Title

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Virus, Phosphorus, and Nitrogen Removal in Onsite Wastewater Treatment Processes

Abstract

Onsite wastewater treatment systems were operated at the UC Davis wastewater treatment facility for investigation of the fate of indigenous coliphage, nitrogen, and phosphorus in these systems. The treatment systems were selected because of their high efficiency and role in the future of onsite wastewater treatment. The treatment systems included (a) three high porosity, high surface area multi-pass biofilm reactors, (b) two submerged aerated biofilm reactors; one was inoculated with specific bacteria (i.e., bioaugmentation) for enhanced performance, and (c) a traditional septic tank followed by sand infiltration beds. In addition, soil basins were used to further evaluate the fate of contaminants after discharge from a treatment process to the environment. The septic tanks were found to remove less than 12.5 to 23.4 percent of nitrogen, 0 to 6.7 percent of phosphate, and 16.5 to 25.3 percent of virus, from the influent. The textile biofilters were found to remove 35.2 percent of nitrogen, no phosphorus, and 82 percent of virus from septic tank effluent. The sand beds were found to remove 12.8 percent of nitrogen, no phosphorus, and 96.4 percent of virus. After installation of the aeration systems, the sand bed performance improved for all parameters measured. In the soil infiltration system, all virus were removed and nitrogen and phosphorus were reduced to concentrations of 2 mg/L after passing through 30 in of Yolo loam soil.

Introduction and problem statement

The use of onsite treatment processes accounts for a significant amount of wastewater management in the United States, currently estimated to serve around 25 percent of the population (Crites and Tchobanoglous, 1998). A wide variety of processes exist, ranging from wastewater containment and disposal systems, to processes for full treatment and reuse (Leverenz et al., 2002). The conventional septic tank and leachfield are designed to remove particulate material and some of the organic load to facilitate long-term infiltration of effluent into soil. It has been found, however, that many conventional septic and leachfield systems are failing as indicated by effluent surfacing or adversely impacting groundwater. Because of the difficulties encountered with conventional septic and leachfield systems, many areas are requiring onsite wastewater treatment systems for new developments as well as retrofitting existing developments. These systems are a watertight alternative to the conventional sewer, and typically at a fraction of the cost due to the avoided infrastructure. Onsite treatment systems may service a single building or, preferably, a number of buildings (e.g., a small community or subdivision). To protect water resources and human health, these systems should be properly designed and meet certain performance standards. The effluent concentration of nutrients and pathogens are needed to characterize the effectiveness of onsite wastewater treatment systems.

Systems used for nitrogen removal typically operate by first subjecting the wastewater containing reduced nitrogen, such as the effluent from a septic tank, to an aerobic environment where nitrification can occur. Following nitrification, a carbon source must be added to the nitrified wastewater to create an anoxic, or reduced condition. Complete nitrogen removal is easily accomplished if the carbon source used is applied at the correct concentration and on an ongoing basis. However, the use of an external carbon source may be undesirable in some situations because of the additional maintenance needs and operating costs. An alternate method of denitrification utilizes the carbon present in the wastewater, typically primary or septic tank effluent, to create a reducing environment. The most common example being when nitrified effluent is blended with septic tank effluent in an anoxic tank. Because the carbon containing wastewater also may contain a significant concentration of nitrogen, complete nitrogen removal is limited.

Phosphate is of concern in aquatic systems where phosphorus may serve as a limiting nutrient, such as near lakes and rivers. In onsite wastewater treatment systems, the removal of phosphorus is usually accomplished through precipitation with polyvalent metal ion salts or adsorption on a material surface, examples include expanded clay aggregates and iron containing materials. Phosphorus removal in municipal activated sludge plants is generally accomplished through biological uptake and subsequent sludge wasting and removal activities. Regular sludge removal is not viable for most onsite treatment systems due to their dispersed nature and the complexity of sludge management processes.

