United States
Environmental Protection
Agency

National Risk Management
Research Laboratory
Ada, OK 74820

Research and Development

CR-823808-01-0

EPA

ENVIRONMENTAL RESEARCH BRIEF

Evaluation of Alternative Constructed Wetland Systems for Swine Wastewater Treatment

Frank J. Humenik[1], Patrick G. Hunt[2], Ariel Szogi[3], M. Rice[3], S. Broome[4], G. Stem[5] and C. Smith[6]

Abstract

Water quality problems associated with confined swine production have become a national focus. There is an urgent need to find functional and affordable treatment methods. Therefore, investigations were conducted on pretreatment nitrification of wastewater before treatment by constructed wetlands. The main wetlands were 3.6 × 33.5 m with two cells in series. In these wetlands, mass reduction of nitrogen (N) (ammonia plus nitrate) and total phosphorus (TP) were about 90% and 70 %, respectively, when N loading was at 3 kg/ha/day. At 10 kg N/ha/day the mass removal was greater, but the mean N removal efficiency dropped to 68%. At the higher rates TP removal was less than 20%. It was determined that the wetlands were nitrate-N limited for denitrification; hence, nitrification experiments with overland flow and media filtration were conducted.

The pilot-scale overland flow (OLF) treatment system was a 4 × 20 m plot with 2% slope. In the sandy soil of this coastal plain site, a liner was required for overland flow to function as a surface flow system and protect ground water quality. Total N treatment efficiencies were affected by the duration of the application. Longer duration of treatment (8 hrs/day) had higher efficiencies (70%) than shorter duration (4 hrs/day) of treatments (35% to 42%). This was to be expected, since the objective of this experiment was to promote nitrification rather than the optimal nitrification/denitrification blend. The nitrate-N recovery in the outflow was 5% to 7% of the TN mass inflow. As expected, TP removal was low for the OLF in this mode of operation.

A pilot scale media filter reactor (MFR) for nitrification, that consisted of a 1-m^3 tank filled with marl gravel, provided effluents with high nitrate-N levels (>200 mg/L). To maintain high nitrification rates, it required an input of alkalinity to maintain a nonacidic environment in the wastewater. Although, the reduction of initial levels of total suspended solids (TSS) and chemical oxygen demand (COD) concentrations was significant, further reduction of oxygen demand by solids removal prior to media filter treatment may be necessary to attain long term high nitrification rates. The long-term removal of TP

[1] College of Agriculture and Life Sciences, Animal Waste Management Programs, North Carolina State University, Raleigh, NC 27695
[2] USDA-ARS, Coastal Plains Soil, Water, and Plant Research Center, Florence, SC 29501
[3] Biological and Agricultural Engineering Department, North Carolina State University, Raleigh, NC 27695
[4] Soil Science Department, NC State University, Raleigh, NC 27695
[5] USDA-Natural Resources Conservation Service, Raleigh, NC 27609
[6] USEPA, National Exposure Research Laboratory, Athens, GA 30605

Printed on Recycled Paper

was limited by the sorption capacity of the gravel.

When nitrified wastewater was added in batch applications to wetland microcosms the nitrogen removal rate was four to five times higher than when non-nitrified wastewater was added. Wetland microcosms with plants were more effective than those with bare soil. This was likely due to the low soluble carbon of the wastewater. These results suggest that vegetated wetlands with nitrification pretreatment are viable treatment systems for removal of large quantities of nitrogen from swine wastewater.

Research Brief

Site Characteristics

The research site, a nursery operation of 2600 pigs (average weight = 13 kg) uses a flushing system to recycle liquid from a single-stage lagoon. The average liquid volume of the lagoon was 4,100 m^3. On a mass basis, the lagoon liquid contained only 17% of the TN* which entered the lagoon (Szögi et al, 1996). Typically, the lagoon effluent contained 365 mg/L of total Kjeldahl nitrogen (TKN), mostly (> 95%) as ammonia-N, 93 mg TP/L and 740 mg COD/L.

