Application of a Series of Continuously Fed Aerated Tank Reactors System for Recycling of Swine Slurry Nutrients

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Abstract

Single tank aeration systems operated in batch mode or sequential batch reactors based on intermittent aeration are generally applied for swine manure treatment in order to reduce nutrient content and odor. This study evaluated the feasibility of aerobic biological treatment conducted in a serial arrangement of continuously fed aerated tank reactors configuration with swine slurry on a pilot-scale. Compared to municipal wastewater treatment swine slurry rich in nutrients and solids requires different treatment standards for the applied methods to be economically and ecologically relevant. This study presents a sequential process scheme, in which biological treatment serves as a means of achieving a pH raise. This makes it possible to separate part of the nitrogen by stripping and enhances slurry precipitating/coagulation characteristics without substantial carbon or nitrogen loss in gaseous form (which is the opposite to that in a conventional active sludge process). The system was run with a hydraulic retention time (HRT) of three to four days (whole system), and a feedback of 0.8 ± 0.2. During treatment, total organic carbon (TOC) reduction varied between 2.4% and 14.6% and the total nitrogen concentration change was less than 3%. Nearly 50% of the total phosphorus was reduced. The results indicated that the odor of liquid manure had decreased efficiently at best to a level at which there was no odor or only very faint odor. Concurrently, manure pH rose to 8.7.

Keywords: swine manure, aerobic treatment, serial, feedback, odor, total treatment

1. Introduction

For environmental and economic reasons, recycling the nutrients of livestock manure has become increasingly important for reducing the use of mineral fertilizers for crop production, particularly in the intensive animal production areas. Considerable efforts are currently underway to develop practical and affordable ways to reduce manure odor and recycle manure nutrients.

Aerobic processes have been common in the treatment of contaminated effluents due to their ability to convert contaminants into less harmful substances. The activated sludge process represents the most widespread technology for wastewater treatment. The process is not directly usable for manure treatment due to the relatively concentrated state of manure compared to waste water; that is, it has relatively high dry matter and nutrient contents and buffer capacity. However, aeration of animal slurry as a method of removing the offensive odor has attracted a certain amount of interest. Biodegradation of organic compounds related to odor generation (Westerman & Zhang, 1997; Zhu, 2000) decreases the odor intensity. Complete aerobic treatment (analogous to sewage treatment) demands high energy input and may be economically unprofitable.

Commercial odor control agents have also been applied. However, the effectiveness of additives, particularly commercially available products, has been a subject of debate (Pain et al., 1987; Ritter, 1981; Zhu et al., 1997). Masking, disinfecting and oxidizing agents can provide short-term control of malodor, but because the capacity of these additives is finite, they require frequent reapplication. Microbial-based digestive additives may offer a solution to this problem as they are regenerative; however, such additives appear to have been developed without a thorough understanding of the microbiological processes that occur in livestock wastes. Grubbs (1979) claimed

that the key to successful bacterial additives is that the added culture must become the dominant strain within the microbial community. At the very least, the added microorganisms must be able to grow, reproduce and become a part of the indigenous community. This would require them to be successful within the required environmental parameters, including temperature, pH, dissolved oxygen concentration, nutrient availability and the ability to withstand potential toxins.

Complete aeration, with the goal of reducing the biological oxygen demand (BOD), suspended solids and nutrients to achieve requirement levels for discharge to surface waters, is not an ecological option for liquid manure. Therefore, the manure treatment approach should be different from that of waste water and the ultimate goal should be complete nutrient recycling. This could be achieved through the following steps: (1) partial separation of phosphorus (in plant available form) and solid material prior to aerobic biological treatment; (2) conversion of manure through biological treatment into a form that enables further fractionation of manure effluent, (3) N separation with air stripping after the reduction of manure solid matter and biological pH raise (Alitalo et al., 2012) and (4) only after phosphorus and nitrogen removal and subsequent buffer capacity reduction; chemical treatment with reduced amounts of chemical coagulants, such as iron salts, aluminium salts or polymers.

This paper presents the results of the study concerning aerobic biological treatment. The general aim of the study was to test how moderate or only slight aeration influences manure slurry properties when conducted in the specially designed reactor system. More specifically, the study investigated whether it is possible to efficiently raise slurry pH without turning ammonium to nitrate with aeration treatment or losing it in gaseous form or losing a substantial fraction of the carbon. The study also investigated whether the slurry-precipitating characteristics can be strengthened and how the system influences odor.

