and a loss of river ecological functions, along with the establishment of factories and coal mines around the middle and upper reaches of the river. The latter is responsible for the significant pollution of the Shili River. However, Yuhe Wetland has a rich biodiversity and is a natural "purification pool", and the Yuhe Wetland Park has been reconstructed and designed at the site of the old thermal power plant. The large amounts of fly ash accumulated on the original site, along with various other industrial wastes, are the raw materials of the wetland water purification base. To remove pollutants from industrial wastes and to improve the water quality, the in land river wetland system has been formed by using river depressions and irrigation canals, creating artificial wetlands.

1.2. Data collection

The data collection methods included field investigation, relevant data collection, and actual operation; data were collected between January 2021 and October 2021. A vertical section structure map of the study area was drawn based on precise measurement and exploration. Because of the large size of the study area, the image only expressed the intuitive topographic relief. Regional geographic information was obtained via Mapbox satellite images and Google Earth satellite images. Before accepting relevant data, we investigated the study site to determine the main landscape characteristics of the area and reduce the prediction variables during data observation.

1.3. Analysis and evaluation of base soil

To analyze the influence of base soil composition on sewage treatment, the soil composition with different ratios was constructed (Table 1). Such data can be used to explore the complex relationship between wetland soil water purification efficiency and base soil ratio. When selecting different base materials, considering that the study area is located in a dry, cold, and windy zone, we selected materials that are less affdected by climatic factors, namely ceramsite, activated carbon, zeolite, and chaff (Table 2). Based on the parameters of the soil matrix of the four samples, zeolite and ceramsite have a relatively rough surface, which is conducive to physical adsorption, whereas chaff has a smooth surface.

Assuming that the temperature is constant, we used Equations (1) and (2) to reflect the adsorption capacity of the matrix for N and P:

$$Qe = K_1 \mathrm{Ce}\ 1/n; \quad (1)$$

$$Qe = \mathrm{Qmax} K_2 \mathrm{Ce}(1 + K_2 \mathrm{Ce}) - 1, \quad (2)$$

where Qe is the equilibrium adsorption capacity, mg/g; K_1 is a constant reflecting the adsorption capacity of the

Table 1. Types and characteristics of the soil matrix in the study area

Soil type	Permeability	Ventilatory	Water content	Nutrient content	Fertilizer retention capacity
Sandy soil	▽	▽	△	△	△
Sandy loam					
Sandy clay					
Silty loam					
Clay loam					
Clay					

Table 2. Substrate soil composition study

Microscopic parameters	Ceramsite	Activated carbon	Zeolite	Chaff
Specific surface area/(m^2/g)	33.23	35.72	3.35	1.35
Micropore volume/(cm^2/g)	8.25×10^{-2}	2.20×10^{-1}	1.22×10^{-2}	3.81×10^{-3}
pH	10.89	6.87	8.01	5.99

matrix; n is a constant reflecting the adsorption strength of the matrix; Ce is the equilibrium solution concentration, mg/L; K_2 is a constant reflecting the matrix adsorption energy level; Qmax is the maximum adsorption capacity, mg·g^{-1}.

1.4. Selection of aquatic plants

To determine which plant species have a higher purification capacity, plant growth as well as N and P levels in the water were used as prediction variables, and the influence of each variable on the plants was predicted. Surface water evaporation in the study area is extensive, with an average value of 957 mm over several years. We therefore selected local aquatic plants that are adapted to the climate of the study area (Figure 2), namely *Typha orientalis* Presl., *Phragmites australis* (Cav.) Trin. ex Steud., *Scirpus validus* Vahl., *Lythrum salicaria* L., and *Scirpus planiculmis* Fr. Carry out the investigation. Prior to the experiment, the laboratory was disinfected, and the 2-month-old seedlings were planted into barrels, with three plants in each barrel and five barrels per species. Sewage from the centralized discharge area of an industrial wastewater plant was added, and samples were taken in intervals of 1 and 5 months to determine biomass, total N, and total P. Pollutant removal was recorded and transformed into prediction variables. They dealt with the possibility of prediction variables for the respective essential characteristics and purification capacity of the five sample plants (Table 3).