Pathogens are of concern because of the possibility that these disease-causing organisms will travel to and persist in groundwater, followed by human ingestion. A variety of indicators are used to characterize the ability of an onsite treatment system to remove biological agents, including total coliform counts, fecal coliform counts, and coliphage counts. The mechanisms of microbial destruction in biological wastewater treatment systems is not well understood, but experiments by Emerick et al. (1997) provide some insight. It was found that coliphage removal in intermittently dosed sand filters was a function of the wastewater dose volume and frequency. The thin liquid film flow over the attached growth organisms resulted in absorption of the virus and destruction within the biofilm. The removal of virus in septic systems and alternative onsite treatment systems is, however, not well characterized.

Objectives

The research conducted was focused on the following topics:

- Characterization of nitrogen transformation and removal in representative onsite wastewater treatment systems, including process limitations to complete nitrogen removal.
- Evaluating the potential for septic tanks, onsite treatment systems, sand beds, and soil infiltration for the removal of phosphorus.
- Coliphage removal in septic tanks, onsite treatment systems, and in soil.

Materials and methods

The results provided in this report were obtained from experiments conducted at the wastewater treatment experimental and pilot facilities located at the UC Davis wastewater treatment facility. Wastewater was obtained from headworks of the UC Davis wastewater treatment facility following communition and coarse screening. The wastewater was then distributed to septic tanks for experimental treatments, as described below.

Treatment processes. Three basic treatment processes were used for characterizing the performance of onsite wastewater treatment processes: (1) Treatment of septic tank effluent using a multi-pass textile biofilter, followed by distribution to soil containers; (2) Treatment of septic tank effluent using a submerged aeration process. The aeration device was placed directly in the second compartment of a septic tank and effluent was discharged separately to shallow sand filters and soil containers. In addition, one experimental treatment was inoculated with bacteria reported to increase treatment efficiency; and (3) Discharge of septic tank effluent separately to shallow sand filters and soil containers without additional treatment.

The textile biofilters used in this study have been previously described in Leverenz et al. (2001). The principle of operation is a high porosity synthetic textile used for biofilm attachment and growth. The high surface area facilitates a high biomass concentration that is able to accomplish biochemical reaction at a high rate. These biofiltration modules were operated at a septic tank effluent loading rate of 33 $gal/ft^2 \cdot d$ and a recirculation ratio of 2 to 1. The textile biofilters were dosed 150 times per day with 25 L per dose. The septic tank used for influent conditioning had a volume of 2000 gal and was operated with a 2 day hydraulic retention time (HRT), distributing 330 gal/d to each biofilter module. The anoxic tank had a liquid volume ranging from 170 to 200 gal for denitrification. Soil basins were filled with local Yolo loam soil and equipped with a shallow pressure distribution system. Textile biofilter effluent was loaded to the soil basins at a rate of 1 $gal/ft^2 \cdot d$. Pans were embedded in the soil for capturing samples at different depths.

Three additional 1200 gal septic tanks (loaded at 330 gal/d each) were used to condition effluent before discharge to sand beds. The sand beds were loaded to 10 $gal/ft^2 \cdot d$ until clogging occurred. A steady-state rate of infiltration of 0.8 to 1.2 $gal/ft^2 \cdot d$ was obtained under the clogged conditions. Circular (with diameter of 4 ft, depth of 2 ft) galvanized tanks were used as containers for the sand beds, with three units per septic tank. The sand beds consisted of a gravel underdrain, 12 in of medium sand (ES = 0.5 mm, UC = 3), and 8 in of gravel on top of the sand for distribution of septic tank effluent.

Data was collected on the septic tank and sand bed system from July 2003 until March 2004, when aeration processes were installed in the second compartment of two of the septic tanks. The submerged aeration process used was installed in the second compartment (1/3 volume) of a 1200 gal septic tank. A 40 W diaphragm type linear air pump was used to deliver air to a flexible membrane type fine bubble diffuser for aeration purposes. One of the aeration systems was installed with a bacterial inoculum, a process known as bioaugmentation. The inoculum consists of mostly Bacillus species, initially in spore form, mixed with compost and growth factors. The bacteria used was the Maintain D inoculum supplied by American Biosystems (Roanoke, VA, http://www.americanbiosystems.com) and were reportedly selected for their high enzyme production. Upon initiation of the aeration process, the clogged condition of the sand beds was mitigated (Leverenz et al., 2004). The aeration process was operated for 6 weeks until operational problems developed, primarily high effluent BOD_5 and TSS concentrations, and the manufacturer recommended stopping the process.

