THE EFFECT OF INCREASING THE ORGANIC CARBON CONTENT OF SEWAGE ON NITROGEN, CARBON, AND BACTERIA REMOVAL AND INFILTRATION IN SOIL COLUMNS

by

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INTRODUCTION

Denitrification is the only reaction capable of removing the tremendous quantity of nitrogen applied when high-rate land filtration systems are used for renovating sewage water. For example, the total nitrogen applied amounted to about 28,000 kg/ha/yr when 91 m/yr of sewage water was applied at the Flushing Meadows project (Bouwer, Lance, and Riggs, 1974). Experiments with laboratory soil columns used as models of the field basins of the Flushing Meadows project showed that 30% net nitrogen removal could be expected with the sewage water and flooding schedules used (Lance and Whisler, 1972), and nitrogen removal estimated from field data agreed with the laboratory results (Bouwer, Lance, and Riggs, 1974).

To determine what factors limited nitrogen removal to only 30% of the applied nitrogen, the conditions for denitrification were examined. They are (1) NH_4-N must be oxidized to NO_3-N; (2) the NO_3-N must move through a reduced zone; (3) organic carbon must be present in the reduced zone as an energy source for denitrifiers (Lance, 1972). The laboratory experiments showed that NH_4-N from the sewage water was adsorbed by the soil exchange complex, nitrified during the drying period, and resulting nitrates were leached from the soil in a concentrated nitrate peak. Data from oxidation-reduction electrodes showed that nitrate collected from the columns passed through a reduced zone. Since these first two conditions were met in the soil columns, denitrification was apparently limited by the amount of organic carbon available as an energy source for denitrifiers.

Several studies have shown that adding methanol to agricultural wastewater or nitrified sewage effluent before it was applied to anaerobic sand or gravel columns resulted in almost complete denitrification (English et al., 1974, St. Amant and McCarty, 1969; Smith et al., 1972, and Sword, 1971). Since the nitrogen source in these studies was almost all NO_3-N, only denitrification had to occur. Secondary sewage effluent is completely different because most of its nitrogen is NH_4-N, which requires that both nitrification and denitrification occur in the soil profile. Also, some organic carbon is available in sewage water, whereas agricultural wastewater contains very little organic carbon.

The objectives of this study were to determine (1) if a shortage of organic carbon limits denitrification when soils are intermittently flooded with secondary sewage effluent, (2) the removal of dissolved organic carbon at different carbon concentrations during high-rate soil filtration (40-50 cm/day), and (3) the effect of increased dissolved organic carbon concentrations on soil clogging and movement of fecal coliform bacteria.

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PROCEDURE

Eight 250-cm-long, 10-cm-diameter polyvinyl chloride pipes packed with soil taken from the Flushing Meadows rapid infiltration basins were flooded with secondary sewage effluent (Bouwer, Lance, and Riggs, 1974). The flow system and flooding procedure were described previously (Lance and Whisler, 1972). The soil was a loamy sand (89% sand, 8% silt, and 3% clay). Four levels of organic C were maintained by flooding two columns with unamended secondary sewage effluent (15 ppm C) and three sets of two columns with different levels of organic C (50, 150, and 200 ppm C) added to the secondary sewage effluent as dextrose. The dextrose was mixed with sewage water in 10-l jugs and the carbon-enriched effluent was applied to the columns with a Mariotte siphon to maintain a 15-cm pressure head at the soil surface. The jugs were replaced daily by other jugs with a fresh supply of carbon-enriched sewage water. Since some of the organic C decomposed in the jug, the sewage water was sampled at the beginning and ending of every 24-hr period and analyzed with a Beckman total carbon analyzer to determine the average organic C concentrations actually entering the columns. Oxidation-reduction electrodes were placed at 2, 10, 20, and 40 cm depths.

The columns were flooded on cycles of 9-days flooding alternated with 5-days drying. Infiltration rates were determined by weighing the column outflow daily. Each day's cumulative outflow was sampled and analyzed for the various nitrogen components and for organic C. A Technicon auto analyzer was used for NO_2^-, NO_3^-, NH_4^+, and organic-N analyses. The fecal coliform membrane filter procedure was used for fecal coliform counts.

RESULTS AND DISCUSSION

NITROGEN REMOVAL WITH DEXTROSE

When dextrose was added to the sewage water, N removal increased progressively with each increment of added carbon (Fig. 1). Flooding with 150 ppm organic C sewage water (average C entering the column) resulted in almost complete denitrification. The average NO_3^- and NO_2^- concentrations were below 0.1 ppm after the first flooding cycle with carbon-enriched sewage. Apparently, one flooding cycle was adequate to build up the microbial population. Nitrogen removal declined somewhat after three cycles, due to an increase in the NH_4-N concentration of the reclaimed water. The increase in NH_4-N was probably caused by a reduction in oxygen entering the soil during the dry period due to soil clogging which caused incomplete nitrification.

