STUDIES ON THE TRANSPORT AND TRANSFORMATION OF NITRATE NITROGEN IN BIORETENTION

by

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Bioretentions represent a prevalent stormwater runoff management technique in urban areas, frequently employed to address the treatment of pollutants in runoff. However, the efficacy of nitrate-nitrogen removal by bioretention systems is subject to variation due to a multitude of environmental factors. In this study, three bioretentions (B1, B2, and B3) were constructed to investigate the migration and transformation characteristics of nitrate nitrogen in bioretentions under different soil mediums (sandy soil, sandy soil + newspaper, and sandy soil + wood chips). The findings indicated that the efficacy of nitrate nitrogen removal varied with different media types, with sandy soil augmented by wood chips demonstrating the optimal removal performance, followed by sandy soil combined with newspaper, and sandy soil alone exhibiting the least efficient removal. The B3 plant retention system demonstrated the optimal removal efficacy among the three mediums examined. The B2 medium exhibited a secondary level of effectiveness, while the B1 medium exhibited the least efficient removal capacity. With an increase in hydraulic retention time, there was a corresponding increase in the removal rate of the three bioretentions, but a concomitant decrease in the removal rate. The addition of carbon source, whether it be newspaper or wood chips, led to the swift activation of the phytoretention system, thereby enhancing the rate of nitrate nitrogen removal over a brief period.

Keywords: *bioretention, nitrate nitrogen, transport transformation, soil medium, hydraulic residence time*

Introduction

The accelerating process of urbanization has given rise to a series of significant environmental challenges, with the contamination of urban stormwater runoff being a prominent example. Nitrate nitrogen contamination in particular has garnered attention due to its substantial presence and the subsequent adverse effects it inflicts on water bodies [1, 2]. These effects include the promotion of eutrophication and the depletion of dissolved oxygen, both of which can have deleterious consequences for the ecological environment and human health [3]. As an eco-friendly water treatment technology, the plant retention system has been widely used in urban stormwater runoff treatment due to its advantageous features, including ease of operation and low energy consumption [4, 5].

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The extant literature on this subject is predominantly focused on the removal of pollutants by phytorestoration systems [6]. However, there is a paucity of research on the removal effect of nitrate nitrogen and its migration and transformation characteristics [7]. This technology utilizes the natural processes of plant root systems and soil microorganisms to absorb, degrade, and transform pollutants present in stormwater [8, 9]. However, there is a paucity of in-depth research addressing the impact of medium type and plant species on nitrate nitrogen removal in bioretention [10, 11].

The objective of this study is to construct three distinct bioretentions for the purpose of investigating the effects of bioretentions on nitrate nitrogen transport and transformation characteristics in various soil media. The objective of this study is to analyze the influence factors and mechanisms of different mediums and plant retention systems on nitrate nitrogen removal effects. The findings of this study will provide a theoretical basis for optimizing the design of plant retention systems. This study will also explore the influence of different hydraulic retention times on nitrate nitrogen removal and analyze the change rule of its removal rate.

Materials and methods

Experimental set-up

In this study, three bioretentions (B1, B2, and B3) were constructed. System B1 is a conventional bioretention, system B2 is a conventional bioretention with an additional plant retention experimental column, and system B3 is a conventional plant retention system with an additional plant retention experimental column with a sealed top treatment. The experimental column set-up is illustrated in fig. 1. The migration and transformation characteristics of nitrate nitrogen in bioretentions were investigated under varying soil mediums, including sandy soil, sandy soil augmented with newspaper, and sandy soil combined with wood chips.

