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Nitrite and Nitrate Removal Efficiencies of Soil Aquifer Treatment Columns

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Abstract

Bench-scale soil column experiments were performed to examine the effects of soil type and infiltration conditions on the removal efficiencies of wastewater nitrites and nitrates during the biological ripening phase of soil aquifer treatment (SAT) columns. SAT was simulated in three 1-m-high soil columns packed with 3 different natural agricultural soils having sandy clay loam (SCL), loamy sand (LS) and sandy loam (SL) textures. All columns were equipped with tensiometers and soil-water sampling ports, and received secondary effluent from a wastewater treatment plant with a conventional biological treatment system. Soil columns were ponded with wastewater to a depth of 2.5 cm above the soil surface and operated under 2 different alternating wet and dry cycles, 7 days wet/7 days dry and 3 days wet/4 days dry. The effect of wetting and drying periods on SAT nitrogen removal performance was assessed comparing nitrite and nitrate removal rates of 7 days wetting/7 days drying and 3 days wetting/ 4 days drying cycles. Infiltration rate and the length of wetting period were important parameters affecting nitrogen removal efficiency of SAT columns. Denitrification performance of the columns decreased significantly when the infiltration schedule was switched from 7 days wetting/7 days drying to 3 days wetting/4 days drying cycles. LS soil operated with 7 days wetting/7 days drying cycles had the highest (95%) nitrogen removal performance. SCL and SL soils can be operated under both 7 days wetting/7 days drying cycles and 3 days wetting/4 days drying cycles to meet the denitrification/nitrification requirements of SAT.

Key words: Soil aquifer treatment, Wastewater, Nitrite and nitrate removal.

Introduction

The use of soil aquifer treatment (SAT) systems is becoming common practice in arid and semi-arid regions as a means of achieving additional water treatment benefits and storage of water to meet the growing water demand by reuse of wastewater for non-potable purposes. During SAT, treated wastewater is intermittently ponded in the surface spreading basins to recharge groundwater. The ponded wastewater percolates through an unsaturated soil or vadose zone to an underlying, unconfined aquifer for storage. Then the recharged water is available for reuse through recovery wells.

Previous studies indicated that the performance of SAT systems is primarily controlled by soil type, effluent pretreatment and wet and dry cycle times (Quanrud, 1996; AWWA Research Foundation, 1998; Houston, 1999). Depending on these factors, significant improvements in water quality can be obtained. The major water quality concerns associated with reuse of wastewater subjected to SAT include dissolved organics, nitrogen species, and pathogens. These contaminants present in the wastewater effluent are removed or transformed by physical, chemical and/or biological processes in the vadose zone primarily, and subsequently in the aquifer.

Nitrogen species present in the recharged wastewater before SAT usually include various forms of inorganic and organic nitrogen. Significant nitrification and simultaneous denitrification can occur during SAT, providing removal of nitrogen from the system (Kanarek *et al.,* 1993). Although the effects of these mechanisms have been studied extensively, the problem of how to enhance unsatisfactory denitrification to meet the relevant nitrate regulations and standards has not been fully illuminated and explicitly quantified. Results of previous research indicate that SAT systems tend to promote nitrification of influent wastewater and transform a large fraction of influent nitrogen to nitrate, as long as aerobic conditions are predominant. Nitrate-nitrogen is one of the most common reasons why groundwaters do not meet drinking water standards if drinking water aquifers are involved during SAT applications. A considerable amount of carbon source, nitrate-N, and anoxic conditions, i.e. sufficient BOD levels in the wastewater effluent, should be available to promote denitrification. A major factor affecting the denitrification rate is the duration of wet and dry cycles. Denitrification can be enhanced by using longer wet and dry cycles. However, ammonia breakthrough can occur under continuous recharge conditions (Bouwer *et al.,* 1980; Idelovitch and Michail, 1984; Amy *et al.,* 1993; AWWA Research Foundation, 1998). Based on the evaluation of soil type and the duration of wet and dry cycles, the AWWA Research Foundation (1998) suggests that secondary wastewater effluents require soils with significant cation exchange capacity to adsorb ammonia, and that they require longer wet and dry cycles to induce anoxic and aerobic cycling. The longer wet cycle times allow for the development and maintenance of anoxic conditions needed for denitrification, while the longer dry cycle times allow for the re-establishment of aerobic conditions needed for nitrification. Cation exchange capacity prevents breakthrough of ammonia to the groundwater due to ion exchange.

The objective of this study was to examine the effects of soil type and infiltration conditions on the removal efficiencies of wastewater nitrites and nitrates during the biological ripening phase of SAT. Rates of nitrification/denitrification in the soils during wastewater application were compared. Effects of dissolved oxygen concentration on nitrite/nitrate removal efficiencies of the soils were discussed. The effect of wet and dry periods on SAT nitrogen removal performance was assessed comparing nitrite and nitrate removal rates of 7 days wetting/7 days drying and 3 days wetting/4 days drying cycles.

Materials and Methods

Column design

Three different soils with sandy clay loam (SCL), loamy sand (LS) and sandy loam (SL) textures, (Soil # 1, Soil # 2 and Soil # 3, respectively) were used in laboratory-scale soil column experiments. Physical and chemical characteristics of the column soils are given in Table 1. Prior to packing, a fine metal screen was placed at the bottom to prevent clogging of the column outlet. Soils were packed into three 1-m-long, 14.0 cm o.d., and 13.5 cm i.d. acrylic columns using a packing device and 3-cm thick soil lifts. Each lift was packed by taking an equal number of strokes from the packing device. Packing of lifts continued until the thickness of soil in the column reached a height of 88 cm, leaving 12 cm headspace for ponding of wastewater above the soil surface. Total mass of soils in the columns and corresponding bulk densities and porosities of the packed soils are given in Table 2.

