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Controlling Nitrogen Removal from Urban Wastewater in Constructed Wetlands with Native Vegetation in Beijing

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Abstract. Excess nitrogen in urban wastewater effluent exacerbates eutrophication in water bodies, whereas nutrient-rich effluents can be reused for beneficial purposes, such as irrigation and agriculture. Therefore, controlling nitrogen removal is essential to meet water discharge quality standards and support sustainable water management, aligning with Sustainable Development Goal 6, which states to improve water quality, wastewater treatment, and safe reuse. This study investigates the control of nitrogen removal in urban wastewater using vertical flow constructed wetlands (VFCWs) with three native plants in Beijing: Phragmites communis, Typha orientalis, and Acorus calamus, pumice as substrates, and a COD/N ratio of 15/1. The objective is to identify the most suitable plant for producing effluent that meets key standards for water reuse. Synthetic influent was derived from a modified Hoagland solution. Water quality parameters, including dissolved oxygen, ammonium nitrogen concentration, nitrate nitrogen concentration, and total nitrogen, were continuously monitored over 17 days. Results showed that all three plant species significantly reduced the ammonium nitrogen concentration, with Typha orientalis performing the best. Due to the limited oxygen and short stabilization time, there is less nitrification and denitrification; therefore, the paper concludes that nitrogen removal is achieved through phytoremediation and pumice absorption. While the effluent quality met the criteria for reuse in urban landscaping, it did not meet the standard for discharge into the environment. The findings suggest that with improved system design, such as longer stabilization and added aeration, VFCWs could serve as a sustainable wastewater management solution.

Keywords: Vertical flow constructed wetland, ammonium nitrogen, phytoremediation, nitrification, denitrification

1. Introduction

Urban wastewater accounted for 76.05% of the total wastewater generated in Beijing in 2024 [1], and this water contained excess nitrogen, which could cause eutrophication when directly discharged into the water body. Nitrogen was also a valuable nutrient for agriculture and urban landscaping within the city. Additionally, 13.80% of the city's total water consumption was used for agriculture and urban landscaping [1]. Therefore, instead of solely removing nitrogen, it was a more sustainable way to reuse the urban wastewater for irrigation. This approach also aligns with the

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United Nations' Sustainable Development Goal 6, which emphasizes ensuring the availability and sustainable management of water and sanitation for all.

The effluent after treatment should meet several standards for either reuse or discharge into the water bodies. For reuse in urban landscaping, the standard concentrations of ammonium nitrogen and dissolved oxygen levels from the effluent were shown in Table 1 (GB/T 18920-2020). For discharge into Type IV or V water bodies (Table 2), the standard concentrations of BOD5, ammonia nitrogen, and total nitrogen (TN) from the effluent are shown in Table 3, according to China's integrated discharge standard for water pollutants (DB 11/307—2013).

Table 1. Standards and limits for recycled water use in urban landscaping, cleaning, fire protection, and construction activities (GB/T 18920-2020)

Parameters	Limiting Value
Ammonia Nitrogen / (mg/L)	≤8
Dissolved Oxygen / (mg/L)	≥2.0

Table 2. Environmental quality standards for surface water (GB 3838-2002)

Type	Applicability
Type I	Mainly applicable to source water and national nature reserves.
Type II	Mainly applicable to first-level protection zones of centralized surface water sources for domestic drinking water, habitats of rare aquatic organisms, spawning grounds for fish and shrimp, and feeding grounds for fish larvae and juveniles, etc.
Type III	Mainly applicable to second-level protection zones of centralized surface water sources for domestic drinking water, overwintering grounds for fish and shrimp, migration channels, aquaculture areas, and fishery waters such as swimming zones.
Type IV	Mainly applicable to general industrial water use areas and recreational water areas with no direct human contact.
Type V	Mainly applicable to agricultural water use areas and general landscape water bodies.

