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Nitrification options for pig wastewater treatment

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Abstract Nitrification is a necessary and often limiting process in animal waste treatment for removal of nitrogen as N_2 through biological nitrification/denitrification systems. We evaluated three technologies for enhancing nitrification of pig lagoon wastewater prior to denitrification: overland flow, trickling filter, and a bioreactor using nitrifying pellets. The overland flow system consisted of a 4 × 20-m plot with 2% slope with a subsurface impermeable barrier receiving a total N loading rate of 64–99 kg N ha^{-1} day^{-1}. Total N removal efficiency ranged from 36 to 42%, and 7% of the total N application was recovered in the effluent as nitrate. The trickling filter consisted of a 1-m^3 tank filled with marl gravel media which supported a nitrifying biofilm. Lagoon wastewater was applied as a fine spray on the surface at hydraulic loading rates of 684 litres m^{-3} day^{-1} and total N loading rates of 249 g m^{-3} day^{-1}. The media filter treatment transformed up to 57% of the inflow total N into nitrate when wastewater was supplemented with lime. The nitrifying pellets technology used acclimated nitrifying cells immobilised in 3–5 mm polymer pellets. Pig wastewater was treated in an aerated fluidised reactor unit with a 15% (w/v) pellet concentration. Nitrification efficiencies of more than 90% were obtained in continuous flow treatment using total N loading rates of 438 g N m^{-3} day^{-1} and hydraulic residence time of 12 h. Two conclusions are suggested from this research: (1) that substantial nitrification of pig lagoon wastewater can be attained particularly using aerobic treatments with enriched nitrifying populations, and (2) that large mass removal of N from pig wastewater may be possible by sequencing nitrification and denitrification unit processes.

Keywords animal wastewater; ammonia removal; nitrification; nitrifiers; hogs; swine; pigs; piggery

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INTRODUCTION

Livestock waste disposal has become a major environmental problem in the United States due to the rapid growth of large-scale, confined animal production. These concerns include ammonia (NH_3) emissions, contaminated ground and surface water, and fish kills. Modern pig production facilities in the south-eastern United States use flush or pit-recharge systems to remove manure from the confinement houses. The flushed waste is mostly treated and stored in anaerobic lagoons before land application. The problem is that large, concentrated herds generate large amounts of waste in a relatively small area. As a consequence, many counties in the United States southern seaboard produce more manure nitrogen (N) than available cropland can absorb (Barker & Zublena 1995; Gollehon et al.

2001). These land limitations result in overloaded land applications causing pollution of water and air. A few estimates of NH_3 emissions from anaerobic lagoons in North Carolina indicate fluxes in the range of 0.6–104 kg NH_3-N ha^{-1} day^{-1} (Arogo et al. 2003). Hutchinson et al. (1972) showed that plants can serve as sinks of significant quantities of NH_3 from air, but atmospheric deposition of NH_3 in areas of intensive animal production may be in excess of what plants can absorb (Walker et al. 2000). It is critical, therefore, to develop functional and affordable alternative methods of N management that will reduce ammonia emissions.

Nitrification is becoming an increasingly important component in total farm management systems, to the point where the effectiveness of any biological nitrogen removal system that includes a nitrification step treatment depends on the ability of nitrifying organisms to oxidise ammonia (Martinez 1997). Ammonia is in solution as the ammonium ion (NH_4^+) and un-ionised or free ammonia (NH_3). These two forms of ammonia are in equilibrium, controlled by the solution pH and temperature (Anthonisen et al. 1976). Nitrifiers oxidise NH_4^+ to nitrite (NO_2^-), then to nitrate-N (NO_3^-). Nitrification is a very limiting process in animal waste treatment, but a necessary condition to be able to remove large amounts of nitrogen using biological nitrification/denitrification systems (Loehr et al. 1973). Once in NO_3^- form, the transformation of N into N_2 (or denitrification process) needs two conditions: a source of carbon and an anaerobic environment. These conditions are typically found in wetlands or liquid manure storage units. In a related study, Szögi et al. (2003) showed that constructed wetlands can remove large amounts of N from pig wastewater through denitrification, but their performance is limited by NO_3^- availability. Using a nitrification pretreatment in constructed wetlands, Humenik et al. (1999) reported total N removal potentials of 14 000 kg ha^{-1}, which was more than five times the N removal obtained without nitrification pretreatment.

