STUDIES ON THE THREE-PHASE TRANSPORT OF AMMONIUM NITROGEN IN BIORETENTION

by

Ying MEI[a], Yuying GAO[b], Xiaohan ZHU[a], Yajun XIANG[a*], DongXu SUN[a], and YanYan JING[a]

[a]School of Energy and Power Engineering, Inner Mongolia University of Technology, Hohhot, China
[b]School of Resources and Environmental Engineering, Inner Mongolia University of Technology, Hohhot, China

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Bioretention, a management strategy employed to address non-point source pollution in urban settings, has emerged as a prevalent method for the treatment of pollutants in stormwater runoff. However, there is a paucity of research on the ammonium nitrogen transport process in the gas-liquid-solid three-phase of bioretention. The present study investigates the distribution of ammonium nitrogen in a gas-liquid-solid three-phase system. To this end, the study adds various proportions (0%, 2%, 4%, 6%, 8%, and 10% by volume) of soil fillers (newspaper, wood chips, and humus leaves) to sandy soil, plants ryegrass, and constructs a laboratory phytoretention system to artificially simulate rainfall. The distribution of ammonium nitrogen in the gas-liquid-solid three-phase system of the sandy soil, with different proportions of soil fillers, was investigated. The study focused on the distribution of ammonium nitrogen in the gas-liquid-solid three-phase system of the phytoretention system. The present study explores the alterations in the system of ammonium nitrogen transport within the gas-liquid-solid three-phase configuration. The volatile accumulation of ammonia in the sandy soil group accounted for 4.67% of the ammonium nitrogen input. The ammonia nitrogen content of the sandy soil group that was discharged from the system with rainwater accounted for 0.24% of the total ammonia nitrogen input. The percentage of soil ammonia nitrogen accumulation to ammonia nitrogen input for the sandy soil group was 51.84%.

Key words: *bioretention, ammonium nitrogen, soil media*

Introduction

The rapid advancement of urbanization has brought to the forefront of international scientific research and social concern the issue of urban non-point source pollution. Urban non-point source pollution is characterized by randomness, wide distribution of pollution sources, and a complex composition of pollutants [1]. Stormwater runoff is the primary vector of non-point source pollution in urban areas, transporting a diverse array of pollutants, including nutrients, heavy metals, pathogenic microorganisms, and toxic substances. The level of nitrogen pollution in stormwater runoff in China is more significant compared to developed countries [2, 3]. Research has indicated that more than half of the nitrogen pollution in rivers, lakes, and oceans is attributable to stormwater runoff [4]. A plethora of pollution control strategies have been examined, and it has been demonstrated that bioretention has the capacity

* Corresponding author, e-mail: 1009508363@qq.com

to significantly remove metals and suspended particulate matter in stormwater runoff. However, it has also been observed that bioretention is relatively unstable in terms of nutrient removal, particularly nitrogen [5]. The efficacy of nitrogen removal in bioretention systems is influenced by a multitude of factors, including hydraulic conditions (liquid phase), the properties of the media (solid phase), and ammonia volatilization (gas phase) [6].

The transport and transformation of ammonium nitrogen in soil is influenced by a variety of ecological factors. The migration pattern of ammonium nitrogen in bioretention is not yet fully understood. The study objective was to determine the content of ammonium nitrogen in soil and rainwater runoff. To this end, simulated rainwater experiments were conducted, and the content of ammonium nitrogen in soil and rainwater runoff was determined. The study also revealed the migration process and analyzed the characteristics of the distribution of ammonium nitrogen in the gas-liquid-solid three-phase distribution in the bioretention.

Materials and methods

Experimental materials

The soil utilized in the experimental setting was 1 mm sieved sandy soil obtained from the riverside of Juhaitan Village, situated within the administrative boundaries of Jungar Banner in Ordos City, Inner Mongolia Autonomous Region. This soil was deemed to be free from contamination.

