# Water Quality Improvements of Wastewater from Confined Animal Feeding Operations after Advanced Treatment

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Current trends of animal production concentration and new regulations promote the need for environmentally safe alternatives to land application of liquid manure. These technologies must be able to substantially remove nutrients, heavy metals, and emissions of ammonia and odors and disinfect the effluent. A new treatment system was tested full-scale in a 4360-swine farm in North Carolina to demonstrate environmentally superior technology (EST) that could replace traditional anaerobic lagoon treatment. The system combined liquid–solids separation with nitrogen and phosphorus removal processes. Water quality was monitored at three sites: (i) the treatment plant as the raw manure liquid was depurated in the various processes, (ii) the converted lagoon as it was being cleaned up with the treated effluent, and (iii) an adjacent traditional anaerobic lagoon. The treatment plant removed 98% of total suspended solids (TSS), 76% of total solids (TS), 100% of 5-d biochemical oxygen demand ($BOD_5$), 98% of total Kjeldahl nitrogen (TKN) and $NH_4$–N, 95% of total phosphorus (TP), 99% of Zn, and 99% of Cu. The quality of the liquid in the converted lagoon improved rapidly as cleaner effluent from the plant replaced anaerobic lagoon liquid. The converted lagoon liquid became aerobic (dissolved oxygen, 6.95 mg $L^{-1}$; Eh, 342 mv) with the following mean reductions in the second year of the conversion: 73% of TSS, 40% of TS, 77% of $BOD_5$, 85% of TKN, 92% of $NH_4$–N, 38% of TP, 37% of Zn, and 39% of Cu. These findings overall showed that EST can have significant positive impacts on the environment and on the livestock industries.

There are major concerns regarding the generation of large amounts of manure by confined animal feeding operations (CAFOs) within relatively small geographic areas and the potential to impair ground and surface water quality due to soil leaching or runoff of land-applied nutrients (Gollehon and Caswell, 2000; Szogi and Vanotti, 2003). A shift in the industry over the past decade toward fewer but larger operations has raised concerns over the use and disposal of animal manure. In the USA, land application of manure, a preferred disposal method, may be difficult and costly to implement on CAFOs if restrictions on land application increase the amount of land required for spreading (Ribaudo et al., 2003). For confined animal operations in the USA, 60% of available nitrogen (N) and 70% of available phosphorus (P) were in excess of the amount of manure N and P that could be assimilated on the farms that produced them (Gollehon et al., 2001). In addition, about 20% of the farm-level excess N and 23% of the farm-level excess P exceeded the land assimilative capacity at the county level (Kellog et al., 2000). Therefore, substantial amounts of manure N and P need to be moved at least off the farms, and some manure needs to be transported longer distances beyond county limits to solve the distribution problems of these nutrients. A major problem in sustainability of CAFOs is the imbalance between N and P in the manure (USEPA, 2003). Nutrients in manure are not present in the same proportion needed by crops. For example, a typical N:P ratio (4:1) in swine manure is generally lower than the mean N:P ratio (8:1) taken up by major crops and pastures (USDA, 2001). Thus, when manure is applied based on a crop's N requirement, there is a P buildup in soil and increased potential for P losses through runoff and subsequent eutrophication of surface waters (Sharpley et al., 2003).

Anaerobic lagoons are widely used to treat and store liquid manure from confined swine production facilities. Environmental and health concerns with the lagoon technology include emissions of ammonia (Aneja et al., 2000; Szogi et al., 2006), odors (Loughrin et al., 2006a; Schiffman et al., 2001), pathogens (Sobsey et al., 2001; Vanotti et al., 2005a), and water quality deterioration (Mallin, 2000). Thus, there is a major interest in developing alternative swine manure treatment systems that can address these environmental and health problems.



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**Abbreviations:** BOD, biological oxygen demand; CAFO, confined animal feeding operation; COD, chemical oxygen demand; DO, dissolved oxygen; EC, electrical conductivity; EST, environmentally superior technology; GHG, greenhouse gas; LAW, live animal weight; NDN, nitrification–denitrification; $NH_4$–N, ammonia nitrogen; PAM, polyacrylamide; TKN, total Kjeldahl nitrogen; TP, total phosphorus; TS, total solids; TSS, total suspended solids; VSS, volatile suspended solids.

Widespread objection to the use of anaerobic lagoons for swine manure treatment in North Carolina prompted a state government–industry framework to give preference to alternative technologies that would eliminate anaerobic lagoons as a method of treatment. This framework established an agreement between the government and the swine industry to develop and demonstrate environmentally superior waste management technologies (ESTs) that could meet the following five environmental performance standards: (i) eliminate the discharge of animal waste to surface waters and ground water through direct discharge, seepage, or runoff; (ii) substantially eliminate atmospheric emissions of ammonia; (iii) substantially eliminate the emission of odor that is detectable beyond the boundaries of farm; (iv) substantially eliminate the release of disease-transmitting vectors and airborne pathogens; and (v) substantially eliminate nutrient and heavy metal contamination of soil and ground water (Williams, 2001).

In March 2006, five of the 18 technologies tested under this agreement were shown to be capable of meeting the environmental performance criteria necessary for the technologies to be considered ESTs (Williams, 2004, 2005, 2006). Only one of the five selected technologies treated the entire swine waste stream on-farm and provided dewatered manure solids amenable for transport off farm and land application or generation of value-added products with additional treatment. The other four selected technologies further processed separated manure solids using composting, high-solids anaerobic digestion, or gasification processes that produced a variety of products, such as class A composts, organic fertilizers, and energy.

Consequently, in July 2007 the State of North Carolina enacted Senate Bill 1465, which made permanent the five environmental performance standards of an EST as a requirement for the construction of new swine farms or expansion of existing swine farms in North Carolina (NC General Assembly, 2007). It also established a Lagoon Conversion Program that provides financial incentives to assist producers in the conversion of anaerobic swine lagoons to ESTs.

The on-farm technology used liquid–solid separation, nitrification/denitrification, and soluble P removal processes linked together into a practical system. It was developed to replace the anaerobic lagoon technology commonly used in the USA to treat swine waste (Vanotti et al., 2005b). The technology effectively replaced anaerobic lagoon treatment by discontinuing loading of liquid manure into the lagoon. In turn, recycled clean water promoted the conversion of the anaerobic lagoon into an aerobic pond.

The objective of this study was to report the water quality improvements by the alternative on-farm technology during a 2-yr evaluation period operating at full scale. In addition, we describe water quality changes in the converted lagoon during a 3-yr period by comparing it with an adjacent conventional lagoon with a similar production management.

## Materials and Methods

### Site Description

The study was conducted on Goshen Ridge Farm near Mount Olive, Duplin County, North Carolina. The operation had three swine production units under identical animal production and waste treatment management. Each production unit had six barns with 4360-head finishing pigs and a traditional anaerobic lagoon for treatment and storage of manure, but only two production units were used in this study (Fig. 1). Manure was collected under the barns using slatted floors and a pit-recharge system typical of many farms in North Carolina (Barker, 1996). During traditional management, liquid manure contained in the pits was completely drained weekly by gravity to the anaerobic lagoons. After treatment in the lagoon (retention time, 180 d), the liquid was sprayed onto nearby fields growing small grains and forages. The lagoon liquid was also used to recharge the barn pits to facilitate flushing of the newly accumulated manure. Lagoon dimensions, monthly average live animal weight (LAW) computed from farm production records, and N loads are presented in Table 1.