With wastes rich in carbonaceous materials, such as pig wastewater, the nitrifying bacteria compete poorly with heterotrophic micro-organisms. Nitrifiers need oxygen, lower organic carbon, a surface area, and a growth phase before sufficient numbers are present for effective nitrification. These concepts are illustrated in the nitrification experiments of Blouin et al. (1989). They first tried to nitrify stabilised pig waste through aerobic treatment. Ammonium-N, which was in high concentration (c. 1000 mg $litre^{-1}$), was not oxidised after 49 days of incubation. However, when the same waste was first inoculated with enriched nitrifying populations (10^6–10^7 most probable number (MPN) ml^{-1}), only 5 days were needed to obtain complete nitrification. In another nitrification experiment of pig lagoon wastewater using encapsulated nitrifiers, Vanotti & Hunt (2000) found that the rate of nitrification was extremely slow in a control without added nitrifiers, where most of the ammonia was lost by air stripping. In contrast, the use of large populations of nitrifying bacteria entrapped in polymer resins offered much faster nitrification rates and avoided the problem of NH_3 volatilisation losses.

The purpose of this research was to examine options for nitrification treatment of pig wastewater that could reduce the impacts animal production units can have on soil, air, and water quality. The nitrification options included overland flow with impermeable barrier, trickling filter, and encapsulated nitrifier technologies.

MATERIALS AND METHODS

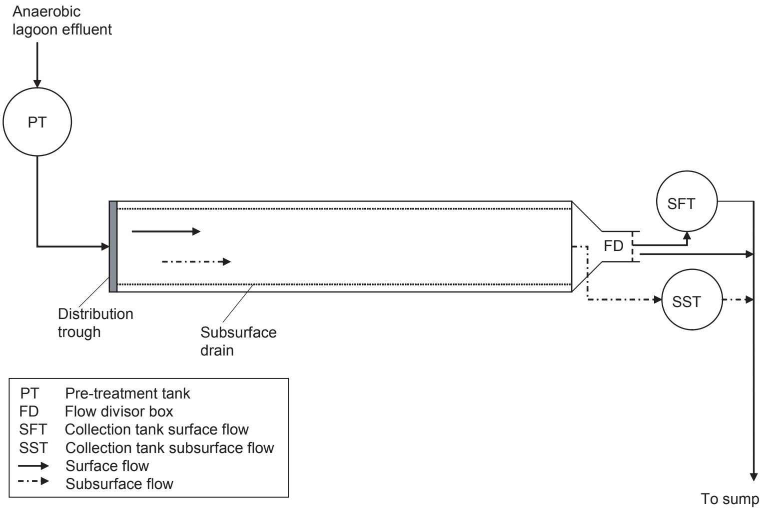
Site

The research site was located at a nursery operation of 2600 pigs (average weight = 13 kg) near Kenansville, Duplin Co., NC. The nursery operation used a flushing system to recycle liquid from a single-stage anaerobic lagoon. The average liquid volume of the lagoon was 4100 m^3. All nitrification experiments were conducted with liquid from this anaerobic lagoon. Typically, the lagoon effluent contained an annual average of 365 mg $litre^{-1}$ of total Kjeldahl nitrogen (TKN), 347 mg $litre^{-1}$ of NH_4^+-N, 0 NO_2^--N and NO_3^--N, 740 mg COD $litre^{-1}$, and a pH of 8.2.