The sandy soil, *S*, was filled with 0%, 2%, 4%, 6%, 8%, and 10% of newspaper, *B*, wood chips, *M*, and humus leaves, *F*. The newspaper utilized in this study was 15 mm in length and 2-3 mm in width. The selection of materials included pine wood chips and humus leaves with a particle size of less than 2 mm. The types of the three soil fillers and the symbols used to represent them are shown in tab. 1.

The volume of rainfall resulting from artificially simulated rainwater (for which a 5% catchment area indicates that the area of the plant retention system is 5% of the total area of the impervious area [7]) is calculated using the following equations:

$$W = \frac{H \times S}{5\%} \tag{1}$$

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

The rainfall height for this experiment was 3 mm/h (moderate rain) and the radius of the planter was 7.5 cm.

$$W = \frac{0.3 \times 3.14 \times 7.5^2}{5\%} = 1059\ \text{mL} \approx 1100\ \text{mL} \tag{2}$$

Table 1. Types and proportions of soil additions

Soil fill	Fill-in-the-blank					
	Sandy soil+0%	Sandy soil+2%	Sandy soil+4%	Sandy soil+6%	Sandy soil+8%	Sandy soil+10%
Newspapers (*B*)	*S*	*S*+2%*B*	*S*+4%*B*	*S*+6%*B*	*S*+8%*B*	*S*+10%*B*
Wood chip (*M*)	*S*	*S*+2%*M*	*S*+4%*M*	*S*+6%*M*	*S*+8%*M*	*S*+10%*M*
Carrion leaf (*F*)	*S*	*S*+2%*F*	*S*+4%*F*	*S*+6%*F*	*S*+8%*F*	*S*+10%*F*

Three-phase transport experiments for ammonia nitrogen

The bioretention primarily utilized sandy soil as the medium, with the sandy soil comprising the system being filled with varying proportions of newspaper, wood chips, and humus leaves for artificial rainwater simulation experiments. The initial rainwater concentration was determined to be 2 mg/L. To formulate the rainwater, NH_4Cl was utilized, and the volume of rainwater used in this experiment was 1.1 L. The duration of water intake was approximately one hour.

Potting experiments were conducted in the laboratory and at 6-day intervals, an artificial rainfall simulation experiment was repeated three times. Each experimental group was replicated twice. In each artificial rain simulation, the effluent from the basin's base was collected in a plastic beaker for the purpose of determining the quality of the water and the ammonia nitrogen content.

Soil samples were collected at the conclusion of each artificial rain simulation, on the third day, and on the sixth day in the upper and lower layers for the purpose of determining the ammonia nitrogen and nitrate nitrogen content of the soil. The number of days and symbols assigned to the first, second, and third artificial rain simulations are: 1, 3, and 6 for the first simulation; 1, 3, and 6 for the second simulation; and 1, 3, and 6 for the third simulation. Ammonia was collected five times a day for six days following each artificial rain simulation. The device employed for the collection of ammonia was the plant retention experimental device for dynamic simulation control of ammonium nitrogen in three-phase media [8].

Experimental analysis methods

The determination of ammonia is carried out in accordance with the national standard, entitled *Determination of ammonia in ambient air and waste gas: Nano reagent spectrophotometric method HJ 533-2009*.

The determination of ammonia nitrogen in water is carried out in accordance with the national standard entitled *Determination of Ammonia Nitrogen in Water, Nano Reagent Spectrophotometric Method HJ 535-2009.*

The determination of ammonia nitrogen in soil samples was conducted in accordance with the national standard, *Determination of soil ammonia nitrogen, nitrite nitrogen, nitrate nitrogen, potassium chloride solution extraction – spectrophotometric method HJ 634-2012.*

Microsoft EXCEL 2024 and ORIGIN2022 software were used for data processing and data analysis.

Results and discussion

Sandy soil was used as the main medium, to which newspaper,wood chips and humus leaves were added in different proportions. Under the condition of planting ryegrass, artificial rainfall simulation was carried out, and water, soil and gas samples were collected to measure the contents of water ammonia nitrogen, soil ammonia nitrogen,soil nitrate nitrogen and ammonia gas, and to explore the accumulation of ammonia nitrogen and nitrate nitrogen contents by soil.