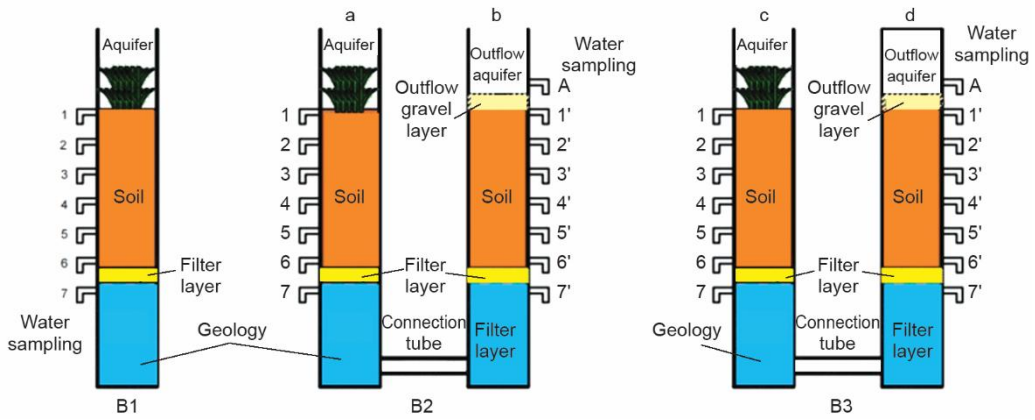

Figure 1. Schematic of three bioretentions

Soil and medium

The soil was characterized by a sandy texture, with a 0.25 mm sieve size, collected from the unpolluted riverside in the vicinity of Juhetan Village, Jungar Banner, Ordos City, Inner Mongolia Autonomous Region. The soil medium utilized in this study comprised sandy soil, newspaper, and wood chips, with ryegrass serving as the plant material. The medium

used in this study was a mixture of sandy soil and newspaper and wood chips, with the wood chips comprising 5% of the total volume by weight. The wood chips were obtained from pine wood chips and sieved at a mesh size of 0.25 mm. The newspaper was cut into pieces measuring 15 mm by 2 to 3 mm.

Stormwater runoff simulation

In this study, artificial rainfall simulation was utilized. During the period of rainfall in Hohhot City, the NO_3^--N (in terms of N) concentration of the pavement runoff at each sampling point was detected, with an average value of 6 mg/L. The arithmetic mean was 6 mg/L. The artificial rainfall simulation was prepared with KNO_3, and the NO_3^--N concentration of the pollutant was configured to be 6 ±0.51 mg/L. The rainfall volume of simulated artificial rainwater is calculated by eqs. (1) and (2) [12]:

$$W = \frac{HS}{5\%} \tag{1}$$

where W [mL] is the precipitation volume, H [cm] – the precipitation height, and S [cm^2] – the device cross-sectional area.

In this study, a rainfall height of 3.2 cm was chosen and the radius of the experimental column was 10 cm:

$$W = \frac{3.2 \times 3.14 \times 10^2}{5\%} = 20096 \text{ mL} \approx 20 \text{ L} \tag{2}$$

From the previosu calculation, the amount of artificial simulated rainwater is 20 L.

Experimental and test methods

In this study, a flooding time of 5 days was employed, which was determined based on the longest continuous rainfall days in Hohhot. Water and soil samples were collected at the sampling port at 3-hour, 6-hour, 9-hour, 1-day, 2-day, 3-day, 4-day, and 5-day intervals following the simulation of rainfall events.

The collected water samples were subsequently analyzed according to the timeframe stipulated by the national standard method for NO_3^--N and NO_4^+-N content in water samples, respectively.

The soil samples were obtained and subsequently analyzed in accordance with the established national standard method, entitled *Determination of Ammoniacal Nitrogen, Nitrite Nitrogen, and Nitrate Nitrogen in Soil: Extraction of Potassium Chloride Solution – Spectrophotometric Method* (HJ 634-2012). Microsoft EXCEL 2024 and ORIGIN2022 software were used for data processing and data analysis.

Results and discussion

Removal of nitrate nitrogen by bioretentions in different medium

The mean nitrate nitrogen removal percentage under various conditions was 10%, 30.7%, and 38.4%, respectively. The mean nitrate nitrogen removal rate by the various media was found to be sandy soil + wood chips > sandy soil + newspaper > sandy soil, in descending order. This finding suggests that increasing the variety of mediums can enhance the efficacy of nitrate nitrogen removal, with wood chip filling demonstrating superior performance compared

to newspaper filling. Denitrification reaction is predominantly reliant upon the presence of microorganisms operating under anoxic or anaerobic conditions, wherein organic matter functions as the electron donor. The organic carbon source has been identified as a critical factor in determining denitrification efficiency. Sandy soil, characterized by its low organic matter content, exhibits reduced effectiveness in the removal of nitrate nitrogen. The utilization of newspaper and wood chips as solid phase cellulosic carbon sources has been demonstrated to provide microorganisms with growth sites and organic carbon. A study was conducted to determine the efficacy of wood chips and newspaper in the removal of NO_3^--N. The results indicated that wood chips exhibited superior performance in this regard. This phenomenon can be attributed to the high carbon content of wood chips and their exceptional permeability. The high carbon content of wood chips enabled them to maintain denitrification over an extended period, thereby facilitating the release of a greater quantity of organic carbon, fig. 2.