Sampling. Sampling was conducted weekly during the periods of steady-state operation. Samples were collected in 1 L or 0.5 L containers and analyzed the same day for most parameters. When appropriate, samples were stored at 4 °C until measurements could be made. All wastewater samples were collected as grab samples.

Analytical methods. The methods of analysis used are based on those found in Standard Methods (1998) or as recommended by the manufacturer, as described below.

- Five day biochemical oxygen demand (BOD_5) was determined by preparing 3 dilutions, bracketing the expected value (Method 5210 B, 1998). Dissolved oxygen (DO) was measured with a YSI 59 DO meter (YSI Incorporated, Yellow Springs OH) and YSI 5905 BOD Probe and used according to the membrane electrode method (4500-o G, 1998).
- Total and volatile suspended solids (TSS and VSS, respectively) were determined by gravimetric analysis (Method 2540, 1998).
- Indiginous coliphage was measured by plaque forming units (PFU) plate count method using E. Coli #15597 as the host organism. Plates were incubated for 8 to 12 hours at 37 °C before counting plaques.
- Phosphate, nitrate, and nitrate samples were filtered through a 0.2 μm syringe filter and then measured using a Dionex ion chromatograph equipped with an anion exchange column.
- Ammonia was measured using a Conductivity detector (338) from Timberline Instruments (Denver, CO).
- TKN samples were determined using Hach Digestahl units (Method 4500-N_{org}).
- Turbidity was estimated with a Hach Turbidimeter (Model #2100A, Hach Company, Loveland CO).

Results and discussion

The primary findings of this study are related to effectiveness of the bioaugmentation and the efficiency and operational characteristics of the treatment processes for the removal of indigenous coliphage virus, dissolved phosphorus, and total nitrogen. These parameters are discussed below and summarized in Table 1. In addition to these parameters, several conventional parameters were also measured, including BOD_5, TSS and VSS. A summary of these measurements is presented in Table 1.

Bioaugmentation. The performance of the aeration process in which the bacillus bacterial inoculum was added was not different from the control aeration process without the bioaugmentation. Several possibilities exist to explain this apparent lack of effectiveness: (1) the bacterial inoculation rate was too low to out compete the indigenous organisms, (2) the indigenous bacteria in the system are equally effective at wastewater treatment as the bacteria that were added artificially, or (3) there was a problem with the bioaugmentation which inhibited the bacteria, for example predation. Additional studies are needed to characterize which of these possibilities resulted in the failure of the bioaugmentation. Field studies are currently underway to investigate the nature of these systems.

Virus removal. As described above, the virus removal capability was evaluated using indigenous coliphage. It is expected that the removal of human viruses will have similar removal characteristics as indicated by the naturally occurring coliphage, given the similarity in size and structure. The coliphage concentration measured in the effluent of various processes is shown in Fig. 1 for the sand beds, and in Fig. 2 for the textile biofilters. Note that the probability distributions shown in Figs. 1 and 2 are log-normal in nature, and that the summary data shown in Table 1 are computed as the geometric mean and geometric standard deviation (Tchobanoglous et al., 2003). There was a small removal of coliphage in the septic tank processes, 16.5 and 25.3 percent for the septic tank feeding the textile biofilters and sand beds, respectively. In addition, virus survival with soil depth is shown in Fig. 3.

Using the data shown in Figs. 1 and 3, the range of expected results can be determined. In the medium sand bed, receiving septic tank effluent, virus removal is on the order of 96 percent. In the loam soil however, receiving effluent from the textile biofilters processes, no virus was detected after the depth of 18 inches. The possibility of virus breakthrough in sandy soils receiving septic tank effluent is important to the design of onsite wastewater management systems. In many cases, sandy soil is selected for citing of leachfield systems due to the high permeability of these soils, however, the possibility of virus transport to groundwater is increased. As shown in Table 1, the virus removal capability of the sand beds was improved when the aeration system was added to the septic tank, with an average virus removal of 99.2 percent. The aeration process that included bioaugmentation was not found to have different results compared to the non-bioaugmented aeration process, and these data have thus been combined for the purposes of the statistical analysis shown in Table 1.