Effect of different soil fillers on water quality ammonia nitrogen

As illustrated in fig. 1, the impact of sand soil, comprising varying proportions of newspaper, wood chips, and humus leaves, cultivated with ryegrass, on the elimination of ammonia nitrogen from water quality is demonstrated. The mean percentage of ammonia nitrogen in sand soil group removed was 92.86%. The average removal of ammonia nitrogen from water quality was 99.96%, 74.12%, and 99.92%, respectively, when sandy soil was filled with different proportions of newspaper, wood chips, and humus leaves. The water quality ammonia nitrogen removal rate of 99% with different proportions of newspaper and humus leaves was attributed to the lower volume of rainwater and lower hydraulic loads simulated in this experiment. These conditions prolonged the contact time between rainwater and sandy soil as well as plants. [9]. The removal of ammonia nitrogen was enhanced by the incorporation of various fillers into the sandy soil, with all fillers exhibiting a lower filler ratio. This phenomenon is attributed to the capacity of soil filler to provide adsorption sites, with NH_4^+-N being adsorbed through its interaction with the active sites on the soil filler. When the concentration of NH_4^+-N in the solution is known with certainty, and the amount of soil filler is increasing, the combining sites will compete for adsorption. This will result in a reduction in the amount of adsorption per unit area [10]. At the end of multiple simulated rainfall experiments, intact, shredded newspaper and wood chips were still present, but humus leaves were not intact. The main reasons for the slow rate of newspaper degradation are that

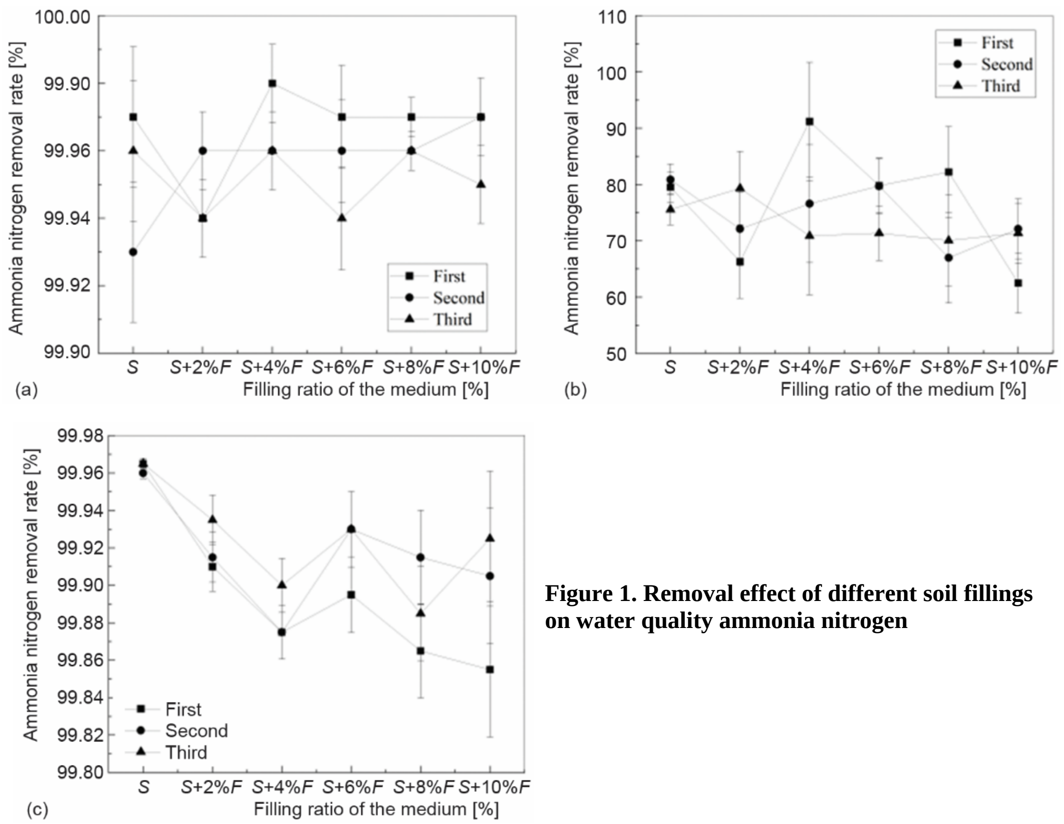


Figure 1. Removal effect of different soil fillings on water quality ammonia nitrogen