Overland flow treatment

The treatment unit consisted of a 4 × 20-m plot with 2% slope (Fig. 1). The sides and bottom of the unit were lined with plastic after excavation to a 20-cm depth and filled with the same loamy sand topsoil (86% sand, 10% silt, and 4% clay). A plastic liner was used as an impermeable barrier for the overland flow to avoid leaching and protect groundwater quality. Vegetation in the overland flow plot consisted of a mixture of fescue (*Festuca arundinacea* Schreb.), bermuda grass [*Cynodon dactylon* (L.) Pers.], and reed canarygrass (*Phalaris arundinacea* L.). Wastewater flowed by gravity from the anaerobic lagoon to a storage tank. Then, the lagoon wastewater was pumped from the storage tank and applied onto the

Fig. 1 Schematic diagram showing the basic configuration of the overland flow treatment unit.



overland flow plot. A trough at the inlet of the treatment unit received and distributed the wastewater evenly across the surface plot. The surface flow was collected at the end of the plot by a six-slot flow divisor box. Thus, one-sixth of the total surface runoff was captured and routed through a pipe into a storage tank located at the end of the plot. The subsurface flow was collected by a subsurface drain and routed to a second tank at the end of the plot. Inflow, surface, and subsurface flows were measured with mechanical flow meters when tanks were emptied. Lagoon liquid was applied 5 days a week with hydraulic rates of 2.5–3.0 cm day^{-1}. The overland flow system was managed to support surface rather than subsurface flow. Preliminary tests on application timing showed that the sandy soil was highly permeable and that applying 2.5–3.0 cm wastewater during 8-h periods often failed to provide a surface runoff of the lagoon wastewater. Therefore, in order to obtain a functional surface runoff, applications during the evaluation period (1996 and 1997) were reduced to 4 h each day. Five-day composite samples for N analysis were obtained from inflow, surface, and subsurface flow with automated refrigerated samplers (ISCO Corp., Lincoln, NE)[1].

Samplers were fed from the pipe lines that routed wastewater inflow and both surface and subsurface outflow. The refrigerated samplers maintained water samples chilled (<4°C). A detailed spatial sampling of the surface flow was performed by taking water grab samples downslope from the wastewater application point at 1-m intervals. Water balances indicated that hydraulic losses were similar to the expected local evapotranspiration losses (0.5–0.8 cm day^{-1}).

Trickling filter system

The unit consisted of a 1.5 m dia. × 0.6 m height tank filled with marl gravel (Szögi et al. 1997). Marl gravel was used instead of typical sand media to avoid clogging by pig wastewater. The distribution of the gravel particles was 85% in the 4.7–12.7 mm size class and 14% in the 12.7–19 mm size class, providing a pore space of 57%. The filtration unit was placed inside a tank with a slightly larger diameter to collect the effluent for recirculation. The system was completed with a second tank used for storage of the liquid waste during treatment (Fig. 2). Wastewater flowed by gravity from the anaerobic lagoon to a storage tank. The lagoon wastewater was pumped from the storage tank and applied onto the surface of the trickling filter with four fixed sprinklers. A lime supplement consisting of 100 g day^{-1} of crushed dolomitic lime was applied to the surface of the media filter during the second half of the evaluation period. Lime was added to neutralise acidity produced by the nitrification process, adjusting the water pH within the 7.5–8.5 range (Anthonisen et al. 1976).

Lagoon wastewater was applied as a fine spray on the surface of the media filter at a hydraulic loading rate of 684 litres m^{-3} reactor day^{-1}. The correspond-

[1]Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the US Department of Agriculture.

