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# Constructed Wetlands for Animal Waste Management

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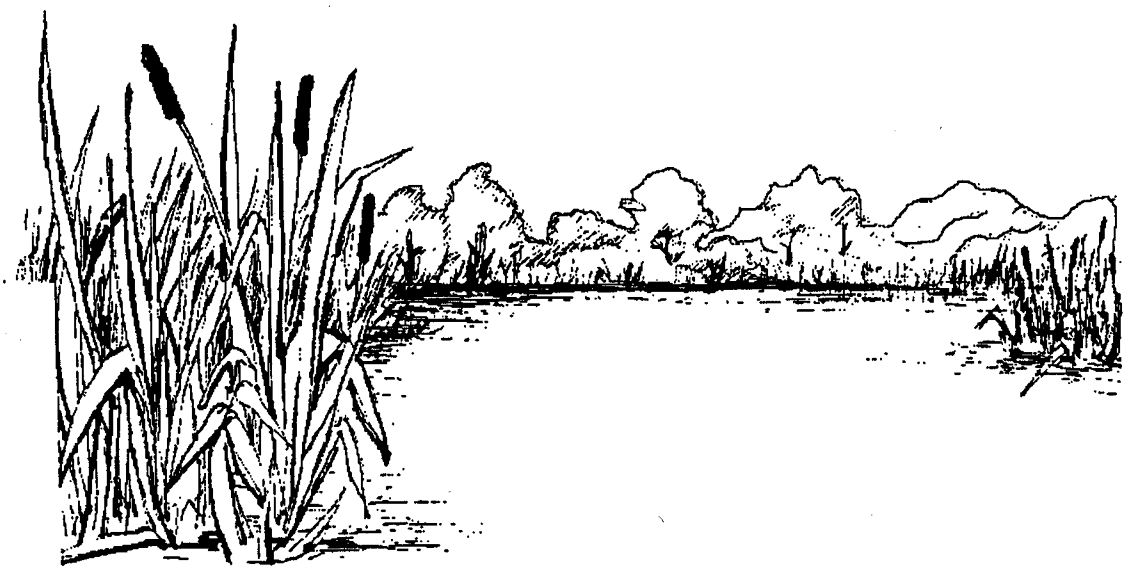

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# Assessment of Constructed Wetlands for Mass Removal of Nitrogen from Swine Wastewater

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## Abstract

Disposal of wastewater generated by confined swine production units is a problem when land is limited. Improperly sized or managed waste treatment systems can cause odor and water pollution problems. Our objective was to compare the mass removal of nitrogen from swine wastewater by the current technology that uses anaerobic lagoon treatment with alternative technologies using constructed wetlands, overland flow, and media filter. Lagoons are a common component of nutrient management systems because they can reduce nitrogen in wastewater up to 80%. However, residual ammonia-N concentrations in the lagoon effluent are very high. When land is limited, constructed wetlands can be a viable component of a system for safe disposal of lagoon effluents. Nitrogen removal efficiencies more than 80% were obtained for wetlands planted to two mixtures of rush/bulrush and cattail/bur-reed plants with N application rates up to 15 kg/ha-day. Two critical aspects of the wetland system are plant tolerance to ammonia-N and nitrification-denitrification rates to transform ammonia into $N_2$. Because levels of ammonia-N tolerated by plants were unknown, the lagoon effluent was diluted with fresh water. A microcosms study showed that wetland plants grew vigorously with ammonia-N concentration levels up to 240 mg/L. Since nitrification seems to be the limiting factor to treat high ammonia loads, aeration of the wastewater may enhance treatment. When lagoon waste was pretreated by overland flow, the N removal efficiency was 59% for a N application rate of 50 kg/ha-day. Ammonia-N in the effluent was reduced to levels that can be efficiently treated by constructed wetlands. In the media filter treatment, up to 32% of the influent TKN was transformed into nitrate-N when wastewater was recycled four times. Either overland flow or media filter offered the opportunity to eliminate the dilution of lagoon effluents prior to wetland treatment. By sequencing nitrification and denitrification processes, advanced wastewater treatment levels could be achieved. Such a system could offer a safer alternative to anaerobic lagoons.

## Introduction

Disposal of livestock wastes has become an important environmental problem in the U.S. due to the fast growth of confined animal production. This is particularly true with modern swine production, which generates large amounts of liquid manure. In North Carolina, many counties are producing more manure-nitrogen than currently grown crops can utilize (Barker and Zublena, 1995). This can result in overloaded land applications causing water pollution problems. Therefore, proper manure management is necessary to prevent this situation.