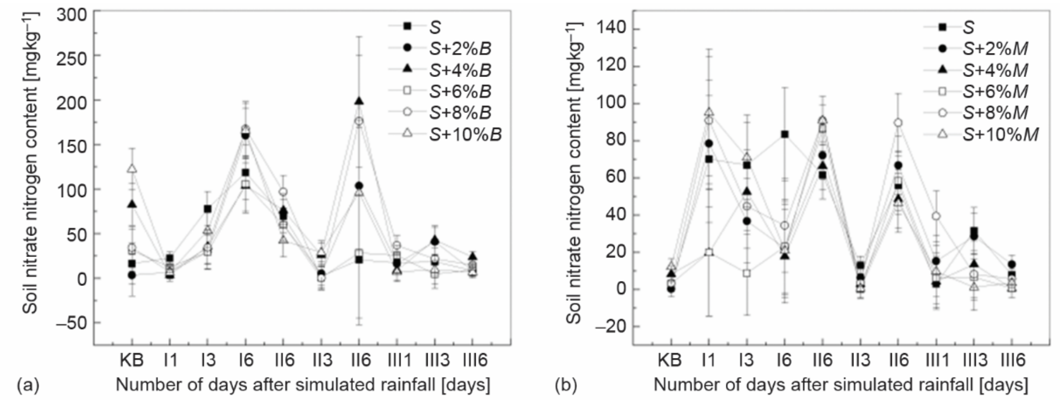
newspapers contain the high molecular weight polymer lignin, which protects the susceptible polymers, and that the presence of ink on the paper reduces the rate of solubilization of cellulose [11]. Volokita [12] carried out an experiment with newspapers and after running them continuously for 6 months, observed that the newspapers lost only 20% of their dry weight, and that no statistically significant difference was found in the chemical between the fresh newspapers and the ones removed from the experimental soil. composition no statistically significant differences were found. Newspaper was used as a soil filler for the bioretention and could be continued as a study in the long term.

Effects of different soil fillers on soil nitrate nitrogen and ammonia nitrogen

The data of soil nitrate nitrogen and ammonia nitrogen content were obtained by calculating the average value of nitrate nitrogen and ammonia nitrogen content of soil surface layer and soil sublayer.

Effects of different soil fillers on soil nitrate nitrogen

Following the application of varying proportions of newspapers, the background values of soil nitrate nitrogen content ranged from 3.61 to 122.35 milligrams per kilogram, as illustrated in fig. 2(a). Subsequent to the initial and secondary simulated rainfall events, a substantial increase in nitrate nitrogen content was observed on the sixth day. However, following the third rainfall event, a decrease in nitrate nitrogen content was evident. This decline