The average virus removal in the aerobic textile biofilter was 82.0 percent. While the removal in the sand bed is greater than in the biofilter, the higher loading rate to the textile biofilter is expected to affect virus removal. The average loading rate to the textile biofilters was increased by a factor of thirty during the experiment. Additional studies are needed to determine the removal mechanism and the importance of process design variables, such as loading rate, in the removal of viruses for textile biofilters-type systems. The low turbidity of effluent from the sand beds and textile biofilters may facilitate the use of ultraviolet (UV) light for disinfection. The requirement of disinfection for onsite treatment systems is expected to be required in areas where the possibility of groundwater impacts is high.

Phosphorus removal. None of the processes under consideration were able to remove a significant amount of phosphorus. Negligible amounts of phosphorus were removed by passing water through septic tanks (Figs. 4 and 5), filtration through sand beds (Fig. 4), and textile biofiltration (Fig. 5). There may have been some short-term uptake in the sand beds receiving effluent from the aerated systems, 12 percent as computed from the data shown in Table 1. However, as shown in Fig. 3, approximately 61 percent of phosphorus was removed after passage through twelve inches of soil. Adsorption and/or precipitation of phosphorus in the soil is expected to eventually reach equilibrium and allow influent phosphorus to pass through. The phosphorus concentration in the water reached an asymptote around the value of 2 mg/L, at soil depths greater than 18 inches.

The removal of phosphorus in onsite wastewater treatment systems and in some sandy soils (depending on the content of polyvalent metals in the soil) is not expected based on the findings of this research. Even after passage through 30 inches of loam soil, an average 2 mg/L of phosphorus was found in all samples. Therefore, if phosphorus removal is deemed necessary, a process specifically designed for phosphorus removal should be used. A description of these systems may be found in Leverenz et al. (2002).

Nitrogen removal. There was a small change in the concentration of nitrogen entering and exiting the septic tanks, 23.4 and 12.5 percent reduction for the septic tanks loading the textile biofilters and sand beds, respectively, as shown in Figs. 6 and 7. While some nitrogen accumulates in the sludge zone of the tank, the long time frame over which this occurs and the amount of nitrogen tied up in particulate material entering septic tanks can not be relied upon for significant nitrogen removal. It should be noted that any nitrite or nitrate nitrogen discharged to a properly operating septic tank will be readily denitrified, while reduced nitrogen will readily pass through anaerobic and anoxic processes.

In the sand beds, an average nitrogen removal, relative to the septic tank effluent, of 12.8 percent was measured (Fig. 6). Because the septic tank effluent was not nitrified, this nitrogen loss is expected to have come from biological uptake and filtration and entrapment of nitrogen containing particulate matter. In sandy soils with low cation exchange capacity and receiving septic tank effluent, a large fraction of nitrogen may reach the groundwater or migrate to surface waters under the appropriate flow conditions. Alternately, when the effluent was pre-nitrified using the aeration process, an addition 13 percent (25.8 percent total) nitrogen removal was obtained. This additional removal may have occurred through additional organic matter entrapment and microscale denitrification, where small anoxic pockets and sufficient organic matter exist to support denitrification. However, it should be noted that the oxidized nitrogen moved readily through the sand beds.

