Weekly material fluxes (in tons per week) in the system

Performance Evaluation of a Full-Scale Innovative Swine Waste-to-Energy System

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Abstract

Intensive monitoring was carried out to evaluate the performance of a full-scale innovative swine waste-to-energy system at a commercial swine farm with 8640 heads of swine. Detailed mass balances over each unit of the system showed that the system, which includes a 7600 m³ anaerobic digester, a 65-kW microturbine, and a 4200 m³ aeration basin, was able to remove up to 92% of the chemical oxygen demand (COD), 99% of the biological oxygen demand (BOD), 77% of the total nitrogen (TN), and 82% of the total phosphorous (TP) discharged into the system as fresh pig waste. The overall biogas yield based on the COD input was 64%, a value that indicates that even greater environmental benefits could be obtained with process optimization. Overall, the characterization of the materials fluxes in the system provides a greater understanding of the fate of organics and nutrients in large scale animal waste management systems.

Keywords: anaerobic digester; biogas; methane; nutrient management; swine waste

1. Introduction

Concentrated animal feeding operations (CAFOs) have been growing rapidly in the US over the past 30 years as part of an agricultural trend towards large-scale and corporate-owned and -operated livestock production. Although CAFOs increase animal production at a lowered cost, they have caused many ecological and environmental problems, among which the most challenging is associated with the substantially increased and concentrated animal waste production (Spellman and Whiting, 2007; Abouelenien et al., 2014; Fernandez-Lopez et al., 2015). If not handled properly, the massive quantities of animal waste cause odor nuisances, methane and ammonia emissions, release of disease transmitting vectors and airborne pathogens, and nutrient and heavy metal contamination to surface water and groundwater. Therefore, sound environmental practices, especially the adoption of effective animal waste management systems, are essential to the sustainable development of CAFOs.

North Carolina is the second largest swine producer in the US and accounts for over 10% of domestic swine production (USDA, 2015). Nonetheless, the management of swine waste has always been a challenge to the state's swine industry and raised significant public awareness. Currently, in most domestic swine CAFOs, waste is directed to on-site anaerobic lagoons for storage and partial treatment, and lagoon effluent is applied to cropland for nutrient management (Cheng et al., 2002; Kinyua et al., 2014). However, lagoon and sprayfield systems are far from perfect and their true environmental impact has been questioned. Contaminants from swine waste can enter the environment through leakage from poorly constructed lagoon, overflow during major precipitation events, or runoff from recently irrigated farm fields (Aneja, 2003). Lagoons

are also breeding grounds for flies, possibly antibiotic resistant bacteria and other vectors (McKinney et al., 2010). Lagoons are also known to be large emitters of ammonia (Lahav et al., 2013), which cause local air pollution and together with organics such as skatole, indole, and low molecular weight carboxylic acids, cause significant odor nuisances. Finally, the rich organic conditions in the lagoons stimulates anaerobic biological reactions, in particular the production of methane (up to 5.6 kg CH₄ per head of swine per year (Sharpe and Harper, 1999)), which is a greenhouse gas that is about 21-25 times more potent than CO₂ over a 100-year time frame (Reay et al., 2010). The situation in North Carolina is aggravated by the fact that the state has a high concentration of industrial swine farms in a small geographic area. This results in excess nutrient supply and land application, thus imposing environmental risks to rural communities (Xu et al., 2012). Therefore, it is desirable to develop innovative waste management systems to help swine farmers effectively reduce their emissions, control nutrients, and possibly produce renewable energy through proper management of methane. To this end, anaerobic digestion is a promising approach to convert organic wastes to energy. While it is commonly applied for sludge reduction and energy generation at municipal sewage treatment plants (Iranpour et al., 2002), its use at animal farms is surprisingly small, with only 39 U.S. swine farms having installed anaerobic digesters (USEPA, 2015). Further, very few of these are included in comprehensive waste management systems.

In order to demonstrate a possible solution to swine waste concerns, Duke University led the development and field testing of an innovative and comprehensive swine waste-to-energy management system. This system is the first in North Carolina to

meet the state's Performance Standards of the Animal Waste Individual permit, generate renewable energy, and reduce nutrient and greenhouse emissions at the same time. The system was installed at the Loyd Ray Farms (LRF) which is a feeder-to-finish facility permitted for 8640 heads of swine operation located in Yadkinville, North Carolina. The **comprehensive** system includes an anaerobic digester for organics-to-biogas conversion, a microturbine for electricity generation, and an aeration basin for water polishing and nitrogen management. The system includes various recycle lines to maximize energy production and treatment efficacy. Still, design and operation are simple and operation only requires minimal maintenance. There are no complex controls and, with the exception of the microturbine, the system uses mostly off-the-shelf equipment already familiar to farmers. The system is not patented in order to facilitate its deployment.