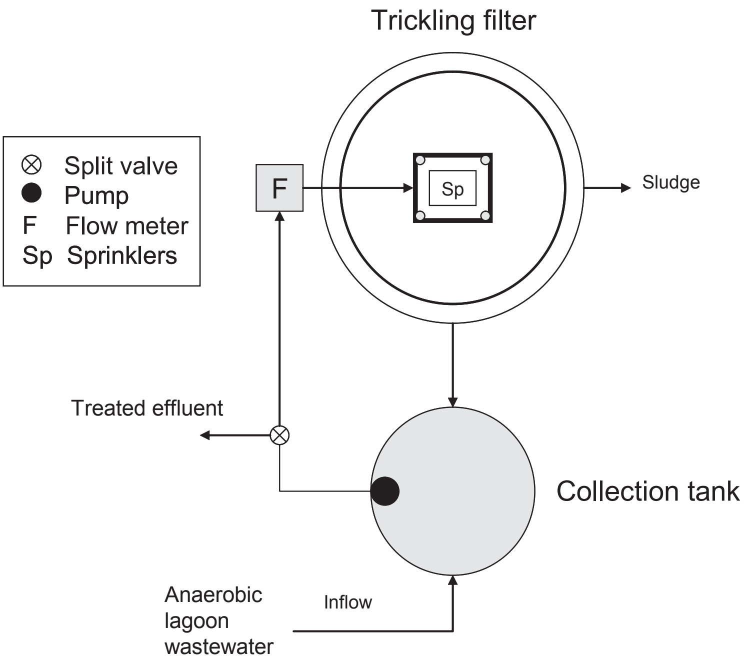


Fig. 2 Schematic diagram of the experimental trickling filter with marl gravel media.

ing average total N loading rate was 249 g N m^{-3} day^{-1}. The pilot unit was operated from March to July 1997, 5 days a week during 12-h periods (6 a.m.–6 p.m.) under intermittent flow mode in order to enhance aeration inside the media. The intermittent flow was controlled by a timer that turned a pump on and off in 12-min intervals. During the pump operation, the liquid was pumped from the storage tank at a rate of 9.5 litres min^{-1}. This flow was proportionally split by a ball-valve to maintain a flow rate of 7.6 litres min^{-1} to the surface of the filter and 1.9 litres min^{-1} rate to the outflow of the system. During the same 12-h operation time interval, the lagoon wastewater flowed by gravity into the storage tank with a float-valve maintaining a 757-litre volume of wastewater in the tank. The flow was measured with a mechanical flow meter, and grab samples, one from the inflow and one from the outflow, were collected daily for water analysis. Water samples were preserved by immediate refrigeration (<4°C).

Encapsulated nitrifiers reactor

An active culture of acclimated pig wastewater nitrifying bacteria was prepared from overland flow soil seed. The ammonia strength of the salts medium was gradually increased to overcome inhibitory effects caused by high levels of free ammonia in pig wastewater, similar to procedures used for acclimation of marine nitrifiers (Furukawa et al. 1993). Acclimated nitrifying cells were immobilised in 3–5 mm polyvinyl alcohol polymer cubes. Details of the immobilisation technique and experimental apparatus used in the nitrification experiments are described by Vanotti & Hunt (2000) and Vanotti et al. (2003). Pig lagoon wastewater was treated under continuous flow in a nitrification tank equipped with a screen to retain the pellets and an aeration system to ensure appropriate fluidisation of the pellets (Fig. 3). Pellets were added at 15% (w/v) pellet to total tank volume ratio. The total N loading rate was adjusted to 238–1349 g N m^{-3} day^{-1} by varying the flow rates within the range of 1.0–7.2 m^3 day^{-1}. These flow rates provided hydraulic retention time treatment in the range of 24–4 h, respectively. Each flow rate was maintained for 1 week. Influent and effluent water samples were collected daily at days 3–7. Alkalinity was supplemented using a pH 8.5 $CO_3^{=}/HCO_3^{-}$ buffer. All experiments were conducted in duplicate.

Water analyses and nitrogen mass balance

Water samples were packed on ice and transported to the laboratory where they were analysed with an automated analyser (Technicon Instruments Corp., Tarrytown, NY) using EPA methods (USEPA 1983):

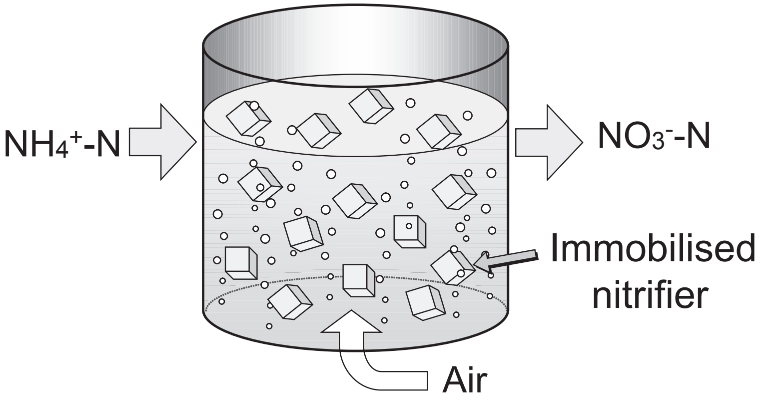


Fig. 3 Schematic diagram of reactor used for continuous treatment of swine wastewater with nitrifying pellets.

