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# Assessment of bioretention pilot-scale systems for urban stormwater management

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ABSTRACT

Currently, bioretention was applied in many developed countries because it was considered as a solution for reducing the impacts of climate change and urbanization. Bioretention is mainly composed of engineered soil and plants, wherein several pollutant treatment mechanisms and stormwater regulation capabilities were integrated within the system. In this research, 2 bioretention pilot scales were developed to treat urban runoff in which the Type A has *Rhododendron indicum Linnaeus* plant species and the Type B has *Spiraea japonica* plant species. Both pilot scales attained high pollutant removal efficiencies for TSS and COD by having a removal of approximately 90%. However, for other pollutants such as nitrogen, phosphorus and metals, the type-A system shows high removal efficiencies compared to type-B. In order to determine the suitable design characteristics, the pollutant removal of each system were analyzed with varying length and depth. The results show that more than 50% of TSS, TP, Total Zn and Total Pb were reduced at the distance of 50% and 60% of total length and depth respectively. Lastly, it was found out that the obtained nitrogen removal was caused by the soil microbial activities, nitrification, de-nitrification and bioremediation.

*Keywords:* Bioretention; Low impact development; Nutrient; Plants; Urban stormwater

## 1. Introduction

Development projects can reduce green spaces and increase impermeable surfaces. These activities contribute several environmental impacts such as water quality deterioration, destruction of ecosystems, and intolerable pollutant discharge. Also, it alters the natural water circulation by increasing the peak flow and runoff [1,2]. The climate and weather changes are accelerating and adding more impacts to the environment. Urbanization and industrialization are the main activities changing the land use in the development projects. These land uses such as commercial, residential, industrial, and agricultural areas are composed of roads, buildings, parking spaces and landscaping areas. The reason for increasing the impermeable areas during urbanization was due to the rapid growth of human and vehicular activities. Especially, the vehicular activities in parking lot and roads can release various pollutants such as metals, toxic chemicals and particulates to the water body during a storm event. The metal pollutants discharged in the water bodies can accumulate on biomass through food chain process and can possibly affect the human health. The fine particles released from the impermeable surfaces can also give harmful impact to the fishes by intoxicating their respective habitat [3,4].

As a response, the Korean Ministry of Environment (MOE) established the “Comprehensive Measures for Nonpoint Source (NPS) Pollution Management” in March 2004 to protect the 4 major rivers from NPS discharges. Based

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on the results of the mentioned project until 2011, the MOE revised the comprehensive NPS management measures in 2012 [5]. The revised measures include regulation, policy, technology development and management of the 6 main fields, i.e., urban, agricultural, forest, research, advertisement and program. The first phase of the project was the formulation of policy foundation, identification of the causes of pollution and possible technologies for NPS mitigation. The second phase was mainly focused on the management of pollution sources by applying best management practice (BMP) projects with regards to site specific conditions, setting the mentioned technologies for monitoring and develop design standards for the treatment facilities. Lastly, the third phase was solely focused on the application of low impact development (LID) techniques. Recently, the MOE included the legal liability of LID in the established environmental laws [5–7].

Several types of LID techniques such as bioretention, infiltration trench, tree box filter, retention basin, vegetated swales and planters are implemented for stormwater management. Most of the LID techniques use natural treatment mechanisms in restoring the natural water circulation cycle. The natural treatment mechanisms are performed by a combination of biological and physico-chemical processes. The microorganisms and plants are the main components for the biological process that assist in reducing the nutrients and organics present in runoff. There are many mechanisms on the physico-chemical process such as sedimentation, adsorption and ion exchange [8]. The LID can be applied anywhere with small land space; thus, it is considered as a decentralized facility [9–11]. Among the LID techniques, bioretention is considered as the representative system because it includes many functions that other techniques provide. However, there are still several factors to consider before applying any LID technique including characteristics of soil, plants and climate factors. This research was performed in order to develop a bioretention system suitable for Asian Monsoon region as an effective strategy through its high hydraulic capacity thereby managing the stormwater peak flow, runoff volume and stormwater pollution.