Constructed Wetlands

Three sets of two 3.6 x 33.5 m wetland cells were constructed adjacent to the treatment lagoon in 1992. They contained either natural wetland plants or water-tolerant agronomic plants (Nathanson et al., 1984). Nitrogen results are reported as ammonia plus nitrate-N because organic-N** was present in negligible amounts in the inflow and outflow. Initially, a N (ammonia+nitrate) loading rate of 3 kg/ha/day specified for advanced treatment for stream discharge was used, but it was increased to 10 kg/ha/day during the second year. These loading rates were obtained by mixing the lagoon liquid with fresh water before it was applied to the wetland. Nutrient removal efficiency was similar in both rush/bulrush and cattail/bur-reed plant systems (Table 1). Mean mass removal of N was 94% at the loading rate of 3 kg/ha/day and decreased to 68% at the higher rate of 10 kg/ha/day. Phosphorus mass removal efficiencies ranged from 40% to 100% at TP loading rates <1 kg/ha/day and varied from 20 to 80% when TP loading rates were 1 to 4 kg/ha/day. Flooded rice yield was 4.5 Mg/ha, and soybean grown in saturated culture yielded 2.8 Mg/ha. Redox conditions were highly anaerobic in the soils of all wetlands. Denitrification enzyme assays indicated that the wetland soils were nitrate limited for denitrification (Hunt et al., 1995).

---

* TKN is the sum of NH_3-N plus organic-N.

** TKN is the sum of NH_3-N plus organic-N

Table 1. Nitrogen loading rates and mass removal efficiencies for the constructed wetlands, Duplin Co., NC (June 1993-January 1995). Data from Szogi et al. (1995).

Nitrogen	*System*	*Mass Removal*
3 kg ha/day	*Rush/bulrush*	*94*
	Cattail/bur-reed	*94*
10 kg ha/day	*Rush/bulrush*	*63*
	Cattail/bur-reed	*73*

% Mass Removal = % mass reduction of N (NH_3-N + NO_3-N) in the effluent with respect to the nutrient mass inflow.

Conclusion

These results suggest that constructed wetlands are excellent for mass removal of N from swine lagoon liquid. However, at the high loading rates necessary for substantive mass removal, constructed wetlands do not produce an effluent acceptable for discharge. Mass N removal by wetlands should be increased by pre-wetland nitrification treatment of wastewater such as overland flow or media filtration.

Overland Flow

The OLF treatment unit consisted of a 4 x 20 m plot with 2% slope. It was constructed in the summer of 1995 (Szögi et al., 1996). Sandy loam topsoil was excavated to 20 cm. Then, a plastic liner was installed and covered with the excavated topsoil. The OLF was planted to a mixture of fescue, coastal bermuda grass, and reed canary grass. After grass cover was established, lagoon liquid was applied five days a week. Applications, with hydraulic rates of 2.5 to 3.0 cm/d, were made in eight hours in 1995. In 1996 and 1997 applications were reduced to four hours to increase the surface effluent flow. Hydraulic losses ranged from 0.5 to 0.8 cm per day for the three seasons: August-December 1995, August-December 1996, and March-August 1997. These values are well within the range of expected evapotranspiration losses.

Ammonia and nitrate-N concentrations in samples of surface runoff water taken at 1 m intervals down slope confirmed that nitrate-N, which was negligible in the inflow, increased with distance from the application point (Fig. 1). The reduction of ammonia + nitrate-N concentration after treatment was small (13%) with respect to the inflow. This lower concentration was probably due to denitrification (Humenik et al., 1975; Hunt and Lee, 1976). However, the main process was nitrification because of the high hydraulic loading rate. Wastewater treatment by OLF resulted in substantial reduction of ammonia-N concentrations on the surface outflow (30%). Ammonia-N concentrations remained constant in the first 5 m of the OLF plot but started to decline beyond 5 m. At this distance, nitrate-N concentration increased up to 30% of the initial 300 mg ammonia-N/L. These changes are similar to those reported by Carlson et al. (1974). Beyond the 17 m distance from the application point, the nitrate-N in the surface runoff quickly declined with a corresponding increase on ammonia-N concentrations. This was likely due to the mixing of surface and subsurface streams at the outlet of the plot. Other detailed sampling at 1-m intervals downs slope (data not presented), indicated that nitrification was variable along the OLF with respect to time elapsed since application started. Nitrate-N production declined in time along the OLF. This resulted in lower recoveries of nitrate-N in the outflow than what was expected from data presented in Figure 1.