351.2, 350.1, and 353.1 for TKN, nitrate-N (NO_3^-+ NO_2^--N), and ammonium-N (NH_4^+-N), respectively. Alkalinity was determined by acid titration to the bromocresol green endpoint (pH = 4.5). The three water treatment systems were evaluated as single reactors using mass balance and treatment efficiency approaches. Nitrogen mass balances were calculated using flow and N concentration data. The treatment efficiency was calculated as mass reduction of N in the effluent relative to N mass in the inflow. For the trickling filter, treatment efficiencies were estimated using only inflow N concentration reduction in the effluent relative to the N concentration in the inflow.

Table 1 Nitrogen concentration in the inflow, surface, and subsurface outflow of the overland flow system.

	Inflow (mg litre^{-1})	Outflow: Surface (mg litre^{-1})	Outflow: Subsurface (mg litre^{-1})
1996			
TKN[a]	239 ± 7[b]	163 ± 7	116 ± 13
NH_4^+-N	196 ± 5	142 ± 5	90 ± 10
NO_3^--N	0	7 ± 1	43 ± 6
1997			
TKN	348 ± 17	283 ± 33	176 ± 32
NH_4^+-N	319 ± 18	224 ± 25	138 ± 28
NO_3^--N	0	28 ± 8	50 ± 14

[a]TKN = total Kjeldahl nitrogen. [b]Data are means ± SEM; n = 7 (1996) and n = 14 (1997).

RESULTS AND DISCUSSION

Overland flow

In typical overland flow, nitrification occurs when a thin film of water is in close contact with a nitrifying population at the soil surface. It also offers the advantage of partial denitrification in the underlying saturated soil layer (Hunt & Lee 1976). The major difference between the system tested in our study and typical overland flow systems was the use of an impermeable barrier to capture the subsurface flow. This impermeable barrier was a major improvement with respect to typical overland flow systems established on sandy soils because it eliminated the problem of nutrients leaching into groundwater.

In 1996 and 1997 trials, both surface and subsurface outflow had significant reduction of TKN and NH_4^+-N concentrations with respect to the inflow (Table 1). Performance data of the overland flow treatment during 1996 (Aug–Dec) and 1997 (Mar–Aug) indicated that this treatment can remove large amounts of nitrogen per unit area (Table 2). The higher inflow concentrations resulted in higher application rates in 1997 due to changes in lagoon N concentration. On a mass basis, average total N removal efficiency was 35% in 1996 and 42% in 1997, which is equivalent to 22.4–41.6 kg N ha^{-1} day^{-1}, respectively. These efficiencies are in agreement with previous work (Humenik et al. 1975) also showing total N removal efficiencies of 35% for pig lagoon wastewater treated using hydraulic loads of 1.8 cm day^{-1} on 17-m overland flow plots without impermeable barrier. The low nitrate recovery values observed after treatment (Table 2) suggest that simultaneous denitrification occurred in the saturated soil layer, a typical feature of overland flow systems (Hunt & Lee 1976). In a related study, denitrification enzyme activity (DEA) assays indicated that the overland flow soil had an average denitrification rate of 7.2 ± 0.3 g N m^{-2} day^{-1} (72 kg ha^{-1} day^{-1}) for 1996 and 1997 (T. A. Matheny, USDA-ARS pers. comm. 1997). This observation could explain most of the N gaseous losses indicated by the mass balances.