The nitrogen control strategy used in the textile biofilters utilized alternating oxidizing and reducing conditions, by multi-pass effluent recirculation to an anoxic tank, to promote denitrification (Leverenz et al., 2001). A probability analysis of the effluent nitrogen from the textile biofilters is presented in Fig. 7. The average nitrogen removal is these systems was 35.2 percent, based on the nitrogen concentration in the septic tank effluent. The style of denitrification used in the textile biofilters utilizes the organic matter in the septic tank effluent, when blended with the nitrified septic tank effluent, to create an anoxic zone where the oxidized nitrogen can serve as the electron acceptor. The endpoint of the reduction reaction is the formation of nitrogen gases, which are ventilated out of the system. There are some limitations to the amount of denitrification possible using this method that were determined during this study: (1) the use of nitrogen containing septic tank effluent for the anoxic component of the reaction results in residual nitrogen in the final effluent, (2) the low carbon to nitrogen ratio of septic tank effluent used in this study, (3) and high amount of oxidation which occurs in the textile biofilters. To resolve these problems, an external carbon source not containing nitrogen may be used for the anoxic reaction, however, this increases the maintenance needs of the system and lowers the overall system reliability. Based on these observations, it is hypothesized that single-pass denitrification may be possible through manipulation of the nitrification reaction with carbon limited wastewater.

The textile biofilters effluent was subsequently discharged to the soil basin, as described above, and the nitrogen profile in the soil is shown in Fig. 3. As shown in Fig. 3, the nitrogen concentration after passing through 30 inches of soil is around 2 mg/L, present as nitrate nitrogen. The kinetics of nitrogen removal in the soil are demonstrative of need for adequate soil between water sources and soil infiltration systems to allow time for passive nitrogen removal. However, after passage through only 6 inches of soil, the effluent was below the drinking water standard of 10 mg/L for nitrate. Pre-nitrification and low soil loading rates in the upper soil horizon are considered critical for nitrogen control in soil based infiltration systems.

Conclusions

The incorporation of a bacillus bacterial inoculum was not found to affect the aeration treatment process for the parameters that were measured. Additional studies are needed to characterize the effectiveness of the inoculation process to determine if this may have been responsible for the ambiguous performance.

The ability of onsite wastewater treatment processes to remove viruses and the nutrients phosphorus and nitrogen was evaluated. It was found that textile biofiltration and percolation through sand beds result in 82.0 and 96.4 percent virus removal, respectively. Septic tanks were found not to provide adequate virus removal. Infiltration of effluent from the textile biofilters was found to remove all viruses after passing through 18 inches of Yolo loam soil. Phosphorus removal was not found to occur significantly in any of the systems studied except for in the soil basin, where 61 percent phosphorus reduction occurred after passing through 18 inches of soil. The removal of phosphorus will require specifically designed treatment processes if it is to be accomplished independent of soil based infiltration systems. Partial nitrogen removal occurred in the septic tanks by the accumulation of nitrogen containing solids in the sludge zone of the tank. In the sand bed 12.8 percent nitrogen removal occurred, while 35.2 percent nitrogen removal occurred in the multi-pass textile biofiltration systems.

The use of onsite wastewater treatment systems have several important advantages over centralized treatment systems. Characterization of their performance and operational characteristics will allow for these systems to be applied appropriately to meet desired treatment goals and be protective of water resources and human health.

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Table 1

Summary of parameters measured during testing of onsite wastewater treatment systems