Liquid manure from hog operations typically is stored and treated in anaerobic lagoons prior to land application. However, treatment of animal wastes before terminal application is necessary when land is limited. Thus, constructed wetlands have received considerable attention as a pretreatment method for wastewater renovation that could reduce land requirements and prevent over-application (Hammer, 1989, and Hunt, et al., 1995b).

Constructed wetland systems are capable of removing nitrogen by nitrification, denitrification, volatilization of ammonia, and plant uptake. Since anaerobic lagoon effluents are rich

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in ammonia-N ($NH_3$-N), the rates of nitrification and denitrification to convert excess $NH_3$-N into $N_2$ are critical to the efficiency of these systems. Of these two processes, ammonia nitrification is the most limiting factor in wetlands. Also, the tolerance of wetland plants to high $NH_3$-N levels is critical for a successful wetland treatment. An aerobic pretreatment to convert $NH_3$-N to nitrate-N such as overland flow (Hunt and Lee, 1976; Overcash et al., 1976) or media filter (U.S. EPA, 1971) before wetland treatment could improve nitrogen removal by wetlands.

Currently, discharge of animal wastewater to surface waters is not allowed. Thus, mass reduction of nutrients is the goal for constructed wetland treatment. In this paper, we compare the mass removal of nitrogen from swine wastewater by the present technology using anaerobic lagoons with constructed wetlands, overland flow, and media filter technologies.

## Materials and Methods

### *Anaerobic Lagoon*

A single-stage lagoon system was used to treat the waste generated by a pig nursery in Duplin County, N.C. The production unit had a capacity of 2600 pigs with an average weight of 13 kg (28 lbs). The waste was conveyed out of the pig house by a flushing system. The system used siphon-flush tanks activated four times a day. Thus, the lagoon wastewater recirculated at a rate of about 2100 L/1000 kg live mass per day. The lagoon had a total 4100-$m^3$ liquid volume with a top surface area of 2400 $m^2$.

### *Constructed Wetlands*

Four, 3.6-×33.5-m, wetland cells were constructed adjacent to the anaerobic lagoon in 1992. They were divided into parallel sets of two end-on-end connected cells. In 1992, wetland system 1 was planted with a mixture of rush (*Juncus effusus*) and bulrushes (*Scirpus americanus, Scirpus cyperinus* and *Scirpus validus*) and wetland system 2 was planted to bur-reed (*Sparganium americanum*) and cattails (*Typha latifolia and Typha angustifolia*). Wastewater application to the cells started with low total nitrogen loading rates. A more detailed description can be found in Hunt et al. (1994).

In the first year, lagoon wastewater was diluted with fresh water and applied at a total N rate of 0.3 g/$m^2$-day (3 kg/ha-day). The N loading rate was increased to 0.8 g/$m^2$-day or 8 kg/ha-day during the second year, and to 1.5 g/$m^2$-day or 15 kg $ha^{-1}$ $day^{-1}$ in the third year. Although dilution is not practical on actual waste treatment systems, it was necessary because of unknown tolerance levels of wetland plants to $NH_3$-N.

Wetland plants tolerance to $NH_3$-N was investigated in a wetland microcosm. The wetland microcosm consisted of eighteen 0.5-×2-m cells. Half of the cells were planted to a mixture of common rush (*J. effusus)* and softstem rush (*S. validus)* and the other half was used as a control (no plants). The soil depth was 18 cm and the flooding depth was 10 cm. The experimental design was a 2×3 factorial with plants and no plants treated with fresh water, half strength and full strength wastewater. The retention time was 2 weeks. The cells were dosed three times daily with a total of 7.1L/day. Full-strength lagoon effluent had $NH_3$-N concentrations of 400 to 480 mg/L. The loading rate was about 3.0 g TN/$m^2$-day (30 kg/ha-day) for the full strength treatment. Above ground biomass and number of stems were measured for both plant species in order to assess their tolerance to $NH_3$-N loads.