The LRFs system was first started in May 2011. In 2015, the system has been working efficiently with minimum maintenance, with an average uptime of 85%, a total power generation of 321 MWh, and a total greenhouse gas destruction of 1988 tons of CO₂ equivalent that year (2436 tons in 2014). Although the system is operating satisfactorily, it is important to quantify the mass flows between the various treatment units to better understand the system's operation and optimize its effectiveness. Thus, intensive monitoring was carried out in August 2014 and March 2015 by conducting mass balances of chemical oxygen demand (COD), BOD (biochemical oxygen demand), total nitrogen (TN) and total phosphorus (TP). The results of these detailed determinations provide insight on the fate of the contaminants and support the

development of a better understanding of the complex dynamics of large manure management systems.

2. Materials and Methods

2.1. System description

The Loyd Ray Farms is a feeder-to-finish swine operation with approximately 8640 heads of swine housed in nine barns. Figure 1 shows the schematic of the innovative swine waste-to-energy system, which includes a 7600 m³ covered ambient temperature anaerobic digester, a 65-kW microturbine, and a 4200 m³ aeration basin.

As will be explained later, on average, 1320 m³ of wastewater was treated weekly resulting in hydraulic retention times (HRT) of 40 days in the anaerobic digester and 22 days in the aeration basin. Sludge is not wasted continuously, but instead some is removed every 1-2 years on an as-needed basis. Thus sludge residence time (SRT) in the system can be considered to be greater than 2 years.

The pits in pig barns for waste collection are flushed once a week (normally two barns per day Monday through Thursday, one barn on Friday and none over the weekend) and the wastewater flows by gravity to the anaerobic digester via a manhole. The anaerobic digester is built in-ground and has a clay-bentonite liner and a high density polyethylene (HDPE) cover. In the digester, the organic materials are converted to biogas by anaerobic microorganisms. The biogas produced (55-70% CH₄, 30-45% CO₂, ~1000 ppm_v H₂S) is collected by perforated gas collection pipes which encircle the digester, routed to a gas skid (Model CGS-50 by Unison Solutions, Dubuque, IA) for conditioning and then combusted in a 65-kW microturbine (Model C65 by Capstone, Chatsworth, CA). The electricity generated by microturbine is used for running the

innovative system and supplementing normal farm operating needs. The excess biogas is stored under the digester cover or, when necessary, routed to a flare to be combusted for methane destruction. The digester effluent flows to the aeration basin, where intermittent aeration is applied so that ammonium undergoes partial nitrification followed by denitrification, and organics are further degraded. The treated liquid is pumped from the settling zone of the aeration basin to flush the pits in the pig barns while a small volume of liquid overflows to the existing lagoon for storage before used for irrigation. Excess nitrifying activated sludge in the aeration basin is periodically pumped to the digester for sludge reduction and improved biogas production.

2.2. Sampling scheme

The summer intense monitoring was carried out August 27 through September 2, 2014. It was carried out only after steady-state was achieved in the system, as assessed by weekly monitoring of the system for over two years. The system had been at (pseudo) steady-state for about one year prior to the monitoring reported herein. Regular monitoring of the system's performance allowed to define the variability of the process and ensured that the data collected during intensive monitoring were representative of regular operation. During the regular monitoring, the COD, BOD, TN, and TP concentrations of the digester effluent were stable and between 7930-8480 mg L⁻¹, 1090-1320 mg L⁻¹, 1890-2200 mg L⁻¹, and 473-540 mg L⁻¹, respectively, while those of the aeration basin effluent were 4540-5610 mg L⁻¹, 402-520 mg L⁻¹, 1330-1570 mg L⁻¹, and 357-442 mg L⁻¹, respectively. Since the farm operates by removing finished pigs from one house at a time, then refilling with feeder pigs rather than an "all in, all out"

schedule, the extent of cyclic fluctuations for the entire system is minimal. Thus the sampling results from that week are representative for all weeks that summer. This was verified by selective 1-day monitoring events as well as comparison to long-term average concentrations (results not shown). To evaluate treatment efficacies of anaerobic digester and aeration basin, liquid samples were taken from three sampling points: a) the manhole where the waste flushed from the pits converge prior to entering the digester, b) the digester effluent pipe which is also the aeration basin influent, and c) the settling zone of the aeration basin where water is taken for pit flushing (Figure 1).