## 2. Materials and methods

### 2.1. Design of the pilot-scale bioretention

Two types of pilot scale bioretention were developed to simulate the behavior of typical bioretention system treating urban stormwater runoff. Fig. 1 shows the schematic of the 2 types of the pilot scale bioretention with dimensions of 1.5, 0.4 and 0.6 m for the length, width and depth respectively. There were 9 ports on the side of the system intentionally installed to observe the pollutant behavior with respect to length and depth. Four layers of filter material were placed with an order of bottom gravel layer, middle sand, middle soil, and top layer wood chip. The geotextile was installed as the base filter material and served as additional cover for the filter media. Coconut mat was placed above the gravel, sand and soil layers to prevent the possible transferring of filter media. Table 1 summarizes the characteristics of each bioretention type. In addition, the *Rhododendron indicum Linnaeus* (RL) and *Spiraea japonica* (SJ) plant species were selected and applied in the bioretention type A and type B, respectively. The reason for the selection of these plant factors such as availability of plant species in Korea, cost of plant, blooming season of the flower,

Table 1
Characteristics of each bioretention pilot-scale type

| Type | Plant | Media | Surface area | Storage volume | Total volume |
|---|---|---|---|---|---|
| A | *Rhododendron indicum Linnaeus* (RL) | Woodchip (10–20 mm), Sand (2–5 mm), Gravel (20–30 mm), Soil | 0.6 $m^2$ | 0.178 $m^3$ | 0.36 $m^3$ |
| B | *Spiraea japonica* (SJ) | | | | |

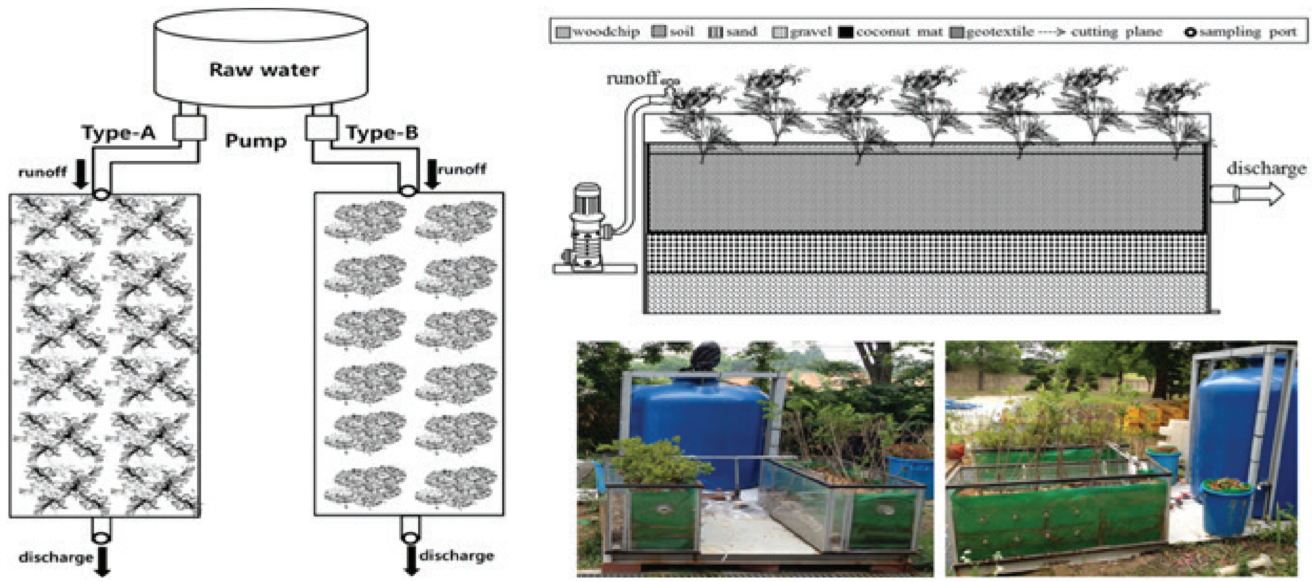



Fig. 1. Schematic diagram of the modular bioretention pilot-scale systems.

application of similar species of plants in other countries, ability of plant to adopt in varying soil conditions and adaptability to sun exposure were the bases of selecting the plants to be used in the bioretention technology developed.