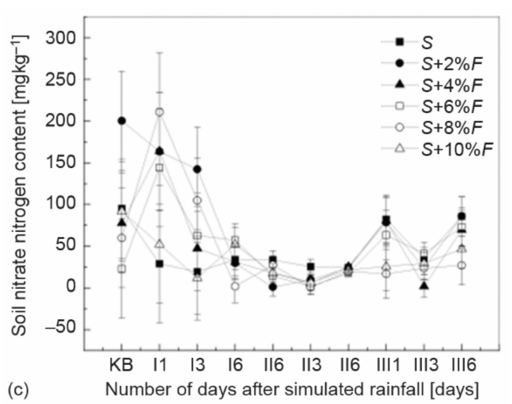
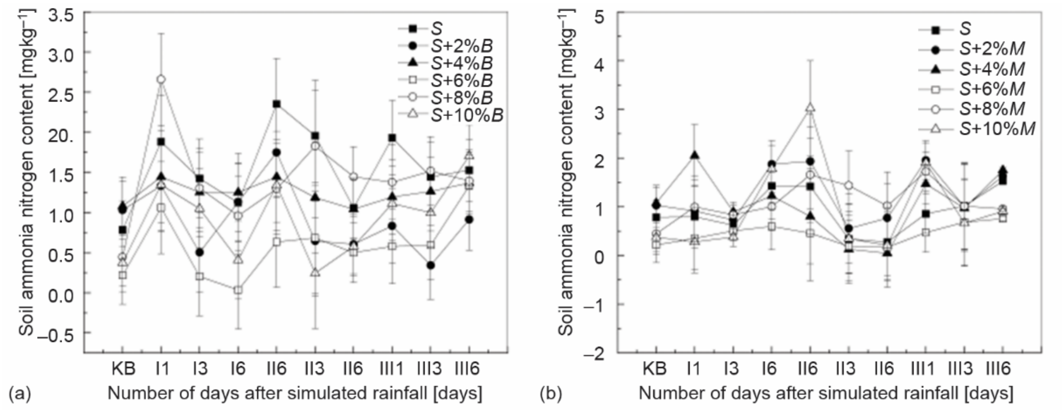


Figure 2. Removal effect of different soil fillings on soil nitrate nitrogen

may be associated with a reduction in the soil oxidizing capacity. As demonstrated in fig. 2(b), the background values of soil nitrate nitrogen content exhibited a range of concentrations, with varying proportions of wood chips utilized in the filling process. These concentrations ranged from 0.36 mg to 12.24 mg per kilogram of soil. Following the initial and secondary simulated rainfall events, a substantial increase in nitrate nitrogen content was observed on the first day. This phenomenon is likely attributable to the action of rainfall, which has been shown to promote the release and migration of nitrogen from the soil. Subsequent to the third occasion, the nitrate nitrogen content exhibited a tendency to increase and subsequently decrease. The incorporation of varying proportions of humus leaves resulted in a range of background soil nitrate nitrogen content values, ranging from 23.24 mg to 200.46 mg per kilogram, as illustrated in fig. 2(c). During the initial simulated rainfall event, the nitrate nitrogen content exhibited elevated levels on the first day. Subsequent to the second occasion, a marked decline in nitrate nitrogen content was observed. Subsequent to the third occasion, the nitrate nitrogen content exhibited an increase. However, it remained below the level that was observed following the initial simulated rainfall event. The incorporation of humus leaves has been demonstrated to modify the structure and properties of the soil, thereby impacting soil nitrogen transport and transformation. The simulation of rainfall has been demonstrated to promote nitrogen cycling processes in the soil and to provide oxidization capacity in the soil layer of the used plant retention system [13].

Effects of different soil fillers on soil ammonia nitrogen

Subsequent to the implementation of this procedure, the composition of the mixture was examined, as illustrated in fig. 3(a). The background values of soil ammonia nitrogen content ranged from 0.22-1.08 mg/kg, and the soil ammonia nitrogen content of each group was generally higher than the background value after several artificial simulated rainfalls, indicating that the NH_4^+-N in the rainfall was mainly adsorbed and retained by the soil. The soil ammonia-nitrogen content exhibited a consistent decrease in the presence of the filled 6% newspaper. Following each simulated rainfall event, a significant increase in soil ammonia N content was observed on the first day. However, this increase subsequently decreased gradually, reaching its lowest value on the sixth day. Subsequent to the incorporation of varying proportions of wood chips, as illustrated in fig. 3(b), the background value of soil ammonia nitrogen content ranged from 0.22 mg/kg to 1.08 mg/kg. The soil ammonia nitrogen content of each group exhibited a heightened level in comparison to the background value subsequent to the implementation of several artificial simulated rainfalls. The ammonia nitrogen content exhibited a marked increase following each simulated rainfall, subsequently decreasing in a gradual manner, particularly on the third day of the third cycle, when the content was found to be lower. Subsequent to the incorporation of varying proportions of humus leaves into the sandy soil, as illustrated in fig. 3(c), the background value of soil ammonia nitrogen content ranged from 0.55 mg/kg to 1.91 mg/kg. Following multiple artificially simulated rainfall events, the ammonia nitrogen content of all treatment groups exhibited a heightened level relative to the background value. Following each simulated rainfall event, a marked increase in ammonia nitrogen content was observed, which subsequently decreased over time. This decline was particularly pronounced on the sixth day, when the content was observed to be at its lowest point. The phenomenon may be associated with the saturation of soil adsorption of ammonia nitrogen and the subsequent release process. Subsequent to the second and third instances, the ammonia nitrogen content exhibited a decreasing trend with the increase of drying time, reaching its highest value on the first day after each simulated rainfall.



