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Use of a multi-layer column device for study on leachability of nitrate in sludge-amended soils

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Abstract

This paper described a multi-layer column device constructed with six cylindrical polythene tubes with installation of Rhizon soil moisture samplers (Rhizon SMS). The feasibility of using the column device to collect soil solution and percolate and to monitor leachability of nitrate in two sludge-amended soils was evaluated under glasshouse conditions. The soil moisture sampler in the device was demonstrated to be a non-destructive, simultaneous, sequential, convenient and rapid sampling tool for multiple-site porewater extraction. The device provided an in situ monitoring technique for leachability of nitrate in a soil profile following application of the anaerobically digested sewage sludge. The monitored results showed that surface soil amendment of the sewage sludge increased markedly the concentration of nitrate in the soil solutions at depths of 10–30 cm in a neutral paddy soil and at 30–50 cm in an acid red paddy soil. This amendment also largely increased nitrate in the percolates of the acid red soil. The movement and distribution patterns of nitrate in the profile were related to soil types, profile depths and experimental periods. Land application of sewage sludge may pose a risk in groundwater contamination of nitrate.

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1. Introduction

During last two decades more than 300 new treatment plants had been built up throughout the China. Although a few years ago the national-wide treatment proportion of wastewater was only 5–20%, large quantities of 300 000 tones of sewage sludge (DM basis) were

annually produced (Zhou et al., 1999). With continually high-speed industrialization, urbanization and ever-increasing population, more treatment plants and subsequently larger quantity of sewage sludge can be expected in the near future of China. In this country the municipal wastewater is usually mixed with industrial wastewater in the present pipe system and the mixed wastewater is often merely subjected to a primary treatment process. Therefore, the resulting sludge usually contains high concentrations of nitrogen, organic carbon and potentially toxic metals such as zinc, copper, chromium and nickel (Qiao and Luo, 2001a). With the merits of low expenditure and recycling of essential nutrients and organic matter, land application of sewage sludge has become the most popular and potential means in China,

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but much attention has been also paid to the safe disposal of the sewage sludge and its products due to the potential pollutants (Qiao et al., 2000).

Several investigations have been made recently on the accumulation of sludge-borne metals in the edible parts of important crops in China (Qiao and Luo, 2001b,c; Qiao et al., 2001). Another major concern is the possibility that sludge-derived nitrate may leach down the soil profile and pollute groundwater and contribute to the eutrophication of surface waters. Field studies showed that factors affecting nitrate leaching from sewage sludge applied were sludge type, application time, application method and crop (Shepherd, 1996; Insam and Merschak, 1997). In order to evaluate and predict the NO_3^- leaching risk and potential contamination of waters, a multi-layer column device incorporating soil moisture samplers (Rhizon SMS) was designed and used to investigate the leachability of sludge-derived environmental pollutants in soil. The use of suction samplers may allow simultaneous and sequential sampling of soil pore water at different depths of the soil profile and provide an in situ non-destructive sampling method (Hesslein, 1976; Shaw and Prepas, 1989; Ugo et al., 1999; Song et al., 2003). The Rhizon SMS has been used previously in experiments for extraction of rhizosphere soil solution (Luo et al., 2000) and lake sediment pore water (Song et al., 2003).

The main objective of this study was to evaluate the feasibility of using a multi-layer column device to collect soil solution and leachate and to monitor the dynamics of nitrate leaching in two sludge-amended soils under glasshouse conditions.

2. Materials and methods

2.1. Soil and sewage sludge

The two types of soil used were collected from the three layers as 0–20 cm, 20–40 cm and 40–60 cm in a profile at 10 different sites within a field. Each soil was air-dried and passed through a 2 mm nylon sieve and mixed to get a homogeneous soil sample of each original field layer before use. One soil was a one-year fallow paddy soil of pH 7.3–7.6 (Gleyi-Stagnic Anthrosol) from Changshu Ecological Experiment Station, Jiangsu Province of China, representing a typical agricultural soil in Yangtse River Delta region (as Changshu paddy soil in this paper), and the other was an acid red paddy soil of pH 5.7–6.7 (Agri-Udic Ferrosol) collected from a paddy field at Yingtian Ecological Experiment Station, Jiangxi Province, representing a typical red soil in the subtropical region of China (as Yingtian red soil). The selected properties in the two soils are listed in Table 1.

The anaerobically digested sewage sludge used was collected from a wastewater treatment plant in Wuxi city

Table 1

The selected properties of the soils and sewage sludge used

Soil/sludge	Depth (cm)	pH (in water)	OM (g kg ⁻¹)	TN (g kg ⁻¹)	Soil density (g cm ⁻³)
Changshu paddy soil	0–20	7.6	37.0	1.59	1.31
	20–40	7.4	30.9	0.99	1.55
	40–60	7.3	21.5	0.44	1.54
Yingtian paddy soil	0–20	5.7	36.3	1.89	1.26
	20–40	6.2	14.8	0.77	1.32
	40–60	6.7	12.5	0.64	1.19
Sludge		6.7	232	21.7	

of Jiangsu Province. The fresh sludge had a dry matter content of 24.5% and was air-dried to 57% dry matter (DM) and sieved to less than 2 mm before mixing with the soils. The selected properties in the sludge are also listed in Table 1.