Mean application rates for TN and TP were similar in 1995 and 1996. In 1997, the TN application rate was about 32% higher than in 1995 and 1996. These differences are due to higher concentrations of N in the anaerobic lagoon and in the inflow to the OLF (Table 2). In 1995, the surface flow was consistently lower than the subsurface flow in days without rainfall, and occasionally the surface flow was non existent. Therefore, the duration of the application was reduced in 1996 and 1997 in order to have a daily measurable surface runoff. With the shorter duration, treatment efficiency was reduced by about half.

The TP treatment efficiency dropped from 64% in 1995 to 21% in 1997 indicating that the OLF system had a limited capacity for sustained removal of phosphorus (Table 2). The lowest efficiency for phosphorus removal was obtained in 1997 when application rates were about 60% higher than in 1995 and 1996. Although the OLF system was not designed to remove phosphorus, early in the project an attempt was made to remove phosphorus by addition of alum (aluminum sulfate) to the lagoon wastewater prior application onto the OLF. This pre-treatment was discontinued because of the large amount of alum required for an adequate removal of phosphorus and the enormous amount of sludge generated by the addition of alum.

Conclusions

The OLF system can treat a large amount of nutrients per unit area. Total N treatment efficiencies were affected by the duration of the application. Longer duration of treatment (8 hrs/day) had higher efficiencies than shorter duration (4 hrs/day) of treatments (35% to 42%).

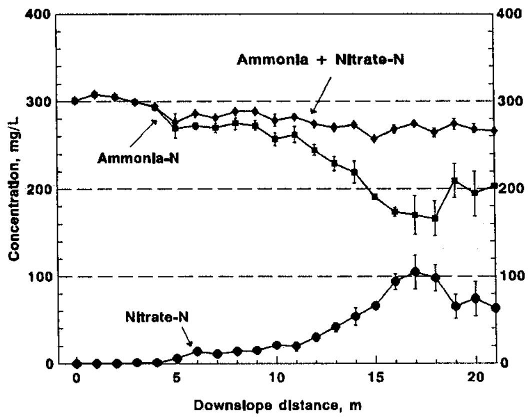

Figure 1. Changes in ammonia-N, nitrate-N and ammonia + nitrate-N concentrations of surface flow with distance from the application point along the OLF plot. Samples were taken three hours after starting application. Data points represent means (n=3), and vertical bars are one standard error of the mean.

Table 2. Mean daily application rates, wastewater application schedule, and nutrient treatment efficiencies of the overland flow system for 1995, 1996, and 1997.

	Mean Application Rates kg/ha/day		*Wastewater Application Schedule*		*Treatment Efficiencies** %*		
Year	*TN **	*TP*	*Duration hrs/day*	*Days No.*	*TN*	*TP*	*NO_3-N† Recovery*
1995	*70*	*11*	*8*	*79*	*70*	*64*	*5*
1996	*64*	*8.5*	*4*	*85*	*35*	*32*	*7*
1997	*99*	*24.2*	*4*	*60*	*42*	*21*	

* *Total Nitrogen = Total Kjeldahl Nitrogen (TKN) + Nitrate-Nitrogen (NO_3-N).*
***Efficiency = (total nutrient mass input - total nutrient mass output/ total nutrient mass in)×100*
† Nitrate-N Recovery = (NO_3-N mass outflow/TKN mass inflow)×100.

Removal of phosphorus also declined as rates increased. Subsurface flow concentration of nutrients indicated that on sandy soils OLF systems require a liner to avoid groundwater contamination.

Media Filter

The MFR consisted of a tank (1.5 m diameter 0.6 m height) filled with marl gravel. The marl gravel had an equivalent calcium carbonate content of 300 g/kg. Gravel particle size distribution was 85% in the 4.7 to 12.7 mm size class and 14% in the 12.7 to 19 mm size class. Pore space of the filtration unit was 57%. The MFR had four sprinklers that provided a fine spray of lagoon liquid. The filtration unit was placed inside another tank with a slightly larger diameter to collect the effluent for recirculation. Performance of the MFR was assessed by the daily change of nutrient content from inflow and outflow in batch and intermittent flow treatments.