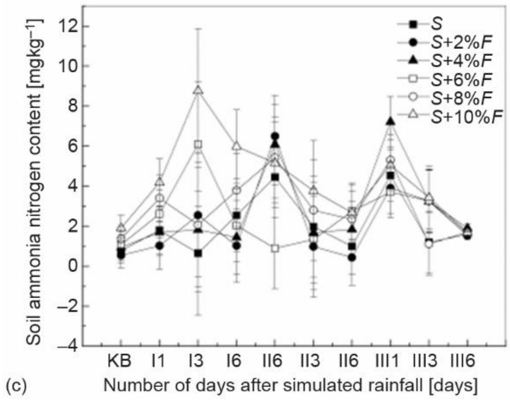
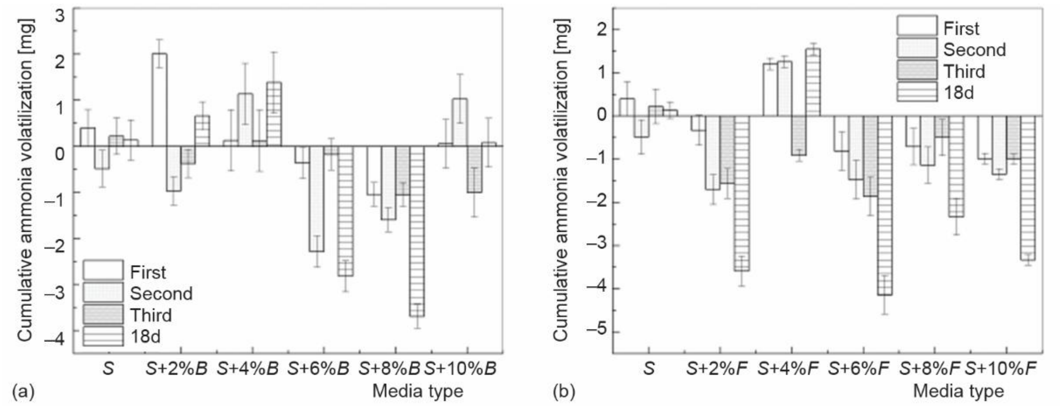


Figure 3. Removal effect of different soil fillings on soil ammonia nitrogen

As illustrated in fig. 3, the background value of soil ammonia nitrogen content is lower when sandy soil is filled with different proportions of newspaper, wood chips, and humus leaves. The initial day of artificial simulated rainfall has been observed to result in an increase in soil ammonia nitrogen content. The predominant method for addressing ammonia nitrogen in the plant retention system is through the process of adsorption. This adsorption can occur in close temporal proximity to the inflow of artificial rainwater, with a predominant occurrence in the upper portion of the plant retention system. The ammonia nitrogen is adsorbed in substantial quantities when it comes into contact with the negatively charged filtered colloidal particles [14]. Consequently, this results in an augmentation of soil ammonia nitrogen content on the initial day of artificial simulated rainfall. Concurrently, following an extended period of desiccation, the rehydration of the soil has been observed to induce the efflux of nitrogenous nutrients [15].