Table 1. Physical and chemical characteristics of soils used in columns.

Variable	Soil # 1	Soil # 2	Soil # 3
Sand (%)	53.28	78.28	70.28
Silt (%)	24.00	10.64	14.64
Clay (%)	22.72	11.08	15.08
USDA soil classification	SCL	LS	SL
Water saturation (%)	47.5	30.5	35.0
pH (saturation paste)	8.02	8.27	8.20
Organic matter content (%)	2.25	0.78	1.43
Cation exchange capacity (meq/100 g)	16.8	9.4	13.8

Table 2. Values of soil mass, soil volume, bulk density, porosity and total pore volume for soil columns.

Column Soil	Soil Mass (g)	Total Soil Volume (cm^3)	Packed Density (g/cm^3)	Porosity	Total Pore Volume (cm^3)
SCL	16,100	12,500	1.29	0.51	6375
LS	22,280	12,500	1.78	0.33	4125
SL	18,210	12,500	1.46	0.45	5625

The design of the experimental setup was similar to that used by Quanrud *et al.* (1996). Each column was equipped with 4 tensiometer ports, 4 ceramic soil-water sampling ports, 1 water inlet port and 2 constant head overflow ports (facing each other at equal heights) at the top, and 1 column outlet at the bottom. Tensiometers were installed at depths of 15, 30.5, 45.5 and 65.5 cm from the top of the columns. All tensiometers were connected to manometers. A manometer/tensiometer system was used to measure soil water potential. Sampling ports were installed at depths of 21, 39, 54.5 and 75 cm from the top of the columns and used for the collection of water samples. Overflow weirs were located at depths of 7 cm and 9.5 cm from the top of the columns and used to maintain the desired constant head at the top of the soil. A schematic diagram of the SAT column system set-up used in this study is shown in Figure 1.

Copper and tygon tubing, and rubber stoppers were used for the construction of porous sampling cups and tensiometers. Round bottom ceramic cups were used as sampling cups. Ceramic cups had an air entry value of 1 bar, an outer diameter of 1.0 cm, and a wall thickness of 0.16 cm. The length of each sampling cup was 12.4 cm while the length of the tensiometers was 10 cm.

Wastewater samples stored in 20 l plastic containers were kept in a refrigerator at around +4 °C in order to minimize the effects of chemical and/or biochemical reactions in wastewater (Eaton *et al.*, 1995). For a longer period of storage, wastewater was sometimes frozen. No additive or preservative was used for preserving wastewater quality. Prior to column applications, wastewater transferred from the refrigerator was warmed to the average wastewater temperature of 20 °C through a water bath (Figure 1). Peristaltic pumps and tygon tubing were used to transfer wastewater to each column. Outer surfaces of the columns and tubing were wrapped with aluminum foil in order to prevent algal growth through the soil during operation.

Column operation

Columns were operated under 2 different operational schedules: 7 days wetting followed by 7 days drying and 3 days wetting followed by 4 days drying cycles. During infiltration, pump speed was set so that a constant head of 2.5 cm was maintained at the top of each column, while minimizing return flow. Overflow weirs were used to maintain a constant head during the wetting cycle. Ponds at the top of the SCL and LS columns were aerated while that of the SL column was not aerated. LS and SL soils had very similar textural compositions; the SL column was not aerated so as to observe the effect of dissolved oxygen (DO) concentration on the process performance of columns with similar soil textures. Column operations started with 7 days wetting/7 days drying followed by 3 days wetting/4 days drying cycles. A total of three 7 days wetting/7 days drying cycles and six 3 days wetting/4 days drying cycles were implemented.

The secondary wastewater was obtained from the Ankara Central Wastewater Treatment Plant (ACWTP). The wastewater treatment train in the ACWTP is a conventional biological treatment system consisting of 2 ½-activated sludge routes running parallel to each other. COD, nitrite, nitrate and TKN contents of influent wastewater are shown in Table 3.

Table 3. COD, nitrite, nitrate and TKN contents of influent wastewater.

Operational Phase	COD (mg/l)	NO_2 (mg-N/l)	NO_3 (mg-N/l)	TKN (mg-N/l)
7 days wetting/7 days drying	40 ± 3.8	1.07 ± 0.31	10.8 ± 2.60	-
3 days wetting/4 days drying	45 ± 4.6	0.82 ± 0.39	9.2 ± 0.22	24.6[1]

[1] Measured only once at cycle 6 of 3 days wetting/4 days drying

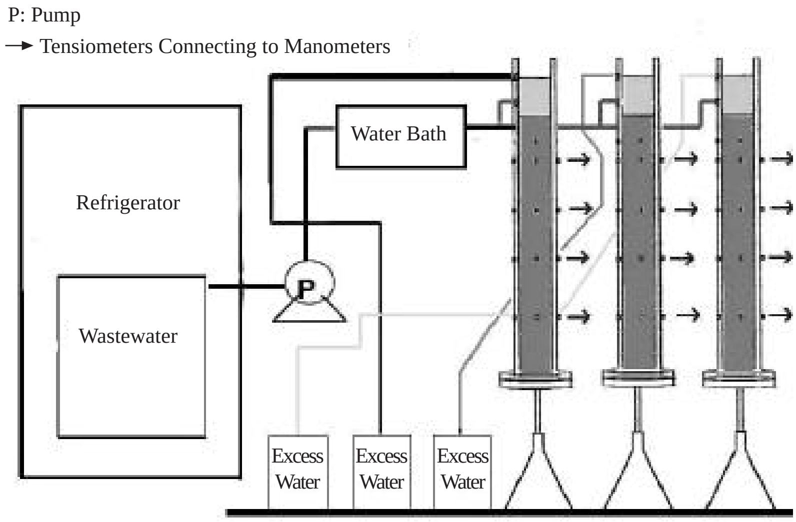

Figure 1. Schematic representation of SAT columns experimental setup.