Every weekday at around 8:30 am, the farmer pulls a plug in one or two pits and turns on the flush pump to start the flushing. After 40-60 minutes, when most of the waste is flushed away, the plug is placed back. The flush pump remains on for a couple of hours until the pit is refilled. Throughout the flush event, liquid samples were taken from the manhole every 3 minutes. At the same time, multiple samples were taken from the digester effluent pipe and the settling zone of aeration basin. Even without flush, there is always a continuous (albeit small) stream of waste flowing into the manhole (thereafter referred to as baseline flow). This is due to the overflow from the pits to the collection pipes mostly from pig waste production, but also from barn cleaning. Multiple baseline flow samples were collected every day throughout the intensive monitoring week and during regular weekly monitoring events. All samples collected were stored in a cooler and then brought back to Duke University for analysis. The liquid samples were analyzed for COD, BOD, TN, $\text{NH}_3\text{-N}$, $\text{NO}_2^-\text{-N}$, $\text{NO}_3^-\text{-N}$, TP, TS, VS, DO, and pH.

In order to perform a mass balance, the flow of liquid circulating between the different units of the system was recorded using two DFM 5.1 Doppler flow meters

(Greyline Instruments Inc., Massena, NY). By installing a probe onto the PVC pipe connecting the manhole and the digester, the volume of liquid flowing from the barns to the anaerobic digester was recorded, while the volume of liquid flowing from aeration basin to pig barns was recorded by installing a probe on the pipe connecting flush pumps and pits. Since the liquid loss from the covered and lined anaerobic digester should be negligible, the volume of liquid flowing from digester to aeration basin is assumed to be the same as that from the pig barns to the digester. Due to the difficulty in measuring a small flow in a large pipe using the DFM 5.1 Doppler flow meter, the total volume of baseline flow discharged into the digester was assumed to be the same as that of fresh water fed to the barns ($\sim 420 \text{ m}^3 \text{ week}^{-1}$). Since the water level in the aeration basin was always at the overflow level throughout the intensive monitoring week, the total volume of liquid leaving the system to the existing lagoon (see Figure 1) should be the difference between the influent and effluent volumes to the aeration basin. This assumes that evaporation or rain is negligible compared to these large numbers. The volumes of biogas flowing to the microturbine and the flare were monitored in real-time by a Rosemount 8800D meter (Emerson Process Management, Shakopee, MN USA) and a FCI ST75 meter (Fluid Components International, San Marcos, CA USA), respectively. The methane concentration of biogas was monitored in real-time by a BlueSens BCP-CH4 meter (Herten, Germany).

The winter intense monitoring was carried out March 13 through March 19, 2015. It was similar, but not as extensive as summer monitoring. Only liquid samples were collected from the digester effluent pipe and the settling zone of aeration basin. Since farm operation is relatively constant, the volumes of liquid flowing between different

system components were assumed to be the same, a reasonable assumption based on over two years of weekly monitoring. Swine waste production rate had been found to be proportional to pig age (results not shown), and thus pig age was used to prorate the influent COD, BOD, TN, and TP loadings. These loadings were 11% higher during the winter sampling campaign.

2.3. Analytical methods

Sample analyses were carried out in our laboratories at Duke University. All the samples were homogenized prior to analysis and thus values reported are all total values (i.e., suspended and soluble). COD, BOD, TN, $\text{NH}_3\text{-N}$, $\text{NO}_2^-\text{-N}$, $\text{NO}_3^-\text{-N}$, TP were measured according to Hach Methods 8000, 8043, 10071, 10031, 8507, and 10127, respectively. Total solids (TS) and volatile solids (VS) were measured according to Standard Methods for the Examination of Water and Wastewater (APHA, 1995). The lignin content of liquid sample was measured according to the method adapted from Sluiter et al. (2008). Dissolved oxygen (DO) and pH were analyzed on-site using a Hach HQ40d portable multi-parameter meter and an Oakton ExoTestr pH2 waterproof pH, respectively. Alkalinity was measured by a Hach Alkalinity Test Kit (model AL-TA).

3. Results and Discussion

3.1. Summer monitoring

3.1.1. Anaerobic digester

Figure 2 shows time series for wastewater total flow rate and total solids in samples from the manhole during a typical flush event (August 29, 2014). Right after the plug was pulled, the flush flow rate rapidly reached its peak value and remained at 80-90 L s^{-1} for about 30 minutes, after which the flow rate decreased gradually until it

dropped below the detection limit (15 L s^{-1}) (Figure 2a). As shown in Figure 2b, while the flush flow rate was high, the total solids of the wastewater remained below 2%, but solids concentration increased rapidly when the flow rate decreased. This is because the solids settling at the bottom of the pits are normally the last to be flushed out. The patterns for flow and total solids on other days were similar and are not shown.