Batch Treatment

Lagoon liquid was applied at a hydraulic rate of 606 L/m^2 cross section/d (1007 L/m^3 reactor volume/d) and recirculated between the MFR and a storage tank up to four cycles or passes during six hours each day (Szögi et al.,1997). Inflow mean concentration was 333 mg/L for TN and 82 mg/L for TP. Mean application rate for TN was 202 g/m^2/d (335 g/m^3/d) and the mean TP application rate was 50g/m^2/d (83 g/m^3/d). The mean water pH was 8.2 units and the mean water temperature was 26.7 °C. The organic loading level was dependent on the treatment capacity of the MFR to reduce COD and TSS levels. Mean concentration of COD and TSS in the inflow were 869 and 521 mg/L, respectively. The MFR removed 54% of COD content after one cycle, but increased cycling did not produce additional COD reduction. Total suspended solids removal after one cycle was 50% of initial levels, and additional cycling reduced TSS levels at a much lower rate of 7% per cycle. Conditions for nitrification in the MFR were favorable with up to 24% of TKN converted to nitrate-N and simultaneous reduction of ammonia-N when wastewater was recycled four times a day. Mean nitrate-N concentration after four cycles was 88 mg/L. In other batch treatment trials nitrification efficiency did not improved with higher number of passes (> 4). Removal efficiencies for total phosphorus (TP) ranged from 37% to 52% (one to four cycles), but long-term phosphorus removal would be limited by the sorption capacity of the gravel.

Intermittent Flow Treatment

The intermittent flow was controlled by a timer that turned a pump on and off in 12 minute intervals. During the pump operation, the liquid was pumped from the storage tank at a rate of 9.5 L/min. This flow was proportionally split by a manually operated ball-valve to maintain a flow rate of 7.6 L/min to the surface of the MFR and a 1.9 L/min rate of outflow from the system. During the same time interval, the lagoon wastewater flowed by gravity into the storage tank with a float-valve maintaining a 757-L volume of wastewater in the tank. Lagoon wastewater was thus applied onto the MFR from 6 a.m. to 6 p.m., five days a week. The MFR was turned off during the weekend. Two grab samples, one from the inflow and one from the outflow, were collected daily at the end of each application for nutrient analysis.

Lagoon wastewater was treated from March 13, 1997 to July 29, 1997. The percentage of nitrification was about 36% without addition of alkalinity. This nitrification rate was significantly improved later on by correcting the alkalinity.

Acidity is a by-product of the biological oxidation of ammonia-N to nitrate-N. Alkalinity in the wastewater neutralizes the acidity produced, but enough alkalinity is necessary to keep the pH between 7.5 and 8.5 to maintain the nitrification process (Anthonissen et al. 1976). During May 1997, spot checks of the inflow indicated that the mean inflow ammonia-N concentration was 357 mg/L and alkalinity was 1950 mg/L. At these levels of alkalinity and assuming optimum conditions for nitrification, only 272 mg/L of ammonia-N could be transformed into nitrate-N (7.2 mg alkalinity/mg NH_3-N). Therefore, the alkalinity was supplemented by adding about 100 g/day of dolomitic lime onto the surface of the MFR from May 27 to July 29, 1997. The results showed that the mean concentration of nitrate-N in the outflow was 56% higher with lime addition than without lime at the same mean levels of TN in the inflow (Table 4). Nitrification efficiency was improved from 36% to 57% by correcting the alkalinity. Inflow and outflow concentrations of TN indicated that N losses were small (Table 3).

Table 3. Mean ($\bar{x}$) concentrations and standard error (SE) of the mean of total Kjeldahl N, ammonia-N, nitrate-N and total N for the inflow, and the outflow of the media filtration unit; and percentage of nitrification estimated from mean concentrations. Wastewater was treated for 46 days without lime and 45 days with lime to correct alkalinity.