2. Materials

This study was conducted on a sow farm located in southwestern Finland. The characteristics of untreated raw manure are presented in Table 1.

Table 1. Characteristics of the untreated swine manure used in this study. Total solids (TS) content (%), total carbon (TC), total organic carbon (TOC), total nitrogen (Ntot), ammonium nitrogen (NH_4^+-N), total phosphorus (Ptot), phosphate phosphorus (PO_4^{3-}-P), calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+) and sodium (Na^+) concentration in mg/L. The mean value of five replicates and standard deviation are shown

	TS	TC	TOC	Ntot	NH_4^+N	Ptot	PO_4^{3-}-P	Ca^{2+}	Mg^{2+}	K^+	Na^+
mean	1.85	4962	3930	2255	1649	451	180	635	203	1188	668
s.d.	0.10	425	41	111	62	102	89	146	64	89	155

3. Method

3.1 Installation of Treatment System

Six continuously fed aerated reactor tanks in a chain, connected by polyvinyl tubing (65 mm in inner-diameter), were operated in series (Figure 1). The volume of the polyethylene tank was 600 L and the hydraulic volume of the total system was 2.96 m^3. The feed-in flow in each tank was to the bottom of the tank and outflow through the crosswise upper corner in relation to the input flow. The surface liquid/effluent level remained constant when liquid manure ran gravitationally from one tank to another. Perforated tubes (1.9 m in length, 16 mm in inner diameter) were installed at the bottom of each tank and were used for aeration and mixing. Air pressure was produced by compressor (OMA CT4-B3800-150) and was divided to each tank by a 'delivery log'. A pressure meter controlled the feed-in air pressure to each tank, which was adjusted by a pressure regulator. Recirculation (feedback) of effluent slurry from the last tank to the first tank was also introduced.

Figure 1. Flow chart of the biological treatment process

In order to set up the system, the tanks were filled in with produced effluent (subcultured inoculant). This inoculant was produced in a similar configuration to that described above. Six 30-L plastic tanks were filled with diluted soil-water (1% v/v) suspension. The suspension was aerated at room temperature (19-22°C), while small amounts (less than 1:50 v/v) of liquid manure were added daily to the first tank. The volume of added manure was gradually increased. However, the additions were scaled to maintain the last tank odorless. The feedback rate from the last tank to the first was 1:1 v/v. This system was operated for over a year prior to filling the 600-L treatment tanks with the produced effluent.

After filling the treatment system with effluent, manure treatment began. Manure was pumped from a reception pit of a sow house into a 1 m^3 plastic subcontainer (Figure 1) in which the solid fraction was separated by sedimentation. The separated liquid manure was fed continuously from the subcontainer into the first tank of the system.

3.2 Experimental Procedure to Examine the Process Operating Parameters

Over a period of two months prior to the actual start of the experimental runs, liquid manure was fed into the process so that the hydraulic retention time (HRT) of a whole system varied between five and ten days and the feedback (recirculation ratio) was approximately 1. Experimental runs were started by adjusting the HRT to four days (whole system) and taking samples after one week (HRT = 4d). Thereafter, the HRT was adjusted to three days (whole system) and the process was run for a three-week period, taking samples after every week (HRT = 3d). Feedback was kept at 0.8±0.2 (recirculation ratio).

In order to evaluate the process conditions, the dissolved oxygen (DO) content and the temperature in each tank were measured with an YSI meter (95/100 FT; YSI Inc., Yellow Springs, USA) and pH with a pH probe (9107BN, Orion, USA). Measurements were carried out daily at a depth of approximately 10 cm.

3.3 Sampling and Analyses

Liquid manure samples from the subcontainer and six tanks were stored at −20°C immediately after collection. Finnish Standard Associations methods were used for total solids (TS) and volatile solids (VS) analysis (SFS 3008). The chemical oxygen demand (COD) was analyzed according to standard SFS 5504 with HACH's closed tubes (dichromate oxidation). The volatile fatty acids (VFAs), total organic carbon (TOC), total phosphorus (Ptot), total nitrogen (Ntot), PO_4^{3-}-P, NH_4^+-N, NO_3^--N, K^+, Mg^{2+}, Ca^{2+} and Na^+ analyses were made as described by Alitalo et al (2012). Analyses were carried out on the total sample for TS, VS, COD, TOC, Ptot and Ntot and on the centrifuged supernatant for VFA, anions and cations.