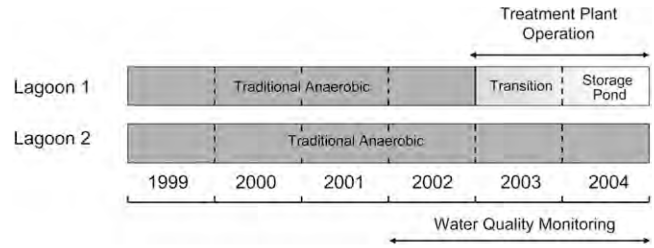


**Fig. 1. Management of studied Lagoons 1 and 2, Duplin County, North Carolina.**

The traditional lagoon system was operational for about 4 yr before the new waste treatment plant started operation in 2003 (Fig. 1). Once operational, the flow of raw manure into the lagoon was discontinued, and the new system treated all the raw manure produced in the barns of Unit 1. Even though animal production management remained the same during 2003–2004 for both units, waste treatment methods were substantially different. Barn pits in Unit 1 were flushed once a week as before, but the raw manure was diverted into a 388-$m^3$ homogenization tank. From there, the liquid manure received continuous treatment. The treatment system combined solid–liquid separation with removal of N and P from the liquid phase (Fig. 2). In addition to a treated liquid stream, the system generated two separated solids streams that left the farm consisting of manure solids and calcium phosphate solids (Fig. 2). As the treatment system provided depuration to the liquid manure and replaced the anaerobic lagoon liquid with clean water, it transformed the anaerobic lagoon in Unit 1 into a treated water pond.

Water quality monitoring of the lagoons was performed during a 3-yr period that included the preceding year (2002) when both lagoons performed traditional anaerobic treatment and the following 2 yr (2003–2004) when Lagoon 1 received

**Table 1. Main characteristics of the two swine production units.**

| Production unit | Lagoon surface | Lagoon volume | Live animal weight (LAW) Steady state† | Live animal weight (LAW) Range | Total N load‡ | |
|---|---|---|---|---|---|---|
| | ha | $m^3$ | ———kg——— | | kg $d^{-1}$ | kg $yr^{-1}$ |
| 1 | 0.90 | 24,145 | 224,581 | 13,205–377,851 | 65.1 | 23,762 |
| 2 | 0.92 | 22,356 | 196,636 | 0–367,769 | 57.0 | 20,805 |

† Monthly means of six barns (2003–2004; $n = 24$; Fig. 3).

‡ Total N load = (kg steady-state LAW × 0.29 kg N/1000 kg LAW $d^{-1}$)/1000.

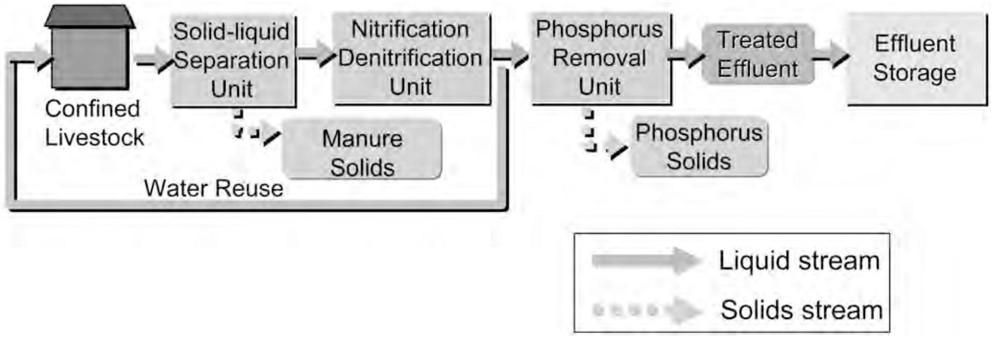


Fig. 2. Schematic diagram of waste water treatment system.

effluent from the alternative treatment system (Fig. 1). To facilitate the comparison of results of water quality monitoring, we used the same 3-yr scale in all the other figures in this study, starting January 2002 (Fig. 1). Atmospheric temperature conditions during the 3-yr water quality monitoring period are shown in Fig. 3. The converted lagoon is referred throughout this article as Lagoon 1, or treated lagoon. The control lagoon using traditional management is referred to as Lagoon 2, or traditional lagoon.

## Alternative Manure Treatment System

As part of the project to demonstrate ESTs to replace treatment lagoons, Production Unit 1 was retrofitted with a new waste management system (Vanotti et al., 2005b). The system was constructed and operated by Super Soils Systems USA (Clinton, NC). The system made use of three process units (Fig. 2). The first process unit in the system separated solids from raw flushed manure using polyacrylamide (PAM) polymer flocculant (Vanotti and Hunt, 1999). Before entering the solid–liquid separation unit, the raw flushed manure was well mixed in a 388-m$^3$ homogenization tank. Solids were separated using an Ecopurin solid–liquid separation module (Selco MC, Castellon, Spain) that included injection of cationic PAM, removal of flocculated solids in a rotary screen, dewatering solids in a belt press, and further separation of residual solids in a dissolved air flotation unit. The application rate of PAM varied from 106 to 178 g m$^{-3}$ (average, 136 g m$^{-3}$), corresponding to the changes in wastewater strength. The separated manure solids were transported off-site to a centralized solids processing facility and converted to organic plant fertilizer, soil amendments, and plant growth media or were used for energy production (Vanotti et al., 2007; Williams, 2004, 2005).

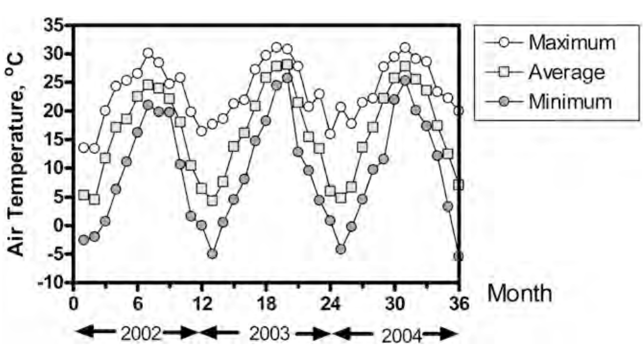


Fig. 3. Air temperature during the 3-yr water quality monitoring period. Data are monthly maximum, average, and minimum of average daily temperatures.

The second process unit treated the liquids after solid separation using a biological N removal system. The project used the Biogreen process (Hitachi Plant Technologies, Ltd., Tokyo, Japan) that removed N via nitrification–denitrification (NDN) processes. Nitrification was performed in an aeration tank (110 m$^3$) that used nitrifying bacteria immobilized in polymer gel pellets (12 m$^3$) to increase the concentration and effectiveness of the bacterial biomass (Vanotti and Hunt, 2000). Air was provided with an 11.2 kW, rotary lobe blower. The hydraulic retention time (HRT) of nitrification averaged 2.8 d. Nitrification transformed $NH_4$–N into $NO_3$–N and depleted >80% of bicarbonate alkalinity. A pre-denitrification configuration transformed $NO_3$–N into $N_2$ gas, where nitrified wastewater was continually recycled to a 263-m$^3$ anoxic denitrification tank at an average rate of 4.4 times the inflow rate. In this tank, suspended denitrifying bacteria (3–6 g L$^{-1}$ mixed liquor suspended solids) used soluble manure carbon contained in the separated liquid to remove the $NO_3^-$. Thus, elimination of ammonia and reduction of carbonate buffering during biological N removal treatment allowed the recovery of P from the liquid when small amounts of lime were added in the third treatment module (Vanotti et al., 2003).