Analytics

Column effluents were analyzed to measure the water quality parameters COD, NO_2, NO_3 and DO. COD analysis was done using the 5220-D closed-reflux colorimetric method (Clesceri *et al.*, 1998). The same method was modified by using 1.0216 g of $K_2Cr_2O_7$ instead of 10.216 g of $K_2Cr_2O_7$ for sample digestion prior to the low range COD measurements. U.S. EPA approved pre-measured kits (HACH) were also used to measure low range COD. NO_2 and NO_3 analyses were done using the HACH pre-measured NitriVer3 14065-99 and Nitraver5 14034-99 reagents, respectively (Hach Company, Loveland, CO, USA). DO was measured using the 4500-O G. membrane electrode method (Eaton *et al.*, 1995). The oxygen-sensitive membrane electrode was calibrated with the sample temperature and elevation was set to 915 m (approximate elevation of the METU Environmental Engineering Laboratory).

Percent removal efficiencies of the measured parameters (i.e. nitrite and nitrate removal efficiencies) were calculated from

$$PR = \frac{Inf - Eff}{Inf} \times 100 \tag{1}$$

where *PR* is percent removal efficiency (%), *Inf* is influent concentration (mg/l), and *Eff* is effluent concentration (mg/l).

Results and Discussion

Hydraulic characteristics of columns

Hydraulic characteristics of the SAT columns, which may have a considerable impact on chemical removal rates, are examined using data on infiltration rate, volumetric water content, hydraulic detention time, and number of pore volumes passed through columns. Soils in columns were assumed to be fully saturated with water under ponded conditions. Hence, saturated water contents of columns are taken as porosity values (see Table 2).

Total operation times and hydraulic characteristics of SAT columns during 7 days wetting/7 days drying and 3 days wetting/4 days drying operational schedules are given in Table 4. During 7 days wetting/7 days drying cycles, average infiltration rates of SCL, LS and SL columns were 7.0 cm/day, 21.0 cm/day and 4.6 cm/day; average hydraulic detention times were 7.0, 1.8 and 8.6 days; and the numbers of pore volumes passed through columns were 3.4, 15.6 and 2.5, respectively. The LS column had the highest infiltration rate amongst the columns in this operational schedule. The infiltration rate for this column was in the range 10-30 cm/day, which was also reported by Quanrud *et al.* (1996) for sand, sandy loam and silt soil columns operated on 7 days wetting periods. During column operation, the average infiltration rate of the SCL column remained relatively constant; on the other hand, the infiltration rates of the LS and SL columns decreased slightly

Table 4. Hydraulic characteristics (infiltration rate, IR, hydraulic detention time, T_d, and number of pore volumes, NPV) of the columns during 7 days wet/7 days dry and 3 days wet/4 days dry cycles.

		Sandy Clay Loam, SCL SCL			Loamy Sand, LS			Sandy Loam, SL		
Operation Schedule	Operation Time (days)	IR (cm/day)	T_d (days)	NPV	IR (cm/day)	T_d (days)	NPV	IR (cm/day)	T_d (days)	NPV
7 days wet/7 days dry	42	7.0	7.0	3.4	21.0	1.8	15.6	4.6	8.4	2.5
3 days wet/4 days dry	42	8.3	5.6	3.3	33.0	1.0	20.4	4.5	9.0	2.0

due to clogging caused by the accumulation of non-degradable suspended solids at the soil surface. Although the LS and SL columns contained soils with very similar textures, the LS column had a consistently higher infiltration rate. This can be attributed to possible non-uniformities that occurred during column packing.

During 3 days wetting/4 days drying cycles, average infiltration rates of the SCL, LS and SL columns were 8.3, 33.0 and 4.5 cm/day; average column hydraulic detention times were 5.6, 1.0 and 9.0 days; and the numbers of pore volumes passed through the columns were 3.3, 20.4 and 2.0, respectively. In general, infiltration rates of the columns remained relatively constant during 3 days wetting/4 days drying cycles, following 7 days wetting/7 days drying cycles. Average infiltration rates of the SCL and SL columns were nearly the same for both cycles, whereas the average infiltration rate of the LS column during 3 days wetting/4 days drying cycles was higher than that of 7 days wetting/7 days drying. Compared to 7 days wetting/7 days drying cycles, average detention times of the SCL, LS columns decreased 25% and 44%, respectively, while the average hydraulic detention time of the SL column increased by 5%.

Nitrate and nitrate removal

The nitrogen species NO_2 and NO_3 were continuously measured during SAT applications. Nitrogen transformation may occur during the SAT process. The presence of DO and organic matter are important for nitrification and denitrification, respectively. Therefore, COD:NO_3-N ratios were calculated to determine the favorability of the denitrification process through the columns. In fact, the ratio of BOD:NO_3-N serves this purpose better than does the ratio of COD:NO_3-N. However, due to a lack of appropriate data, the latter ratio was used. Considering that the ratio of biodegradable to non-biodegradable components of COD would not change significantly during the period of column operations, it can be expected that both BOD:NO_3-N and COD:NO_3-N ratios will show the same general trends.