Changes in both the volume of gas collected and in the redox potential showed that adding dextrose to the sewage water stimulated denitrification. The nitrogen removal data also showed that no other mechanism, such as immobilization of nitrogen in microbial tissue, could account for the quantities of nitrogen eliminated from the sewage water.

Although the stoichiometric equation for denitrification indicates a minimum requirement of 0.7 mg of C/mg NO_3-N, in practice the C:N ratio required varies with the carbon source. St. Amant and McCarty (1969) reported that denitrification of agricultural wastewater required about 1.3 mg of methanol-C/mg NO_3-N. In our experiments high concentrations of organic C (150 ppm) were needed for complete denitrification because the NO_3-N concentrations in the high nitrate peak reached 75 to 100 ppm, depending upon the amount of NH_4^+ adsorbed by the soil and the amount of oxygen entering during the drying period. The C:N ratio of the unamended secondary sewage effluent was about 0.7:1, but this ratio dropped to about 0.2:1 in the water containing the high nitrate peak. The 150 ppm C increased the C:NO_3-N ratio enough for complete denitrification of the nitrate peak. With the 80 ppm C addition, the resulting C:NO_3-N ratio was too low for complete denitrification.

These studies showed that a low C:NO_3-N ratio is the primary factor limiting denitrification during high-rate land filtration of secondary sewage effluents and that denitrification was increased by altering the C:NO_3-N ratio. Relatively small variations in the soluble C content of secondary effluent did not affect nitrogen removal appreciably because a threefold increase in the C concentration was required to substantially increase N removal (Fig. 1).

CARBON REMOVAL - DEXTROSE

Profiles of dissolved organic C concentrations from soil columns flooded with dextrose-enriched sewage showed that much of the highest carbon concentration (150 ppm C) passed through the columns (Fig. 2). At the 240-cm depth organic C concentration remaining in the water was usually 90 to 100 ppm. The decrease between the 240- and 250-cm depth was probably due largely to aerobic decomposition caused by oxygen entering the gravel layer at the bottom through the outlet.

When dextrose-amended sewage with 80 ppm C was applied to the columns, the water sampled at 240-cm depth contained nearly 30 ppm C. The water from columns flooded with sewage amended to 40 ppm C had only 2 to 5 ppm more C than the 5- to 7-ppm C concentration measured in water from columns flooded with unamended sewage water (15 ppm C). About 5 ppm organic C was present when secondary sewage effluent from the same sewage plant was filtered through 9 m of sand and gravel during field experiments (Bouwer, Lance, and Riggs, 1974). Some organic compounds in sewage are apparently quite resistant to degradation, since some organic C is also present after chemical treatment (Shuval and Gruener, 1973).

The rate of C removal usually was highest in the top 20 cm, but removal continued at all depths. At the 5- to 10-cm depths, a slight increase in the C concentration indicated that some suspended organic material must have been partially decomposed near the surface and moved into the soil as soluble organic C compounds.

Redox potentials showed that after flooding with dextrose-amended sewage the soil columns were in a highly reduced state which indicated that most of the decomposition was by anaerobic reactions.

Decomposition rates among various wastewaters vary. For example, Thomas and Bendixen (1969) reported different degradation rates for septic tank and secondary effluents applied to sand columns. Thus, the exact concentration of organic carbon removable from different waste effluents by high-rate land filtration cannot be determined from our data since most of the organic material was dextrose. However, experiments using dextrose could be used to establish the maximum concentrations of organic C because dextrose is easily degraded. The maximum concentration of organic C removed was approximately 50 ppm. The amount of organic C removed when 80 ppm C was added was almost as much as that removed when 150 ppm C was added. Yet, 150 ppm C was needed for complete denitrification, probably because the high-nitrate concentrations were present in the soil columns for only 2 to 3 days. The high-carbon concentration was needed during this time for denitrification but was not needed during the remaining 6 to 7 days of flooding. Therefore, much of the C was not utilized. The amount of organic C removed from wastewater during high-rate infiltration can probably be increased by increasing the wastewater detention time in the soil. This can be done either by (1) decreasing the infiltration rate below the 30-cm/day rate used in our experiments or by (2) increasing the length of travel by the wastewater. The infiltration rate can be decreased by selecting a finer textured soil, reducing ponding depth, or compacting the soil surface.