The feedback of slurry from the last tank results in a dilution effect. This was accounted for by incorporating the effect of the feedback solution into the calculations as follows:

$$[(C_{in}*Q_{in})+(C_{back}*Q_{back})]/[Q_{in}+Q_{back}] \tag{1}$$

where C_{in} is the feed-in concentration, Q_w is the feed-in volume, C_{back} is the feedback concentration, and Q_{back} is the feedback volume. The difference between the analyzed and the calculated concentration in the 1st tank is the reduction due to coagulation or precipitation. Changes during processing are calculated as concentration changes between the 1st and the 6th treatment tank.

3.4 Evaluation of Odor

Manure samples for odor intensity determinations were taken from the subcontainer and the tanks of treatment system at the same time as the samples for chemical analyses. The odor intensity using a ranking method was determined in a laboratory using a panel score (consisting of five to eight panelists) within two hours of sampling (Powers, 2004). The panelists were required to indicate the subjective strength of the odor of samples according to the following scale derived by Paduch (1988), 0 no odor; 1 very faint odor; 2 faint odor; 3 distinct odor; 4 strong odor; 5 very strong odor; and 6 extremely strong odor.

3.5 UV/Visible

For the UV/Vis measurements, an Agilent 5438 spectrophotometer was used. The absorption spectra were measured from 200 to 900 nm. Microbe filtrated samples (through 0.45 μm pore size bacteriological filters, Whatman) were measured in 3ml quartz cuvettes with a 1.0cm optical path.

3.6 Statistical Analyzes

The statistical differences between the different HRT values in TS, VS, TOC, COD, VFA, odor and nutrient contents were determined using the MIXED procedure of SAS (Littell et al., 1996). The data was analyzed as a randomized block design (the subcontainer and six reactor tanks as block factors). The data during processing (six reactor tanks) was also analyzed with linear regression analyzes of SAS to evaluate the influence of tank on odor, TS, VS, TOC, COD, VFA and nutrient contents, respectively.

4. Results

4.1 Temperature, DO and pH

During the experimental runs, the temperatures in the tanks varied between 15.6 and 21.1°C and the DO content from 0.6 to 7.2 mg/L. As Table 2 shows, when HRT = 3d the DO content in the aeration basins was slightly lower and its variation was wider than with parameters of HRT = 4d.

Table 2. DO-content (min–max, mg/L) in tanks (1 to 6) of treatment system with different hydraulic retention time (HRT), four and three days, respectively

HRT (d)	Tank 1	Tank 2	Tank 3	Tank 4	Tank 5	Tank 6
4	1.5–5.5	4.4–5.9	4.1–6.9	3.8–7.1	3.4–5.5	4.7–7.2
3	0.7–5.5	0.6–5.4	1.0–5.8	1.1–6.5	0.8–4.9	0.9–6.0

The pH in the first tank was approximately 0.8 pH-units higher than that of the untreated manure and, at the end of the process (tank 6), generally rose above pH 8.5 (Table 3).

Table3. pH-values (min–max) in subcontainer (untreated manure, tank 0) and tanks (1 to 6, biologically treated manure) of treatment system with different hydraulic retention time (HRT), three and four days, respectively

HRT (d)	Tank 0	Tank 1	Tank 2	Tank 3	Tank 4	Tank 5	Tank 6
4	7.1–7.4	8.0–8.3	8.2–8.4	8.3–8.5	8.3–8.6	8.3–8.6	8.3–8.6
3	7.2–7.4	8.2–8.3	8.2–8.4	8.3–8.6	8.4–8.6	8.4–8.7	8.4–8.6

4.2 TS, VS, TOC and COD

There was a slight decrease in the TS levels of liquid manure during the course of treatment (Figure 2A). Some sedimentation to the bottom of the treatment tanks might have occurred despite continuous aeration. Part of the loss could be attributed to the breakdown of organic matter by the metabolic action of micro-organisms. Determined TS reduction in the first tank ranged from 5.9% (with HRT = 3) to 7.5% (with HRT = 4) when feedback dilution reduced TS content from 4.3% (with HRT = 3) to 5.9% (with HRT = 4). Thus, the amount that

was precipitated or coagulated in the first tank was 1.6% (difference between the analyzed and the calculated concentrations) irrespective of treatment run. TS reduction, during processing (from tank 1 to tank 6), ranged from 3.8% to 6.1%. The highest TS reduction (6.1%) was achieved with HRT = 4, (R^2=0.864; $p<0.01$, Table 4). Total TS reduction (untreated slurry – 6th tank) was 9.5-13.2% after treatment.