7 days wetting and 7 days drying cycles The average influent NO_2-N concentration of the SCL, LS and SL columns was around 1 mg/l. NO_2-N distributions through the SCL, LS and SL columns are given in Figure 2. In all 3 columns, there was a drastic decline in NO_2-N concentration within the top 9 cm of soil, and thereafter concentrations did not change significantly with depth. NO_2 concentration changes within the same wetting period of a cycle were also observed. As shown in Figures 3 and 4, initial sampling was done at the end of the first wetting day, while the final sampling was done at the end of the final, i.e. the seventh, wetting day. During cycle 2, the SCL and LS columns had 2 nitrite spikes during flooding, but the SL column had only 1 nitrite spike (Figure 3). However, formation of nitrite spikes was

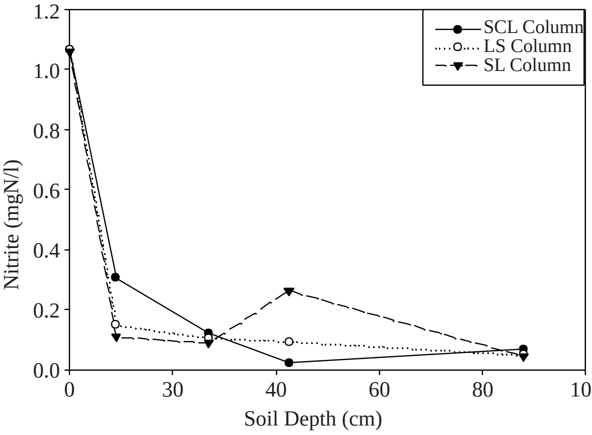

Figure 2. Nitrite distributions through the SAT columns during 7 days wetting/ 7 days drying cycles.

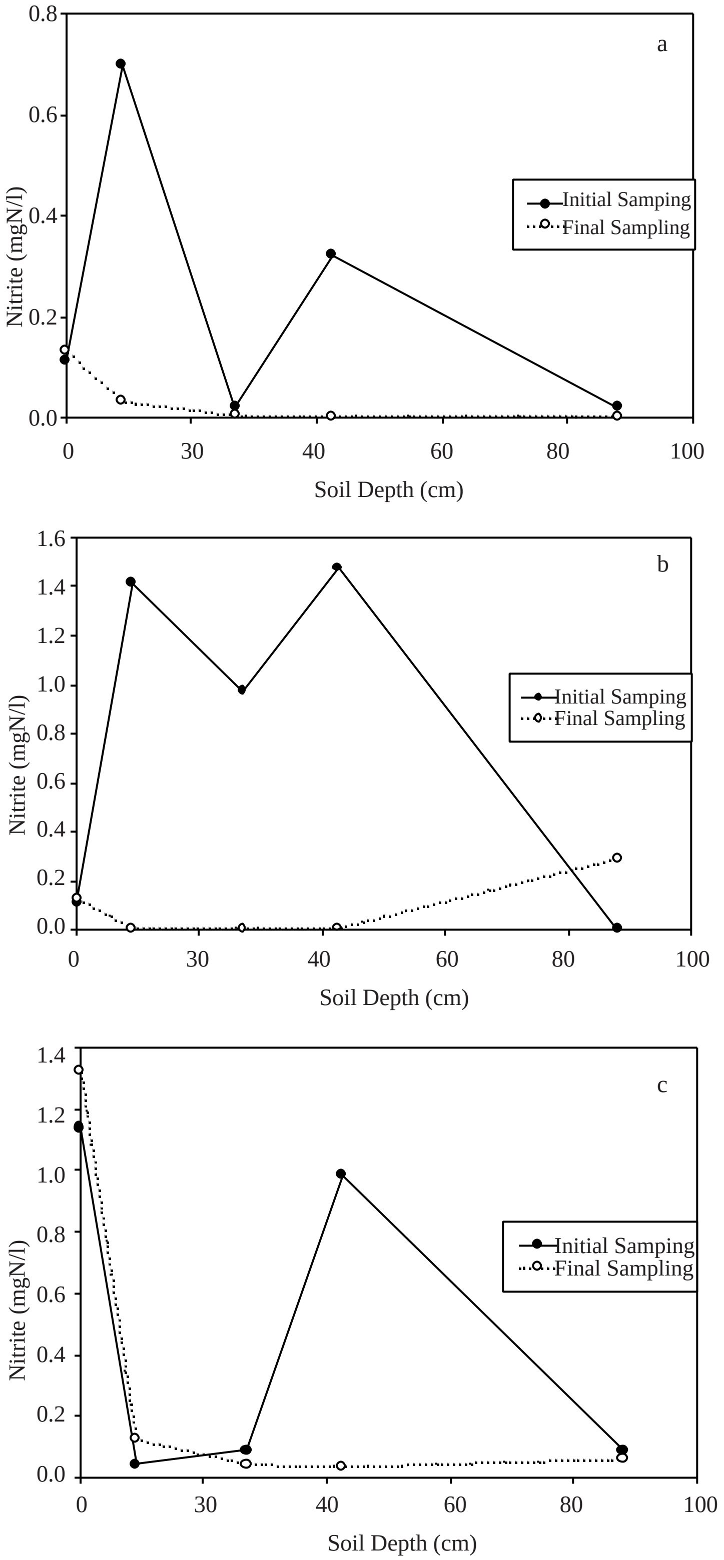

Figure 3. Nitrite distribution through (a) SCL, (b) LS, and (c) SL columns at the beginning and end of the wetting period of cycle 2 of the 7 days wetting/7 days drying cycles.