		No Lime		*With Lime*	
		Inflow	*Outflow*	*Inflow*	*Outflow*
		mg/l			
Parameter					
TKN	$\bar{x}$	*366*	*221*	*363*	*114*
	SE	*9*	*8*	*7*	*10*
NH_3-N	$\bar{x}$	*340*	*193*	*334*	*106*
	SE	*3*	*8*	*5*	*9*
NO_3-N	$\bar{x}$	*0*	*133*	*2*	*208*
	SE	*0*	*10*	*2*	*13*
*TN**	$\bar{x}$	*366*	*354*	*365*	*321*
	SE	*9*	*7*	*7*	*9*
Nitrification			*36%*		*57%*

* *TN = TKN + NO_3-N*
** *Nitrification = (NO_3-N out)*100 / (TN in)*

Conclusion

When alkalinity was corrected, the MFR provided effluent with high nitrate-N levels that can be further treated in constructed wetlands or be returned to the anaerobic lagoon for denitrification. Although, the reduction of initial levels of TSS and COD concentrations was significant, further reduction of oxygen demand by solids removal prior to MFR treatment may be necessary to attain long term high nitrification rates. The long-term removal of TP was limited by the sorption capacity of the gravel.

Microcosm Studies

Effects of Swine Lagoon Liquid on the Growth of Wetland Plants

The objectives of the microcosm study were to determine the effect of swine lagoon effluent on two wetland plant species, *Juncus effusus* and *Scirpus validus,* and the effects of the vegetation on N removal. The experimental design was a randomized complete block, 2×3 factorial with 3 replications. The three effluent variables were full strength, half strength, and a freshwater control. The vegetation variables were a mixed planting of *Scirpus validus* and *Juncus effusus* compared with no plants. Each of the 18 microcosms had a surface area of one m^2 (2.0 x 0.5 m). Each microcosm was lined with PVC film, filled with sandy loam topsoil to a depth of 22 cm, and planted with eighteen plants of each species.

The lagoon liquid and freshwater treatments were applied using pumps controlled by timers set to apply a total of 7 liters per day in three equal applications. Outflow pipes were set to maintain a water depth of no greater than 10 cm and the outflow was collected in barrels buried at the end of each microcosm. The collection barrels were sampled every two weeks to determine water volume and nutrient concentrations in the water. The hydraulic loading rate of 7 liters per day of full strength effluent supplied about 3 g/m^2/day (30 kg/ha/day)of nitrogen and 0.7 g/m^2 /day (7kg/ha/day) of phosphorus.

During the spring (March to mid-May) plant growth was greatest in the full strength treatment. Total aboveground biomass harvested on May 18, 1995 was 422 g/m^2 for the control, 989 g/m^2 for the half strength treatment and 1810 g/m^2 for the full strength. The amount of N present in the plant tissue at the time of harvest was 4.5 g/m^2 (control), 46.9 g/m^2 (half strength), and 61.1 g/m^2 (full strength). These amounts are equivalent to the N contained in only two days effluent applications.

During most of the growing season, there was no outflow from the vegetated microcosms receiving either half or full strength liquid. With no outflow there was, in effect, 100% treatment. The wetland microcosms were a sink for 15 kg/ha/day for the half strength treatment and 30 kg/ha/day for the full strength. The hydraulic loading rate was well below optimum for the amount of growth that occurred in response to nutrient inputs from the effluent. In early June, water requirements for growth in the full strength treatment exceeded the supply, resulting in a die back of the vegetation. Data from the full strength treatment collected after that time were disregarded.

Sequencing Nitrification-Wetland Treatments

A second microcosm wetland study was established in 1996 to assess sequencing nitrification-wetland treatments. The three treatments were 1) wetland plant treatment; 2) mineral soil + C source (glucose amended) with no plants; and 3) mineral soil with no plants (control). The experiment was a 3x2 factorial (6 treatments) in a randomized complete block design with three replications per treatment. The wastewater was applied in two consecutive batches.

In the first batch, application wastewater enriched with nitrate was applied to the microcosm wetland units at a rate of 190 kg nitrate-N/ha and a retention time of four days. Differences in removal were not significant between the wetland plant treatment and the mineral soil + C source. Results showed about 80% removal of nitrate by treatment 1 (wetland plants) and 2 (mineral soil + C) compared to 14% by treatment 3 (the control with no plants). This removal potential is equivalent, on an annual basis, to about 14,000 kg N/ ha, which is 5.4 times higher than the N removal without nitrification pretreatment. This indicates that the capacity of mass N removal by wetlands can be significantly increased by nitrification pretreatment.

In the second batch application, the wetland plant treatment removed just 58% of the initial nitrate applied (102 kg/ha) compared to the mineral soil + C with no plants treatment that removed 100% of the initial nitrate, while the control (soil) treatment had the lowest removal rate with 31% of the initial nitrate level. These second consecutive treatments indicated that constructed wetlands may become C limited for denitrification when a high mass load of nitrate is applied continuously.