### *Aerobic Treatments*

Two aerobic treatment units that consisted of overland flow and one media filter were constructed next to the anaerobic lagoon in summer 1995. The overland flow system consisted of a 4-×20-m plot with 2% slope. The sides and bottom of the overland flow plot were lined with a plastic liner after excavation to a 20-cm depth, and filled with the same sandy loam topsoil. Vegetation consisted of a mixture of fescue, coastal bermudagrass, and reed canary grass. Lagoon liquid was applied with hydraulic rates of 2.5 to 3.0 cm/day during 8-hour periods. Surface flow was collected at the end of the plot by a trough and passed through a 6-slot flow divisor and stored in a tank. Subsurface flow was collected by a subsurface drain routed to a second tank at the end of the plot. Inflow, surface, and subsurface flow were measured with mechanical flow meters when tanks were emptied. Hydraulic losses were similar to the expected evapotranspiration losses (0.5 to 0.8 cm/day). Nitrogen was applied at a rate of 5.4 g TN/$m^2$-day (54 kg/ha-day). Three-day composite samples were obtained with automated samplers for nutrient analysis.

The media filter was similar to a trickling filter. The unit consisted of a 1.6-m diameter by 0.6-m tall tank filled with marl gravel. Marl gravel was used instead of typical sand media to avoid clogging by suspended solids in the lagoon liquid. The distribution of the gravel particles was 85% in the 4.7- to 12.7-mm size class and 14% in the 12.7- to 19-mm size class, providing a pore space of 57%. The filtration unit was placed inside another tank with slightly larger diameter to collect the effluent for recirculation. The system was completed with a second tank used for storage of the treated lagoon liquid. Lagoon wastewater was applied as a fine spray on the surface of the media filter. The hydraulic loading rate was 1010 L/$m^3$ reactor volume/day (606 L/$m^2$ reactor area-day). Lagoon wastewater was applied continuously and circulated four times through the media filter during 6-hour period. The average application rate for TN was 330 g/$m^3$-day (198 g/$m^2$ reactor area-day). The flow was measured with a mechanical flow meter, and grab samples for water analysis were obtained at the end of each of the first and fourth recirculation cycles.

### *Wastewater Analyses*

Water samples were packed in ice and transported to the laboratory for analysis. Total Kjeldahl Nitrogen (TKN), nitrate-N ($NO_2$+ $NO_3$-N), and $NH_3$-N were analyzed using U.S. EPA methods 351.2. 350.1, and 353.1, respectively (Kopp and McKee, 1983). Total suspended solids (TSS), chemical oxygen demand (COD) and pH were analyzed using EPA methods 160.3, 410.4, 150,1, respectively.

### *Nitrogen Mass Balance*

Mass balances for N were calculated using flow and nutrient concentration data on a three-day basis for the constructed wetlands and the overland flow. The mass balance was used to estimate the specific reduction (expressed as mass reduction of nutrient per area per day). The mass removal or treatment efficiency was calculated as mass reduction of a nutrient in the effluent relative to the nutrient mass inflow.

## Results

### *Anaerobic Lagoon Treatment*

The pig-house effluent (Table 1) was low in TS (0.18 %) and TSS, because of the large volume of lagoon water (2100 L/1000 kg live mass per day) used for flushing the house, but still high in TKN concentration. The TKN components are $NH_3$-N from the lagoon wastewater, and inorganic N ($NH_3$-N) and organic N supplied by fresh manure. We made two assumptions to estimate the total N inflow into the lagoon. First, we assumed that 38% of the N in the fresh waste was in organic form (Barker and Zublena, 1995). Second, we assumed that N in the lagoon wastewater used for flushing is 100% $NH_3$-N. Under these two assumptions we estimated a total inflow of 16.8 kg N/day into the lagoon. On a mass basis, we estimated that 83% of N entering the lagoon was lost in gaseous form, 13% remained in the lagoon effluent, and 4% was in the settled sludge. These estimates are consistent with average N losses for swine operations in North Carolina (Barker and Zublena, 1995). Anaerobic lagoon treatment is an effective way to reduce high TKN and COD levels in swine operations. Most of the nitrogen in this system is lost in gaseous form. The residual levels of ammonia in the lagoon are not a problem if enough land is available for land application.

### *Constructed Wetlands*

Constructed wetlands showed great promise by removing more than 80% of the applied N (Table 2). Nitrogen removal efficiency was similar in both rush/bulrushes and bur-reed/cattails plant systems. Initially, a loading rate of 3 kg N/ha-day was used to evaluate if stream discharge requirements could be achieved. This low loading rate was selected to meet the Tennessee Valley Authority criteria for advanced wastewater treatment (Hammer, 1994). Because stream discharge concentration requirements could not consistently be achieved, the loading rate was increased to 8 kg N/ha-day during the second year and to 15 kg N/ha-day during the third year with the goal of maximum nitrogen mass reduction. At the highest application rate and 300 application days, wetlands could have an average annual removal rate of 3700 kg N/ha. This high nitrogen removal rate was likely due to microbial conversion of excess nitrogen in the wastewater to N gas via nitrification-denitrification processes. In a related study, Hunt, et al. (1995a) showed that these wetlands had prevalent anaerobic conditions and were nitrate limited. These conditions indicated that some direct loss of ammonia via volatilization could not be disregarded. Consequently, we investigated alternative nitrification treatments that would lower potential loss of ammonia and eliminate dilution with fresh water prior to wetland treatment.