Essentially, the characteristics of VS changes were similar to those of TS (Figure 2B). During processing, the reduction was 5.3% with HRT = 3 and 7.5% with HRT = 4. The difference in change in VS between the different HRT values was significant ($p< 0.001$, Table 4). However, this difference was likely due to initial VS concentration difference between the two experiments.

The TOC concentration reduction of liquid manure varied between 2.4% (with HRT = 3) and 14.6% (with HRT = 4) during the course (from tank 1 to tank 6) of treatment (Figure 2C). The amount of dissolved inorganic carbon (DIC) was reduced from 1520 mg/L (with HRT=3) and 1606 mg/L (with HRT=4) before treatment to 1351 mg/L (with HRT=3) and 1288 mg/L (with HRT=4). Thus, CO_2 was released from the system during treatment. The effect of aerobic biological treatment on COD varied between experimental runs (Figure 2D). During processing the COD reduction of 39.3% was achieved with HRT = 4d, whereas the reduction with HRT = 3d was only 11.8%.

Figure 2. Total solids (A), volatile solids (B), total organic carbon (C) and chemical oxygen demand in subcontainer (0 untreated manure) and tanks (1 to 6, biologically treated manure) of treatment system with hydraulic retention time of three and four days, respectively. Error bars indicate standard deviation

4.3 Characteristics of N, P, Ca^{2+}, Mg^{2+}, K^+ and Na^+

The Ntot concentration of untreated liquid manure varied between 1482–1535 mg/L and Ptot concentration ranged from 78–87 mg/L (Figure 3A and B). The low concentration of phosphorus was probably caused by the sedimentation/separation of slurry solid matter in the subcontainer (Figure 1). The Ntot concentration only decreased significantly when HRT = 4 (R^2=0.901; $p<0.01$, Table 4). In other words, the Ntot concentration changes during processing were less than 3% regardless of the treatment run. No significant change in NH_4^+-N concentration was determined during the experimental runs (Figure 3A). However, the majority of the nitrogen

was in ammonia form 1309–1344 mg/L. The amount of nitrate was small, with its concentration varying between 9.9 and 31.2 mg/L.

The greatest Ptot concentration changes occurred in the first tank, when the analyzed reduction was 21–30%. The Ptot reduction due to coagulation or precipitation in the first tank varied from 6.2% to 8.0%. Ptot reduction, during processing, ranged from 16% with HRT=3 (R^2=0.684; p<0.001, Table 4) to 28% with HRT=4. In the final treatment tank, 31–49% of the original untreated manure containing Ptot was removed and the greatest reduction was obtained with treatment parameters HRT = 4 (which was significantly different from HRT=3). Phosphate phosphorus concentration changes were only minor, irrespective of the treatment run (Figure 3B).

Figure 3. Total nitrogen or NH_4^+-N (A), Total phosphorus or orthophosphate phosphorus (B), Ca^{2+} (C), Mg^{2+} (D), K^+ (E) and Na^+ (F) ion concentrations (mg/L) in subcontainer (0 untreated manure) and tanks (1 to 6, biologically treated manure) of treatment system with hydraulic retention time of three and four days, respectively. Error bars indicate standard deviation

Magnesium and calcium ion concentration changes were similar to those of total phosphorus (Figure 3C, D). In the first treatment tank, the determined Mg^{2+} and Ca^{2+} concentration declines were 30–39% and 0–12%, respectively. The amount that was precipitated or coagulated in the first tank ranged from 10 to 11% with Mg^{2+},

respectively, from 0 to 3% with Ca^{2+}. The process time reduction in Mg^{2+} concentration ranged from 23% with HRT=3 (R^2=0.745; p<0.001, Table 4) to 39% with HRT=4 (R^2=0.963; p<0.01, Table 4) and Ca^{2+} concentration from 6% with HRT=3 to 7% with HRT=4 (R^2=0.862; p<0.01, Table 4), respectively, depending on the treatment run. The greatest Ca^{2+} ion concentration change was observed with treatment parameters HRT = 4, when 36% of the Ca^{2+} had been removed; with HRT = 3, only a 5–12% decline of the original Ca^{2+} concentration took place.