Results from these and previous experiments (Lance, Whisler, and Bouwer, 1973) showed that most of the organic C in secondary sewage effluent would be removed by a high-rate land filtration system. However, most effluents from food processing plants, dairies, and feedlots contain many times the maximum 50-ppm organic C concentration removed by the soil columns. Thus, most of the organic C probably would not be removed if these wastewaters were applied in a high-rate system with application rates and conditions similar to our study. Further research will be needed to determine if primary sewage effluent can be renovated in a high-rate system.

INFILTRATION RATES

Infiltration rates ranged from 49 to 59 cm/day when all columns were intermittently flooded with secondary sewage effluent only for a base period of two flooding cycles. These data are similar to those from previous experiments with soil columns where infiltration rates were relatively stable during a number of 9-day flooding alternated with 5-day drying cycles (Lance and Whisler, 1972).

Adding dextrose to the sewage effluent did not affect infiltration rates during the first cycle (Table 1). The average infiltration rates during the next two cycles were 27% to 45% lower than rates during the base period. Tensiometer readings indicated that clogging developed internally rather than at the surface, which could be caused by increased gas production. This effect was noted in a previous report (Whisler, Lance, and Linebarger, 1974) where changes in tensiometer readings, changes in infiltration rate, and the expulsion of gas by the column occurred simultaneously.

The heavy load of suspended solids present in the secondary effluent during the last four flooding cycles greatly reduced infiltration in all columns. The infiltration rates were also expressed relatively by averaging the infiltration data for the second and third dextrose treatment and the four dextrose and suspended solids treatment cycles in Table 1 and dividing by the average infiltration rate for the base period to produce Fig. 3. The relative infiltration rates of columns flooded with sewage effluent high in suspended solids, but with no added C declined almost as much as columns flooded with sewage containing both dextrose and suspended solids. This showed that for the most part the effects of suspended solids and dissolved C were not additive. This happened because they were exerted in different parts of the soil profile. Tensiometers showed that the suspended solids reduced surface permeability, while dissolved carbon reduced internal permeability.

Avnimelech and Nevo (1964) reported a linear correlation between polyuronide concentration in the sand and clogging when organic material was incorporated into sand columns. Decreasing the C:N ratio of the organic material from 80 to 6 or adding inorganic N minimized the amount of polyuronide found and reduced soil clogging. The C:N ratio of the secondary sewage effluent used in our studies was about 1 originally and increased to only about 6 when the C concentration was increased to 150 ppm by adding dextrose. This may explain why adding carbon failed to induce surface clogging by the microbial byproducts since such clogging usually occurs near the surface of soils flooded with wastewater where organic materials and microorganisms tend to concentrate (Gilbert, Robinson, and Miller, 1974). Its also possible that the bubbling of gases from our columns reduced surface clogging by disrupting the soil surface.

Infiltration rates for field recharge basins (which were the source of the sand used in our soil columns) averaged 1.07 m/day for six basins during their initial infiltration with sewage water (Bouwer, Rice, and Escarcega, 1974). After a few months of intermittent flooding, the rates declined to about 0.75 m/day. Rice (1974) observed a similar decline to a reasonably stable level in soil columns packed with material from these basins. The original infiltration rates were restored when the columns were flushed with carbon dioxide, a water-soluble gas, immediately before flooding. Thus, the long-term clogging was apparently due to pore blockage by entrapped gases. He found that infiltration rate reductions below this stable level were caused by deposition of suspended solids on the soil surface. Davenport, Lembke, and Jones reported a reduction in hydraulic conductivity due to gas buildup in a column flooded with a solution containing nitrate and methanol.

Our results indicate that clogging of sands flooded with secondary sewage effluent is due to entrapped gases and suspended solids. As the carbon content increased, clogging increased because of entrapped gases, but clogging leveled off as the C concentration increased.

FECAL COLIFORM REMOVAL

Samples taken through ceramic sampling units were not reliable for absolute bacteria counts because laboratory tests showed that the ceramic strained out the bacteria even though the average pore diameter was several times larger than that of bacterial cells. The samples from the 0 to 250 cm levels were taken at the column inlet and outlet and did not pass through ceramic. The increase in bacteria between the last sampling port (240 cm) and the outlet (250 cm) illustrates the ceramic straining effect (Fig. 4). All of the decrease between the 0 and 2 cm levels was not due to soil straining. The internal samples indicated that some bacteria were removed throughout the profile.