By the end of the week, a total of 900 m^3 of flush water had been discharged into the digester. Figure 3 shows the concentrations and loading rates of COD, BOD, TN, and TP of the wastewater discharged into the digester during the same flushing event. The COD, BOD, TN, and TP concentrations were consistent with that of the total solids, indicating that the solids in the waste contained high concentrations of organics and nutrients (the solids and soluble fractions are discussed later in connection with Table S1). At the end of the flush event, the COD, BOD, and TP concentrations of the liquid samples were 8-10 times that of the starting concentrations. However, the ending TN concentration was only 3 times as high. This is consistent with the fact that a high percentage of the TN in the wastewater comes from pig urine and is soluble. The major form of nitrogen was $\text{NH}_3\text{-N}$, which made up 70% of TN. This $\text{NH}_3\text{-N}$ came from the hydrolysis of organic nitrogen in the pig waste and the accumulated ammonium in the flush water. $\text{NO}_2^-\text{-N}$, $\text{NO}_3^-\text{-N}$ were negligible in the wastewater flowing into the digester, indicating that the pits were anaerobic. The BOD concentrations were only 32-55% of the COD concentrations. This low value should be relatively typical for swine farms that recycle liquid from the lagoon/digester to flush pits, as this practice results in the accumulation of non-biodegradable organics in the system. The non-biodegradable organics usually come from cellulosic fibers and lignin which are part of the animal feed

ration and end up in feces (Andreadakis, 1992; Chynoweth et al., 1999). The lignin made up 16.4% of the total solids. Chynoweth et al. (1999) reported that fresh swine waste had 4.4% lignin and only 3% of it could be removed in an anaerobic digester. Since the liquid was recycled at the Loyd Ray Farms, it is not surprising to find that the lignin content in the waste was higher than reported by Chynoweth et al.. The loading rates of COD, BOD, TN, and TP observed during the summer intensive monitoring week are shown in Table 1. They reveal that the total amounts of COD, BOD, TN, and TP discharged into the digester were **significant. Examination of the standard errors also reveals that the method was reliable with generally between 2 and 4% uncertainty on the values determined.**

Outside regular flush times, multiple samples were taken from the manhole to determine the nutrients concentrations of the baseline flow. They were relatively stable, with average COD concentrations of $14.5 \pm 0.5 \text{ g L}^{-1}$, BOD of $6.2 \pm 0.3 \text{ g L}^{-1}$, TN of $2.1 \pm 0.2 \text{ g L}^{-1}$, and TP concentrations of $0.66 \pm 0.06 \text{ g L}^{-1}$. By assuming that the volume of baseline flow from the pits to the digester is identical to the volume of fresh water consumed by the pigs ($\sim 420 \text{ m}^3 \text{ week}^{-1}$), the total amount of contaminants entering the digester with the baseline flow can be calculated (Table 1). With these values, the total volume of wastewater and mass of nutrient discharged to anaerobic digester per week can be calculated; it is 1320 m^3 per week carrying 22.6 t COD, 9.3 t BOD, 3.1 t TN, and 1.0 t TP.

As will be discussed later, these loadings include nutrients cycled through the system, i.e., returned from the aeration basin to the pits. Thus, monitoring of the digester and aeration basin effluents was warranted to close the nutrients balance on

the system. Sampling from these points proved much simpler as concentrations of contaminants were relatively constant throughout the day and during flushes. This is because the large volumes of these bioreactors and their good mixing caused them to behave as ideally mixed reactors. Specifically, the digester was equipped with two 7.5 HP pumps providing mixing to the digester content 12 h day^{-1} , and thus, the digester effluent was uniform throughout the summer monitoring week. Therefore, the average concentrations ($\text{COD} = 8.2 \text{ g L}^{-1}$, $\text{BOD} = 1.1 \text{ g L}^{-1}$, $\text{TN} = 2.0 \text{ g L}^{-1}$, $\text{TP} = 0.51 \text{ g L}^{-1}$) were used for calculating mass flows. These weekly mass flows are reported in Figure 4, while uncertainties on the weekly mass flow determined by error propagation are reported in Table S2.

The mass flows in and out of the anaerobic digester allow calculation of the removal of COD, BOD, TN, and TP in the digester which was 52 ± 2 , 84 ± 2 , 15 ± 3 , and $33 \pm 3\%$, respectively. These values will be discussed in detail later. The removal of COD and BOD was due primarily to the conversion of biodegradable organics to biogas. This can be matched to the biogas production recorded by gas meters. The volume of biogas stored under the inflated cover did not change significantly ($\pm 10\%$ based on visual estimates) during the intensive monitoring week, thus the biogas production was assumed to be the same as the combined consumption by the microturbine and flare. During that week, a total biogas utilization of 5760 m^3 was recorded. Based on the theoretical yield of $350 \text{ m}^3 \text{ CH}_4 \text{ t}^{-1} \text{ BOD}$ (Spellman and Whiting, 2013) and the measured average biogas CH_4 concentration of $65 \pm 2\%$ during the steady-state period, a total reduction of 10.7 t BOD was expected that week. This is 37% higher than the measured BOD reduction of 7.8 t week^{-1} but slightly lower than the COD reduction of 11.8 t week^{-1} .