2.2. A multi-layer column device

A schematic diagram of the multi-layer column device is shown in Fig. 1. This device consists of two main parts: six sections of cylindrical polythene tube and six Rhizon soil moisture samplers (Rhizon SMS: Rhizosphere Research Products, Doderstraat 62, 6706 JG Wageningen, The Netherlands). Each column has a diameter of 15 cm, a height of 70 cm and six tube sections with different lengths of 10 cm (half for soil), 5, 5, 5, 20, 20 and 5 cm (the bottom 5 cm for spreading fine sand) from the top to bottom, experimentally representing for soil layers of 0–5, 5–10, 10–15, 15–20, 20–40, 40–60 cm in a profile, respectively. The six separated sections can be well jointed and sealed during an experiment and can

Fig. 1. Schematic diagram of the multi-layer column device used in the glasshouse study.

also be separated again for soil sampling after completion of an experiment. Each section has a small hole drilled in the middle on the tube sidewall for installation of Rhizon SMS for extraction of soil solution at different layers in a profile. The soil moisture samplers are inserted through rubber stoppers to the holes at depths of 2.5, 7.5, 12.5, 17.5, 30, 50 cm of soil profile, respectively, and the stoppers are sealed with silicone glass cement. The slightly leaned bottom of column was made for easy collection of soil leachate. A simple drip irrigation system above the column is used to control water flow rate.

2.3. Leaching experiment

A thickness of 5 cm acid-washed fine sand was spread on the bottom of each column for filtration of soil water. The <2 mm air-dried subsamples of each soil were carefully placed in the different sections of columns on basis of original depth layer in the field and bulk density. The processes started by filling the bottom 40–60 cm section of the column with the mixed soil subsample from the field layer of 40–60 cm, followed by 20–40 cm layer using the mixed soil from the field layer of 20–40 cm, and then 10–20 cm section using soil from the original soil layer of 0–20 cm. The soil placed in the 0–10 cm part of the column was also from the original field layer 0–20 cm, but was subjected to one of the following treatments: (1) no application of sewage sludge (control, designated CK in Figs. 2–4), and (2) sewage sludge applied at the rate of 60 t ha⁻¹ (designated sludge). The

application rate was selected on basis of our previous experiment (Qiao and Luo, 2001b,c). There were three replicates for each treatment. The leaching experiment was conducted at 25–34 °C in a glasshouse in the Nanjing Institute of Soil Science, Academia Sinica.

During the period of leaching experiment, a portion of 50–100 ml of distilled water on basis of evaporation and transpiration was daily dropped through the above-mentioned drip system to each column soil for keeping soil moisture with 50–70% of water holding capacity. The dripping point was in the center of column just 1 cm above the soil surface. The dripping speed was about 50 ml h⁻¹. Though the preferential flow could not be avoided completely, the macro flow and the flow along the edge might be minimized by the uniformity of grounded soil and the well controlled irrigation system.

Soil solution samples were extracted at the depths of 2.5, 7.5, 12.5, 17.5, 30, 50 cm in the column soil profile in months of 1, 2, 4, 8 after beginning of the leaching experiment by using plastic syringes connected to the moisture samplers previously installed on each tube section sidewall (Fig. 1). The soil solution from depths of 12.5 and 17.5 cm in the first month was combined and analyzed for NO₃⁻ as a single sample representing the 10–20 cm layer (as shown in Fig. 2) because the individual sample at each depth were too small to analyze at that time. The leachate that had percolated through the bottom of column was also collected on the same dates.

The concentration of nitrate in the extracted soil solution and percolate was determined by using the

Fig. 2. Effect of sewage sludge on dynamic of solution NO₃⁻ concentrations in the Changshu paddy soil profile.

Fig. 3. Effect of sewage sludge on dynamic of solution NO_3^- concentrations in the Yingtan red paddy soil profile.

Fig. 4. Effect of sewage sludge on dynamic of NO_3^- concentrations in the percolated solutions of two soils.

Ultraviolet Spectrophotometry (Xie and Wang, 1998). The results are presented as the mean values of three replicates.

3. Results and discussion

3.1. Soil solution sampling in the multi-layer column device

At selected sampling dates, six 25-ml clean plastic syringes were connected to the PVC tubes of the six

moisture suction samplers at different fixed depths of the column device. About 30–60 min were usually required to extract 20 ml of soil solution by vacuum applied using the syringe, the exact time depending mainly on the moisture content, soil texture and depth. The extracted solutions were clear and ready for analysis as the porous polyester tube of the sampler has average pore size of 0.1 μm (Wu and Luo, 1999). This extraction method avoided the direct exposure of the solution sample to air with consequent changes in chemical composition, was less laborious than methods involving centrifugation and filtration and created a convenient multiple-site sam-

pling technique with non-destructive, simultaneous and sequential advantages. The multi-layer column device provided a possibility for in situ monitoring leaching dynamic of soluble and mobile substances in a soil profile.