Virtually no change was observed in the concentrations of monovalent cations (potassium and sodium) during the treatment process (Figure 3E, F).

Table 4. Statistical differences between the different HRT values in TS, VS, TOC, COD, VFA, odor, and nutrient contents determined with the MIXED procedure of SAS. Level averages (between HRT = 3 and HRT = 4), which have no common letters (a, b) differ from the paired comparison, significant at the 5% risk level. Statistically significant difference (HRT=3, HRT=4) *, ** and *** at the probability level of 0.05, 0.01 and 0.001, respectively. Linear regression analyses (intercept, factor, R2 and p-values shown)

	Analyses of variance		Linear regression			
	HRT (days)	Level average	Intercept	Factor	R^2	p-value
TS	3[a***]	5.4	5.28	-0.04	0.214	<0.053
	4[b***]	4.9	5.02	-0.06	0.864	<0.007
VS	3[a***]	2.3	2.27	-0.04	0.229	<0.045
	4[b***]	1.9	1.94	-0.03	0.771	<0.021
TOC	3[a***]	1118	1032	-4	0.083	<0.719
	4[b***]	951	1042	-35.5	0.716	<0.036
COD	3[a**]	2800	2647	-51.4	0.056	<0.347
	4[b**]	1917	2553	-191	0.589	<0.075
VFA	3[a***]	433	480.9	-8.6	0.821	<0.013
	4[b***]	359	436.9	-2.9	0.046	<0.392
Odor	3	2.5	2.82	-0.1	0.135	<0.133
	4	2.2	3.41	-0.5	0.939	<0.001
Ntot	3[a***]	1519	1512	-1.5	0.024	<0.536
	4[b***]	1433	1453	-5.6	0.901	<0.004
NH_4^+-N	3[a**]	1359	1331	2.5	0.031	<0.483
	4[b**]	1311	1319	-2.8	0.25	<0.313
Ptot	3[a***]	62.9	68.1	-2.3	0.684	<.0001
	4[b***]	53.7	59.4	-2.5	0.613	<0.066
PO_4^{3-}-P	3[a*]	21.5	23.6	-0.8	0.567	<0.084
	4[b*]	19.8	22.1	-0.8	0.81	<0.015
Ca^{2+}	3[a***]	123	152	-2.5	0.053	<0.356
	4[b***]	149	152.6	-2.3	0.862	<0.008
Mg^{2+}	3[a**]	31.1	35.3	-1.7	0.745	<.0001
	4[b**]	27.1	33.7	-2.5	0.963	<0.005
K^+	3[a**]	9878	966	0.8	0.007	<0.735
	4[b**]	969	979	-2.7	0.387	<0.187
Na^+	3	365	359	-0.2	0.002	<0.876
	4	366	371	-1.6	0.741	<0.028

4.4 Odor

Biological treatment of manure significantly reduced the odor intensity compared to that of untreated manure (Figure 4A). The untreated liquid manure was evaluated as having a very strong odor. The best odor reduction results were obtained with HRT = 4; in the sixth tank, no odor or only a very faint odor was evaluated (R^2 = 0.939; p<0.01, Table 4). Odor reduction was sensed in the first treatment tank, but a clearer decline (faint odor) was observed in the second tank. Thereafter, odor reduction ceased at about at this level with HRT=3, but continued with HRT=4.

Figure 4. Odor intensity (A), VFAs (mg/L) (B), linear regression equations for odor intensity versus VFA (C) and VS (D) in treatment tanks during treatment runs. Respectively, VFA versus TS (E) and VS (F) in treatment tanks during treatment runs. Error bars indicate standard deviation

The VFAs concentration was a less sensitive measure of the odor than the evaluated odor intensity. Generally, the total VFAs level of below 230 mg/L corresponds to manure without an offensive odor (Burton, 1992). The VFA concentrations in the present study, however, were much higher and varied from 330 mg/L to 484 mg/L, although odor intensity was reduced to a level of no odor or only a very faint odor (Figure 4B, C). The VFA concentration of untreated liquid manure varied between 404–484 mg/L. The highest VFA reduction during

processing (13%) was achieved with HRT=4, whereas the reduction with HRT=3 was 3%. Linear regression equations for odor intensity versus VFA and VS showed strongly significant correlation with HRT= 4, but a low correlation with HRT=3 (Figure 4C, D). A high correlation was found for VFA versus TS and VS, irrespective of treatment runs (Figure 4E, F).