The discrepancy with the BOD reduction probably stems from the conditions for BOD analysis (aerobic conditions, 20 °C, and 5 days), and for anaerobic digestion ($T > 20$ °C, anaerobic conditions, average residence time of 40 days). Thus, it is likely that some organics not degraded in the standard BOD test were degraded in the anaerobic digester. It suggests that COD or biomethane potential (Angelidaki et al., 2009) are probably better metrics for assessing organic removal and biogas production potential. The 10.7 t BOD equivalent per week also allows calculation of an overall methane yield based on the total COD weekly input (16.8 t week) which was 64%. This suggests that there is significant potential for energy recovery optimization. After anaerobic digestion, a significant fraction of COD and BOD (37% and 27%, respectively, see Table S1) are in soluble form, indicating effective hydrolysis of organic solids. More detailed characteristics of the suspended and soluble fractions in the anaerobic digester can be found in Table S1.

The removal of nitrogen and phosphorus in the anaerobic digester (15% and 33%, respectively) was not investigated in detail. Removal is most probably associated with precipitation of organic solids (e.g., struvite) and microbial growth. The alkalinity of digester content was in the range of 6930-7700 mg L⁻¹, which is sufficient to maintain a suitable pH (7.5) for methanogenesis.

3.1.2. Aeration basin

The digester effluent is introduced near the bottom of the aeration basin to avoid ammonia stripping. Jet aerators in the basin provide intermittent aeration to create an environment that allows partial nitrification and denitrification. A typical operation schedule consists of 1 h idle, 1 h of mixing, and 2 h of aeration while mixing. This

aeration ($2040 \text{ m}^3 \text{ h}^{-1}$, 12 h d^{-1}) provides roughly 47 t of oxygen per week, a value about two to three times larger than the COD and ammonia oxygen demand combined. However, oxygen transfer efficiencies are never 100%. Estimates of oxygen transfer efficiencies from similar jet aerators by others suggest efficiencies ranging from 18-25% while our own measurements using a floating hood and an oxygen gas sensor indicated a transfer efficiency around 30%. As a result, the aeration basin remained anaerobic most of the time, with only short incursions above 0.5 mg L^{-1} dissolved oxygen generally at the end of the aeration phase.

Treatment in the aeration basin reduced the COD, BOD, TN, and TP concentrations to 5.5, 0.4, 1.4, and 0.4 g L^{-1} , respectively. The flow meter recorded a total of 1050 m^3 of liquid pumped from the settling zone of aeration basin to the pits during the intensive monitoring week. Assuming that the total volume of liquid overflowing to the existing lagoon is the difference between the volume of influent and that of effluent (losses to evaporation were negligible), there was a total of 270 m^3 of liquid overflowing from the aeration basin to the lagoon per week. The total amounts of COD, BOD, TN, and TP pumped back to pig barns and overflowing to the existing lagoon are reported in Figure 4 and uncertainties on these numbers can be found in Table S2.

The major form of nitrogen in the aeration basin was $\text{NH}_3\text{-N}$. $\text{NO}_2^-\text{-N}$ and $\text{NO}_3^-\text{-N}$ concentrations were very low due to the mostly anaerobic conditions of the basin combined with the high activity of denitrifiers which reduced nitrite and nitrate immediately after they were produced by nitrification. In a simple experiment, liquid from the aeration basin was brought back to the lab and placed in 250 mL flasks. The

headspace was purged with nitrogen gas and the content was spiked with 50 mg L⁻¹ NO₃⁻-N. All the nitrate was consumed within 24 h, indicating a high denitrifier activity. Our previously published **laboratory study on nitrification of swine wastewater** (Xu et al., 2014) showed that the accumulation of NO₂⁻ and NO₃⁻ might be observed during system startup but would quickly be consumed once denitrifiers grew. It is also likely that shortcut nitrification-denitrification (i.e., partial nitrification to nitrite followed by full denitrification) was occurring because of the low dissolved oxygen (<0.5 mg L⁻¹) that prevails in the basin. The loss of NH₃-N due to stripping was measured cursorily using a buoyant convective flux chamber (results and methods not shown). These measurements revealed that N losses by stripping did not exceed 0.1 t TN week⁻¹. The pH of liquid in aeration basin was ~8.0, which was higher than that of digester effluent (7.5). This is probably due to 1) the stripping of CO₂ and H₂S, which are typical acidic gases saturated in digester effluent (Effenberger, 2008), and 2) to the denitrification process, which increases the pH.