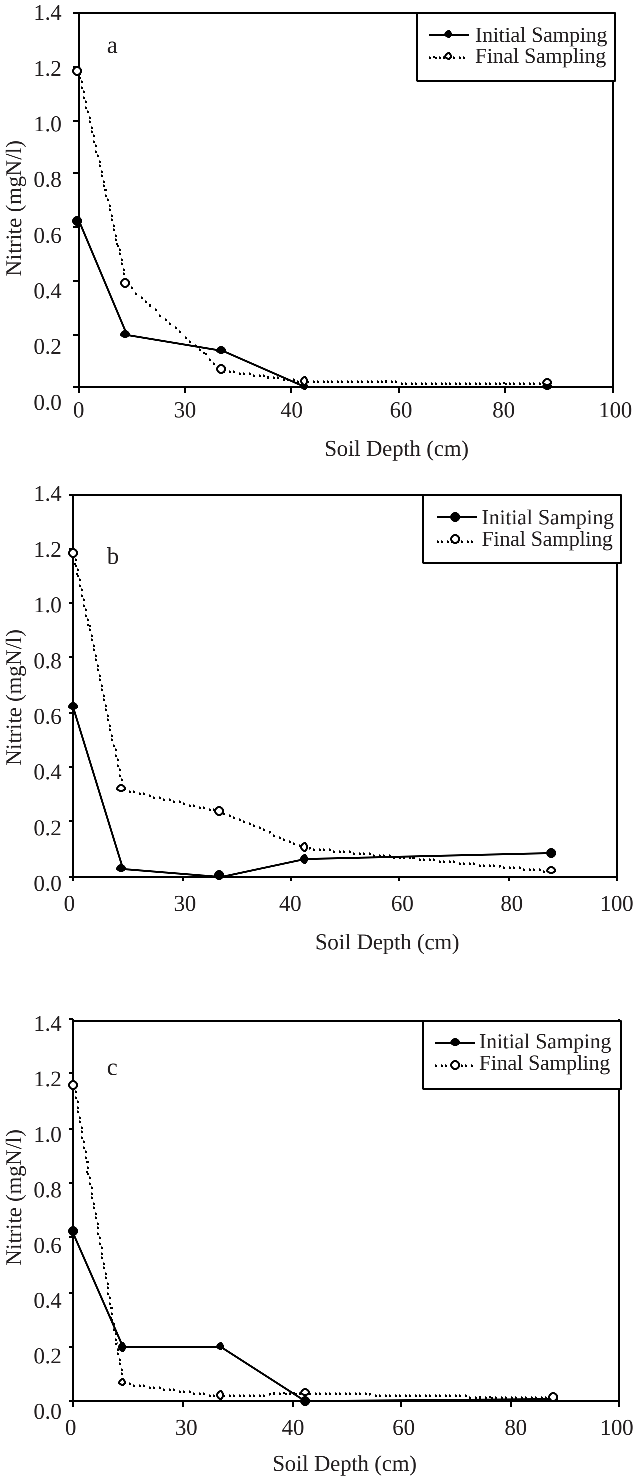

Figure 4. Nitrite distribution through (a) SCL, (b) LS, and (c) SL columns at the beginning and end of the wetting period of cycle 3 of the 7 days wetting/7 days drying cycles.

not observed at the beginning or end of the wetting period of cycle 3 (Figure 4). This finding showed that nitrite spikes were not continuously repeated during each flooding. Overall nitrite removal rates of SCL, LS and SL columns were 94%, 95% and 96%, respectively.

One set of NO_3-N sample data was obtained for columns during the third cycle of 7 days wetting/7 days drying cycles. Nitrate profiles of the columns are shown in Figure 5. The measured influent, 9 cm, 21 cm and 42 cm, and effluent NO_3-N concentrations for the SCL column were 12.3, 5.2, 7.2, 0 and 1.2 mgN/l, respectively. The highest reduction occurred in the top 9 cm soil layer during this cycle; denitrification was effective in this layer during cycle 3. Overall NO_3-N reduction efficiency for SCL was 90%. Water samples were taken from the LS column during the same period (cycle 3). The respective influent, 9 cm, 21 cm and 42 cm, and effluent NO_3-N concentrations for the LS column were 12.3, 6.9, 8.4, 6.9 and 0.9 mgN/l. Overall NO_3-N reduction for the LS column was 93%. Influent, 9 cm, 21 cm and 42 cm, and effluent NO_3-N concentrations for the SL column were 12.3, 4.5, 3.6, 0 and 3.3 mgN/l, respectively. The top 9 cm soil layer in the SL column was the most effective layer of denitrification. Overall NO_3-N reduction efficiency of the SL column was 73%.

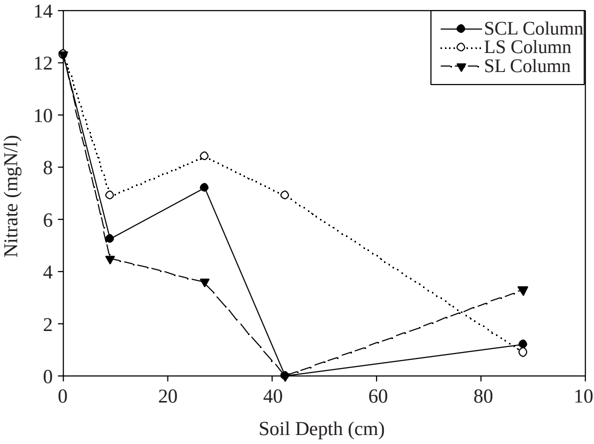

Figure 5. Nitrate distribution through the SAT columns during cycle 3 of the 7 days wetting/7 days drying cycles.