Table 3. Integrated discharge standard of water pollutants for industrial and landscaping water (DB 11/ 307—2013)

Parameters	Limiting Value
BOD_5	6
Ammonia Nitrogen / (mg/L)	1.5 (April to November) 2.5 (December to March)
Total Nitrogen / (mg/L)	15

Constructed wetlands (CWs) had been recognized as effective and cost-efficient methods for removing nitrogen [2-4]. The two main factors in CWs that remove nitrogen are bacteria and plants. Bacteria in the substrate facilitate nitrification and denitrification to treat nitrogen, while plants contribute to nitrogen removal through phytoremediation. In addition, CWs also provided other

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ecosystem services, such as storm protection and providing habitat for animals, which helped to enhance biodiversity [5].

The main types of CWs were horizontal and vertical flow-constructed wetlands (VFCWs), and a previous study showed that vertical systems performed better in ammonium removal compared to horizontally constructed wetlands [6]. The results from other studies showed that the efficiency of nitrification and denitrification in the soil was affected by the different substrate types, such as pumice, cocopeat, and mineral wool [7]. Pumice was the substrate that could produce the effluent that met the standard for both discharging into surface water and irrigation water [7]. Moreover, a vertical subsurface wetland that added pumice had been proven effective in removing organic matter, nitrogen, and phosphorus [8]. Therefore, pumice was being chosen as the substrate for this study.

Furthermore, the physiological characteristics of microorganisms and the chemical composition of the VFCW were affected by the COD/N ratio [9]. By regulating the availability of oxygen, this ratio consequently affects the rates of nitrification and denitrification. Based on the evidence from the literature, a COD/N ratio of 15/1 has been shown to enhance TN removal [7]. Ratios higher than 15/1 may deplete dissolved oxygen, inhibiting nitrification, while a lower ratio may lead to insufficient denitrification.

Most previous studies had focused on maximizing nitrogen removal, and these tests had been conducted in other regions with different climates and plant species [7]. Therefore, this study will focus on evaluating the ability of three native emergent plants in Beijing to remove nitrogen, not only maximizing N removal but also finding the potential reuse of nitrogen in urban wastewater.

2. Experimental design

This study evaluates the nitrogen removal efficiency of these emergent plants in Beijing by using a VFCW system. It aims to identify the most suitable plant for treating effluent for several water management purposes, such as discharging it into surface water or safely reusing it for agricultural and urban landscaping.

2.1. Substrata and plant selection

Pumice was used as a substrata since it meets the requirements for both discharging into surface water and irrigation. Additionally, a COD/N ratio of 15:1 was employed [7]. The pH of pumice inside the water is 7, the concentration of its organic matter is less than 1%, its surface area is 2.4 square meters per gram, and it has a porosity of 72% [7].

Three native plant species common under the Beijing wetland climate were chosen: *Phragmites communis*, *Typha orientalis*, and *Acorus calamus*. They were chosen based on their prevalence in the Beijing wetland, resilience, and ability to absorb nitrogen through phytoremediation [10]. Twenty of each were bought .

2.2. Influent preparation

The synthetic influent was based on a modified Hoagland nutrient solution, with tap water serving as the base. The composition of the solution includes [11]: 250 mg L^{-1} methanol added to achieve a 15:1 COD: N ratio, with methanol serving as the carbon source. The influent contains 10 mL P buffer of $Na_2HPO_4.2H_2O$ (Tianjin Zhonglian Chemical Reagent Co., Ltd, 99%) and KH_2PO_4, added as $NaH_2PO_4.12H_2O$ (Tianjin Zhonglian Chemical Reagent Co., Ltd, 99%), and 50 mg L^{-1} of NH_4^+,

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added as NH_4Cl (Sinopharm Chemical Reagent Co., Ltd, 99.5%), to represent typical nitrogen concentrations in wastewater.

The P buffer helps to maintain the influent pH level around seven throughout the experiment. Influent was placed in four plastic bottles at each VFCW corner to ensure continuous flow.