Spatial sampling of the surface runoff water along the plot revealed that nitrification activity was apparent in the first 5 m of the plot (Fig. 4). Beyond this point, the concentration of nitrate gradually increased up to a maximum occurring at 17 m down slope. At this distance, NO_3^--N increased up to 30% of the initial 300 mg NH_4^+-N $litre^{-1}$. Further than the 17-m distance from the application point, NO_3^--N concentrations declined in the surface runoff with a corresponding increase in NH_4^+-N. This was probably due to rapid soil saturation near the end of the plot and inhibitory effect of anoxic wastewater on nitrification. Highest nitrification rates occurred during the first 2–3 h of application as shown by the NO_3^--N concentration levels in Fig. 4. However, nitrification rapidly declined by the end of the application period due to soil saturation of the overland flow plot. Reduction of N (NH_4^+ + NO_3^--N) in surface water concentration outflow was small (<13%) with respect to the inflow (Fig. 4). This result suggested that gaseous losses due to NH_3 volatilisation were probably small in surface runoff water.

Trickling filter

An acclimation period of 6 weeks was needed to develop a functional nitrifying biofilm on the surface of the media, indicated by stabilisation of the nitrification activity. Acidity is a by-product of the biological oxidation of NH_4^+-N to NO_3^--N. Alkalinity in the wastewater neutralises the acidity produced, but enough alkalinity is necessary to keep the pH between 7.5 and 8.5 units to maintain the nitrification process (Anthonisen et al. 1976). Furukawa et al. (1993) indicated that inorganic carbon availability is usually the rate-limiting factor for nitrification of high strength NH_4^+-N wastewater. Therefore, performance of the unit was evaluated for 91 days after acclimation without and with lime addition (Table 3). A lime supplement consisting of 100 g day^{-1} of crushed dolomitic lime was applied onto the surface of the media filter during the second half of the evaluation period. Although the natural alkalinity of

Table 2 Treatment performance of pig lagoon wastewater with overland flow.

Year	Total N application rates[a] (kg ha^{-1} day^{-1})	Evaluation period (days)	Total N removal efficiency[b] (%)	NO_3^--N recovery[c] (%)
1996	64	85	36	7
1997	99	60	42	7

[a]Total N = total Kjeldahl nitrogen + NO_3^--N (inflow nitrate concentration = 0). [b]Total N efficiency = ((TN mass inflow – TN mass outflow)/TN mass inflow) × 100. [c]Nitrate-N recovery = (NO_3^--N mass outflow/TKN mass inflow) × 100.

Table 3 Treatment of pig lagoon wastewater with trickling filter.

Nitrogen form	No lime[a]		Lime	
	Inflow	Outflow	Inflow	Outflow
TKN[b] (mg $litre^{-1}$)	366 ± 9[c]	221 ± 8	363 ± 7	114 ± 10
NH_4^+-N (mg $litre^{-1}$)	340 ± 3	193 ± 83	34 ± 5	106 ± 9
NO_3^--N (mg $litre^{-1}$)	0	133 ± 10	2 ± 2	208 ± 13
TN[d] (mg $litre^{-1}$)	366 ± 9	354 ± 7	365 ± 7	321 ± 9
Nitrification[e]	26%		57%	

[a]Wastewater was treated 46 days without lime and 45 days with lime (100 g day^{-1}) to correct alkalinity. [b]TKN = Total Kjeldahl nitrogen. [c]Data are mean ± SEM concentrations. [d]Total N = TKN + NO_3^--N. [e]Nitrification efficiency = (NO_3^--N conc. outflow/TN conc. inflow) × 100.

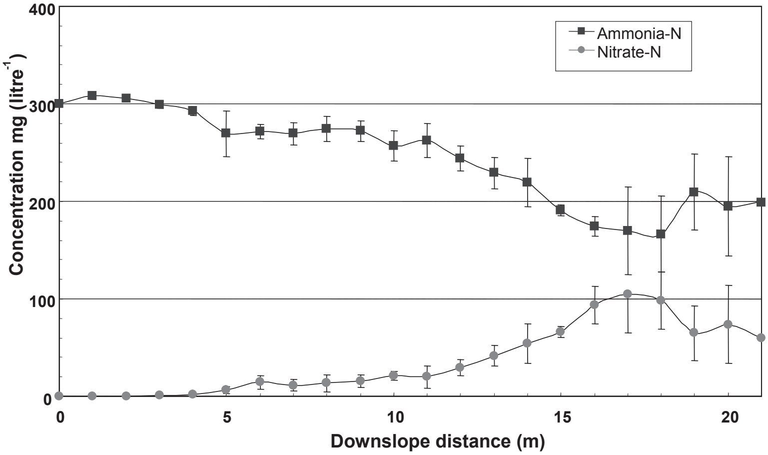


Fig. 4 Changes in ammonium-N, nitrate-N concentrations of surface flow with distance from the application point along the overland flow plot. Samples were taken 3 h after starting application. Data points represent means ($n = 3$), and vertical bars are ±1 SEM.