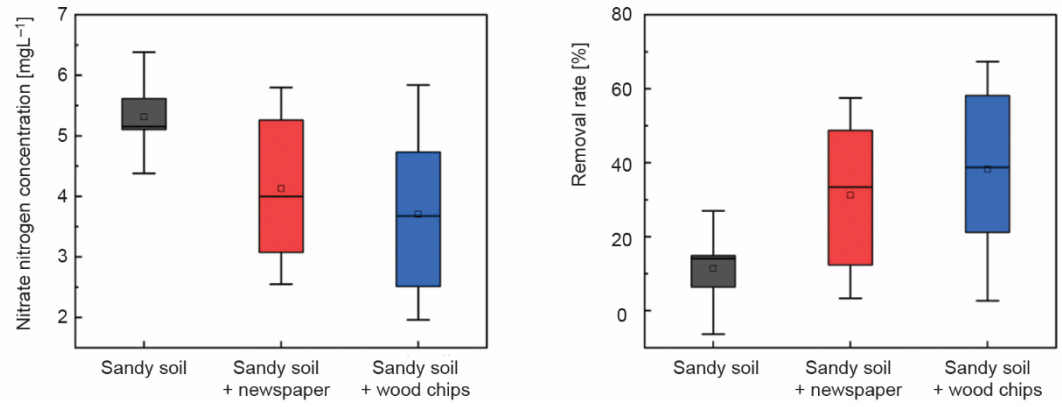

Figure 2. Removal of NO_3^--N by different medium

Influence of different bioretentions on the removal of nitrate nitrogen

When sandy soil was utilized as the soil layer medium, fig. 3 demonstrates that B3 exhibited the optimal nitrate nitrogen removal, with an average removal rate of 38.2%. The B2 demonstrated an average removal rate of 22.4%, while B1 exhibited a comparatively low average removal rate of 10%. With respect to the system's structural design, B1 adopts a conventional single-column configuration, while B2 and B3 exhibit a double-column design. The double-column structure of the system increases the residence time of simulated rainwater, thereby enlarging the contact area between nitrate nitrogen and the medium. This, in turn, increases the opportunity for denitrification. The B3 employs a sealed design at the top, effectively segregating the system from the external oxygen. This reduces the utilization rate of oxygen in the system and creates a more favorable anoxic environment for denitrification of nitrate nitrogen.

As illustrated in fig. 3, the addition of newspaper to the system resulted in enhanced nitrate nitrogen removal, with B3 exhibiting the highest removal efficiency, averaging 58% removal. This was followed by B2, which demonstrated an average removal rate of 46.2%, and B1, with an average removal rate of 30.7%. The nitrate nitrogen removal rate of each system was found to be significantly elevated by the incorporation of newspaper, in comparison to scenarios where only sand and soil were utilized as the medium. The utilization of newspaper as a carbon source has been demonstrated to provide an increased supply of electron do-

nors for denitrifying bacteria, thereby promoting denitrification processes. The cellulose present in newspaper materials undergoes rapid decomposition, resulting in the consumption of substantial amounts of oxygen. This process subsequently creates a more favorable anoxic environment, which is a pivotal factor influencing the denitrification rate.