In the third process unit, P was recovered as calcium phosphate solid (Vanotti et al., 2003), and pathogens were destroyed by the alkaline environment (Vanotti et al., 2005a). The effluent from the biological N treatment was treated with hydrated lime in a 0.3-m$^3$ reaction chamber. The pH of the process was kept at 10.5 to 11.0 by a pH probe and controller linked to the lime injection pump. The reaction produced calcium phosphate precipitate, which was separated in a settling tank. The P precipitate (24.4 ± 4.5% $P_2O_5$) was further dewatered in filter bags and transported off-site for use as plant fertilizer (Vanotti et al., 2007).

The system treated an average of 39 m$^3$ d$^{-1}$ of raw manure flushed from the barns. An internal loop recycled N-treated water to refill the barn's pit recharge system (13 m$^3$ d$^{-1}$), and the clarified effluent from the P removal unit (26 m$^3$ d$^{-1}$) was stored in Lagoon 1 (Fig. 2) and later used for crop irrigation. For a detailed description of the full-scale treatment system, see Vanotti et al. (2007).

## Water Sampling

For the wastewater treatment system, composite liquid samples were collected twice per week over a period of 20.5 mo (April 2003 to December 2004) with the system operating at steady state. Samples were taken from the following four points of the treatment system: (i) the homogenization tank containing raw flushed manure, (ii) after solid–liquid separation treatment, (iii) after biological N treatment, and (iv) from the final effluent after P treatment (Fig. 1). Each sample was the composite of four subsamples taken over a 3.5-d period using refrigerated automated samplers (Sigma 900max; American Sigma, Inc., Medina, NY).

For the lagoons, liquid samples were collected monthly over a period of 36 mo (January 2002 to December 2004) to monitor water quality characteristics before and after Lagoon 1 conversion compared with traditional management in Lagoon 2 (Fig. 1). Samples were taken from lagoon supernatant within a 0.30-m depth. Two 1.0-L composite samples were obtained from each lagoon by mixing in a bucket eight subsamples collected around the lagoon using a 500-mL polyethylene dipper with a 3.6-m handle.

### Water Analysis

All water quality analyses were performed according to Standard Methods for the Examination of Water and Wastewater (APHA, 1998). Total solids (TS), total suspended solids (TSS), and volatile suspended solids (VSS) were determined according to Standard Method 2540 B, D, and E, respectively. The TSS were that portion of TS retained on a 1.5-μm glass microfiber filter (Whatman grade 934-AH; Whatman, Inc., Clifton, NJ) after filtration and drying to constant weight at 105°C, and VSS was that portion of TSS that was lost on ignition in a muffle furnace at 500°C for 15 min. Chemical analyses consisted of chemical oxygen demand (COD) and 5-d biochemical oxygen demand ($BOD_5$), ammonia ($NH_4$–N), nitrate plus nitrite ($NO_3$ + $NO_2$–N), total Kjeldahl N (TKN), total P (TP), soluble P (SP), potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), copper (Cu), zinc (Zn), pH, and electrical conductivity (EC). For COD determination, we used the closed reflux, colorimetric method (Standard Method 5220 D), and BOD was determined using the 5-d BOD test (Standard Method 5210 B). The orthophosphate ($PO_4$–P or soluble P) fraction was determined by the automated ascorbic acid method (Standard Method 4500-P F) after filtration through a 0.45-μm membrane filter (Gelman type Supor-450; Pall Corp., Ann Arbor, MI). The same filtrate was used to measure $NH_4$–N by the automated phenate method (Standard Method 4500-$NH_3$ G) and $NO_3$ + $NO_2$–N by the automated cadmium reduction method (Standard Method 4500-$NO_3^-$ F). The ammonia method determined total ammoniacal N that included ionized ($NH_4^+$) and un-ionized ($NH_3$) forms. Total P and TKN were determined using acid digestion (Gallaher et al., 1976) and the automated ascorbic acid and phenate methods adapted to digested extracts (Technicon Instruments Corp., 1977). The organic P fraction was the difference between total P and $PO_4$ analyses, which included condensed and organically bound phosphates. The organic N fraction was the difference between Kjeldahl N and $NH_4^+$–N determinations. The pH was determined electrometrically (Standard Method 4500-$H^+$ B), and EC was determined by Standard Method 2510 B. Alkalinity was determined by acid titration to the bromocresol green endpoint (pH 4.5) and expressed as mg $CaCO_3$ $L^{-1}$ (Standard Method 2320 B). The K, Ca, Mg, Na, Cu, and Zn were determined using

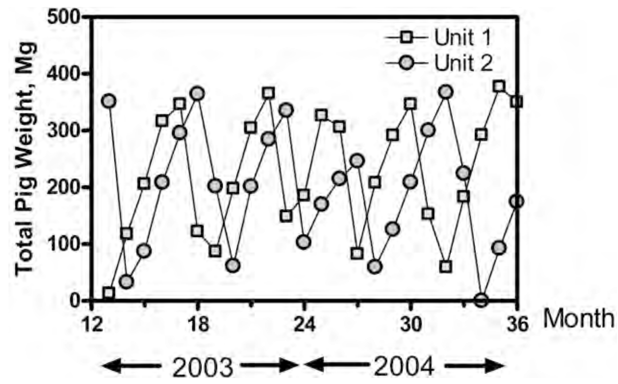


**Fig. 4. Total live weight of pigs at Goshen Ridge farm (Units 1 and 2 containing six barns each) showing growing cycles during demonstration of the new wastewater treatment system.**

nitric acid/peroxide block digestion (Peters, 2003) and inductively coupled plasma analysis (Standard Method 3125 A). Oxidation-reduction potentials were measured in the lagoon liquid at the time of sampling using a Ag/AgCl reference electrode and corrected to standard hydrogen electrode (Eh) values (Standard Method 2580 B).

Data management, descriptive statistics (PROC MEANS), regression (PROC REG), and mean comparison (PROC UNIVARIATE) analyses were performed with version 6.03 of SAS (SAS Institute, 1988).

## Results and Discussion

### Livestock and Manure Changes with Production

Total weight of pigs and corresponding growing cycles in Units 1 and 2 (six barns each) during the 2003–2004 period are shown in Fig. 4. Production cycles were distributed gradually among barns on the farm from Barns 1 to 6 in Unit 1 to Barns 1 to 6 in Unit 2. New batches of pigs were received January-February 2003, June-July 2003, November-December 2003, March-April 2004, and July-August 2005 in Unit 1 and approximately 1 to 2 mo later in Unit 2 (Fig. 4); therefore, the operation produced about 2.5 growing cycles per year. The total pig weight in both production units was similar, averaging about 225,000 kg in Unit 1 and 200,000 kg in Unit 2 (Table 1), but varied greatly from 0 to about 378,000 kg within the livestock production cycles (Fig. 4). Consequently, the strength of the manure also varied greatly (Fig. 5). For example, the TSS concentration in the raw manure varied from 1000 to 31,000 mg $L^{-1}$, COD from 2000 to 45,000 mg $L^{-1}$, TKN from about 370 to 3100 mg $L^{-1}$, and TP from 70 to 1310 mg $L^{-1}$ (Fig. 5). These changes occurred gradually over a 2- to 3-mo period, which helped the bacteria in NDN to acclimate to the N fluctuations.