2.3. VFCW setup and operation

Mesocosm-scale VFCWs were constructed in three individual glass containers, each measuring 25 cm × 25 cm × 25 cm, to simulate real-world wetland conditions in a controlled environment. Each container contains 1.06 liters of influent inside the plastic bottles, which were changed every day. 90L influent was prepared in total. There was a hole with a diameter of 20mm at the bottom of the side of the glass containers, with a pipe connected to the collection box for effluent. One thousand two hundred glass beads, each with a diameter of 1.2 cm, were placed at the bottom of each container to prevent clogging of the outlet. The glass beads piled up to approximately 4.8 cm in height. The experimental setup is based on the previous research conducted by Sithamparanathan et al. [7].

The experiment included three experimental groups. All systems contained pumice as the substrata, filled to a depth that can achieve a hydraulic retention time (HRT) of 1 to 2 days. The three experimental groups are *Phragmites communis*, *Typha orientalis*, and *Acorus calamus*. No controls with no plants were included since the focus was solely on the effect of different plants on the removal of N. Also, in real life, no wetland has no plants. The experimental setup was located in a biology lab at room temperature.

The experimental setup was acclimatized over three days to establish a stable, neutral pH in all VFCWs, thereby creating a condition that supports a neutral to slightly alkaline pH range. This condition was optimal for each experimental unit to undergo the nitrification and denitrification processes at the beginning of the study. Influences were introduced into the systems to facilitate acclimation and experimental progress.

The systems were operated with an intermittent watering system. The VFCW was watered intermittently with 1.06 L of influent per day, resulting in a hydraulic loading rate (HLR) of 18 mm/day. By doing this discontinuous watering, oxygen got a chance to go into the VFCWs, which could help to prevent hypoxia that would result in no nitrification and denitrification. The influent was changed daily, and the effluent was collected twice a week and preserved in the refrigerator at a constant low temperature.

2.4. Sample collection and analysis

Samples were collected every week for one month. The collection was used to analyze dissolved oxygen (DO), NH_4^+, NO_3^-, and TN. DO was measured using the DO sensors.

The ammonium nitrogen and nitrate nitrogen were measured using the test kits (Kyoritsu Chemical-Chek Lab., Corporation) and spectrophotometer (Vernier). In this study, six standard solutions were prepared for both ammonium nitrogen and nitrate nitrogen to make standard curves for interpreting the concentration of ammonium and nitrate nitrogen. For ammonium nitrogen, the control group consists of distilled water at zero parts per million (ppm). The remaining standard solutions have concentrations of 3.33 ppm, 6.67 ppm, 10 ppm, 13.3 ppm, and 20 ppm. Each standard solution had a total volume of 3 mL. The standard solution is prepared by adding 0.5 mL, 1 mL, 1.5 mL, 2 mL, and 3 mL of a 20 ppm ammonium nitrogen stock solution, respectively, and then diluting to 3 mL with distilled water. For nitrate nitrogen, the control group was also distilled water.

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The other standards were prepared at concentrations of 8.33 ppm, 13.3 ppm, 25 ppm, 33.3 ppm, and 50 ppm by adding volumes of 0.5 ml, 1 ml, 1.5 ml, 2 ml, and 3 ml of a 50 ppm nitrate nitrogen stock solution, respectively, and diluting to 3ml with distilled water. Then, effluent samples were filtered through filter paper to remove particulates. Four replicates from each experimental group were then collected in test tubes, and two of each were used for testing the two chemical concentrations. Test kits were added, allowing the chemicals to react with each other. After the reaction was complete, the absorbance of each sample was measured using a spectrophotometer. The concentrations of ammonium nitrogen and nitrate nitrogen in the effluent samples were determined by calculating the concentration by the equation given by the standard curve.