The number of fecal coliforms in the sewage water increased from 4.2×10^5 to 5.5×10^7 per 100 ml when dextrose was added. Apparently, adding an energy source resulted in a favorable environment in the sewage reservoir for reproducing fecal coliforms. As the number of bacteria entering the column increased, the number passing through it increased. The columns flooded with unamended sewage removed 99.95% of the fecal coliforms, as compared with 99.8% removal by columns flooded with dextrose-amended sewage. However, only 180 fecal coliforms/100 ml of sample were found in water from columns flooded with unamended secondary sewage effluent, whereas 6,500 fecal coliforms/100 ml were found in samples from columns flooded with dextrose-enriched effluent.

Regrowth of coliforms in wastewater is not unusual. For example, Idaho field studies indicated a regrowth of coliforms in beet sugar wastewater (Furfari, 1960). However, regrowth has usually been attributed to the nonfecal section of the total coliform group. Geldreich (1967) stated that fecal coliforms require a more favorable nutrient supply and environment than are usually found in polluted streams. Deaver and Kerri (1969) reported no regrowth of fecal coliforms in a river below a sewage treatment plant outfall. Although the conditions of our experiment were not comparable to most streams or lakes, these data show that conditions which encourage regrowth of fecal coliforms can occur and sometimes the dissolved organic C content of wastewater should be considered when fecal coliforms are used as an indicator of microbial contamination.

SUMMARY AND CONCLUSIONS

Soil columns were intermittently flooded with secondary sewage effluent adjusted to different soluble carbon concentrations by adding dextrose. Nitrogen removal was increased from 30% to 90% by increasing the soluble carbon content of the sewage water to 150 ppm. This showed that organic C content of secondary sewage effluent does limit denitrification in a high-rate land filtration system. It also showed that both nitrification and denitrification can be achieved in the same soil profile by alternating flooding and drying periods.

The 150-ppm C concentration is about six times larger than the average N concentration of the sewage water. However, the intermittent wetting and drying cycles resulted in concentrating most of the nitrogen in a nitrate peak, which was leached from the soil during the first 3 days of the flooding period. The high organic C concentration was needed to provide a $C:NO_3-N$ ratio adequate for complete denitrification of the nitrate peak. Since the high C concentration was needed only when the nitrate peak moved through the soil, much of the carbon passed through the soil columns.

The maximum concentration of organic C removed by the soil columns was 50 ppm. These results and those of previous experiments indicated that most of the organic carbon can be removed from secondary sewage effluents by high-rate land filtration (Bouwer, Lance, and Riggs, 1974; Lance, Whisler, and Bouwer, 1973). Carbon removal by high-rate land filtration probably would not be adequate for most vegetable processing plant or animal waste effluents. Further research is needed to determine if most of the carbon would be removed from primary sewage effluent by high-rate land filtration. Also, further research is needed to determine if denitrification can be stimulated by adding carbon in a pulse at the beginning of the flooding period to coincide with the movement of the nitrate peak through the soil or if various forms of carbon-rich waste could be used to supply carbon. Applying primary effluent, or even raw sewage, might result in more nitrogen removal if other problems such as removal of organic material and soil clogging could be dealt with.

Infiltration rates were reduced by about 34% (average of 6 columns at three rates of added C), by adding dextrose to secondary sewage effluent. Reductions due to suspended solids and increased soluble C were not additive. Suspended solids increased resistance to water flow near the soil surface, while dissolved organic carbon increased resistance below the soil surface. Clogging by suspended solids seemed a more serious problem than clogging from increased dissolved carbon content of secondary sewage effluent. This may not be true when wastewater with a high C:N ratio is applied to soils.

Adding organic C to secondary sewage effluent increased the population of fecal coliform bacteria entering the soil and resulted in passage of more coliforms through the soil. This suggests that more research may be needed on interactions between organic C concentrations and fecal coliform numbers to clarify relationships between numbers of fecal coliforms and pathogenic bacteria.

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Table 1. Infiltration rates of soil columns intermittently flooded with secondary sewage effluent enriched with different levels of organic carbon.*

Cycle No.	Organic carbon level (average ppm) 15 (sewage only)	50	80	150
	cm/day			
	Dextrose			
1	61	52	49	61
2	49	34	27	40
3	55	37	27	46
	Dextrose + suspended solids			
1	37	27	24	30
2	40	24	21	37
3	34	34	18	27
4	30	34	18	27

* Infiltration rates during the base period when no dextrose was added were 59, 51, 49 and 59 cm/day for columns used for the 15-, 50-, 80-, and 150-ppm C treatments, respectively.