Table 4 Treatment of pig lagoon wastewater with encapsulated nitrifiers.

HRT (hours)	Total N loading rate[a] (g N m^{-3} reactor day^{-1})	Ammonium removal efficiency[b] (%)	Nitrification efficiency[c] (%)
24	238	94	100
20	272	93	100
16	342	96	96
12	438	91	91
8	668	60	62
6	926	54	54
4	1349	42	42

[a]Total N = total Kjeldahl nitrogen + NO_3^--N (inflow nitrate concentration = 0). [b]Ammonium removal efficiency = ((NH_4^+-N conc. inflow – NH_4^+-N conc. outflow)/TN conc. outflow) × 100. [c]Nitrification efficiency = (NO_3^--N conc. outflow/TN conc. inflow) × 100.

the lagoon wastewater (1950 mg $litre^{-1}$) was enough to neutralise the H^+ generated by full nitrification of c. 270 mg $litre^{-1}$ of NH_4^+-N (7.2 mg alkalinity per mg NH_4^+-N), the nitrification performance of the unit was greatly enhanced by the lime supplement (Table 3). Therefore, our results suggest that the positive effect of lime was due to increased alkalinity, supplied by the dolomitic lime in equilibrium with the progress of nitrification and acid formation. Losses by ammonia volatilisation during treatment were small as represented by the total N balance.

Encapsulated nitrifiers

The immobilisation of micro-organisms in polymer resins is a widely applied technique in drug manufacturing and food processing. The application for municipal wastewater treatment has been developed in Japan (Takeshima et al. 1993). Through the immobilisation process the nitrifying micro-organisms are provided with a very suitable environment to perform at maximum efficiency. The nitrifiers are entrapped in polymer pellets that are permeable to NH_3, O_2, and CO_2 needed by these micro-organisms, resulting in a fast and efficient removal of NH_4^+-N.

Nitrogen loading rates were increased by gradually decreasing the hydraulic residence time (HRT) from 24 h to 4 h (Table 4). Nitrification efficiencies of more than 90% were obtained with total N loading rates lower than 438 g N m^{-3} day^{-1} and HRT higher than 12 h. Although higher loading rates resulted in lower treatment efficiencies, the total amount of nitrate produced was higher, with the maximum nitrate production rate obtained with HRT of 4 h. Higher efficiencies (75–100%) may be useful for total systems designed to meet stream discharge requirements (Fig. 5). However, if the objective is to

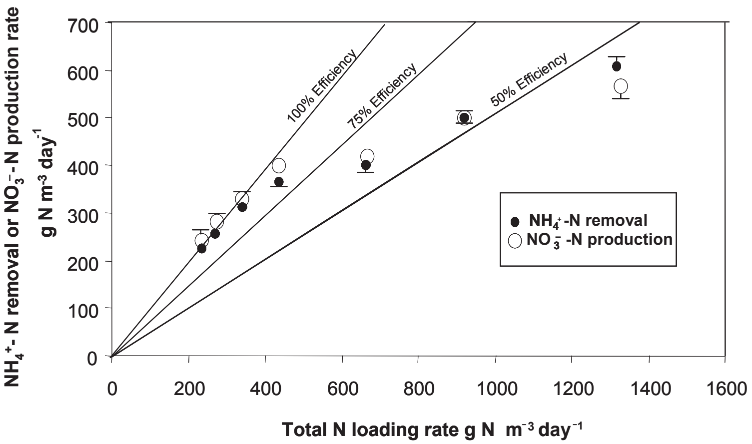


Fig. 5 Nitrification efficiency of nitrifying pellets with continuous flow at increasing loading rates. Data points represent means ($n=2$), and error bars represent 1 SEM.