3 days wetting and 4 days drying cycles The influent NO_2-N concentrations for all columns ranged between 0.26 and 1.353 mgN/l, with an average of 0.8 mgN/l. NO_2 distributions through the columns during 3 days wetting/4 days drying cycles are shown in Figure 6. In the SCL column, NO_2 concentrations decreased with soil depth, and the highest NO_2 removal occurred over the soil thickness between a 9 cm soil depth and the exit of the column. In the LS column, there was a decreasing trend of NO_2 with soil depth down to 42 cm; however, effluent NO_2 concentrations exceeded the influent concentration. This NO_2 spike may result from continuing nitrification near the exit of the column where aerobic conditions may exist. In the SL column, NO_2 concentration decreased sharply within the top 9 cm of the soil and there was not a significant NO_2 removal following this zone.

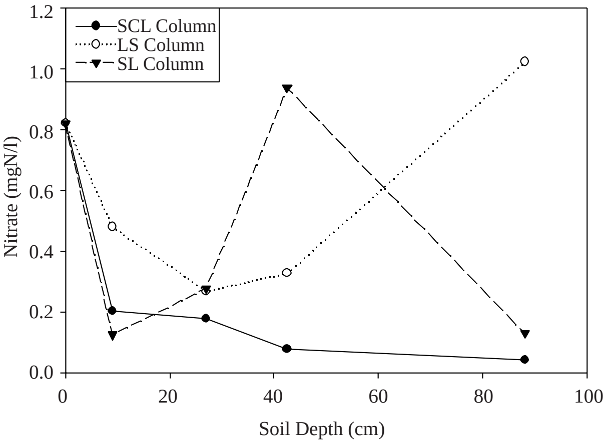

Figure 6. Nitrite distribution through the SAT columns during the 3 days wetting/4 days drying cycles.

In the SCL column, NO_3-N influent concentrations ranged between 5.31 and 18.58 mgN/l, with an average of 9.50 mgN/l. Influent COD to influent NO_3-N ratios of the SCL column for each wet-dry cycle are given in Table 5. The highest and the lowest ratios occurred during cycles 4 and 5, respectively. Nitrate distribution through the SCL column during 3 day wetting/4 day drying cycles is shown in Figure 7. The bottom 46 cm soil zone removed a significant amount of NO_3 during all cycles except in cycle 2. During cycle 2, COD removal efficiency was very high and DO depletion through the bottom 46 cm soil zone was also high. Hence, anoxic conditions could prevail in this layer, as indicated by the high COD:NO_3 ratio (7.5) for the same cycle. Some NO_3 reduction occurred in the presence of anoxic conditions. The cycles having higher COD:NO_3 ratios were cycles 2, 3 and 4. Nitrate removal efficiencies of these cycles were 92%, 76% and 100%, respectively. Cycle 5, with the lowest COD:NO_3 ratio, had only 41% removal.

Table 5. Influent COD to influent NO_3-N ratios for SAT columns during 3 days wetting/4 days drying cycles.

SAT Column	COD/NO_3 Ratio Cycle # 1	Cycle # 2	Cycle # 3	Cycle # 4	Cycle # 5	Cycle # 6
SCL	4.9	7.5	7.2	9.4	1.8	2.6
LS	10.8	6.0	7.2	9.4	1.9	2.7
SL	8.4	7.3	9.7	9.4	1.7	2.5

Formation of nitrate spikes was another concern during 3 days wetting/4 days drying cycles. Figures 8 and 9 show nitrate concentration distributions through the SCL column during initial and final sampling of cycles 2 and 3 of the 3 days wetting/4 days drying schedule. Initial sampling was done at the end of the first wetting day, and final sampling was done at the end of the third wetting day. About 1.5 to 2.0 days elapsed between the initial and final sampling. Nitrate concentrations at greater depths of 9 cm, 27 cm and 42 cm in the column were at least 100% greater than influent nitrate concentrations during the initial sampling. However, NO_3 concentrations at the same depths fell drastically below influent nitrate concentrations during the final sampling. Cycle 3, following cycle 2, exhibited similar nitrate behavior during flooding. From the comparison of these figures (Figures 8 and 9) it can be concluded that, unlike nitrite, nitrate spike formation is repeated during each cycle. Overall nitrate removal efficiencies for the SCL column from cycle to cycle ranged between 41% and 100%; and average nitrate removal efficiency of the SCL column was 64%.

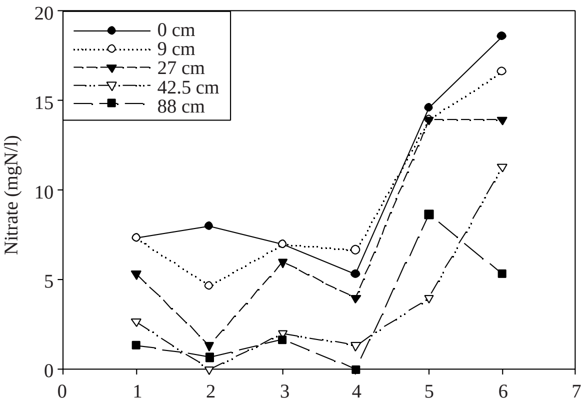

Figure 7. Nitrate distribution through the SCL column during 3 days wetting/4 days drying cycles.

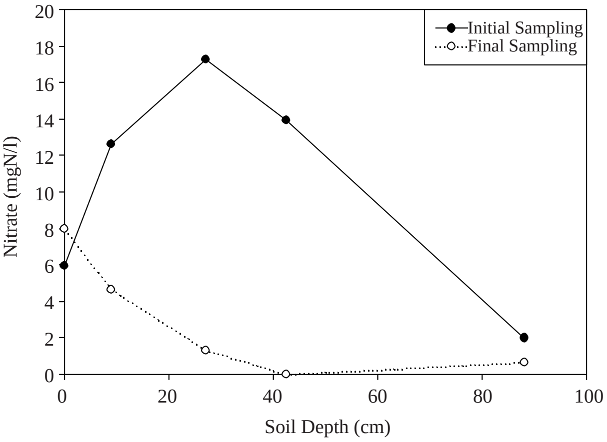

Figure 8. Nitrate concentrations through the SCL column during cycle 2 of the 3 days wetting/4 days drying cycles.