### *Plant Tolerance to Ammonia*

In the wetland microcosm units, both *Juncus effusus* and *Scirpus validus* grew vigorously in half and full strength lagoon effluent (Table 3). Above-ground biomass values from the half strength treatment were in the same range as of those measured in the constructed wetland with rush/bulrush plants (system 1) in May 1995 (Szögi et al., 1996). Plants in the full strength effluent died during an extremely dry period, but it was not apparent whether this was due to the high concentration of effluent or the dry conditions. Wetland microcosms units with plants were more effective than units with no plants in removing N from the lagoon effluent with an efficiency as high as 99% (Broome, 1996).

### *Aerobic Pretreatment of Lagoon Effluents*

#### *1. Overland flow*

Overland flow has several characteristics that make it an attractive method for pretreatment of wastes. In overland flow, nitrification occurs when a thin film of water is in close contact with the nitrifying population at the soil surface. It also offers the advantage of partial denitrification of $NO_3$-N in the underlying saturated soil layer (Hunt and Lee, 1976). High hydraulic rates in overland flow systems are not uncommon; Hegg and Turner (1983) reported loading rates as high as 2 cm/day. Our overland flow system had an average 2.7 cm/day hydraulic loading rate. This high hydraulic rate was necessary to obtain measurable surface flow at the end of the plot. Our results show that the overland flow system was effective in reducing the concentration of TSS, COD, TKN, and $NH_3$-N in both the surface and subsurface effluents (Table 4). The increase in $NO_3$-N concentration in both effluents is an indication that nitrification occurred. The pH of the effluents did not change with respect to the lagoon wastewater inflow, and probably some $NH_3$-N volatilization losses occurred.

Overland flow systems can remove significant amounts of nitrogen. Humenik et al. (1975) obtained 35% N removal from swine lagoon wastewater treated on 17-m overland flow plots with a 1.8-cm/day hydraulic loading. With our system, a mass loading rate was applied at 5.4 g $NH_3$-N/$m^2$-day (54 kg/ha-day). At this high N loading rate, a mean TN 3.2 g/$m^2$-day (32 kg/ha-day) removal rate was obtained during the August to December 1995 period. The respective total N removal efficiency was 59%.

*2. Media Filter*

Sand filters have become popular for small waste generators especially where soil conditions are not suitable for subsurface disposal systems (Rubin et al., 1994). These recirculating sand filters provided excellent oxygen demand and suspended solids removal as well as high degree of nitrification (Hines and Favreau, 1975; Mote et al., 1991). The use of gravel to avoid clogging in our experimental unit also allowed for very good natural aeration of the applied lagoon wastewater, rapid vertical flow rates and some phosphorus sorption.

Results in Table 5 show high removal of TSS with efficiencies of 50% to 71% with one and four cycles, respectively. Results on COD showed no difference in efficiency (54%) with one or four cycles. Removal efficiencies were 11% and 22% for TN with one and four cycles, respectively. The $NO_3$-N (mg/L) to TKN (mg/L)×100 nitrification ratio (Loehr et al., 1973) was used to estimate the proportion of TKN in the influent that was converted to $NO_3$-N. With four cycles, a nitrification ratio of 24% was obtained with data from Table 5. A nitrification ratio of 32% was obtained with wastewater recycled four times during the August to December 1995 period. We concluded that this method might provide effluents with $NH_3$-N levels that can be tolerated by wetland plants according to the results obtained in the microcosm study and eliminate the problem of dilution with fresh water prior to wetland treatment.

## Summary

The goal of the studied wetland systems was to maximize nitrogen removal to protect soil, air and water quality. Wetlands by themselves cannot remove sufficient amounts of N to meet stream discharge requirements, but do show promise for high rates of N removal. Since wetlands are nitrate limited the mass removal rate can be increased by nitrifying the effluent prior to wetland application and at the same time eliminate dilution. By sequencing nitrification and denitrification processes, advanced wastewater treatment levels could be achieved. Such a system could offer a safer alternative to anaerobic lagoons.