4.5 Physico-Chemical Changes Due to the Treatment

Slurry color changed from grayish green to dark brown. The visually observed darkness intensified from one tank to the next. More clearly, the color change was observed in microbe filtered slurry samples (Figure 5). The absorbance spectra of samples taken from the last tanks samples showed higher absorbance than the untreated and first tank samples (Figure 6). The samples showed the maximum absorption at λ=382 (untreated slurry) and λ=383 (treated slurry), while the corresponding absorbance values were 2.244 for the untreated slurry, 2.695 for the first tank, 3.060 for the second tank, 4.000 for the fourth tank, and 3.079 for the sixth tank. Single peaks were detected in absorption spectras where the observed absorption maximum located. The rest of the spectrums were nearly featureless, showing decreasing absorbance with increasing wavelength.

Figure 5. Color intensification during biological treatment process. Microbe-filtered liquid manure samples from left to right: untreated manure, first, second, fourth and sixth tanks of the treatment system. During biological treatment, the color of the liquid manure changes from greyish-green to dark brown

Figure 6. The absorbance spectra of samples

5. Discussion

Swine slurry is known to differ considerably in its chemical features from municipal wastewater. However, the applied methods often follow the conventional treatment scheme originally designed for wastewater treatment, or for the chemical industry.

5.1 Primary Treatment before Biological Treatment

Part of the manure solid content was separated prior to aeration treatment simply by sedimentation, which facilitated a 0.53–0.58% TS content. This TS content is very low and was due to low raw slurry TS content (1.1-1.2%) before sedimentation step. According to Zhu et al. (2008), in order to reduce aeration time and rates, the manure TS content should not exceed 1%. Although in the present study this was achieved by mere sedimentation, generally the raw slurry TS content is considerably higher, on average 3.5% (Vilajvuuspalvelu, 2012), in which case to achieve the less than 1% solids content becomes considerably more challenging.

Slurry properties, such as inherent high buffering capacity and neutral carbohydrates (cellulose, hemicellulose (Chen et al., 2003)), make chemical precipitation difficult. It is often necessary to have high amounts of coagulants; which makes the approach economically unprofitable. Another drawback is that, when iron or aluminium coagulants are used, P in Al- or Fe –precipitates are typically unavailable for field crops. Flocculation agents and/or gravity sedimentation are often used to reduce TS content to a level which makes it possible to remove carbon and nitrogen in gaseous form during secondary treatment. Suzuki (2010) reported an average swine waste water suspended solid (SS) content of 1200 mg/L obtained with a dewatering device with flocculants or gravity sedimentation as the primary treatment.

5.2 Aeration Treatment with an Alternative Goal

An ecologically sound approach would recycle carbon back to the soil, rather than release it into the atmosphere as carbon dioxide. During treatment, from 3.8 to 6.1% of TS was removed with HRT = 3 and HRT = 4, respectively. The respective aeration rates varied from 0.6 to 6.5 mg/L with HRT=3, and from 1.5 to 7.2 mg/L with HRT=4. Only less than 15% of the carbon was removed. Comparing the obtained results to other studies is difficult, because the presented system includes a series of six continuously fed aerated tank reactors operated with feedback, while in other systems usually one reaction tank is used. Also the intensity of aeration varies from study to study and affects the decomposition of solids. Zhang et al. (2004) reported 1.6–11.1% of TS removal during five days aeration when initial slurry TS level was 0.5–4.0% under 35mV oxidation-reduction potential in single reactor system while TS removal percentages varied from 8.4% to 30.5% with increasing aeration to 3.0 mg/L O_2. Suzuki (2010) reported average effluent concentrations of both SS and BOD 58 mg/L in activated sludge treatment of swine wastewater (over 95% reduction in SS concentration during activated sludge processing). Only a highly efficient primary treatment prior to strong aeration would allow these values to be achieved with manure slurry. The price would be the binding of phosphorus in a form that is unusable for plants, losing part of the carbon as carbon dioxide to the atmosphere and changing nitrogen into nitrate, often further denitrified to N_2.