### Water Quality Improvements by Advanced Treatment

#### System Performance

The waste water treatment performance data obtained during full-scale operation are presented in Table 2, which shows the values of various water quality indicators as the liquid passed through each treatment module and the overall efficiency of reduction for these parameters. The on-farm system

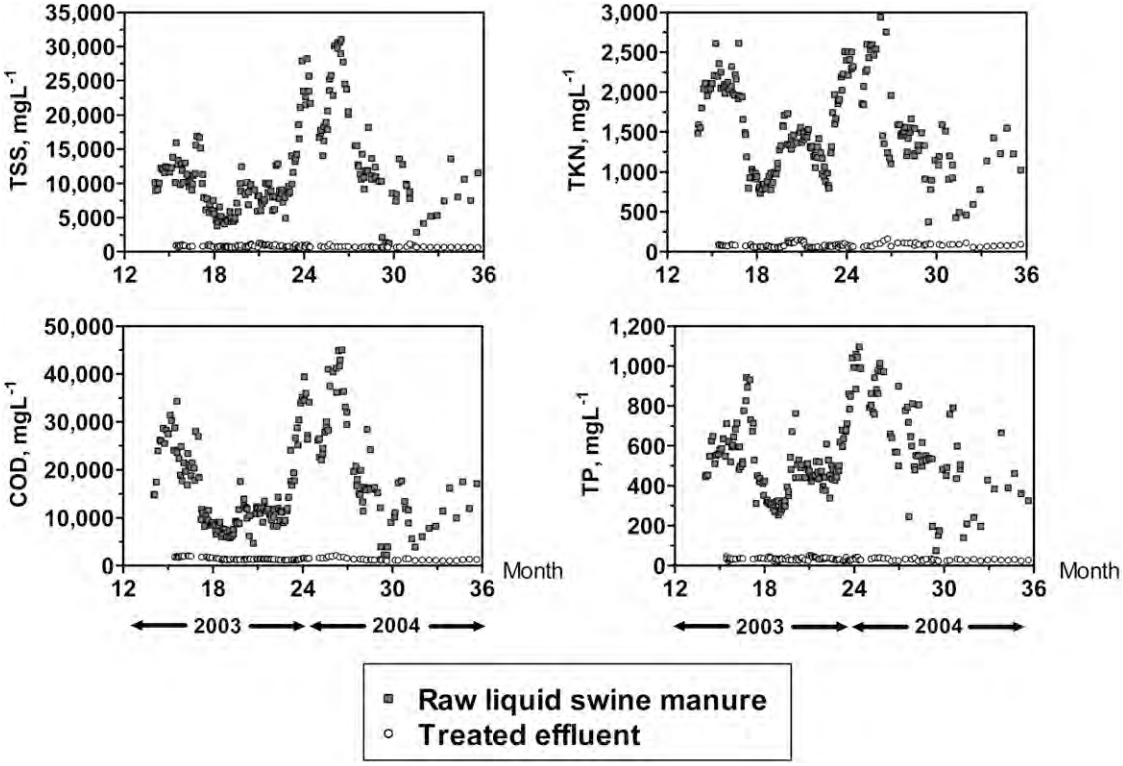


**Fig. 5. Water quality changes in flushed swine manure after advanced treatment. COD, chemical oxygen demand; TKN, total Kjeldahl nitrogen; TP, total phosphorus; TSS, total suspended solids.**

removed 98.0% of TSS, 99.0% of VSS, 75.5% of TS, 97.5% of COD, 99.7% of $BOD_5$, 98.3% of TKN and $NH_4$–N, 95.5% of TP, 94.7% of soluble P, 99.3% of Zn, 99.1% of Cu, 91.0% of S, 51.4% of EC, and 84.7% of alkalinity. These high treatment efficiencies were obtained consistently during a 2-yr period with average daily air temperatures ranging from −5.4 to

**Table 2. Wastewater treatment plant performance and system efficiency at Goshen Ridge Farm.†**

| Water quality parameter | Raw flushed swine manure | Treatment step: After solid–liquid separation | After biological N treatment | After P treatment | System efficiency |
|---|---|---|---|---|---|
| | mg $L^{-1}$‡ | | | | % |
| TSS | 11,612 ± 6746 | 811 ± 674 | 134 ± 75 | 232 ± 152 | 98.0 |
| VSS | 8587 ± 5623 | 559 ± 459 | 83 ± 57 | 82 ± 48 | 99.0 |
| TS | 13,412 ± 6337 | 3994 ± 1542 | 3669 ± 714 | 3282 ± 640 | 75.5 |
| COD | 16,758 ± 9910 | 3122 ± 2074 | 612 ± 217 | 413 ± 185 | 97.5 |
| $BOD_5$ | 3046 ± 2341 | 923 ± 984 | 40 ± 44 | 10 ± 16 | 99.7 |
| TKN | 1501 ± 567 | 895 ± 298 | 43 ± 34 | 26 ± 25 | 98.3 |
| $NH_4$–N | 838 ± 311 | 796 ± 297 | 31 ± 34 | 14 ± 19 | 98.3 |
| $NO_2$ + $NO_3$–N | 1.5 ± 4.5 | 0.4 ± 2.6 | 228 ± 110 | 235 ± 116 | – |
| Organic N | 658 ± 360 | 98 ± 93 | 14 ± 14 | 12 ± 14 | 98.2 |
| TP | 566 ± 237 | 168 ± 53 | 149 ± 33 | 26 ± 16 | 95.4 |
| Soluble P | 131 ± 39 | 116 ± 33 | 138 ± 28 | 7 ± 7 | 94.7 |
| Organic P | 428 ± 218 | 47 ± 42 | 12 ± 16 | 17 ± 15 | 96.0 |
| K | 1162 ± 328 | 1073 ± 317 | 1044 ± 228 | 997 ± 244 | 14.2 |
| Ca | 314 ± 171 | 59 ± 25 | 49 ± 23 | 142 ± 97 | 54.8 |
| Mg | 229 ± 112 | 26 ± 21 | 21 ± 9 | 9 ± 5 | 96.1 |
| Zn | 31.2 ± 16.4 | 1.4 ± 1.8 | 0.5 ± 0.4 | 0.2 ± 0.3 | 99.3 |
| Cu | 32.0 ± 16.8 | 1.5 ± 1.8 | 0.6 ± 0.3 | 0.3 ± 0.3 | 99.1 |
| S | 167 ± 86 | 25 ± 12 | 19 ± 6 | 15 ± 6 | 91.0 |
| Na | 250 ± 71 | 235 ± 68 | 227 ± 52 | 215 ± 48 | 14.0 |
| Alkalinity, mg $CaCO_3$ $L^{-1}$ | 5001 ± 1695 | 4154 ± 1463 | 624 ± 470 | 763 ± 353 | 84.7 |
| pH | 7.64 ± 0.22 | 7.93 ± 0.26 | 7.29 ± 0.70 | 10.53 ± 0.63 | – |
| EC, mS $cm^{-1}$ | 9.88 ± 2.96 | 9.72 ± 2.90 | 5.27 ± 0.89 | 4.80 ± 1.05 | 51.4 |

† Data are means ± SD for 180 sampling dates (15 Apr. 2003–31 Dec. 2004). BOD, biological oxygen demand; COD, chemical oxygen demand; EC, electrical conductivity; TKN, total Kjeldahl nitrogen; TP, total phosphorus; TS, total solids; TSS, total suspended solids; VSS, volatile suspended solids.