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***Table 1. Characteristics of the pig-house effluent when entering the anaerobic lagoon. Data from Vanotti and Hunt (1996).***

| Constituent | Unit | Concentration |
|---|---|---|
| Total Solids | $g\ L^{-1}$ | 1.83 |
| Suspended Solids | $mg\ L^{-1}$ | 335 |
| Chemical Oxygen Demand | $mg\ L^{-1}$ | 1370 |
| Total Kjeldahl Nitrogen | $mg\ L^{-1}$ | 374 |
| Organic Nitrogen | $mg\ L^{-1}$ | 88 |
| Ammonia Nitrogen | $mg\ L^{-1}$ | 286 |
| PH | | 8.1 |

***Table 2. Nitrogen loading rates and mass removal efficiencies for the constructed wetlands, Duplin Co., N.C.***

| Nitrogen Loading rate† | System | Mass Removal ‡ % |
|---|---|---|
| $3\ kg\ ha^{-1}\ d^{-1}$ | Rush/bulrush | 94 |
| | Cattails/bur-reed | 94 |
| $8\ kg\ ha^{-1}\ d^{-1}$ | Rush/bulrush | 88 |
| | Cattails/bur-reed | 86 |
| $15\ kg\ ha^{-1}\ d^{-1}$ | Rush/bulrush | 85 |
| | Cattails/bur-reed | 81 |

*† Expressed as TN.*

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

***Table 3. Above ground biomass and stem density of plants in a microcosms study treated with fresh water and lagoon wastewater at half and full strength (means ± one standard error, May 1995). Data from Broome (1996).***

| | Above-ground Biomass $g\ m^{-2}$ | | Stems Density Stems $m^{-2}$ | |
|---|---|---|---|---|
| Treatment | *Juncus* | *Scirpus* | *Juncus* | *Scirpus* |
| Fresh Water | 129 ± 11 | 293 ± 28 | 334 ± 58 | 590 ± 56 |
| Half Strength | 835 ± 412 | 812 ± 154 | 966 ± 504 | 794 ± 83 |
| Full strength † | 688 ± 263 | 1122 ± 178 | 1208 ± 75 | 1230 ± 118 |

***† Full strength ammonia-N concentration range = 400 to 480 mg $L^{-1}$.***

*Table 4. Characteristics of the influent wastewater and overland flow effluent separated in surface and subsurface flow (mean ± one standard error from August to December 1995).*

| Constituent | Unit | Influent Wastewater | Surface Effluent | Subsurface Effluent |
|---|---|---|---|---|
| Total Suspended Solids | $g\ L^{-1}$ | 0.25 | 0.21 | 0.11 |
| Chemical Oxygen Demand | $mg\ L^{-1}$ | 446 ± 28 | 372 ± 33 | 207 ± 19 |
| Total Kjeldahl Nitrogen | $mg\ L^{-1}$ | 250 ± 12 | 128 ± 16 | 78 ± 8 |
| Ammonia Nitrogen | $mg\ L^{-1}$ | 198 ± 5 | 110 ± 6 | 73 ± 5 |
| Nitrate Nitrogen | $mg\ L^{-1}$ | 0.2 | 24 ± 3 | 30 ± 3 |
| pH | | 8.4 | 8.3 | 8.2 |

*Table 5. Characteristics of the influent wastewater and media filter treated effluent (mean ± one standard error, August 16-23, 1995).*

| Constituent | Unit | Influent Wastewater | One cycle Effluent | Four cycles Effluent† |
|---|---|---|---|---|
| Total Suspended Solids | g L-1 | 0.52 ± 0.11 | 0.26 ± 0.02 | 0.15 ± 0.02 |
| Chemical Oxygen Demand | $mg\ L^{-1}$ | 869 ± 117 | 432 ± 35 | 403 ± 40 |
| Total Kjeldahl Nitrogen | $mg\ L^{-1}$ | 327 ± 16 | 257 ± 14 | 180 ± 9 |
| Ammonia Nitrogen | $mg\ L^{-1}$ | 236 ± 19 | 182 ± 14 | 147 ± 7 |
| Nitrate Nitrogen | $mg\ L^{-1}$ | 6 ± 2 | 40 ± 5 | 80 ± 4 |
| PH | | 8.6 | 8.5 | 8.4 |

*† The lagoon wastewater was passed once through the media filter (one cycle) and then re-circulated three more times (four cycles).*