3.1.3. Pig barns

The total mass of nutrients discharged into the system as fresh manure can be calculated from the difference between the amount reaching the digester and this returned via the flush water. It amounted to a total of 16.8±0.3 t COD, 8.9±0.1 t BOD, 1.64±0.06 t TN and 0.59±0.02 t TP weekly. These correspond to 0.28 kg COD head⁻¹ day⁻¹, 0.15 kg BOD head⁻¹ day⁻¹, 0.03 kg TN head⁻¹ day⁻¹, and 0.01 kg TN head⁻¹ day⁻¹, which are consistent with numbers reported **from direct measurements of excreted manure** (Hamilton et al., 1999). The real discharge of TN by the pigs could be slightly higher than the value **determined here** due to the ammonia emission from the pits,

which was only estimated roughly. Sporadic measurements of the ammonia concentration in the barns' exhaust revealed that the average ammonia concentration in the exhaust was about 4 ppm_v. When calculated based on the nominal fan capacity of 37,000 m³ h⁻¹ per fan (36 fans) and an operation time of 8 h day⁻¹, an estimated 0.2 t NH₃-N left the barns as air emissions per week. This means the real TN discharged by the pigs could be about 0.2 t week⁻¹ more.

3.2. Winter monitoring

As mentioned in the Methods section, monitoring during the cold season was reduced, i.e., the digester and aeration basin outputs were measured, while the digester input was prorated using the pig weight. Loadings during the winter sampling were 11% greater than these during the summer monitoring week.

The results of the winter monitoring are shown in Figure 5. Since the average air temperature at the farm during the winter monitoring week (11 °C) was 14 °C lower than that during summer intensive week, it was expected that the system efficiency would be lower in winter. However, the removal of newly added COD, BOD, TN, and TP by the anaerobic digester were, 68±3, 86±5, 34±11, and 58±8%, respectively, indicating an efficiency comparable to that during summer. This apparent lack of seasonal sensitivity can be the result of in-ground design and the good thermal insulation provided by the biogas stored under the digester cover. Similarly, lower temperatures did not significantly affect the performance of the aeration basin. The removal of COD, BOD, TN, and TP by the aeration basin were, 44±4, 69.5±5, 28±4, and 23±4%, respectively, or 25±3, 13±1, 43±6, and 25±5%, respectively, based on the newly added waste. The

reasons for the significantly better removal of organics in the aeration basin in winter are not clear, but might be associated with the increased DO level at lower temperatures. Still, the performance of system during that week in March may not fully represent the coldest winter months (January and February) when the air temperatures were much lower, and the biogas production which was 30-45% lower.

3.3. Performance evaluation

The removal efficiencies of COD, BOD, TN, and TP by the anaerobic digester, aeration basin and the entire system are reported in Table 2 and plotted in Figure 6. Here, one needs to realize that the only waste input into the system is the pig waste in the barns, and that the waste is circled around the system while undergoing treatment. Thus, removals can be calculated based on the digester or the aeration basin's inputs and outputs, or as the fraction of the fresh waste input removed in either the digester, the aeration basin, or the sum of both.

When removals are calculated with the influent and effluent loadings to each units, the removals are moderate, however they are fractional removals of material circled around. As expected, BOD removal is the highest, in particular in the anaerobic digester, and it exceeds 80%. BOD removal is high in the aeration basin as well as it can be consumed aerobically during the intermittent aeration phases, or consumed by heterotrophic denitrification. This is discussed later with the fate of nitrogen. Yearly average removals calculated based on fresh waste input are even higher (total removal $92\pm5\%$ for COD, $99\pm3\%$ for BOD, $77\pm11\%$ for TN, and $82\pm8\%$ TP, see Table 2). These values reflect the fact that the system is effectively controlling COD, BOD and

phosphorous, and to a lesser extent, nitrogen, although the uncertainty on the nitrogen is fairly large. The removal of phosphorous came as a surprise, since the system was not designed with much consideration for phosphorous. It is likely that phosphorous is taken up by cells for growth, and that some precipitates as struvite or other insoluble phosphorous salts.

Interestingly, the performance was not markedly different between the summer and the winter sampling. Possibly, the coldest months (January-February) were missed by our sampling, although, because of the large volume, the system has a large thermal inertia and modest differences are expected between the winter months. Thus, our numbers indicate that excellent treatment performance is maintained during the cold season despite temperatures in the digester and the aeration basin being in the range of 12-16 °C.