‡ Except for EC (mS $cm^{-1}$) and pH.

31.1°C (Fig. 3) and large variations in the strength of the manure due to typical livestock growth cycles (Fig. 5).

Data in Table 2 show the key contributions of each technology treatment component toward the efficiency of the total system. Solid–liquid separation was effective in separating suspended solids and organic nutrients; most of the volatile and oxygen-demanding organic compounds present in wastewater (VSS, COD, and $BOD_5$) were also removed from the liquid by capturing the suspended solids. This early removal of suspended solids in the treatment train was significant to the biological N oxidation process for the purpose of ammonia control in the liquid system. Instead of the oxygen being used to break down organic compounds, it was used in the subsequent biological aeration treatment to more efficiently convert $NH_4$–N to $NO_3$–N. This approach is important in animal treatment systems because the raw manure effluent contained significant amounts of COD (16,758 ± 9910 mg $L^{-1}$) and $NH_4$–N (838 ± 311 mg $L^{-1}$) (Table 2). However, only 18.6% of the raw manure COD was subject to oxidation in the biological N removal unit, compared with 95.0% of the $NH_4$–N, which allowed efficient $NH_4$–N removal (96.1%) with a lower power requirement for aeration (137 kW h $d^{-1}$). The NDN module consumed the remaining carbon (COD, $BOD_5$) during denitrification and most of the alkalinity during nitrification. Soluble P concentration was not significantly changed by solid–liquid separation or biological N treatment. However, the reduction in alkalinity and $NH_4$ in the preceding steps was a necessary condition for the P removal process (Vanotti et al., 2003). Vanotti et al. (2003) found that, once the natural buffers in swine wastewater ($NH_4$ and carbonate alkalinity) are reduced with the nitrification pretreatment, the subsequent addition of lime rapidly increases the pH of the liquid, thereby promoting formation of P precipitate with small amounts of chemical added. Soluble P was reduced significantly in the P-module, where it was recovered as a high calcium phosphate content material via alkaline precipitation. There, the pH of the system's effluent was raised above 10.0. This rise in pH also destroyed pathogens (Vanotti et al., 2005a), which was an important objective of the treatment system to meet the EST environmental standards. Vanotti (2004) reported on microbial analyses of the liquid in the same full-scale treatment system during the period July–December 2003. Results of these studies showed that NDN treatment was very effective in reducing pathogens and microbial indicators in liquid swine manure and that the P removal step via alkaline Ca precipitation produced a sanitized effluent with reduction of the pathogens to nondetectable levels.

Another environmental benefit associated with the new technology is the reduction of greenhouse gas (GHG) emissions. Vanotti et al. (2008) reported in the same project a 96.9% reduction of GHG emissions with replacement of the lagoon technology with the new technology, from 4972 tonnes of carbon dioxide equivalents ($CO_2$–eq) to 153 tonnes $CO_2$–eq $yr^{-1}$. Total net emission reductions in the 4360-head finishing operation were 4776.6 tonnes $CO_2$–eq $yr^{-1}$ or 1.10 tonnes $CO_2$–eq $head^{-1}$ $yr^{-1}$.

### Solid–Liquid Separation

The efficiency of solid–liquid separation using polymer flocculation was consistently high, with an average separation efficiency of 93.0% TSS and 93.5% VSS (Table 2). This high-separation efficiency was obtained with liquid manure TSS concentrations that varied from about 1000 to 31,000 mg $L^{-1}$ (Fig. 5) and VSS concentrations from about 600 to 24,000 mg $L^{-1}$. The relationship between TSS production in the manure and the weight of the pigs was 1.93 kg TSS/1000 kg LAW $d^{-1}$. The solids separation unit was also effective at removing wastewater constituents associated with the suspended fraction (TSS, VSS) in the manure; it removed 70.2% of the TS, 81.4% of COD, 69.7% of $BOD_5$, 40.4% of TKN, 85.0% of S, and 70% of TP (Table 2). However, polymer separation treatment was not effective on the reduction of $NH_4$–N (5.0%), soluble P (11.5%), Na (6.0%), and K (7.7%), reflecting the fact that solid–liquid separation per se has little effect on the dissolved fraction (Burton, 1997). On the other hand, organic N and P were effectively captured in the separated solids, resulting in average concentration reductions of 85.1 and 89.0%, respectively.

The solid–liquid separation treatment was also effective in the removal of heavy metals Cu and Zn from manure, which was another treatment objective of EST. Initial Cu levels of 32.0 and Zn of 31.2 mg $L^{-1}$ in raw flushed manure were reduced 95.3 and 95.5%, respectively, in this first treatment stage. These trace metals are used as feed additives to promote growth in pigs and produce metal-enriched manure, which has been linked to contamination of soil around CAFOs, with risks of becoming toxic to plants and grazing animals (Lopez Alonso et al., 2000; Bolan et al., 2004). Fortunately, Cu and Zn can be removed effectively from the liquid manure before land application using the polymer-enhanced solid–liquid separation as shown in this study.

### Biological Nitrogen Treatment

The liquid after solids separation contained some remaining oxygen-demanding organic compounds (COD, BOD) and significant amounts of N and P mostly in soluble form ($NH_4$–N and soluble P) as well as alkalinity (Table 1). The biological N treatment module treated $NH_4$–N effectively. A pre-denitrification unit transformed $NO_3$–N into $N_2$ gas by continuously recycling nitrified wastewater into the denitrification tank. This pre-denitrification unit also consumed a large portion of the remaining oxygen-demanding organic compounds (VSS, COD, $BOD_5$). On average, the biological N treatment reduced VSS, COD, and $BOD_5$ by 85.2, 80.4, and 95.7%, respectively, with respect to their concentration in wastewater after solid–liquid separation. Similarly, the biological N treatment reduced 95.7% of the TKN, 95.2% of the $NH_4$–N, and 95.2% of the alkalinity. These high N removal efficiencies were consistently obtained during warm and cold weather conditions and under TKN concentrations in the separated water varying from about 300 to 1730 mg $L^{-1}$. The relationship for N production by pigs and their live weight was 0.29 kg TKN/1000 kg LAW $d^{-1}$. This step produced a relatively clean, oxidized effluent with 31 mg $L^{-1}$ of $NH_4$–N, 228 mg $L^{-1}$ of $NO_3$–N, 134 mg $L^{-1}$ of TSS, and 40 mg $L^{-1}$ of $BOD_5$ (Table 2). Part of this effluent (post-N treatment) was reused on the farm to flush the pits under the barns (Fig. 2). It replaced the dirtier lagoon liquid used for the same task under the traditional management. Pig productivity benefited from this improved environment. For example, the average daily gain of weight for the period 2003–2004 was 0.794 kg pig$^{-1}$ d$^{-1}$ in Production Unit 1 and 0.758 kg pig$^{-1}$ d$^{-1}$ in Production Unit 2, which represents a 4.8% increase in daily gain for the pigs grown in the cleaner environment.

An additional benefit of aerobic biological N treatment is the reduction of odorous compounds. This was another important objective of the EST determination. Loughrin et al. (2006b) measured odor compounds (phenol, p-cresol, p-ethylphenol, p-propylenphenol, indole, and skatole) in the liquid at the successive stages of the same treatment system during September-October 2003. Their results showed that the concentrations of malodorous compounds were reduced by almost 98% in the treated effluent as compared with untreated raw flushed manure. The majority of this odor reduction occurred during the biological N treatment step, specifically during denitrification where over 80% of the $NO_3$–N in the wastewater was removed by the use of soluble carbon remaining in the wastewater after solids separation (Loughrin et al., 2006b).