### *2.2. Experimental data collection and analyses*

The artificial stormwater runoff used in the experimental run of the pilot scales was prepared by collecting sediment from road surfaces. The sediments accumulated from road surfaces were utilized because it adsorbed various types of heavy metals. Also, the bioretention pilot scales were designed to be installed on the landscaping areas to remove the runoff pollutants. Artificial stormwater runoff was introduced into the system with inflow rates ranging from 2 to 6 L/min. During the experimental test run, flow rates at the inflow and outflow were checked at the start of the simulation then every 10 min for 2 h. Grabbed water samples were collected once the artificial stormwater runoff entered into the system and followed by a 30, 60, 90 and 120 min time interval. In order to evaluate each bioretention system, the removal efficiency and event mean concentration (EMC) for the particulates, organics, nutrients and heavy metals were calculated and analyzed. The EMC represents a flow weighted average concentration computed by dividing the total pollutant mass by the total runoff volume for event duration. The flow weighted average is represented by Eq. (1) [12].

$$\mathrm{EMC}(mg/L) = \frac{\sum_{t=0}^{T} C(t)\cdot q_{\mathrm{run}}(t)}{\sum_{t=0}^{T} q_{\mathrm{run}}(t)} \tag{1}$$

where $C(t)$ is the pollutant concentration; and $Q(t)$ is the runoff flow rate discharged at time.

By computing the inflow and outflow EMC of the bioretention systems, the pollutant removal efficiencies of the system represented by percentage (%) may be evaluated. The EMC removal efficiencies were calculated using Eq. (2).

$$\text{Removal Efficiency}(\%) = \frac{\sum_{i=1}^{N} RE_i}{\sum_{i=1}^{N} M(In)_i} \tag{2}$$

where $RE_i$ is the reduction mass; and $M(In)_i$ is the Inflow mass.

## 3. Results and discussion

### *3.1. Characteristics of influent water*

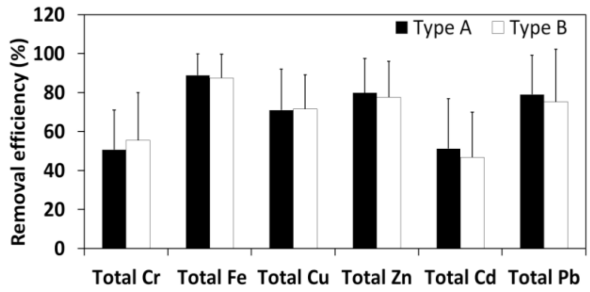
Table 2 shows the statistical summary of the influent water used during the experimental test runs. The preparation of the artificial stormwater runoff was based on the typical pollutant EMC of road runoff [13]. The mean concentrations were 329.3, 166.8, 2.8, and 0.6 mg/L for TSS, COD, TN and TP, respectively. Also, the metal concentrations used in the experimental test runs were based on the typical concentrations found on the road runoff.

### *3.2. Pollutant removal efficiency*

The mean effluent concentrations were significantly reduced from 30.6 to 36.6 mg/L for TSS, 19.0 to 21.5 mg/L for COD, 0.13 to 0.15 mg/L for TP, 49 to 48 μg/L for Total Pb and 185 to 194 μg/L for Total Zn. The pollutant removal efficiency for each water quality parameter was summarized in Fig. 2. The pollutant removal efficiency on both types for TSS and COD were approximately 90% while for the nutrients, the removal efficiency was approximately 60%. Also, both pilot scales showed high metal reduction capabilities by having an approximate 60% removal efficiency for Total Cu, Total Pb and Total Zn. The results implied that the biological and physico-chemical treatment mechanisms of the system were the main cause of the pollutant removal. Especially, physico-chemical mechanisms such as adsorption, filtration and ion exchange are the main reason for reducing the particulates and heavy metal constituents. The organics

Table 2
Characteristics of influent water of bioretention Pilot-scale

| Parameter | Unit | Influent water | |
|---|---|---|---|
| | | Mean | S.D |
| TSS | mg/L | 329.3 | 180.5 |
| COD | | 166.8 | 183.8 |
| TN | | 2.8 | 0.7 |
| TP | | 0.6 | 0.3 |
| $PO_4$–P | | 0.02 | 0.04 |
| $NO_3$–N | | 1.5 | 0.5 |
| $NH_4$–N | | 0.3 | 0.1 |
| Total Cr | μg/L | 127.5 | 72.5 |
| Total Fe | | 8,100 | 5,828 |
| Total Ni | | 93.5 | 56.2 |
| Total Cu | | 116.2 | 104.4 |
| Total Zn | | 559.6 | 350.6 |
| Total Cd | | 59.3 | 60.1 |
| Total Pb | | 97.3 | 92.8 |