		Parameter						
Process	Statistic	Five day Biochemical oxygen demand (mg/L)	Total suspended solids (mg/L)	Volatile suspended solids (mg/L)	Turbidity (NTU)	Total nitrogen (mg-N/L)	Dissolved phosphate (mg-P/L)	Indiginous coliphage (PFU/mL)
Influent to all septic tanks	Mean	129	158.2	137.2	68.9	30.4	5.2	778.4[a]
	Range	26 to 303	16.3 to 394	14.4 to 384	47 to 114	6.2 to 97.6	1.5 to 30.2	20 to 21500[b]
	St. dev.	55.7	80	77.5	30.5	17.4	5.6	3.5
Septic tank for textile biofilters	Mean	54.5	30.7	22.4	51	23.3	4.85	650.3
	Range	24 to 89	12 to 68	9 to 54	35 to 73	11.2 to 117	4 to 19.4	60 to 7500
	St. dev.	15.5	14.4	10.4	13.7	20.5	3.3	3.5
Textile biofilters	Mean	8.2	8	5.5	7.4	15.1	5.15	117.0
	Range	0.8 to 15.3	1 to 43	1 to 33	2.5 to 36.3	7.5 to 28.3	4 to 8.4	18 to 4684
	St. dev.	3.6	7.4	5.8	10	4.3	4.4	2.6
Septic tanks for sand beds	Mean	72.6	21.5	20	115.4	26.6	5.2	581.6
	Range	29 to 122	11 to 56	6 to 55	81.7 to 149	15.1 to 34.2	2.9 to 11.3	15 to 13050
	St. dev.	21.7	9	10.3	47.6	4.6	1.5	23.1
Sand beds	Mean	18.3	5	4.2	17	23.2	5.2	21.1
	Range	2 to 73	0 to 24	0.1 to 24	4.4 to 24.2	13.7 to 32.2	2.4 to 7.2	0.1 to 3940
	St. dev.	14	4.2	4.9	8.3	4.2	0.8	23.1
Septic tanks used with aeration	Mean	63.3	67.5	15	33	28.3	5	97.3
	Range	11 to 178	10 to 119	9 to 68	13.5 to 49.8	23.9 to 35.9	4.1 to 6.7	21 to 990
	St. dev.	48	39.7	26.3	13.2	4.2	0.9	3.7
Sand beds used with aerated tanks	Mean	12.2	2.2	2.5	3.4	21	4.4	0.8
	Range	2 to 22	0 to 6	1 to 4	2.1 to 18.5	17.9 to 28	0.9 to 5.9	0 to 8
	St. dev.	5.9	2.1	1	5.5	3.3	1.5	5.6

[a] Reported as geometric mean

[b] Reported as geometric standard deviation

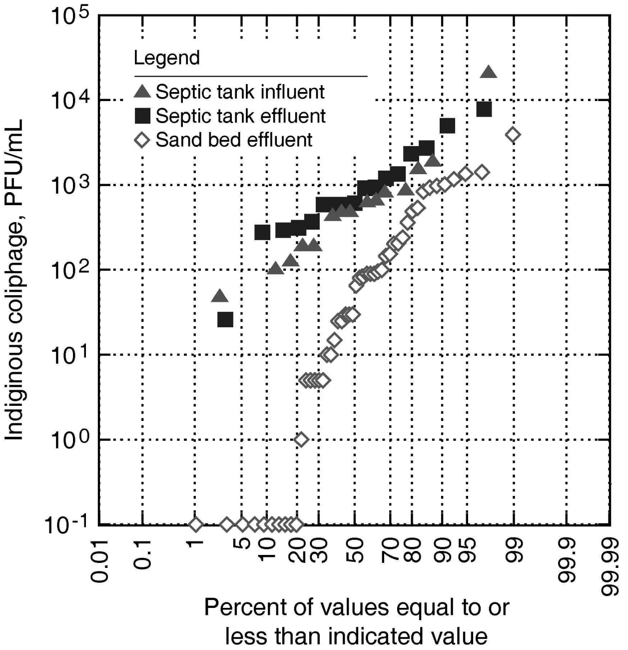

Figure 1
Probability distribution of indigenous coliphage concentrations for influent wastewater, septic tank effluent, and after percolation through a sand bed.

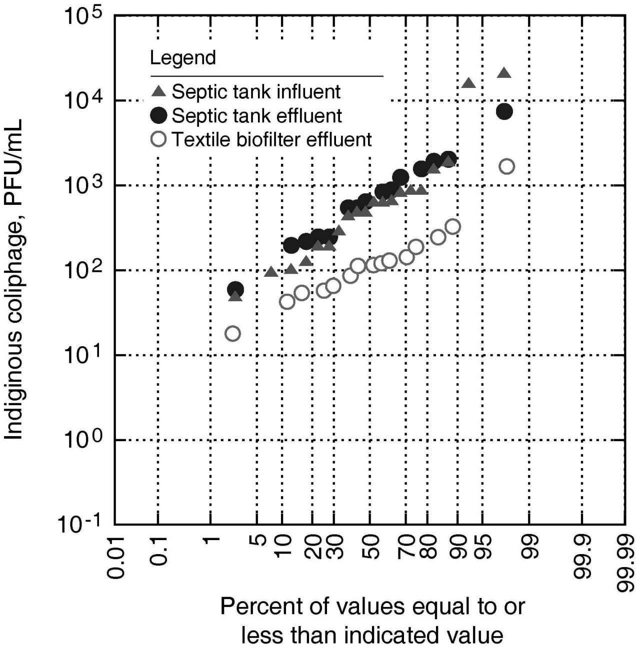

Figure 2
Probability distribution of indigenous coliphage concentrations for influent wastewater, septic tank effluent, and treatment in a textile biofilter.