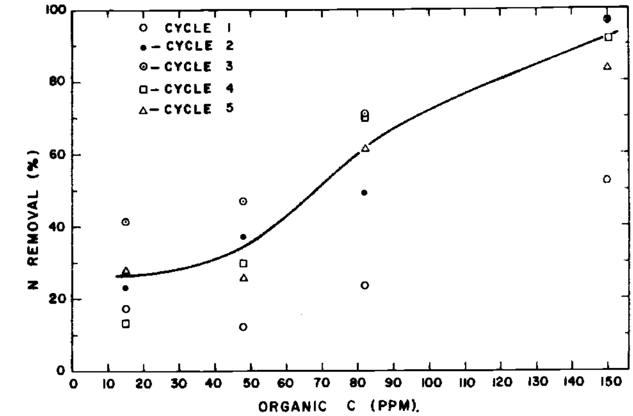

Fig. 1. The effect of the organic carbon content of secondary sewage effluent on nitrogen removal from the sewage by soil columns flooded on cycles of 9-day flooding and 5-day drying. Dextrose was added to the sewage water to provide levels of organic C.

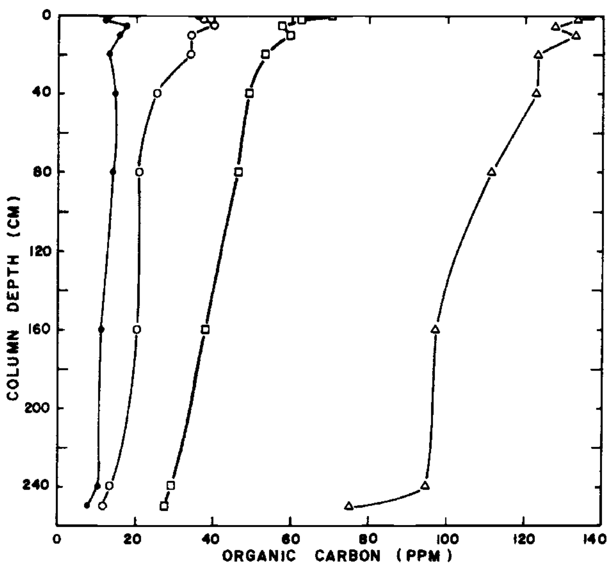

Fig. 2. Organic carbon concentrations of samples from various depths along soil columns flooded with secondary sewage effluent supplemented with different levels of organic carbon as dextrose. (Average organic C concentrations entering the columns were 15(●), 40(○), 80(□), and 150(△) ppm.

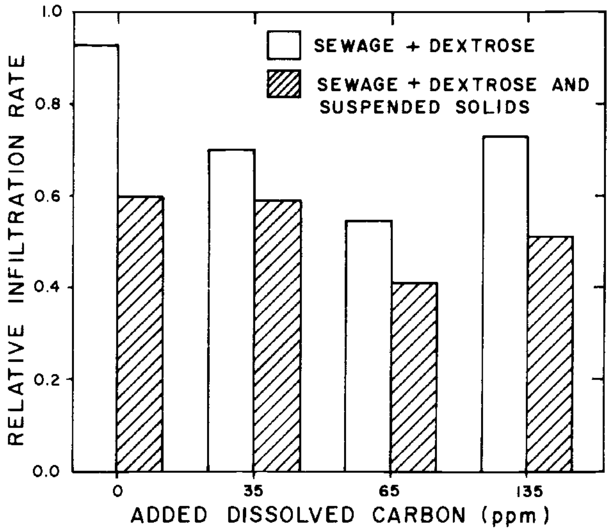

Fig. 3. Relative infiltration rates of soil columns flooded with secondary sewage effluent. Average rates during a base period when all columns were flooded with sewage only were taken as 1.0. Total carbon concentrations were 15, 50, 80, and 150 ppm, and the base period rates for the columns used for the different treatments were 59, 51, 49, and 59 cm/day, respectively.

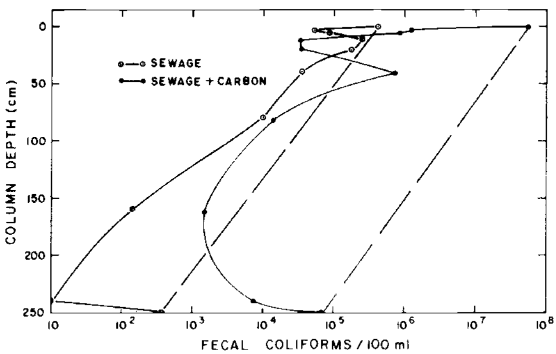

Fig. 4. Fecal coliform counts of samples from various depths along soil columns flooded with secondary sewage effluent supplemented with organic carbon as dextrose.