Figure 2. Landscape effect of selected aquatic plants (source: Plant Photo Bank of China, 2023)

Table 3. Essential characteristics and purification capacities of the different aquatic plant species

Aquatic plant	Essential characteristics	Purified substance	Purification capacity
Typha orientalis Presl.	Fast reproduction, high concentration of heavy metals, strong adaptability, fast growth and strong enrichment ability	Phosphorus, nitrogen COD_{Cr}, BODS, total suspended solids and other pollutants	Typha can absorb NH4+–N, nitrogen and phosphorus
Phragmites australis (Cav.) Trin. ex Steud.	Fast propagation, strong pollution resistance and purification ability	Suspended solids, chlorides, organic nitrogen, sulfate	It can absorb mercury and lead, and the removal rate of phosphorus in water is 65%
Scirpus validus Vahl.	Fast propagation, strong adaptability and strong purification ability	Heavy metals, nitrides, organic nitrogen, phosphate	It has a high removal rate of organic matter, ammonia nitrogen, phosphate and heavy metals in sewage
Lythrum salicaria L.	Fast propagation, strong adaptability and strong purification ability	Heavy metals, phosphorus, nitrogen, suspended solids and other pollutants	The removal rates of NH4+–N and TP were up to 90% and 41%
Scirpus planiculmis Fr. Schmidt.	Extremely fast reproduction, fast growth, strong adaptability and strong purification ability	Phosphorus, nitrogen, COD_{Cr}, heavy metals	It has a high removal rate of organic matter, phosphate and heavy metals in sewage

1.5. Analysis of submerged plant rhizosphere microorganisms

To explore the impact of submerged plant rhizosphere microorganisms combined with aquatic plants on wetland sewage in the study area, the rhizosphere microorganisms carried by the roots of aquatic plants in the above samples were screened to select the dominant strains that can better survive in Yuhe Wetland Park. As decomposers, microorganisms mainly play the role of decomposing organic matter and also promote the improvement of wetland water purification effect to a certain extent. The working mechanism of purified water is to reduce the concentration of pollutants by relying on the metabolic function of organisms, to improve or restore the wetland to its natural state. The sewage purification intensity is also different with different strains. In constructed wetland water purification, because the dominant bacteria grow fast and contain degradable plasmids that can decompose organic matter, they are often used as the main bacteria in water purification. In the base soil and plant root zone treated water, the organic matter on the surface of aquatic plant roots and nearby sewage in the aerobic zone is decomposed into CO_2 and water by the aerobic microorganisms, and most organic nitrides in sewage can be nitrated by nitrifying bacteria.

2. Results and discussion

2.1. Effects of base soil on wetland sewage purification and water purification capacity

The removal of N and P by the soil matrix is mainly based on precipitation and adsorption. The characteristics of the soil matrix will directly affect the sewage purification capacity and the final landscape. The Freundlich isotherm adsorption model (Table 4) can be used to simulate the adsorption characteristics of each sample matrix, where K_1 indicates the strength of the matrix adsorption capacity. Based on the results, zeolite had the lowest adsorption capacity for N and the highest adsorption capacity for P; for chaff, the opposite pattern was observed. Nitrogen adsorption capacity followed the order chaff > ceramsite > activated carbon > zeolite, whereas for P adsorption, the order was zeolite > ceramsite > activated carbon > chaff. The closer the adsorption index n to 1, the more stable the adsorption. For activated carbon, the adsorption index was closest to 1, indicating that the combination of activated carbon and N/P was most stable. Using the Langmuir isotherm adsorption model, the largest Q_{max} (theoretical saturated adsorption capacity) for N was found for zeolite, whereas the largest Q_{max} (theoretical saturated adsorption capacity) for P was observed for ceramsite. The value of K_2 directly indicates the matrix adsorption binding strength.

The adsorption binding strength for N followed the order chaff > zeolite > ceramsite > activated carbon, whereas that for P followed the order ceramsite > zeolite > activated carbon > chaff.

The N adsorption capacity was highest for chaff, although chaff had the smallest theoretical saturated adsorption capacity. At the same time, the P adsorption capacity of chaff adsorption binding strength of chaff was the lowest, with the smallest theoretical saturated adsorption mass. Therefore, at high P concentrations, the use of chaff in constructed wetlands is challenging. Regarding activated carbon, the N adsorption capacity, the theoretical saturated adsorption of N, and the N binding strength were high, while it is vital for Phosphorus, which may be attributed to the fact that Activated carbon itself contains gold ions that can adsorb and precipitate with Phosphorus in sewage, so it has a decisive removal effect on Phosphorus. Higher theoretical N and P adsorption capacities were found for zeolite and ceramsite, indicating that they are most suitable for water purification, most likely because of the high specific surface areas. Therefore, these materials can be used as standard adsorption matrices in the Datong Yuhe Wetland Park. The sediment of a wetland mainly transports the sewage to the ground, through capillaries and siphons, where it is adsorbed and degraded (Zhu & Chen, 2011; Chai et al., 2019; Guo et al., 2013). Soil is therefore important for the growth and reproduction of aquatic plants and microorganisms, restoring the ecological balance of the wetland.