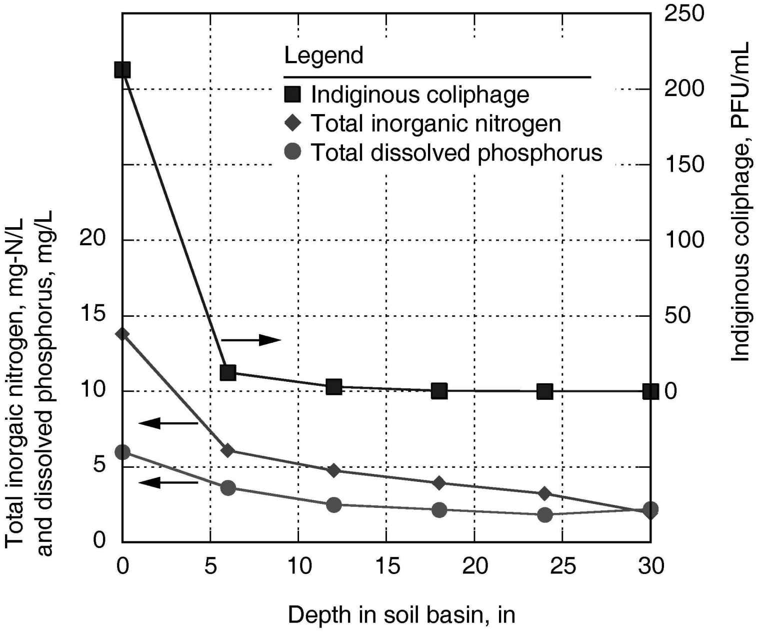

Figure 3
Concentration profiles for indigenous coliphage, total inorganic nitrogen, and total dissolved solids for infiltration into a soil basin

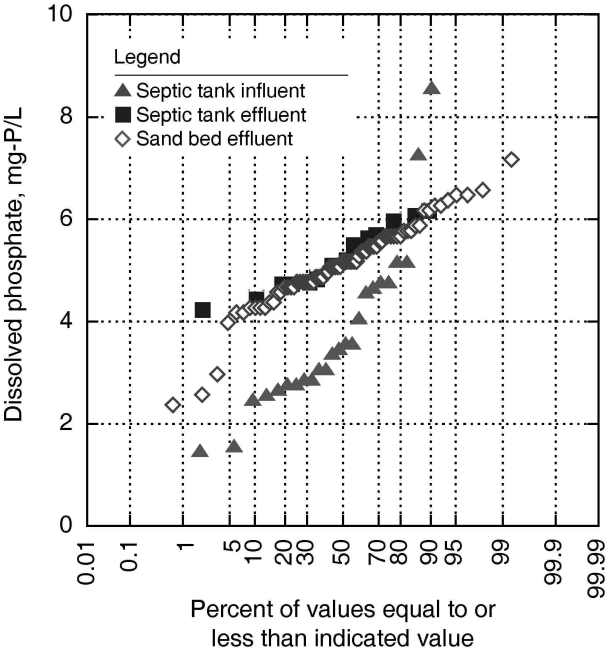

Figure 4
Probability distribution of dissolved phosphate concentrations for influent wastewater, septic tank effluent, and after percolation through a sand bed.