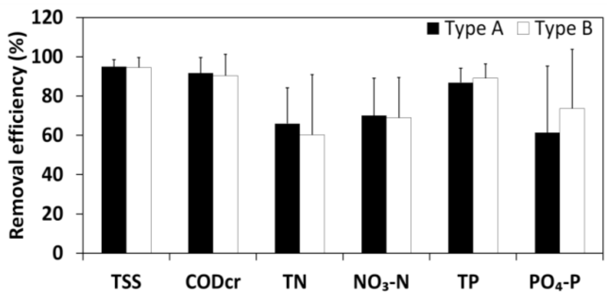



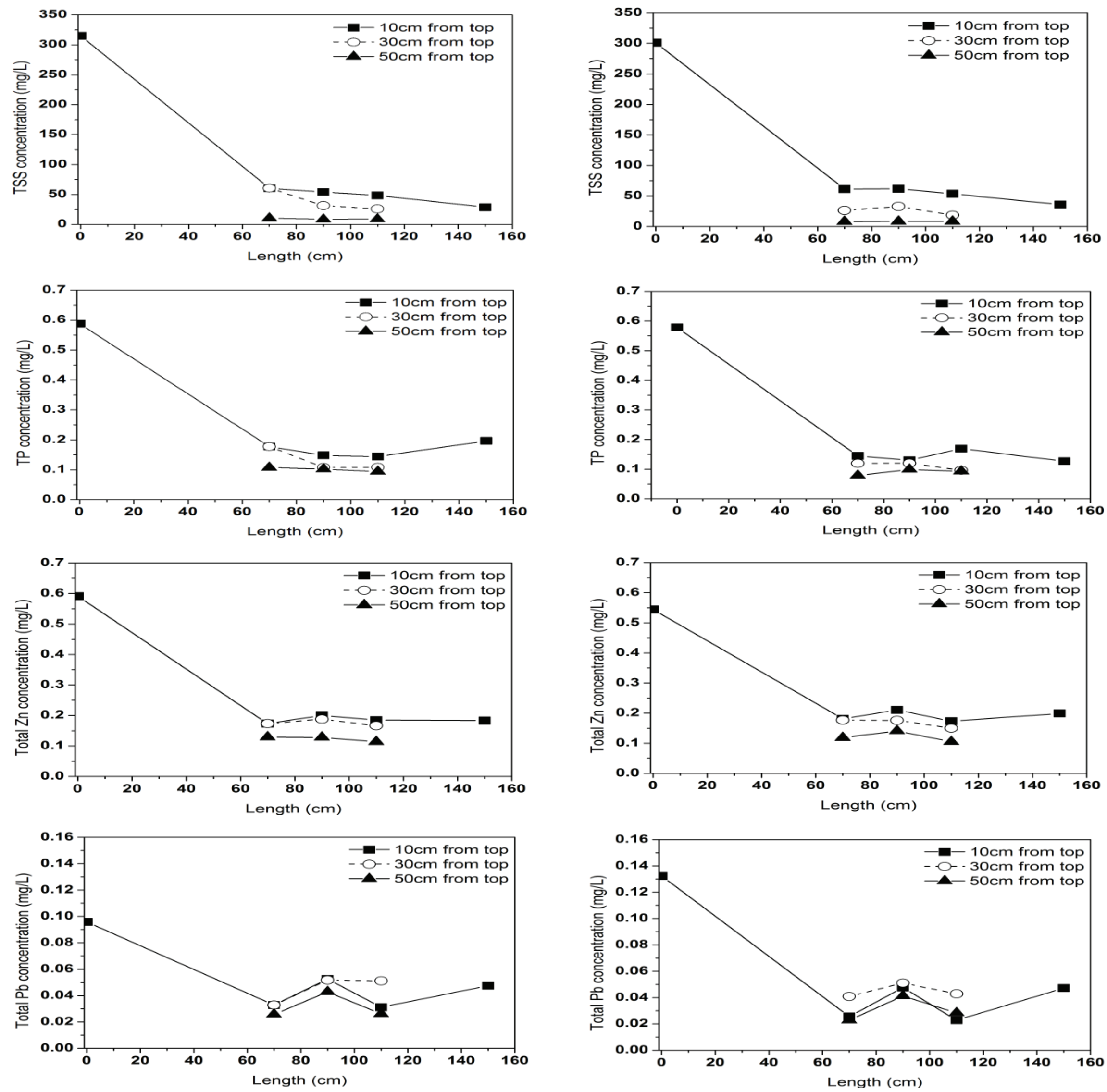

Fig. 2. Pollutant removal efficiency of bioretention systems (mean ± standard deviation).

and nutrients were reduced by soil microbial activities and bioremediation. Comparing the removal efficiencies of TN, $NO_3$–N and $NH_4$–N, the occurrence of nitrification and de-nitrification in soil and media layers were observed.

### *3.3. Concentration variation with respect to length and depth of the facility*

In order to find the optimal depth and length, water samples were collected from 3 vertical and 3 horizontal ports as shown on Fig. 1. The concentration changes with respect to the length and depth of the bioretention system was shown in Fig. 3. Based on the experimental results, the variation in depth was not significantly related with the pollutant removal, which means most pollutants were retained, rejected, and adsorbed on the top layer of the bioretention system. Nevertheless, the optimal depth needed for a bioretention system should be considered for design purposes. The depth of 50 cm was recommended in order to provide sufficient space for plants and effective evaporation depth for the retained water in the soil layer. Moreover, the optimal length of the bioretention system should be evaluated for it is mainly related with production cost of the system. The pollutant fate in horizontal direction showed that most pollutants were reduced until 70 cm. The results implied that most pollutants were reduced by physico-chemical mechanisms (e.g., filtration and adsorption).

Nitrogen can be removed by microbial activities in the soil and bioremediation. In order to find the contribution of the microorganisms with the nitrogen removal, the water samples collected from the 9 ports were analyzed. Fig. 4 shows the fate of $NO_3$–N, $NH_4$–N and TN with respect to length and depth; circles indicates the amount of nutrients




(a) Type-A (b) Type-B

Fig. 3. Pollutant concentration with respect to length and depth of (a) Type-A and (b) Type-B bioretention systems.