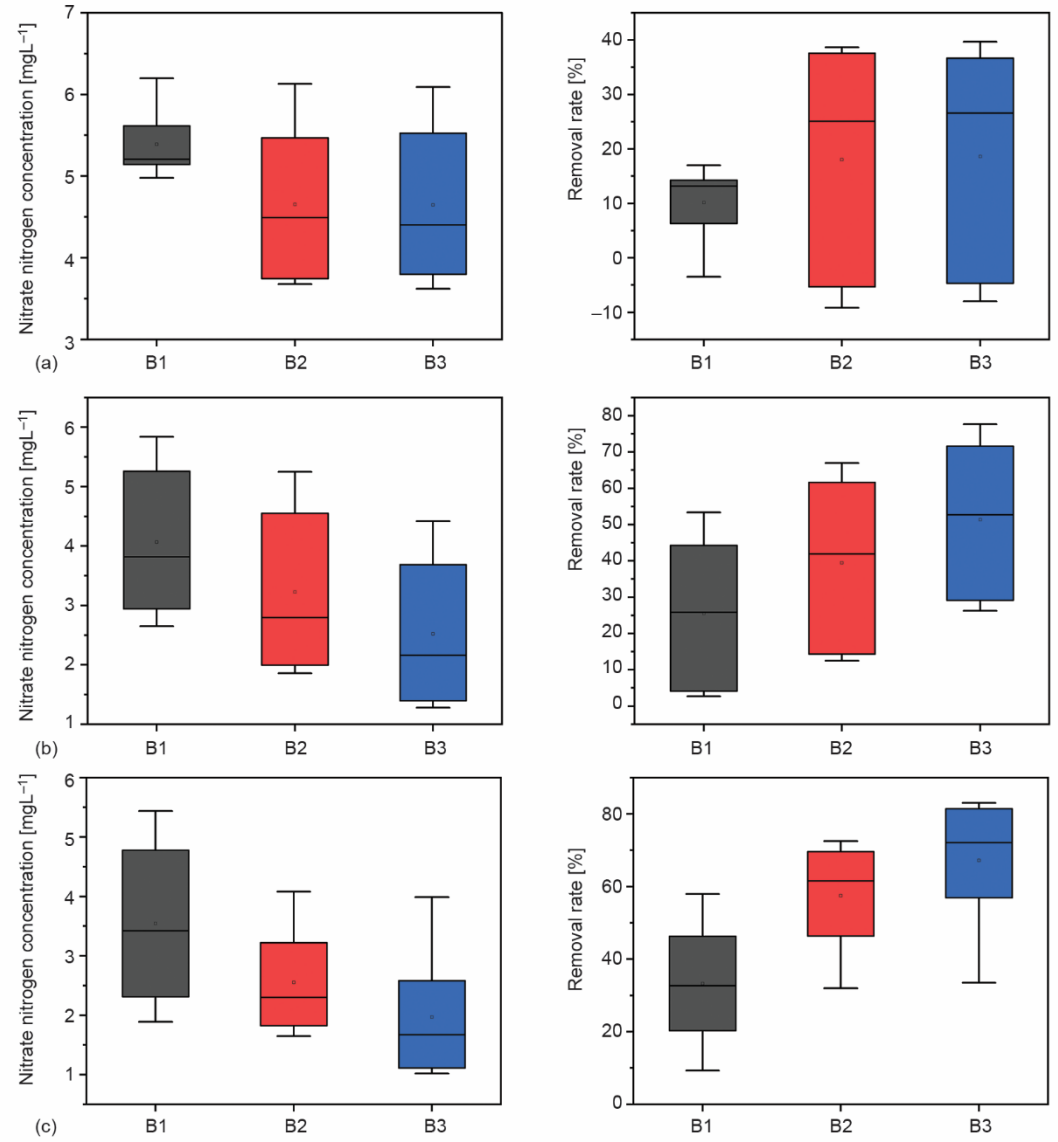

Figure 3. The NO_3^--N removal rate by different medium; (a) sandy soil, (b) sandy soil + newspaper, and (c) sandy soil + wood chips

As illustrated in fig. 3, the addition of wood chips to the B3 system resulted in the most effective nitrate nitrogen removal, with an average removal rate of 67.1%. In comparison, the B2 system exhibited an average removal rate of 56.7%, while the B1 system demonstrated an average removal rate of 38.4%.The integration of sand and wood chips further en-

hanced the nitrate nitrogen removal efficacy of each plant retention system, surpassing the performance of the sand and newspaper medium. The utilization of wood chips as a carbon source has been demonstrated to elicit the release of elevated levels of organic carbon, thereby providing a more substantial electron donor for denitrifying bacteria. The primary component of wood chips is cellulose, a macromolecule that requires substantial oxygen during its decomposition process. This process creates an anoxic environment conducive to denitrification.

Effect of different hydraulic retention times on nitrate nitrogen removal in plant retention system

As demonstrated in fig. 4, in the case of B1, when the soil layer medium is sandy soil, the effluent concentration exceeds the influent concentration when the hydraulic retention time is six hours. This condition may result in the occurrence of soil leaching. With an increase in hydraulic retention time, there was a demonstrable decrease in the concentration of nitrate nitrogen in the effluent water, and the removal rate exhibited a gradual increase. In the sandy soil medium, the NO_3^--N removal rate exhibited minimal fluctuations, attributable to the absence of a carbon source within the system. The incorporation of newspaper or wood chips as a carbon source resulted in a substantial enhancement in NO_3^--N removal, with the removal rate demonstrating a gradual increase over time and eventually reaching a state of stability.