2.5. Data analysis

Nitrogen removal efficiency was calculated for each experimental group (Equation (1)):

$$\text{Removal of efficiency } (\%) = \frac{C_{in} - C_{out}}{C_{in}} \times 100\% \quad (1)$$

Where C_{in} was the nitrogen concentration in the influent (mg L^{-1}), and C_{out} was the nitrogen concentration in the effluent (mg L^{-1})

For nitrification, the difference between the influent NH_4^+concentration and the effluent NH_4^+ concentration was calculated, indicating the conversion of ammonium to nitrate. For denitrification, the difference between the nitrified NH_4^+ concentration and the effluent NO_3^- concentration was calculated, indicating the nitrate reduction [12]. Finally, an ANOVA test was performed using the R programming language via Posit Cloud to determine if there were significant differences in nitrogen removal efficiencies among the three plant species at an alpha level of 0.05. This analysis helps identify the most effective plant species in removing nitrogen from the influent.

3. Result and discussion

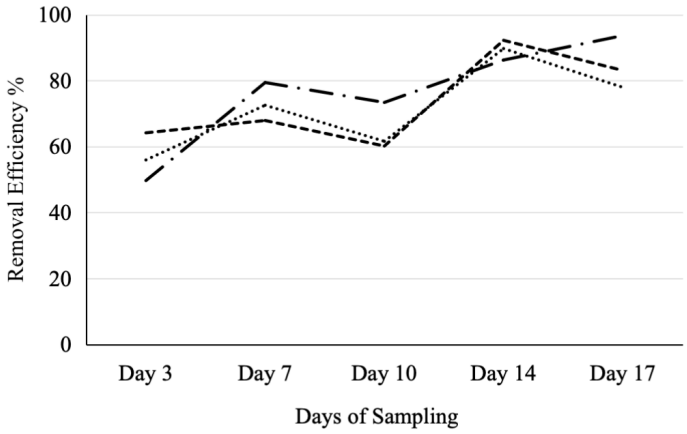


Figure 1. N removal efficiency over 17 days (— · *Typha orientalis*, ····· *Acorus calamus*, - - - - *Phragmites communia,* —— Influent)

The study showed that all three plants chosen, including *Typha orientalis*, *Acorus calamus*, and *Phragmites communis*, were capable of removing NH_4^+. According to Figure 1, the efficiency of

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removal ranges from 71.5% to 76.5% on day 17 after calculating the mean removal efficiency for each group. Since there is a lack of detectable NO_3^- and very low DO concentrations, which are critical for microbial nitrification and denitrification, the experiment suggests that phytoremediation and pumice account for the decrease in $NH4^+$.

3.1. Role of pumice on N removal

This study measured pumice's ability to remove ammonia nitrogen. The results showed that 8.58 mg L^{-1} pumice could be absorbed when it first came into contact with the influent, which is approximately 64.15% of the ammonia nitrogen in the influent. After 17 days, approximately 3.35 mg L^{-1} of ammonia nitrogen remained in the pumice. It could be concluded that on day 3, the nitrogen removal was mainly contributed by pumice; however, as time went by, the main factor removing nitrogen started to become the plant.

The findings suggested that pumice's porous structure and high surface area facilitate the biological process that contributed to the removal of ammonia nitrogen. However, the limited carbon content in pumice may limit its ability to support the denitrification process, as carbon is the primary electron donor [13]. The limitation highlights the importance of substrata selection in VFCWs.

3.2. Limited nitrification and denitrification

The lack of detectable NO_3^- indicates that nitrification was minimal or nonexistent. Nitrification requires an aerobic condition and DO levels typically above 2 mg L^{-1} to allow ammonia-oxidizing bacteria (AOB) and archaea (AOA) to perform microbial activity [14]. However, according to table 4, the DO detected in the study mostly stayed below 1 mg/L, which may restrict aerobic microbial activities. Additionally, the change in temperature throughout the day further inhibits microbial activities [15]. The possible reason for the unstable DO might be that the air conditioner in the room only opened during work hours.