### Phosphorus Treatment

Removal efficiencies of the soluble P using the P-removal module averaged 94.9% for waste water containing 76 to 197 mg L$^{-1}$ soluble P (Table 2). The recovered P precipitate solid had a concentration grade of 24.4 ± 4.5% $P_2O_5$ and was >99% plant available based on standard citrate P analysis used by the fertilizer industry (Bauer et al., 2007). The process is based on the distinct chemical equilibrium between P and Ca ions when natural buffers ($NH_4$–N and alkalinity) are substantially eliminated (Vanotti et al., 2003). Although a high pH (10.5) in the P removal process is necessary to produce calcium phosphate and kill pathogens, the treated effluent is poorly buffered, and the high pH decreases readily once in contact with the $CO_2$ in the air. For example, Vanotti et al. (2003) showed that short-term (2.5-h) aeration treatment of the effluent could create enough acidity to lower the pH from 10.5 to 8.5. However, natural aeration during storage may be equally effective at lowering the pH, as was seen in the converted lagoon described in the following section.

On average, the advanced treatment system reduced total N (TKN + $NO_3$–N) concentration from 1503 to 261 mg L$^{-1}$ (83% reduction) and TP from 566 to 26 mg L$^{-1}$ (95% reduction) (Table 2). In addition to substantial reductions in land requirement due to the reduced N and P loads after advanced treatment, the N:P ratio of the liquid was improved from 2.65 to 10.04. This higher N:P ratio resulted in a more balanced effluent from the point of view of crop use.

## Water Quality Improvements in a Treated Lagoon

### Initial Lagoon Conditions

Table 3 and Fig. 6 show the water quality changes in Lagoons 1 and 2 during the 3-yr monitoring period (Fig. 1). The monitoring period includes a common year (2002) when both lagoons received flushed raw manure from the barns (i.e., traditional anaerobic lagoon management) and the following 2 yr (2003–2004) when Lagoon 1 received the liquid processed through the new treatment plant while Lagoon 2 continued under traditional management. During the initial period when the two lagoons had traditional management, their water quality was similar as determined by a wide variety of water quality indicators (Table 3 and Fig. 6). Average initial annual (2002) concentration of these indicators was not significantly different ($p > 0.05$) between lagoons for TSS, COD, $BOD_5$, TKN, $NH_4$–N, TP, Ca, Mg, Zn, Cu, S, alkalinity, pH, and EC. In the few instances (TS, soluble P, K, and Na) where differences in the initial concentrations between lagoons were statistically significant ($p < 0.05$), the concentrations were a little higher (8–17%) in Lagoon 1.

Although the annual average TKN concentrations of the lagoon liquid under traditional management (Lagoon 1 in 2002 and Lagoon 2 in 2002–2004) varied little from year to year (406 to 521 mg L$^{-1}$; Table 3), the monthly average TKN concentrations varied greatly within a year, from about 300 to 700 mg L$^{-1}$ (Fig. 6). The $NH_4$–N followed the same cyclical variation within a year because it made most (89.2 ± 2.5%) of the TKN in the digested manure liquid. These cycles in the traditional lagoon were longer than the pig production cycles (Fig. 4) and followed a typical weather temperature pattern (Fig. 2), with the lowest N concentrations at the end of summer and highest at the end of winter.

### Lagoon Conversion to Aerobic Storage Pond

Beginning in 2003, manure flush to Lagoon 1 was halted, and 100% of the liquid manure generated in the adjacent six barns was processed through the waste water treatment plant. The quality of the liquid in Lagoon 1 rapidly improved as cleaner effluent from the treatment plant replaced anaerobic lagoon liquid, whereas water quality in Lagoon 2 remained generally unchanged (Table 3). The average flow of treated effluent added to Lagoon 1 was 26 m$^3$ d$^{-1}$ (or 9490 m$^3$ yr$^{-1}$), compared with a lagoon total volume of 24,145 m$^3$. Thus, the mean residence time (HRT) of the treated effluent in the storage lagoon was 2.5 yr, and the renovation rate was about 39% yr$^{-1}$. Statistical tests showed significant differences between Lagoons 1 and 2 in all water quality indicators during the first year of change in management (Table 3). In Lagoon 1, the transition from anaerobic to aerobic water storage was noticeable in the first year of treatment. Average dissolved oxygen (DO) concentrations in 2003 at 0.15 m below the liquid surface averaged 4.86 ± 6.11 mg L$^{-1}$ in Lagoon 1 and 0.25 ± 0.03 mg L$^{-1}$ in Lagoon 2 (Table 3). Corresponding redox potentials (Eh) were 309 ± 38 and 217 ± 6 mV. Differences in DO and oxidation reduction potential (Eh) between Lagoon 1 and 2 were more pronounced the second year of conversion of Lagoon 1, with an average DO concentration of 6.95 ± 6.76 mg L$^{-1}$ and an average Eh of 342 ± 54 mV. A redox potential >300 mV is associated with aerobic, oxidized conditions from the point of view of microbial metabolism (Reddy et al., 2000). In addition to these chemical indicators of aerobic conditions, the lagoon changed color from brown to blue (Fig. 7).

The storage of the treated effluent (Table 2) into Lagoon 1 produced rapid changes in the N concentration. In 2003, annual average TKN and $NH_4$–N and TKN levels in Lagoon 1 declined 56 and 58%, respectively, with respect to Lagoon 2. By 2004, differences in TKN and $NH_4$–N concentrations in Lagoon 1 with respect to Lagoon 2 were even larger; on average, TKN declined 81%, and $NH_4$–N declined 90% (Table 3). These differences in water quality characteristics between lagoons produced remarkable