Effect of different soil fillers on ammonia gas

Subsequent to the filling of various proportions of newspapers, as demonstrated in fig. 4(a), the ammonia volatilization accumulation exhibited disparate trends with the augmentation of the number of artificial simulated rainstorms. The amalgamation of the results from three distinct artificial simulated rainwater experiments demonstrated a conspicuously elevated ammonia volatilization accumulation in the *S*+2%*B* and *S*+4%*B* groups when compared to the sand soil group. This finding suggests that the observed ratio facilitates ammonia volatilization. Newspaper is abundant in carbon and potentially in nitrogen, and it readily undergoes decomposition following simulated rainfall, releasing ammonia or other nitrogenous gases. After filling with different proportions of wood chips, as demonstrated in fig. 4(b), the results of the three artificial rainwater simulations were combined. The *S*+2%*M* group exhibited the largest cumulative ammonia volatilization, which was significantly higher than that of the sandy soil group. This suggests that the filling of 2% wood chips had an obvious promotion effect on ammonia volatilization. The sum of ammonia volatilization accumulation of the remaining experimental groups was less than zero, indicating that the filling of these proportions of wood chips had a certain inhibitory effect on the ammonia release. The addition of wood chips to soil has been demonstrated to enhance various aspects of soil quality, including soil structure, aeration, and water retention. The addition of excessive amounts of wood chips has been shown to result in a reduction in ammonia volatilization accumulation, a phenomenon that can be attributed to the capacity of wood chips to adsorb ammonia. Subsequent to the implementation of varying proportions of humus leaves in sandy soil, as illustrated in fig. 4(c). The amalgamation of the outcomes from the three artificial rainwater simulations demonstrated that the aggregate ammonia volatilization accumulations of the *S*+4%*F* group exhibited a marked increase compared to the sandy soil group. This finding suggests that the incorporation of 4% humus leaves into the soil significantly enhances ammonia volatilization. The sum of ammonia volatilization accumulation of the remaining experimental groups was found to be less than zero, indicating that these proportions of humus leaves had a certain in-



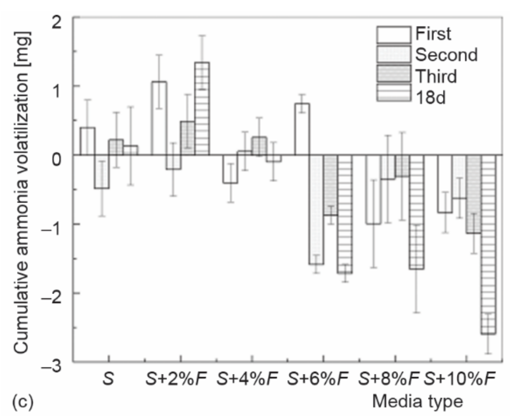


Figure 4. Effect of different soil fillings on the cumulative amount of ammonia gas volatilization

hibitory effect on ammonia release. The incorporation of humus leaves has been demonstrated to modify the redox state of the soil, thereby fostering the production and volatilization of ammonia. In instances where the quantity of humus leaves exceeded a certain threshold, the volatilization of ammonia was hindered by its adsorption effect.

Conclusion

This paper explores the distribution characteristics of ammonium nitrogen in the gas-liquid-solid three-phase system. The experimental design involves filling sandy soil with different proportions of soil fillers (newspaper, wood chips, and humus leaves), planting ryegrass, establishing a laboratory plant retention system, and conducting artificial rainfall simulations. The primary focus is on studying the changes in ammonium nitrogen transport in the gas-liquid-solid three-phase system of the plant retention system under conditions of filling sandy soil with different proportions of soil fillers. The incorporation of 4% newspaper, 2% wood chips, and 4% humus into the sandy soil resulted in a significant increase in ammonia volatilization accumulation compared to the sandy soil group, thereby facilitating ammonia volatilization. The magnitude of ammonia nitrogen removal by sand soil, newspaper, wood chips, and humus leaves was determined to be, in order of magnitude, newspaper > humus leaves > sand soil > wood chips. The incorporation of 6% newspaper, 6% wood chips, and 2% humus into sandy soil resulted in a consistent decrease in soil ammonia nitrogen content, thereby reducing its contribution to the accumulation of ammonia nitrogen. The distribution characteristics of ammonium nitrogen in the gas-liquid-solid three-phase system within the plant retention system were investigated by analyzing the distribution characteristics of ammonium nitrogen in the plant retention system under varying soil filler conditions.

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