Conclusions

Conclusions on the effect of swine lagoon effluent on the growth of wetland plants were: 1) *Scirpus validus* and *Juncus effusus* grew vigorously in lagoon effluent of 50% concentration; the effect of the 100% concentration on growth was inconclusive because of confounding with inadequate moisture; 2) *Scirpus validus* was better adapted to the conditions imposed by the experiment than *Juncus effusus*; 3) During periods of maximum plant growth, water use by plants receiving 50% effluent was twice that of treatments receiving fresh water only.

When nitrified wastewater was added in batch applications to wetland microcosms the nitrogen removal rate was four to five times higher than when untreated wastewater was added. Wetland microcosms with plants were more effective than those with bare soil. These results suggest that wetlands with nitrification pretreatment are viable treatment systems for removal of large quantities of nitrate-N from swine wastewater.

Summary

The goal of studied wastewater treatment systems was to reduce the impacts animal production units can have on soil, air and water quality. Wetlands by themselves cannot produce an effluent which will consistently meet stream discharge requirements in North Carolina even at the low loading rate of 3 kg/ha/day, but do show promise for high nitrogen mass removals. Wetlands can provide even higher nitrogen removal if the wastewater input is nitrified. The overland flow treatment system provided higher levels of nitrogen and phosphorus mass removal and a lower mass of nitrate in the outflow than the media filter reactor which provided lower levels of nitrogen and phosphorus mass removal and a higher mass of nitrate in the outflow. Sequencing nitrification and denitrification processes such as overland flow, media filtration and constructed wetlands can provide high nitrogen removals and advanced wastewater treatment levels. Such systems provide an alternative to anaerobic lagoons with terminal land irrigation. Odor was not judged to be a problem with any of the swine wastewater treatment systems studied.

References

Anthonisen, A.C., R.C. Loehr, T.B.S. Prakasam, and E.G. Srinath. 1976. Inhibition of nitrification by ammonia and nitrous acid. J. Water Pollut. Control Fed. 48:835- 852.

Carlson, C.A., T.B. Delaney, Jr., and P.G. Hunt. 1974. Overland flow treatment of wastewater. U.S. Army Engineer Waterways Experiment Station Miscellaneous Paper Y-74-3.

Humenik, F.J., R.E. Sneed, M.R. Overcash, J.C. Barker, and G.D. Netherill. 1975. Total waste management for a large swine production facility. p. 68-71. In Proceedings of the Third International Symposium on Livestock Wastes. ASAE, St. Joseph, MI.

Hunt, P.G., and C.R. Lee. 1976. Land treatment of wastewater by overland flow for improved water quality. p.151-160. In J. Tourbier and R.W. Pierson, Jr. (eds.) Biological Control of Water Pollution. University of Pennsylvania Press, PA.

Hunt, P.G., T.A. Matheny, A.A. Szögi, and F.J. Humenik. 1995. Denitrification in constructed wetlands for swine wastewater treatment. p. 329. Agronomy Abstracts.

Nathanson, K., R.J. Lawn, P.L.M. De Jabrun, and D.E. Byth. 1984. Growth, nodulation and nitrogen accumulation by soybean in saturated culture. Field Crop Res. 8:73-92.

Szögi A.A., P.G. Hunt, F.J. Humenik, K.C. Stone, and J.M. Rice. 1995. Constructed wetlands for swine wastewater treatment in the Eastern Coastal Plain, USA. p. 675-682. In K.L. Campbell (ed.) Versatility of Wetlands in the Agricultural Landscape. ASAE Publication 701P0995, St. Joseph, MI.

Szögi A.A., P.G. Hunt, F.J. Humenik, S.W. Broome, and J.M. Rice. 1996. Assessment of constructed wetlands for mass removal of nitrogen from swine wastewater. In Proceedings of the 2nd National Workshop on Constructed Wetlands for livestock Treatment. May 15 to 18, 1996, Fort Worth, TX.

Szögi A.A., F. J. Humenik, J. M. Rice and P. G. Hunt. 1997. Swine wastewater treatment by media filtration. J. Environ. Sci. Health, B32(5), 831-843.