**Table 3. Lagoon liquid analyses of two swine lagoons before and after conversion of Lagoon 1 to storage pond.†**

| | Sampling period | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Jan.–Dec. 2002 (before conversion of Lagoon 1) | | | Jan.–Dec. 2003 (first-year conversion of Lagoon 1) | | | Jan.–Dec. 2004 (second-year conversion of Lagoon 1) | | |
| Water quality parameter | Lagoon 1 | Lagoon 2 | Prob > *t* | Lagoon 1 | Lagoon 2 | Prob > *t* | Lagoon 1 | Lagoon 2 | Prob > *t* |
| | mg $L^{-1}$‡ | | | mg $L^{-1}$‡ | | | mg $L^{-1}$‡ | | |
| TSS | 273 ± 58 | 315 ± 52 | 0.0641 | 173 ± 78 | 299 ± 88 | 0.0003 | 75 ± 33 | 297 ± 64 | <0.0001 |
| VSS | 192 ± 55 | 225 ± 59 | 0.0433 | 136 ± 68 | 215 ± 84 | 0.0064 | 59 ± 29 | 190 ± 44 | <0.0001 |
| TS | 3762 ± 286 | 3283 ± 261 | 0.0009 | 2712 ± 519 | 3185 ± 617 | 0.0005 | 2256 ± 172 | 2912 ± 214 | <0.0001 |
| COD | 1692 ± 449 | 1659 ± 453 | 0.7781 | 872 ± 445 | 1482 ± 548 | <0.0001 | 533 ± 184 | 1284 ± 228 | <0.0001 |
| $BOD_5$ | 207 ± 137 | 170 ± 94 | 0.1240 | 131 ± 72 | 214 ± 124 | 0.0114 | 47 ± 16 | 145 ± 90 | 0.0011 |
| TKN | 506 ± 110 | 521 ± 124 | 0.4094 | 230 ± 141 | 522 ± 130 | <0.0001 | 76 ± 35 | 406 ± 80 | <0.0001 |
| $NH_4$–N | 464 ± 100 | 467 ± 121 | 0.9028 | 186 ± 132 | 447 ± 105 | <0.0001 | 37 ± 33 | 364 ± 89 | <0.0001 |
| $NO_2 + NO_3$–N | 0.1 ± 0.2 | 0.1 ± 0.2 | 0.6421 | 4.1 ± 5.8 | 0.4 ± 1.4 | 0.0660 | 20.6 ± 16.5 | 0.0 ± 0.0 | 0.0007 |
| TP | 130 ± 10 | 127 ± 10 | 0.3339 | 103 ± 17 | 118 ± 16 | 0.0005 | 81 ± 6 | 116 ± 11 | <0.0001 |
| Soluble P | 118 ± 6 | 109 ± 9 | 0.0030 | 91 ± 13 | 100 ± 12 | 0.0172 | 68 ± 12 | 105 ± 11 | <0.0001 |
| K | 1145 ± 77 | 981 ± 58 | <0.0001 | 833 ± 102 | 896 ± 59 | 0.0018 | 747 ± 31 | 904 ± 38 | <0.0001 |
| Ca | 33.6 ± 17.0 | 36.9 ± 19.0 | 0.1337 | 28.9 ± 2.7 | 35.7 ± 13.4 | 0.0409 | 27.6 ± 4.9 | 38.7 ± 3.8 | <0.0001 |
| Mg | 7.4 ± 4.1 | 9.1 ± 2.1 | 0.2394 | 14.9 ± 6.6 | 9.9 ± 2.6 | 0.0074 | 26.3 ± 8.6 | 10.4 ± 3.6 | <0.0001 |
| Zn | 0.41 ± 0.27 | 0.44 ± 0.17 | 0.4128 | 0.20 ± 0.10 | 0.38 ± 0.18 | 0.0008 | 0.26 ± 0.12 | 0.43 ± 0.17 | 0.0003 |
| Cu | 0.18 ± 0.12 | 0.18 ± 0.07 | 0.9810 | 0.10 ± 0.03 | 0.28 ± 0.08 | <0.0001 | 0.11 ± 0.05 | 0.41 ± 0.11 | <0.0001 |
| S | 32.8 ± 14.6 | 33.7 ± 12.1 | 0.6041 | 13.9 ± 2.3 | 20.2 ± 2.8 | <0.0001 | 15.7 ± 2.1 | 22.3 ± 4.9 | <0.0001 |
| Na | 237 ± 15 | 215 ± 13 | 0.0008 | 178 ± 21 | 198 ± 14 | <0.0001 | 161 ± 13 | 197 ± 10 | <0.0001 |
| DO | NA§ | NA | | 4.86 ± 6.11 | 0.25 ± 0.03 | <0.0001 | 6.95 ± 6.76 | 1.43 ± 0.97 | <0.0001 |
| ORP, mV | NA‡ | NA | | 309 ± 38 | 217 ± 6 | <0.0001 | 342 ± 54 | 221 ± 10 | <0.0001 |
| Alkalinity, mg $CaCO_3$ $L^{-1}$ | 3100 ± 433 | 2882 ± 489 | 0.0519 | 1731 ± 629 | 2770 ± 504 | <0.0001 | 1100 ± 274 | 2438 ± 409 | <0.0001 |
| pH | 8.03 ± 0.09 | 7.96 ± 0.16 | 0.0592 | 8.06 ± 0.14 | 7.90 ± 0.11 | 0.0210 | 8.04 ± 0.26 | 8.01 ± 0.17 | 0.6840 |
| EC, mS $cm^{-1}$ | 7.74 ± 0.83 | 7.23 ± 0.86 | 0.0482 | 4.93 ± 1.18 | 7.02 ± 0.92 | <0.0001 | 3.52 ± 0.33 | 6.11 ± 0.72 | <0.0001 |
| SAR, meq $L^{-1}$¶ | 10.2 ± 1.7 | 8.5 ± 1.1 | 0.0001 | 6.9 ± 1.6 | 7.7 ± 0.8 | 0.1014 | 5.3 ± 0.6 | 7.8 ± 0.4 | <0.0001 |

† Data are means ± SDs of monthly samples (*n* = 12). BOD, biological oxygen demand; COD, chemical oxygen demand; DO, dissolved oxygen; EC, electrical conductivity; ORP, oxidation reduction potential; SAR = sodium adsorption ratio; TKN, total Kjeldahl nitrogen; TP, total phosphorus; TS, total solids; TSS, total suspended solids; VSS, volatile suspended solids.

‡ Except for ORP, EC, pH, and SAR. ORP values are standard hydrogen electrode (Eh).

§ Not available.

¶ Sodium adsorption ratio = Na/square root [(Ca + Mg)/2], where the solute concentrations are in millimoles of charge per liter.

differences in atmospheric ammonia ($NH_3$) emissions. Szogi et al. (2006) measured $NH_3$ emissions from Lagoons 1 and 2 during 2004. They found a reduction of 90% annual $NH_3$ emission in the converted lagoon with respect to those in the traditionally anaerobic lagoon (a total of 1210 kg $NH_3$–N $yr^{-1}$ from Lagoon 1 vs. 12,540 kg $NH_3$–N $yr^{-1}$ from Lagoon 2).

In general, manure liquid constituents that were unaffected by the treatment system changed little in the treated lagoon liquid, and vice versa. For example, K and Na in the flushed manure were reduced about 14% in the treatment system (Table 2) and about 17 to 18% in Lagoon 1 compared with Lagoon 2 (Table 3 and Fig. 6). On the other hand, reduction of solids (TSS, VSS), TS, organic (COD, $BOD_5$), TKN, $NH_4$–N, TP, heavy metals (Zn, Cu), and salinity (EC) constituents in the treated lagoon liquid were consistent with the function of the treatment. Compared with initial levels (2002) in Lagoon 1, reductions by the second year of adding cleaner effluent (HRT = 2.5 yr) were TSS = 73%, VSS = 69%, TS = 40%, COD = 68%, $BOD_5$ = 77%, TKN = 85%, $NH_4$-N = 92%, TP = 38%, Zn = 37%, Cu = 39%, S = 52%, alkalinity = 65%, EC = 55%, and sodium adsorption ratio = 48%. The pH of the lagoon liquid remained unchanged (8.03–8.04), which is expected when the high pH effluent of the P-removal process is stored under aerobic conditions (Vanotti et al., 2003).

The remarkable improvement of water quality in the converted lagoon showed an additional environmental benefit when advanced treatment technology is retrofitted to a swine operation with an existing anaerobic lagoon (i.e., the clean-up of the lagoon liquid without additional cost to the farmer).

Although the method cleans existing swine lagoons by displacement of dirty liquid with the treated effluent, it does not repair old leaking lagoons. Therefore, when the treatment system is retrofitted into existing swine operations, the use of the former lagoons for temporarily storing treated water is recommended only when the existing lagoons have properly designed and permitted liners (NRCS, 2004). Otherwise, lagoons should be closed and replaced with lined ponds or tanks for the temporary storage of the treated effluent before land application.