Table 4. Dissolved oxygen for three plants

	Day 3	Day 7	Day 10	Day 14	Day 17
Typha orientalis	0.1	0.5	0.4	0.8	0.7
Acorus calamus	0.2	2	0.3	1	0.6
Phragmites communis	0.1	3	0.4	3	0.4

Denitrification depended on the amount of nitrate as the electron acceptor under anaerobic conditions [16]. However, in the experiment, shown in Figure 2, almost no nitrate was detected. Without nitrification, denitrification could not occur, since there wasn't nitrate for the reaction. Therefore, nearly all denitrification measurements were zero in every experimental group. Furthermore, pumice further limits denitrification. The pumice substrata used in the experiment have many small pores and a rough surface that supports plant roots and provides good aeration [17]. However, pumice contains less organic carbon, which is a key source of energy needed by the bacteria to perform denitrification. The limited organic carbon in the system restricts denitrification, even if nitrate is present [13].

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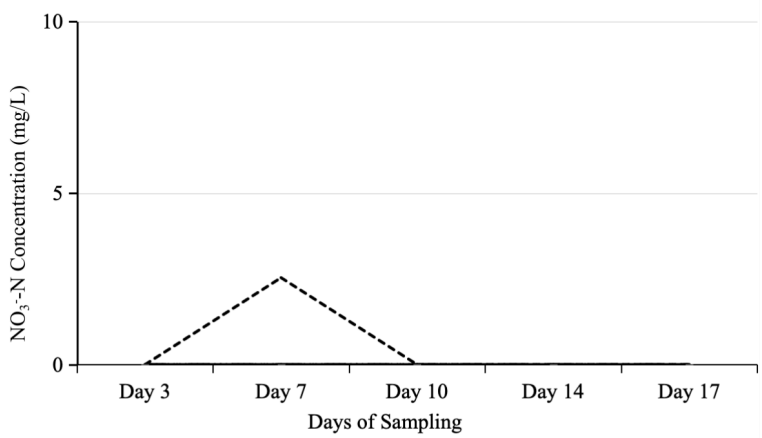


Figure 2. NO_3^- concentration over 17 days (— · *Typha orientalis*, ····· *Acorus calamus*, - - - - *Phragmites communia,* —— Influent)

To test whether there were statistically significant differences in nitrification and denitrification among the three experimental groups, the ANOVA test was performed. After conducting the ANOVA test, a p-value of 0.868 for nitrification indicated no statistically significant differences in nitrification among the groups at the alpha level of 0.05.

There were three reasons why no statistically significant differences exist among the three experimental groups. First, all plants likely perform NH_4^+ uptake similarly, as they had the same environmental conditions and influent. Second, the substrata were always pumice, providing a similar environment that controls the nutrient content and microbial activity. This could minimize the variability for processing nitrogen [13]. Lastly, the relatively short experimental period might have limited observable differences, as more extended periods of study often show greater variations due to changes in root characteristics and microbial activity [18].

These findings align with other studies of VFCWs under similar conditions. A previous study also discovered that NH_4^+ removal was primarily achieved through phytoremediation, with minimal nitrification and denitrification [19].

3.3. Role of phytoremediation on N removal

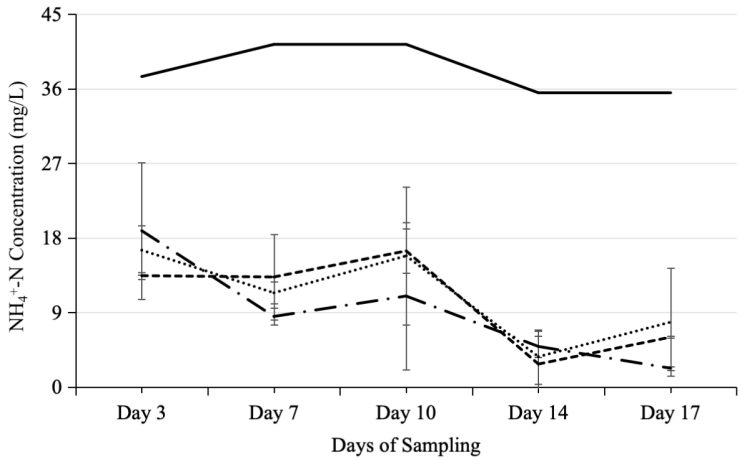


Figure 3. NH_4^+-N concentration over 17 days (— · *Typha orientalis*, ····· *Acorus calamus*, - - - - *Phragmites communia,* —— Influent)

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The observed decrease in the NH_4^+ concentrations for all three experimental groups demonstrated these plants' ability to assimilate NH_4^+ directly as the nitrogen source [13]. The process differed from nitrification and denitrification, which rely on microbial oxidation; direct absorption of NH_4^+ could occur without aerobic microbial conversion. Since there wasn't efficient nitrification and denitrification, the main nitrogen removal in this study was contributed by phytoremediation [14].