Table 4. Parameters of Freundlich and Langmuir isotherm adsorption models for sample matrices in the study area

Sewage impurity	Soil matrix	Freundlich isothermal adsorption model			Langmuir isothermal adsorption model		
		n	K_1	R^2	Q_{max}	K_2	R^2
NH4+–N	Ceramsite	1.64	0.07	0.98	1.47	0.02	0.92
	Activated carbon	1.53	0.02	0.99	0.99	0.01	0.88
	Zeolite	0.65	0.01	0.97	2.00	0.03	0.98
	Chaff	8.87	0.12	0.97	0.21	0.17	0.99
P	Ceramsite	0.49	0.10	0.98	1.28	0.11	0.94
	Activated carbon	0.80	0.06	0.95	1.25	0.05	0.94
	Zeolite	1.90	0.11	0.98	1.16	0.06	0.99
	Chaff	0.57	0.00	0.94	0.80	0.01	0.95

2.2. Impact of aquatic plants on wetland sewage treatment

Table 6 shows the effects of the different plant species on COD, P, and N levels. All species showed similar P removal capacities. The COD removal rate followed the order *Typha orientalis* Presl. > *Phragmites australis* (Cav.) Trin. ex Steud. > *Scirpus validus* Vahl. > *Lythrum salicaria* L. > *Scirpus planiculmis* Fr. Schmidt, whereas the N removal capacity followed the order *Scirpus validus* Vahl. > *Phragmites australis* (Cav.) Trin. ex Steud. > *Typha orientalis* Presl. > *Scirpus planiculmis* Fr. Schmidt. > *Lythrum salicaria* L. Reed showed the highest purification effect; the removal of COD and N *Chelidonium* and *Scirpus* was low, most likely because of the lack of N-fixing microorganisms in their roots (Lu et al., 2007; Liu et al., 2019; Ilyas & Masih, 2017). These results facilitate the selection of plant species for water pollution control in the Yuhe Wetland Park.

In the comparative data analysis (Tables 5 and 6), sewage quality was added as the control. Reed still showed the highest COD removal rate. However, in May, the COD removal rate of *Typha longibracteata* exceeded that of reed. The P removal capacity followed the order *Typha longbracteata* > shallot > reed > *Lythrum* > *Scirpus Scirpus*, whereas the N removal capacity followed the order shallot > reed > *Typha longibracteata* > *Scirpus Scirpus* > *Lythrum*. With the continuous increase in the concentrations, the P removal rates for shallot and reed remained highest, making them a viable option for sewage purification in the Yuhe Wetland Park, along with *Typha orientalis*.

2.3. Impacts of microorganisms on wetland sewage purification

The dominant bacteria in this study were Proteobacteria, Fusobacteria, Planctomycetes, Cyanobacteria, Nitrospirae, Firmicutes, and Bacteroides; when the relative abundance of the soil matrix layer was high, Hydrogenophaga also appeared. The above taxa can promote nitrogen removal in wetlands. And plant roots secrete substances that promote the growth of P and N bacteria, which can indirectly improve the water purification rate.

As reported previously (Cooper et al., 1997), the TN content is strongly correlated to gram-negative bacteria, such as Bacteroidia, Cyanobacteria, Firmicutes, Clostridium, and Proteus, which are involved in denitrification. The main P-removing bacteria in the constructed wetland were *Acinetobacter* and *Pseudomonas*. According to the species quantity clustering heat map, although *Pseudomonas* was found in the Datong Wetland Park, its relative abundance was low and needs to be increased to enhance the purification ability of the wetland.

2.4. Overall water purification capacity

Based on our results, ceramsite can enhance the adsorption strength of other substrates for N and P. A combination ratio of zeolite: ceramsite: activated carbon of 2:2:6 and a ratio of zeolite: ceramsite: activated carbon of 0:2:8 showed the best N and P removal capacities. The ratios of zeolite: ceramsite: activated carbon of 1:3:6 and 2:1:8 were slightly less effective and can be used in less polluted areas (Tables 7 and 8).