3.2. Effect of sewage sludge on NO_3^- concentrations in the soil solutions and percolates

Surface soil amendment with sewage sludge increased substantially the concentrations of NO_3^- in the surface and subsoil solutions compared to the controls in both soils (Figs. 2 and 3). The maximum solution concentration of NO_3^- reached to 100 mg l^{-1} in the sludge-amended Changshu paddy soil and 300 mg l^{-1} in the sludge-amended Yingtan red soil while those in the corresponding controls were $<20 \text{ mg l}^{-1}$ and $<40 \text{ mg l}^{-1}$. In general, sewage sludge also increased NO_3^- concentrations in the percolated solutions, for examples from 0.8 mg l^{-1} in the control treatment to 1.6 mg l^{-1} in the sludged treatment for Changshu soil and from 0.5 to 4.6 mg l^{-1} for Yingtan red soil after 2 months. After 4 months NO_3^- concentration subsequently increased markedly from 4.1 mg l^{-1} in the control to 125 mg l^{-1} in the sludge treatment for the red soil. The results showed a pronounced tendency of nitrate leaching in the sludge-amended soils.

The increase in NO_3^- concentration in the soil solution following surface application of sewage sludge varied with time and differed at different depths (Figs. 2 and 3). In the Changshu paddy soil, the solution NO_3^- concentration at different depths decreased with time, from about 100 mg l^{-1} at 1 month to 15 mg l^{-1} at 8 month. The sludge-derived mg l^{-1} moved down from surface 0–10 cm to the subsoil layer at 10–30 cm. The concentration of NO_3^- in the percolated solution decreased from 1.8 mg l^{-1} at 1 month to 0.5 mg l^{-1} at 8 months. In the Yingtan red soil, the concentration of NO_3^- in the solution decreased dramatically at top 15 cm and increased gradually below 30 cm with time in the profile. The peak concentrations of NO_3^- appeared at 10 cm (300 mg l^{-1}) after 1 month, at 30 cm (200 mg l^{-1}) after 2 months, at 50 cm (250 mg l^{-1}) after 4 months and also at 50 cm (65 mg l^{-1}) after 8 months, indicating a significant downward movement of nitrate following surface amendment of sewage sludge under glasshouse conditions.

The sludge-amended Yingtan acid paddy soil had higher solution concentrations of NO_3^- at the different depths than the sludge-amended Changshu neutral paddy soil. The temporal distribution patterns (Figs. 2–4) of NO_3^- in the red soil and percolated solutions differed markedly from those in the Changshu paddy soil. The former had an increase in NO_3^- concentration at deeper layers of the profile with time while the latter had an opposite trend. The similar tendency also existed

in the percolates of the two soils. The differences in movement and accumulation of NO_3^- in the soil profiles were likely related to the soil properties (Table 1) and soil environment, which will influence the nitrification and denitrification during experiment period. Firstly, with comparison to the Yingtan soil, the Changshu soil had larger soil density (Table 1) and water holding capacity (65% for the Changshu soil and 40% for the Yingtan soil) in the column experiment. The former soil might have resulted in lower Eh and subsequently stronger denitrification (Zhu and Wen, 1990). Secondly, the two soils differed largely in pH, which might also have affected the soil microbial activity and the transformation of N. According to our adsorption study, there was no difference in the adsorption of NO_3^- between the two soils (unpublished data). The Fe or Al oxides in the Yingtan soil might not be the main components affecting the mono-valent anion NO_3^- accumulation and movement. In the present experiment we found that the solution concentrations of NH_4^+ were about ten times lower than the concentrations of NO_3^- (unpublished data). The potential of NH_4^+ leaching along the soil profile might exist, but not largely. Further study will be required for elucidation of those differences between two soils.

4. Conclusions

The combination of different lengths of cylindrical polythene tube with Rhizon soil moisture samplers (Rhizon SMS) permitted the construction of a multi-layer column device. The device created a non-destructive, simultaneous, sequential and convenient technique for multiple-site pore water sampling and provided an in situ monitoring system for leachability of nitrate in a soil profile after surface application of sewage sludge.

The anaerobically digested sewage sludge increased markedly the concentration of nitrate the soil solutions and also in the percolates of acid and neutral soils. The increases varied with soil types, profile depths and experimental periods. Surface soil amendment of sewage sludge posed a risk of groundwater contamination of nitrate. Beneficial recycling of the increasing quantity of sewage sludge applied to agricultural land will become more important in the drive towards sustainable agricultural systems and environmental protection in China. A balance should be achieved between the recycling of plant nutrients to optimize crop production and the control of nitrate and heavy metal pollution to protect the environment and the human food chain. The multi-layer column device used in this experiment may also be a useful tool for study on movement and accumulation of potentially toxic metals and organic substances following soil application of sewage sludge and/or other environmental wastes.

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