As presented in the earlier sections, each week, about 420 m³ of fresh water enters the system, while 270 m³ of treated wastewater overflows to the lagoon. These values may seem low compared to the volume of the entire system (about 14,000 m³), even so, they mean that roughly, the entire volume of the system is exchanged each year. The fraction of the fresh waste discharged to the digester with the overflow amounts to about 9% of the COD, 23% of the TN, and 19% of the TP. The long term fate of these is unknown, but has implications for future systems, in particular those systems designed at farms without a large lagoon or systems to be installed at new farms.

Nitrogen is removed in the system is by a combination of mechanisms that include uptake by growing cells, nitrification and denitrification, precipitation as struvite

or other mineral salts, and stripping. As expected, TN removal in the anaerobic digester was low (~30% of the total fresh nitrogen input) though not insignificant. TN was mostly removed in the aeration basin; this was by design. Some stripping of ammonia probably occurred although estimates made using a buoyant convective flux chamber (results and methods not shown) revealed that stripping was fairly limited ($<0.1 \text{ t TN week}^{-1}$). Because of the conditions in the aeration basin (intermittent aeration, dissolved oxygen below 0.5 mg L^{-1} most of the time), removal of TN was primarily occurring by nitrification, probably to nitrite followed by heterotrophic denitrification, a process also known as shortcut nitrification-denitrification. Assuming that all the TN removed in the aeration basis followed that pathway, 3.8 t of COD would be required per week, based on the stoichiometry of $4.8 \text{ kg}_{\text{COD}} \text{ kg}_\text{N}$ for shortcut denitrification. This is plausible given that roughly 3.5 t of COD removed per week in the aeration basin. If such was the case, little or no COD would be used by aerobic heterotrophs. This is not implausible, given the low dissolved oxygen concentrations prevailing in the aeration basin, and the high affinity of ammonia oxidizing bacteria (AOB) for oxygen, as compared to that of aerobic heterotrophs.

The observed rate of TN removal in the aeration basin was roughly $0.02 \text{ kg N m}^{-3} \text{ d}^{-1}$, i.e., much lower than many engineered systems designed for nutrient control which rates commonly range from 0.1 to $1 \text{ kg N m}^{-3} \text{ d}^{-1}$ (Joss et al., 2009; Sliekers et al., 2002; Im et al., 2001; Third et al., 2001). Earlier research by our team with the same swine waste showed that $\text{NH}_3\text{-N}$ concentrations greater than 800 mg L^{-1} were inhibiting the onset of a nitrification system (Xu et al., 2014). Here, although the $\text{NH}_3\text{-N}$ concentration was initially maintained below 800 mg L^{-1} for a few of months after the restart of the

system, down time caused by equipment failure caused the $\text{NH}_3\text{-N}$ concentration to exceed 1000 mg L^{-1} . This could significantly affect the activity of the nitrifiers and denitrifiers.

4. Conclusions

The novel swine waste-to-energy system was efficient in removing organic waste, producing energy, and managing nutrients year-round. 92% of COD, 99% of BOD, 77% of TN and 82% of TP was removed in the system; a detailed understanding of the contaminants' fate was developed. Nitrogen management was identified as the most sensitive aspect of the system. The COD to biogas yield was 64% suggesting that improved bioenergy generation could be obtained through process optimization. This will require novel approaches to convert the recalcitrant fraction of the COD in the swine waste to organics that are amenable to methanogenesis.

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CAPTIONS

Figure 1. Schematic of the LRFs innovative swine waste-to-energy system and locations of sampling for intensive monitoring, which include a) manhole, b) digester effluent pipe, and c) settling zone of the aeration basin.

Figure 2. a) Flow rate and b) Total solids of the wastewater discharged into digester during a typical flush event (August 29, 2014).

Figure 3. Concentrations and loading rates of a) COD, b) BOD, c) TN, and d) TP in the wastewater discharged into the digester during a typical flush event (August 29, 2014).

Figure 4. Mass flows between different components of innovative system during summer intensive monitoring week. See Table S2 in SI for the standard errors on the numbers reported in this figure.

Figure 5. Mass flows between different components of innovative system during winter intensive monitoring week. See Table S2 in SI for the standard errors on the numbers reported in this figure.

Figure 6. Removal efficiencies of COD, BOD, TN, and TP by the anaerobic digester and the aeration basin presented in (a) percentage (average of summer and winter and based on newly added waste) and in (b and c) tons per week (summer data).

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571 **Table 1.** Total amount of COD, BOD, TN, and TP ($\pm$ standard error) discharged weekly
572 into the anaerobic digester during the intensive monitoring week representative of warm
573 season operation (August 27 to September 2, 2014). The standard errors were
574 calculated using error propagation on the individual measurements.