## Economic Considerations

The annualized cost of the new treatment technology (initial investment financed for 10 yr plus operational costs) for a 6000-head farm is about $132 per 454 kg (1000 lb) steady-state LAW $yr^{-1}$ (Williams, 2007) or its equivalent of $7.13 per finished pig (using an actual turnover rate of 2.5 growing cycles per year). This compares with the cost of traditional anaerobic lagoon technology of about $4.86 per finished pig ($90 per 454 kg steady-state LAW $yr^{-1}$) (Williams, 2007). Direct economic benefits to the producer from implementation of the new technology (and the resulting cleaner environment) include the sale of GHG emission reduction

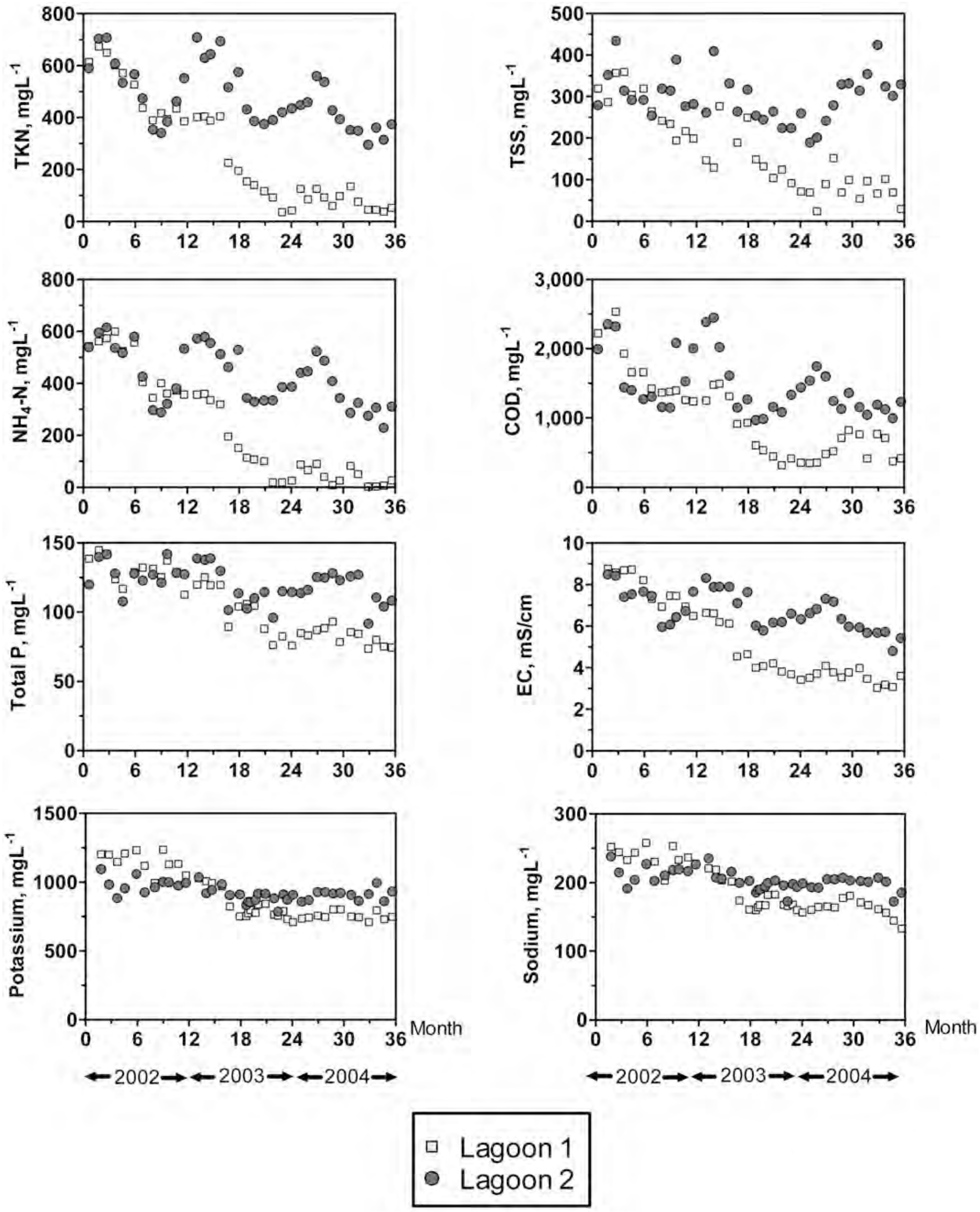


**Fig. 6. Water quality changes in swine lagoons at Goshen Ridge farm (Units 1 and 2). Lagoon 1 received treated effluent during 2003 and 2004, whereas Lagoon 2 received raw flushed swine manure that was the traditional anaerobic lagoon management. COD, chemical oxygen demand; EC, electrical conductivity; TSS, total suspended solids.**

credits and improvements in animal productivity. The benefit from the sale of GHG emission reductions due to installation of the new system in the same 6000-head farm is about \$26,400 $yr^{-1}$, or \$1.75 per finished pig (Vanotti et al., 2008). Additional economic benefits from improvements in animal productivity and health amount to \$91,920 $yr^{-1}$ or \$6.13 per finished pig (Vanotti and Szogi, 2007). The consideration of these benefits makes a difference in determining whether the cleaner technology is economically more or less attractive than the lagoon technology. Combined, the carbon credits and productivity improvement benefits have the potential to pay for all the cost of treatment.

## Summary and Conclusion

We conducted a study to determine the water quality improvements by an alternative on-farm technology operating at full scale during a 2-yr evaluation period. In addition, we evaluated water quality changes in the converted lagoon that were compared with an adjacent traditional lagoon with similar production management. The on-farm system greatly increased the efficiency of liquid–solid separation by polymer injection to increase solids flocculation. Nitrogen management to reduce $NH_3$ emissions was accomplished using nitrification/denitrification. Subsequent alkaline treatment of the wastewater in a P removal unit precipitated P and produced a disinfected liquid

**Fig. 7. Swine lagoon conversion into aerobic pond. Picture on the left shows Lagoon 1 under traditional management (September 2002), and picture on the right shows the same lagoon in September 2003 after the wastewater treatment plant (background) was in operation for about 7 mo.**

effluent. The on-farm system removed 98% of TSS, 76% of TS, 100% of $BOD_5$, 98% of TKN and $NH_4$–N, 95% of TP, 99% of Zn, 99% of Cu, and 51% of EC. These high treatment efficiencies were obtained consistently during a 2-yr period under cold and warm weather conditions with varying strength of the manure from typical livestock growth cycles.

As the treatment system provided depuration to the liquid manure and replaced the anaerobic lagoon liquid with clean water (HRT = 2.5 yr), it transformed the anaerobic lagoon into a treated water pond. The converted lagoon became aerobic, with a DO level of 6.95 mg $L^{-1}$ and a reduction potential (Eh) of 342 mV. By the second year, the following reductions in water constituents were realized: 73% of TSS, 40% of TS, 77% of $BOD_5$, 85% of TKN, 92% of $NH_4$–N, 38% of TP, 37% of Zn, 39% of Cu, and 55% of EC. These reductions showed an additional environmental benefit obtained when advanced treatment technology is retrofitted to a swine operation with an existing anaerobic lagoon; that is, the clean-up of the lagoon liquid without additional cost to the farmer.

Based on the performance results obtained, it was determined that the treatment system met the technical performance standards that define an EST. These findings overall showed that cleaner alternative technologies can have significant positive impacts on the environment and CAFOs.

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