According to Figure 3, *Typha orienta*lis demonstrated the most effective NH_4^+ removal efficiency, consistent with numerous past studies that have proven *Typha* species to be effective in absorbing nitrogen. They demonstrated that *Typha* species are highly effective in nitrogen absorption due to their long roots and rapid growth rates [20]. For *Phragmites communis* and *Acorus calamus*, they also showed significant NH_4^+ uptake, suggesting that different wetland plants can show similar behaviors under similar environmental conditions [15].

3.4. Effluent's practical application

The amount of ammonium nitrogen left in the effluent indicated that it could be safely reused for watering plants and urban landscapes. As shown in Figure 3, on day 14 and 17, the effluent ammonium nitrogen levels were consistently below or equal to 8 mg L^{-1}, meeting the standard for urban greening water reuse (GB/T 18920-2020). Nevertheless, this effluent must have DO greater than or equal to 2 mg L^{-1} to meet the standard.

To achieve this goal, the study suggested adding additional treatment methods, such as aeration for the influent. Increasing the DO not only helped to meet the reuse standards but also supported aerobic nitrification, which converted ammonium into nitrite and nitrate. The nitrite and nitrate, in turn, could provide material for denitrification, and finally convert the nitrogen into a gas form.

However, the effluent did not meet the standards for discharge for these 17 days, but the trend of ammonia nitrogen showed that the nitrogen concentration kept decreasing. Right now, since there's no nitrification and denitrification, this study predicted that after the VFCW was stabilized, and these reactions occurred, then the nitrogen removal efficiency will increase, then the ammonia nitrogen concentration might meet the standard for discharge.

3.5. Limitations and suggestions

However, this study had several limitations. First, the stabilization period lasts only 3 days, which leads to unstable living conditions for the plants. Additionally, there was insufficient time to establish a stable ecosystem and nitrogen cycle. As a result, there was a lack of bacteria for denitrification and nitrification, which ultimately led to almost no nitrification during the experiment. Furthermore, there should be ways such as aeration to increase DO, for this study, a DO always lower than 3 mg L^{-1}, might also be a reason for the absence of nitrification, since it was an aerobic reaction, and within no NO_3^-, which was the product from nitrification, denitrification also could not occur.

Future studies should expand the stabilizing time to ensure a complete nitrogen cycle is formed, allowing the entire VFCW to play its full role in nitrogen removal. Another way to increase nitrification was to directly add nitrifying bacteria to the system, ensuring that nitrification can occur. Also, future studies can add a step of aeration for the influent to increase the DO and allow the aerobic reaction to get enough oxygen.

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4. Conclusion

This study observed that native emergent plants in Beijing, such as *Typha orientalis*, *Acorus calamus*, and *Phragmites communis*, can effectively reduce N concentration in synthetic urban wastewater by using a VFCW system. Even though the system had low dissolved oxygen levels and could not support microbial activity for nitrification and denitrification, the pumice substratum and phytoremediation still removed a significant amount of nitrogen.

The result showed that the ammonia level of treated effluent met the national reuse standard for urban landscaping water (GB/T 18920-2020). This indicated that when the VFCW was being properly designed, it was suitable for reuse and could contribute to water conservation efforts in urban settings.

With further optimization, such as adding aeration to improve the DO level or extending the system's stabilization period. The nitrogen removal efficiency could be enhanced in the future. With further research and development, the VFCW system could become a practical and eco-friendly solution for managing wastewater in cities like Beijing.

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