5.3 Enhancing Precipitation by Aeration in Suspended Rich Solution

The colour of the liquid manure, as well as the liquid's tendency towards flocculation (divalent cations precipitation) changed due to processing. The observed dark colour refers to browning reaction and, consequently, the formation of humus-like compounds (complex dark-coloured polymers, derived from the breakdown of biological residues and from biological metabolites, which undergo polymerisation and/or polycondensation (Stevenson, 1982), which has also been reported by others, such as Juteau et al. (2004). They reported that at higher temperatures the intensity of the effluent color increased and simultaneously decomposition of organic material declined during biological swine manure treatment. In the present study the color was intensified during processing from one tank to the next. The obtained spectrum profiles in the visible region (400-800 nm) had a pattern similar to that observed by Juteau et al. (2004) that is a nearly featureless absorption spectrum showing decreasing absorbance with increasing wavelength. This pattern is consistent with the absorption spectrum of humus compounds (Stevenson, 1982).

Complex recondensation of simple biochemicals formed during biological waste water treatment has also been reported (e.g. Dignac et al., 2000). Dignac et al. (2000) suggested that intense biological activity could enhance recondensation processes in the aeration basins. Compared to waste water, swine slurry contains higher amounts of soluble organic compounds, which probably further increases the recondensation processes during biological treatment in suspended media. The formed refractory organic matter is undesired in traditional waste water treatment, but could be beneficial in slurry treatment. Humus forming reactions would serve as natural coagulants, facilitating precipitation of hardly precipitating compounds and reducing the amount of precipitating chemicals need. The divalent cations, such as Ca^{2+} and Mg^{2+}, easily form stable complex ions by chelation, which forms relatively insoluble precipitation products (Stevenson, 1982). This can be one reason for the decline in the concentration of divalent cations, which continued throughout the treatment.

The low initial concentration of phosphate phosphorus probably caused the negligible phosphate reduction during processing, despite a high pH. According to Zhu et al. (2001) an increase in pH to 8 can reduce soluble P concentration by 80%. The fact that Ptot was 31–49% lower after treatment may be due to enhanced flocculation during treatment and sedimentation at the bottom of the treatment tanks. Juteau et al. (2004) reported 9–19% Ptot reduction and, even without a settling period, sediment build up was observed.

5.4 pH

Biological aeration treatment raised the slurry pH to a pH value of 8.7. Such a pH raise is a well-known effect of manure slurry aeration and has been reported by several authors, such as Zhu et al. (2001) and Stevens & Cornforth (1974). A complex chemical buffering system controls manure pH change. The most important buffer components are total ammoniacal nitrogen, total inorganic carbon (CO_2, HCO_3^-, CO_3^{2-}), VFAs and other organic compounds (e.g. Sommer & Husted, 1995). Previously described reasons for pH changes during aerobic biological treatment can be found in Alitalo et al. (2012).

Part of the pH increase during aerobic biological treatment coincides with an increased CO_2 release from the system in relation to NH_3 as also described by Alitalo et al. (2012) and is attributable to the solubility difference between these two components. In the present study slurry NH_4^+/DIC was larger for the treated compared to untreated manure (the respective NH_4^+/DIC – value for the treated (1.01, with HRT=4; 1.00 with HRT=3) compared to the untreated (0.85 with HRT=4; 0.90 with HRT=3) manure).

5.5 Nitrogen

Aeration may cause nitrogen loss by (1) volatilization of ammonia (at pH 8.8, already 20% of total ammoniacal nitrogen will be in NH_3 molecules at 20°C (Alitalo et al., 2012) and (2) trough biological processes if the oxygen concentration is appropriately adjusted. The most common biological processes include nitrification, which oxidizes ammonium via nitrite to nitrate by autotrophs under aerobic conditions, and denitrification, which transforms nitrate into nitrite, then into nitrous oxide, nitric oxide, and finally to N_2 gas by denitrifying bacteria under anaerobic conditions (Wiesmann,1994).

In the present study, the influence of high pH on Ntot or NH_4^+-N concentrations was less marked. Neither Ntot nor NH_4^+-N concentration reduced significantly during the treatment. Therefore, it is probable that no marked ammonia emissions took place, which was unexpected since high pH in reactor tanks. Ammonium nitrogen was not nitrified to nitrate either in the process. It is likely that the high ammonium concentration, together with high pH and high organic carbon concentration in the treatment chambers, inhibited nitrate formation. According to Li and Zhao (1999), the initial NH_4^+-N concentration should be limited below 100 mg/L in order to avoid any significant inhibition of microbial activity. High-strength ammonia nitrogen inhibits the activity of bacteria, including organics-utilizing bacteria and nitrifying bacteria, and it is well known that high ammonia concentrations cannot be remediated easily by conventional biological treatments. However, if the treatment principle is to preserve carbon and nitrogen in a system, like in the present study, this (inhibiting effect) is rather an advantage.