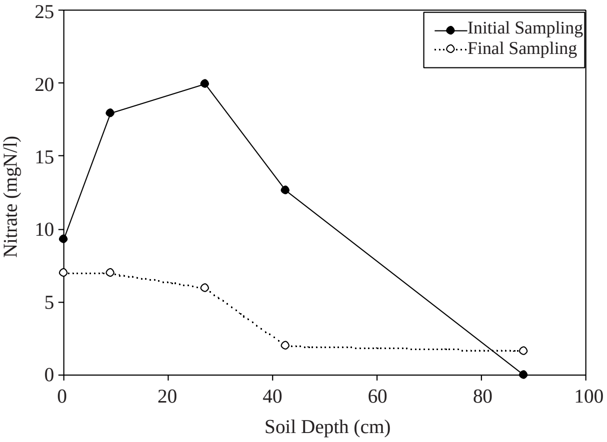

Figure 9. Nitrate concentrations through the SCL column during cycle 3 of the 3 days wetting/4 days drying cycles.

The infiltration rate of the SCL column increased by 19% during 3 days wetting/4 days drying cycles compared to 7 days wetting/7 days drying cycles. Furthermore, the influent NO_3 concentration (9.50 mgN/l) of the 3 days wetting/4 days drying cycles was lower than that of the 7 days wetting/7 days drying cycles. Total pore volumes passed through the SCL column did not change when the operation schedule was switched from 7 days wetting/7 days drying to 3 days wetting/ 4 days drying cycles. Therefore, the 7 days wetting/7 days drying NO_3 load on the SCL column was approximately 30% higher than the same load exerted in 3 days wetting/ 4 days drying cycles. Even though 7 days wetting/ 7 days drying cycles were exposed to a higher NO_3 load, the denitrification performance of these cycles was better. For the SCL column, this performance difference cannot be attributed to the infiltration rate, because the infiltration rate did not change appreciably as a function of operation schedules.

In the LS column, the NO_3-N influent concentration was between 3.32 and 17.91 mgN/l, with an average of 9.12 mgN/l. Influent COD to influent NO_3-N ratios for each cycle are given in Table 5. The highest ratio occurred for cycle 1, and the lowest for cycle 5. Nitrate distribution through the LS column is given in Figure 10. Despite having the highest COD:NO_3-N ratio, during cycle 1 denitrification was not effective and the effluent nitrate was higher than the influent nitrate. Cycle 4 had the second highest COD:NO_3-N ratio, but denitrification was not effective during this cycle either. There was a high nitrate spike at the top soil layer during cycle 4, which was not due to nitrification of nitrite since the nitrite concentration at the top soil layer during cycle 4 was very low and the influent nitrate concentration did not vary significantly with time. This spike may be a result of nitrate leaching from soil. The hydraulic detention time of the LS column was the lowest (1 day) among the 3 SAT columns, and denitrification/nitrification processes do not have fast kinetics. Nitrate ions could be leaching without being reduced. It was also seen that the COD:NO_3 ratio was not by itself enough to induce denitrification in the soil column. The nitrate load on the LS column did not change significantly in the 2 operating schedules. This is an additional supporting argument for linking poorer 3 days wetting/ 4 days drying denitrification performance with an elevated infiltration rate in these cycles.

In the SL column, influent NO_3-N concentrations ranged between 4.64 and 19.2 mgN/l, with an average of 9.12 mgN/l. The ratios of influent COD to influent NO_3-N for each cycle are given in Table 5. Cycle 3 had the highest ratio while cycle 5 had the lowest ratio. NO_3-N concentrations through the SL column during 3 days wetting/4 days drying cycles are given in Figure 11. Nitrate concentrations showed cyclic behavior beginning from the topsoil to a depth of 42 cm. Cycles 1, 3 and 5 had high nitrate concentrations. The top half of the column had nitrifying characteristics, while the bottom half of the column, i.e. the soil profile between 42 cm and 88 cm, had nitrate removing characteristics. In the bottom 46 cm zone of the column, nitrate concentrations were lower than influent nitrate concentrations. Overall nitrate removal efficiencies of cycles 1, 3 and 4 were 59%, 55% and 59%, respectively. However, these removal efficiencies observed in these cycles were not the maximum removal efficiencies. Cycles 2 and 5 with 78% and 74%, respectively, had higher removal efficiencies than did cycles 1, 3, and 4. We cannot say that there is a link between the denitrification performance of the SL column and the infiltration rate. The infiltration rate remained almost constant in both operating schedules, yet the column performed worse in denitrification.

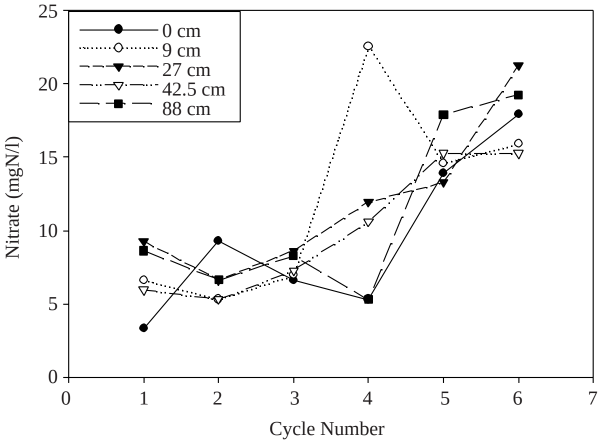

Figure 10. Nitrate distribution through the LS column during 3 days wetting/4 days drying cycles.