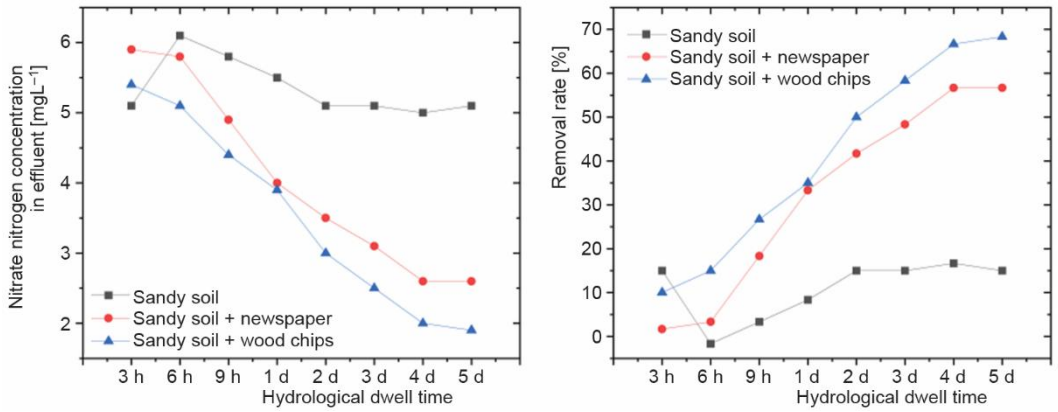

Figure 4. The NO_3^--N removal by B1 bioretention at different hydraulic residence times

As shown in fig. 5, when the soil layer medium is sandy soil, the effluent concentration is slightly higher than the influent concentration at the hydraulic retention time of three hours, and a slight soil leaching phenomenon occurs. When the soil layer medium is sandy soil plus newspaper, the effluent NO_3^--N concentration is higher at six hours than that at three hours. It is possible that the deionized water retained by the cleaning experimental columns mixes with it after simulating rainwater infiltration to make its NO_3^--N effluent concentration lower In B2, the concentration of NO_3^--N effluent decreased with increasing hydraulic retention. In B2, with the increase of hydraulic retention time, the concentration of nitrate nitrogen in the effluent all showed a decreasing trend, and the removal rate gradually increased. When the soil layer medium is sandy soil, a slight soil leaching phenomenon may occur at the initial stage resulting in a slightly higher effluent concentration than the influent concentration, and due to the increase in the contact area between the simulated runoff and the medium, the removal rate of NO_3^--N gradually increased, and eventually stabilized at about 37.5%. When newspaper or wood chips were added to the sandy soil as a carbon source, the

NO_3^--N removal effect was significantly improved. Especially when wood chips were added, the NO_3^--N removal rate increased dramatically in a short period of time due to the rapid release of TOC at the initial stage, and finally stabilized at about 71%. The system with the addition of newspaper then stabilized at 67.4% removal.

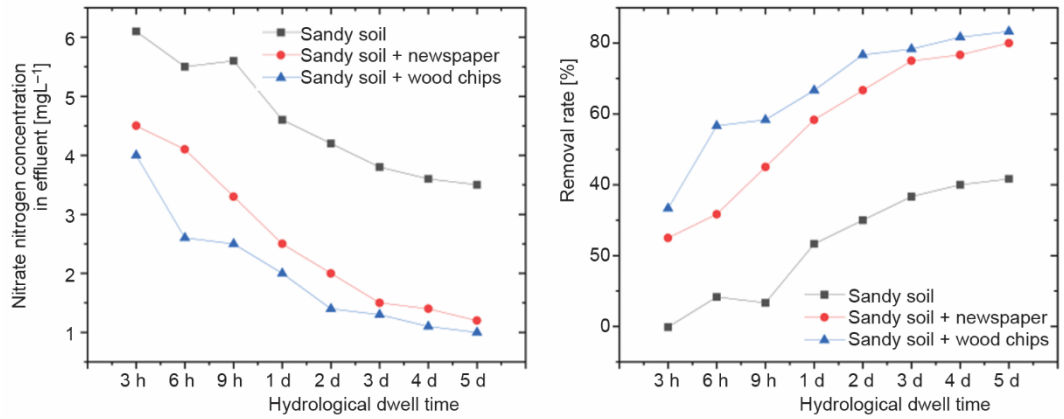

Figure 5. The NO_3^--N removal by B2 bioretention at different hydraulic residence times