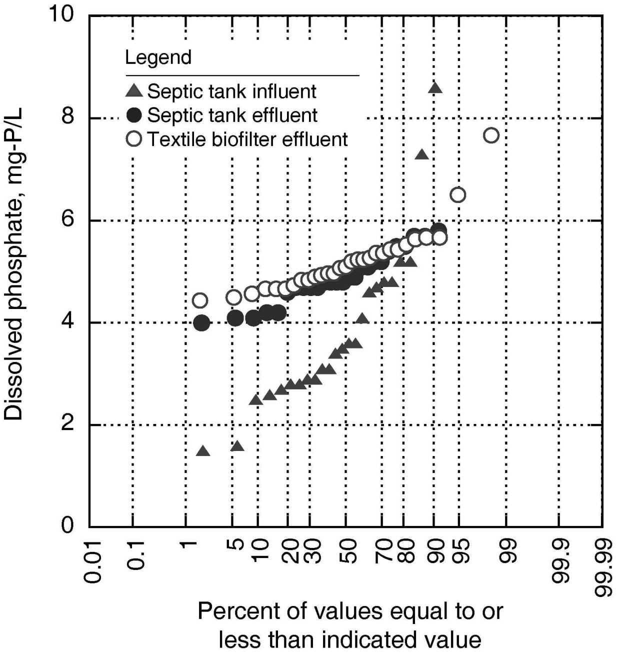

Figure 5
Probability distribution of dissolved phosphate concentrations for influent wastewater, septic tank effluent, and after treatment in a textile biofilter.

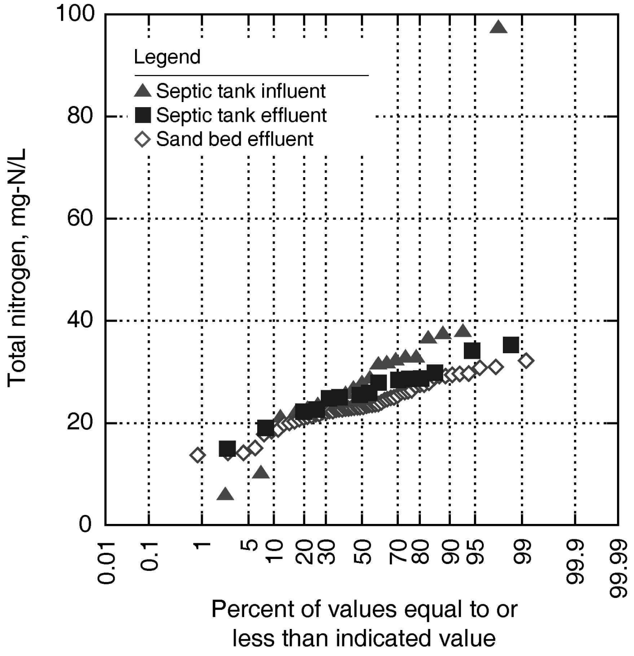

Figure 6
Probability distribution of total nitrogen concentrations for influent wastewater, septic tank effluent, and after percolation through a sand bed.

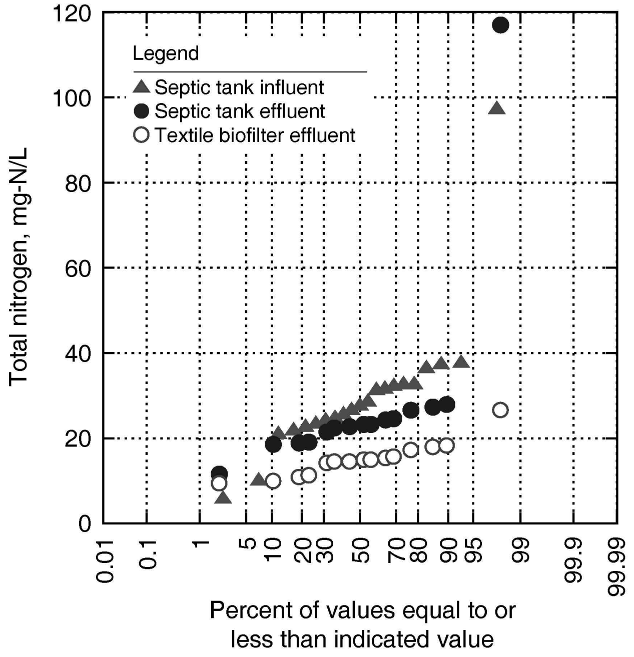

Figure 7
Probability distribution of total nitrogen concentrations for influent wastewater, septic tank effluent, and after treatment in a textile biofilter.