575

576 **Table 2.** Removal efficiencies of COD, BOD, TN, and TP ($\pm$ standard error) by the
577 anaerobic digester, the aeration basin and the entire innovative system. IN/OUT values
578 are calculated using the mass loading entering and leaving each unit, whereas removal
579 based on newly added waste is the mass removed weekly divided by the fresh waste
580 produced weekly by the pigs. See Figures 4 and 5 for mass loadings. Removals values
581 calculated with values from Figures 4 and 5 may be slightly different than in Table 2
582 because of rounding in the figures. No overall removal IN/OUT is reported, since
583 contaminants cycle in the system. The standard errors were calculated using error
584 propagation on the individual measurements and calculated removal values.

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Table 1. Total amount of COD, BOD, TN, and TP ($\pm$ standard error) discharged weekly into the anaerobic digester during the intensive monitoring week representative of warm season operation (August 27 to September 2, 2014). The standard errors were calculated using error propagation on the individual measurements.

Parameter	Date					From baseline flow (t week ⁻¹)	Total (t week ⁻¹)
	8/27 (t day ⁻¹)	8/28 (t day ⁻¹)	8/29 (t day ⁻¹)	9/1 (t day ⁻¹)	9/2 (t day ⁻¹)		
Number of barns flushed that day	2	2	2	2	1		
COD	4.1 $\pm$ 0.1	3.6 $\pm$ 0.1	2.5 $\pm$ 0.1	3.6 $\pm$ 0.1	2.7 $\pm$ 0.1	6.1 $\pm$ 0.2	22.6 $\pm$ 0.3
BOD	1.8 $\pm$ 0.1	1.55 $\pm$ 0.04	1.00 $\pm$ 0.03	1.39 $\pm$ 0.04	0.98 $\pm$ 0.03	2.6 $\pm$ 0.1	9.3 $\pm$ 0.1
TN	0.47 $\pm$ 0.01	0.53 $\pm$ 0.01	0.45 $\pm$ 0.01	0.49 $\pm$ 0.01	0.29 $\pm$ 0.01	0.9 $\pm$ 0.03	3.11 $\pm$ 0.04
TP	0.179 $\pm$ 0.004	0.160 $\pm$ 0.003	0.111 $\pm$ 0.002	0.156 $\pm$ 0.004	0.118 $\pm$ 0.003	0.28 $\pm$ 0.01	1.00 $\pm$ 0.01

Table 2. Removal efficiencies of COD, BOD, TN, and TP ($\pm$ standard error) by the anaerobic digester, the aeration basin and the entire innovative system. IN/OUT values are calculated using the mass loading entering and leaving each unit, whereas removal based on newly added waste is the mass removed weekly divided by the fresh waste produced weekly by the pigs. See Figures 4 and 5 for mass loadings. Removals values calculated with values from Figures 4 and 5 may be slightly different than in Table 2 because of rounding in the figures. No overall removal IN/OUT is reported, since contaminants cycle in the system. **The standard errors were calculated using error propagation on the individual measurements and calculated removal values.**

			Anaerobic Digester	Aeration Basin	Overall
Summer	COD removal	Based on IN/OUT	52 $\pm$ 2%	33 $\pm$ 4%	-
		Based on newly added waste	70 $\pm$ 3%	21 $\pm$ 3%	91 $\pm$ 4%
	BOD removal	Based on IN/OUT	84 $\pm$ 2%	63 $\pm$ 5%	-
		Based on newly added waste	89 $\pm$ 2%	10 $\pm$ 1%	99 $\pm$ 2%
	TN removal	Based on IN/OUT	15 $\pm$ 3%	30 $\pm$ 4%	-
		Based on newly added waste	29 $\pm$ 6%	48 $\pm$ 7%	77 $\pm$ 9%
	TP removal	Based on total waste	33 $\pm$ 3%	22 $\pm$ 4%	-
		Based on newly added waste	56 $\pm$ 5%	25 $\pm$ 5%	81 $\pm$ 7%
Winter	COD removal	Based on IN/OUT	54 $\pm$ 3%	44 $\pm$ 4%	-
		Based on newly added waste	68 $\pm$ 3%	25 $\pm$ 3%	93 $\pm$ 5%
	BOD removal	Based on IN/OUT	82 $\pm$ 2%	69 $\pm$ 5%	-
		Based on newly added waste	86 $\pm$ 5%	13 $\pm$ 1%	99 $\pm$ 5%
	TN removal	Based on IN/OUT	18 $\pm$ 4%	28 $\pm$ 4%	-
		Based on newly added waste	34 $\pm$ 11%	43 $\pm$ 6%	77 $\pm$ 12%
	TP removal	Based on total waste	35 $\pm$ 3%	23 $\pm$ 4%	-
		Based on newly added waste	58 $\pm$ 8%	25 $\pm$ 5%	83 $\pm$ 9%

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