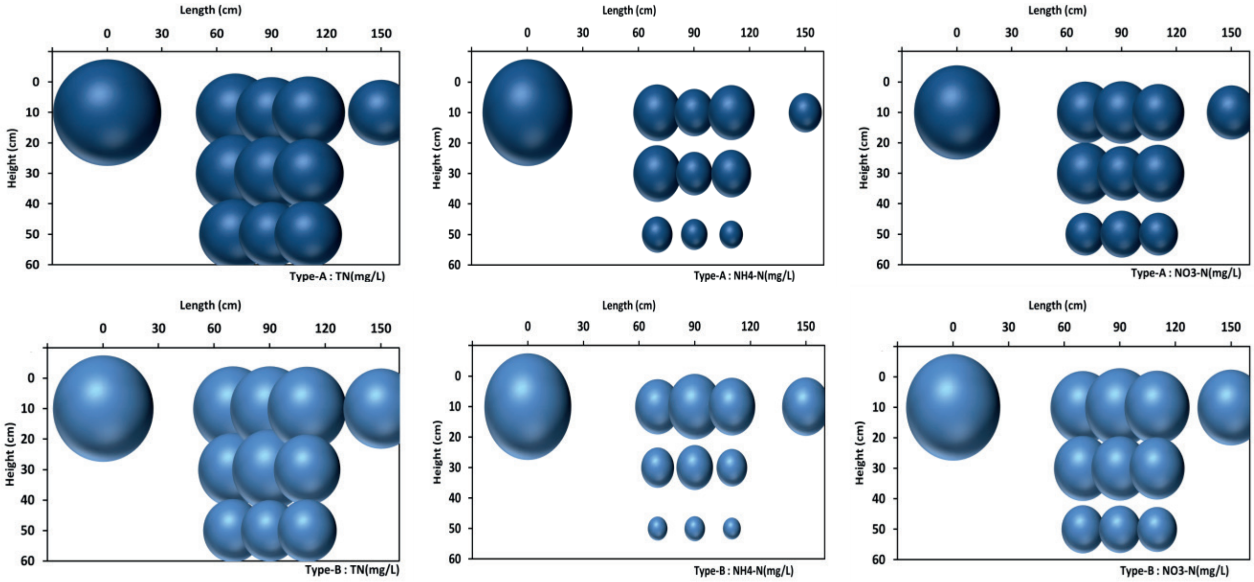



Fig. 4. Concentration of the nitrogen forms of each bioretention system with respect to length and depth.

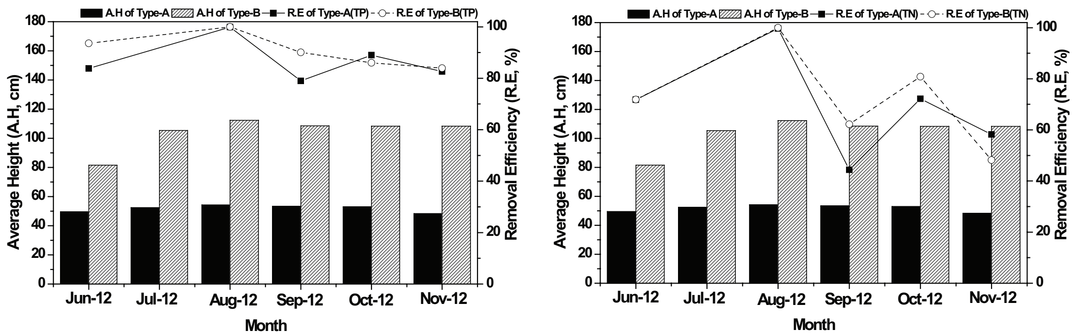



Fig. 5. Average monthly pollutant removal efficiencies and changes in plant height.

present. Influent nutrients in the pilot plant has confirmed that as it goes deeper or away from the influent sections, it becomes smaller. Also based on the findings, TN and $NH_4$–N were mostly removed within 30 cm depth and 70 cm length. The $NH_4$–N was transformed to $NO_3$–N by nitrification and TN was removed by denitrification process. The reduction of $NO_3$–N with length means bioremediation was also involved in the nitrogen removal.

### *3.4. Nutrient removal with respect to plant growth*

According to the fate of nitrogen forms with length and depth, it was revealed that the plants were involved with the nutrient removal. In order to find the contribution of bioremediation with the nutrient removal, the plant growth for each system was observed. The results for the plant growth observation were shown in Fig. 5. It was found out that the RL was grown horizontally while the SJ species grown vertically. However, the type of plant was not related with nutrient removal efficiency even though there was high removal efficiency during the summer season. The results showed that both plants can be applied well on bioretention with high removal efficiency.

## 4. Conclusions

The research was performed to develop a suitable bioretention system for Asian Monsoon climate. The main focus of the experiment was the transformation and transport of pollutants within the bioretention systems having different plant species. Moreover, the optimal bioretention size such as the length and depth was determined. Two pilot scale bioretention systems with *Rhododendron indicum Linnaeus* (type-A) and *Spiraea japonica* (type-B) were developed and tested to assess the respective removal performance. The major findings are as follows:

(1) The bioretention provided high pollutant removal efficiencies for particulates, heavy metals, nutrients and organics through the application of biological and physico-chemical processes. The pollutant removal efficiency on both types of bioretention was approximately

90% for TSS and COD while about 60% for nutrients. Both pilot scales showed high metal reduction capabilities with 60% removal efficiency for Total Cu, Total Pb and Total Zn.

(2) Most pollutants were removed within 30 cm depth and 70 cm length. It means the bioretention can be applied as a small scale facility within small urban areas if the main purpose was to treat runoff pollutants. However, it can be easily scaled up for other purposes such as landscaping and water reuse.

(3) The nitrogen was removed by the soil microbial activities and bioremediation. During the plant growing season in summer, the nitrogen removal was high compared to the other season. Also nitrification and denitrification were observed as an important mechanism for nitrogen removal.

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