As shown in fig. 6, in B3 With the increase of hydraulic retention time, the concentration of nitrate nitrogen in the effluent all showed a decreasing trend, and the removal rate gradually increased. When the soil layer medium is sandy soil, the simulated runoff flow through the system increases the contact area with the medium, and the sealing of the top of the system leads to an anoxic environment, which makes the NO_3^--N effluent concentration higher in the initial stage without the addition of a carbon source, but gradually decreases with time, and eventually stabilizes at a removal rate of about 38%. When newspaper or wood chips were added to the sandy soil as a carbon source, the NO_3^--N removal effect was significantly enhanced. Especially, the system with added wood chips not only provided a carbon source, but also promoted the formation of an anoxic environment, and the NO_3^--N removal rate reached 33.5% at the initial stage and eventually stabilized at about 82%. In contrast, the system with added newspaper stabilized at 73% removal.

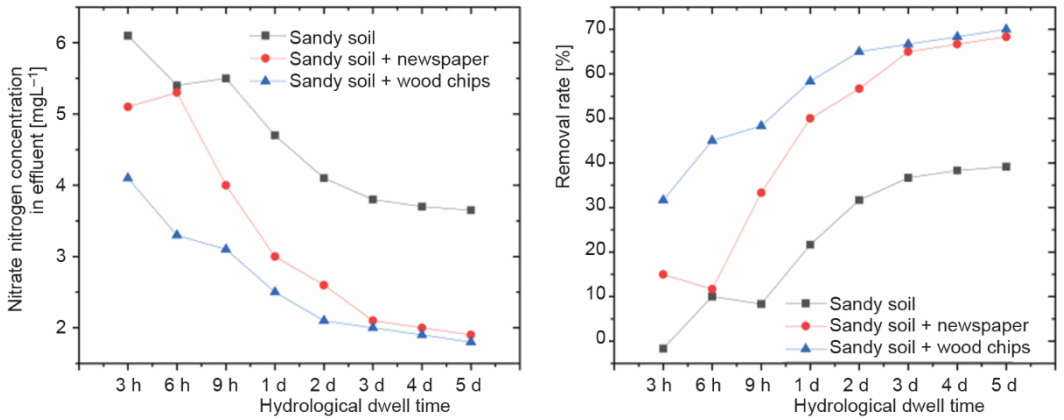

Figure 6. The NO_3^--N removal by B3 bioretention at different hydraulic residence times

The removal of NO_3^--N by the three bioretentions was found to be influenced by the type of soil medium at varying hydraulic retention times. In scenarios where hydraulic retention times were comparatively brief, the bioretentions exhibited a marked capacity to expeditiously and efficiently eliminate NO_3^--N, particularly in soil media comprising sand in conjunction with either newspaper or wood chips. The sand-wood chips combination demonstrated a superior performance in terms of NO_3^--N removal. The soil medium comprising sand and wood chips demonstrated greater efficacy in the removal of nitrate nitrogen. It is plausible that the initial scarcity of microorganisms within the system led to a constrained supply of carbon that was subsequently released from newspaper and wood chips through the agency of microbial activity. Furthermore, wood chips have been observed to release organic carbon through water solubility in the absence of microbial action. This organic carbon can then be utilized by denitrifying bacteria, thereby promoting the denitrification reaction. As the hydraulic retention time was extended from 1 to 5 days, the removal of NO_3^--N by the two media, sand + newspaper and sand + wood chips, gradually approached a state of equilibrium.

Conclusions

In this study, three distinct bioretentions were constructed to investigate the effects of bioretentions on the migration and transformation characteristics of nitrate nitrogen under varying soil medium conditions. The efficacy of nitrate nitrogen removal via different mediums and bioretention methods varied. The combination of sandy soil and wood chips exhibited the optimal removal efficacy, while the mixture of sandy soil and newspaper demonstrated the second-most effective outcome. Conversely, the sandy soil alone exhibited the least efficient removal capacity. Furthermore, increasing the hydraulic retention time has the potential to enhance the removal rate of nitrate nitrogen.

The incorporation of carbon sources, such as newspaper or wood chips, has been demonstrated to enhance the efficacy of bioretention systems in removing nitrate nitrogen. The findings suggest that denitrification is a critical process in the removal of nitrate nitrogen by plant retention systems. The incorporation of a carbon source has been shown to enhance denitrification reactions, underscoring its significance in these biological systems. The efficacy of different bioretentions was examined, and the findings indicated that the incorporation of a phytoretention experimental column or a top-sealed treated phytoretention experimental column led to substantial enhancements in nitrate nitrogen removal.

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