Table 5. Residual levels of COD, phosphorus, and nitrogen in the soil after purification using the different plant species

Sample plant	*Phragmites australis* (Cav.) Trin. ex Steud.	*Scirpus validus* Vahl.	*Lythrum salicaria* L.	*Scirpus planiculmis* Fr. Schmidt.	*Typha orientalis* Presl.
COD	0.0%	0.2%	8.2%	13.6%	1.7%
Phosphorus	0.0%	0.0%	0.0%	0.0%	0.0%
Nitrogen	0.0%	0.4%	23.8%	31.6%	0.0%

Table 6. Removal rates for COD, phosphorus, and nitrogen in the soil for the different plant species

Experimental interval	Pollutants	Sewage static quality (purification rate)	Soil and sewage static mass	*Phragmites australis* (Cav.) Trin. ex Steud. (purification rate)	*Scirpus validus* Vahl. (purification rate)	*Lythrum salicaria* L. (purification rate)	*Scirpus planiculmis* Fr. Schmidt. (purification rate)	*Typha orientalis* Presl. (purification rate)
1 Month	COD	2.0%	45.8%	95.5%	94.3%	89.9%	92.8%	94.7%
5 Month		0.0%	24.4%	64.1%	71.6%	59.8%	52.6%	76.9%
1 Month	Phosphorus	5.0%	43.7%	97.3%	97.9%	89.7%	96.5%	97.6%
5 Month		0.0%	24.4%	67.0%	68.6%	63.8%	57.0%	76.6%
1 Month	Nitrogen	17.5%	41.4%	84.7%	89.5%	71.0%	73.2%	84.1%
5 Month		8.9%	24.2%	77 .0%	83 .4%	45.1%	46.8%	76.1%

Table 7. Description and schematic diagram of the matrix in the purification area

Purification area classification	Comprehensive purification area	Plant bed purification area	Heavy metal purification area	Pathogen purification area	Nutrient purification area
Purification mechanism	Plant purification is used to absorb various pollutants in water and purify water quality	Chemical pollutants in water are removed by microbial decomposition in soil	Aquatic plants are mainly used to absorb and purify heavy metals in water	Aquatic plants mainly purify and remove pathogens in water, and microorganisms adhere to its surface to assist purification	The aquatic plants mainly absorb and purify nutrients (such as N, P etc.)
Schematic diagram of purification principle					

Table 8. Matrix, aquatic plants and microbial assemblages in different purification areas

Purification area classification	Purification elements	Purification object	Soil matrix combination ratio	Aquatic plant	Microorganism
Comprehensive purification area	Soil matrix, aquatic plants, microorganisms	Soil impurities and pollutants in sewage	Zeolite: ceramsite: activated carbon = 2:2:6	*Scirpus validus* Vahl., *Phragmites australis*, *Typha orientalis* Presl.	Proteus, Clostridium, floccus, cyanobacteria, spirochetes, Firmicutes, Bacteroidetes
Plant bed purification area	Soil matrix, aquatic plants, microorganisms	Organic and chemical substances in soil	Zeolite: ceramsite: activated carbon = 1:3:6	*Scirpus validus* Vahl., *Phragmites australis*, *Typha orientalis* Presl.	
Heavy metal purification area	Soil matrix, aquatic plants, microorganisms	Heavy metal	Zeolite: ceramsite: activated carbon = 0:2:8	*Scirpus validus* Vahl., *Phragmites australis*	
Pathogen purification area	Soil matrix, aquatic plants, microorganisms	Escherichia coli, Salmonella and Enterococcus	Zeolite: ceramsite: activated carbon = 2:1:8	*Phragmites australis*	
Nutrient purification area	Soil matrix, aquatic plants, microorganisms	Excess nitrogen and phosphorus	Zeolite: ceramsite: activated carbon = 2:2:6	*Scirpus validus* Vahl., *Typha orientalis* Presl.	

Conclusions

The soil matrix, aquatic plants, and microorganisms selected in this study promote the operation of the constructed wetland and efficiently remove pollutants.

1) Nitrogen and phosphorus are mainly removed via physical adsorption and chemical reactions, which can be simulated and compared by the two isotherm adsorption models of Freundlich and Langmuir. Zeolite and ceramsite are most suitable as the main soil matrix in the construction of wetlands in the study area.

2) The purification effect of a wetland is closely related to its microbial community. The dominant bacteria in the Yuhe Wetland Park were Gram-negative bacteria, and the relative abundance of *Pseudomonas* was low. To enhance the pollutant removal capacity, the abundance of *Pseudomonas* should be increased.

3) Water treatment is achieved via the combination of soil, plants, and microorganisms.

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Author contributions

Wang Wei: methodology, software, writing, and submission of the manuscript; Li Jiaying: investigation, data collection; Jiao Xiang, Ma Zhiqing: software, supervision; Lv Wujie: review the manuscript. All authors read and approved the final manuscript.

Availability of data and materials

The data used in this study are available from the corresponding author upon request.

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