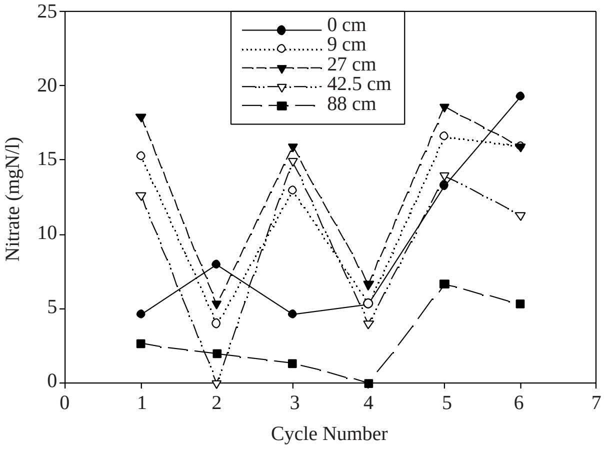

Figure 11. Nitrate distribution through the SL column during 3 days wetting/4 days drying cycles.

Average influent DO values for SCL, LS and SL were 5.1, 5.5 and 2.3 mg/l, respectively (Figure 12). DO profiles of the columns were not significantly different between 9 and 88 cm. Therefore, nitrification trends as affected by DO differences were compared only for the top 9 cm of the LS and SL columns. As the influent of LS had twice as much DO as did the influent of SL, the LS column was anticipated to nitrify more NO_2 to NO_3 than the SL column. Nevertheless, the average NO_2 concentration of the LS column was higher than the average NO_2 concentration of the SL column (Figure 6). Additionally, it was not possible to observe consistently higher NO_3 concentrations in the LS column compared to the SL column for the top 9 cm, either (Figures 10 and 11). Therefore, influent aeration did not have an apparent effect on nitrification. However, consistent DO concentrations exceeding 1 mg/l might have suppressed denitrification regardless of the soil column and sampling depth.

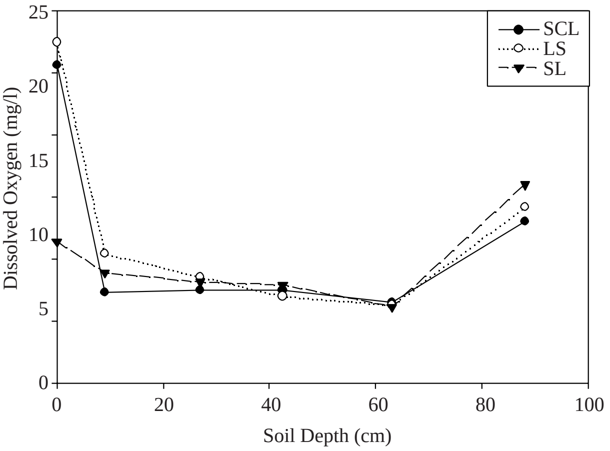

Figure 12. DO concentrations through the columns during 3 days wetting/ 4 days drying cycles.

Conclusions

Column influents were nitrified to a great extent before the application started. This was seen from NH_3 measurements, which were below the detection limits. However, we can also say that nitrification was not complete, as some reasonable NO_2 concentration was also present in the influent. Therefore, the denitrification performance of the soil columns was more important for overall efficiency of the simulated SAT system. The effects of different operation schedules on nitrite and nitrate removal rates of SAT are summarized in Table 6 for purposes of comparison. Results show that 7 days wetting/7 days drying cycles had higher nitrate removal rates compared to 3 days wetting/4 days drying cycles. Denitrification performance of columns decreased significantly when the infiltration operation schedule was switched from 7 days wetting/7 days drying to 3 days wetting/4 days drying cycles; 7 days wetting/7 days drying cycles were superior to 3 days wetting/4 days drying cycles if the treatment objective was denitrification. LS soil, which had the highest infiltration rate compared to the other soils, denitrified secondary effluent during 7 days wetting/7 days drying cycles, while it nitrified the effluent during 3 days wetting/4 days drying cycles. SCL soil had high nitrite and nitrate removal efficiency during both of the operation schedules applied. SL soil followed SCL in terms of nitrite and nitrate removal performance. Infiltration rates and the length of wetting period were 2 important parameters affecting nitrogen removal efficiency of the SAT columns. Although LS soil had high infiltration rates during both infiltration schedules, nitrate removal through the column was very high only during 7 days wetting/ 7 days drying cycles. LS soil operated with 7 days wetting/7 days drying cycles had the best nitrogen removal performance. SCL and SL soils could be operated under both 7 days wetting/7 days drying cycles and 3 days

Table 6. Overall (average) percent NO_2-N and NO_3-N removal rates of each SAT column during 7 days wetting/7 days drying and 3 days wetting/4 days drying cycles.

SAT	7 days wetting/7 days drying		3 days wetting/4 days drying	
Column	NO_2-N (%)	NO_3-N (%)	NO_2-N (%)	NO_3-N (%)
SCL	94	90	93	64
LS	95	93	Λ	Λ
SL	96	73	83	45

Λ Effluent concentration exceeds influent concentration wetting/4 days drying cycles to meet the denitrification/nitrification requirements of SAT. These findings are consistent with the literature. Crites *et al.* (2000) stated that 3 days wetting/4 days drying and 7 days wetting/7 days drying cycles meet infiltration rate maximization and nitrogen removal objectives, respectively.

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