Table 5 Nitrogen mass inflow, treated outflow, and reactor capacity estimated for three nitrification systems treating the anaerobic lagoon effluent of a 2600-head nursery pig farm.

	Inflow	Overland flow	Trickling filter	Encapsulated nitrifiers
			Treated outflow	
NH_4^+-N (kg day^{-1})	5.2	2.2	2.2	0.5
NO_3^--N (kg day^{-1})	0	0.4[a]	3.0	4.7
			Reactor capacity	
Efficiency (%)		42	57	9[b]
Volume (m^{-3})		104[c]	21[d]	12

[a]Nitrate recovery in treated effluent = 7%. [b]NH_3 removal efficiency for a retention time of 12 h and loading rate of 438 g N m^{-3} day^{-1}. [c]Overland flow plot size = 10 × 52 × 0.2 m (1:4 width to length ratio). [d]Filter size = 22.3 m dia. × 0.6-m height.

remove large amounts of N from the lagoon, then a retrofit nitrification unit operated at shorter retention times would be recommended. This strategy has the advantage of reducing the total cost of aeration per unit of nitrate-N produced.

Treatment efficiency and system size comparisons

Treatment efficiency, calculated as mass reduction of N in the effluent relative to N mass in the inflow, can be used to compare the three different nitrification system options. However, the efficiency of each system did not provide a direct measure of the size or capacity of the reactor needed to treat a given mass loading. Therefore, the capacity of each system was estimated using a total N loading rate of 5.5 kg day^{-1} (5.2 kg day^{-1} as NH_4^+-N). This average N loading rate was estimated from lagoon records of the 2600-head pig nursery operation used in our study. The treated N mass outflow and reactor volumes are presented in Table 5 for each system. The treated N mass outflow was estimated using selected treatment efficiencies presented in Tables 2–4 for the overland flow, trickling filter, and encapsulated nitrifiers bioreactor, respectively. As expected for a low-intensity system, the overland flow system had the largest estimated reactor volume (104 m^3). This volume was the result of an overland flow plot size of 10 × 52 × 0.2 m (1:4 width to length ratio) needed to treat 5.2 kg day^{-1} as NH_4^+-N with an efficiency of 42%. The trickling filter supplemented with lime was a medium-intensity system with an estimated reactor volume of 21 m^3 using a treatment efficiency of 57%. The encapsulated nitrifiers bioreactor was a high-intensity system with the smallest estimated reactor volume of the three systems (12 m^3) and a treatment efficiency of 91%.

CONCLUSIONS

Animal waste treatment is a significant agricultural and environmental challenge that needs additional options as a result of expanded, confined animal production. Three technologies were evaluated for enhancing nitrification of pig lagoon wastewater. Overland flow is a low-intensity system that can remove large amounts of N per unit area through nitrification and partial denitrification. Performance data showed N removal rates of 22 to 42 kg N ha^{-1} day^{-1}. Trickling filter is a medium-intensity system that is popular among small waste generators. Our adaptation for animal waste consisted of selection of a marl gravel media, design of an intermittent application schedule to enhance aeration, and lime supplementation. Nitrification efficiency was 57% at total N loading rates of 249 g m^{-3} day^{-1}. Nitrifying pellet technology is a high-intensity system using fluidised bioreactors designed for fast and efficient removal of NH_4^+-N. Nitrification efficiencies of 91% were obtained at total N loading rates of 438 g m^{-3} day^{-1}, and 42% at 1349 g N m^{-3} day^{-1}. When the three systems were compared to treat a given N loading rate (5.2 kg NH_4^+-N day^{-1}) the overland flow had the largest reactor size 10 × 52 × 0.2 m (104 m^3), the trickling filter was smaller (21 m^3) than the overland flow system, and the encapsulated nitrifiers bioreactor was the smallest of the three systems (12 m^3). Two conclusions are suggested from this research: (1) that substantial nitrification of pig lagoon wastewater can be attained particularly using aerobic treatments with enriched nitrifying populations, and (2) that large mass removal of N from pig wastewater may be possible by sequencing nitrification and denitrification unit processes.

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