5.6 Odor

Of all the studies parameters studied, manure processing probably reduced odor the most. Of the studied HRTs, the best odor reduction was achieved with the HRT of the total system being four days. The odor level decreased to faint when the HRT was three days.

Compared to the achieved odor reduction, the VFA reduction was surprisingly small, only 3.1–13.8% during processing. Zhang et al. (2004) reported an over 90% reduction of VFAs during five days' aeration treatment with TS content 0.5–1.0% (aeration intensities 1–3 mg O_2 /L). One explanation could be the low initial VFA concentration in the present study. The other explanation can be in the formation of humus-like compounds. According to the method of esterification (Hach, 1993), the VFAs measurement is based on esterification of the carboxylic acids present in the sample followed by colorimetric determination of the esters produced by the ferric hydroxamate reaction. Therefore, it measures all the compounds containing carboxylic groups, which may have formed. On the other hand, fatty acids represent only a part of odor forming compounds. More than 300 odorous compounds have been identified in swine manure (Hagenstein, 2003).

The odor reduction in aerated systems is frequently explained by oxidation of biodegradable organic material into stable inorganic end products by aerobic bacteria (e.g. Westerman & Zhang, 1997). This study suggests the formation of humus-like compounds with simultaneous marked odor reduction in the absence of extensive aeration. It may be that the odor compounds are involved in the condensation reactions forming humic

compounds. That is, instead of complete oxidation, a part of the odor compounds are forming stable humus-like compounds. This could be one explanation for the effective odor decrease in this present system.

5.7 Benefits of Serial Reactors System

Bioprocesses are frequently vulnerable to malfunctions posed by changes to the quantity or quality in the supply; for example, inhibition of the production of biogas during anaerobic digestion caused by antibiotics (Sanz et al., 1996). A serial system of small reactors is less susceptible to malfunctions than a larger reactor with a volume that equals the total volume of the serial system. The serial configuration prevents interferences from spreading throughout the entire system, because supply to a tank comes solely from the previous tank; for example, tank 3 receives only the effluent from tank 2, and so on. Also, the volume of the flow in a given time from one treatment tank to the next is very small in relation to the total volume of the treatment tank and the total volume of the entire system. Thus, the serial configuration and the feedback both function as a buffer mechanism against process interferences and strengthen the process stability. In addition, it is possible that different functional operations take place in different process tanks, which intensifies the treatment process e.g. odor reduction. Benefits of a serial system have been identified in biogas production, for example (Kanokwan & Angeliadagi, 2009). However, due to the aeration demand of the treatment tanks, it is necessary to assess whether a six-tank system is necessary, or whether, for example a four process tank system would be adequate to achieve the desired result.

6. Conclusions

A series of continuously fed aerated tank reactors system was conducted to treat swine slurry to test how moderate or only slight aeration influences slurry properties, and to determine is odor reduction possible in the absence of extensive aeration simultaneously preserving carbon and nitrogen in effluent. The introduced treatment system reduced odors efficiently. No odor or only very faint odor remained after only four days of processing. Total organic carbon reduction during processing remained under 15%. Treatment also facilitated slurry precipitating/coagulation characteristics, which was observed as a color change and a decline in the concentration of divalent cations and total phosphorus. The pH-value at the end of the treatment rose above pH 8.5, but there was no significant reduction in Ntot and NH_4^+-N concentrations. This treatment is designed to be part of a total treatment system in which part of the P is first separated. After this this described biological treatment and biological pH raise, N is separated with air stripping. Thereafter chemical treatment with coagulants and water separation follows. The presented total treatment scheme enables nutrient recovery and preservation in a concentrated form, which can be used as fertilizers, and recycling of carbon back to soil. Arisen subjects of more detailed future work include the connection between odor reduction and formation of humic-type compounds and fate of inoculant in a treatment system. Thus, our results provide a starting point, rather than the final world.

Acknowledgements

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