Swine waste treatment by self-heating aerobic thermophilic bioreactors

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Abstract

Pig manure represents a very high-strength wastewater that is well suited for a self-heating aerobic thermophilic treatment. Here we report the use of 59-L Aerobic Thermophilic Sequencing Batch Reactors (AT-SBR) to study the treatment of pig manure with a HRT of 6 days. Temperatures up to 75°C were reached without external heating by using Venturi-type aerators but these conditions were detrimental for the respiratory activity of the microflora. For COD removal, better performances were achieved when the temperature was limited to 50°C. However, higher temperatures increased the rate of phosphorus crystallisation and the volatilisation of ammonia. A temperature of 50°C was enough to eliminate faecal coliforms and Campylobacter spp., but 60°C was needed for the efficient destruction of Clostridium perfringens. Consequently, an operating temperature of 60°C appears to be a good compromise. Under these conditions, the BOD₅ decreases from 50.5 to 1.0 g L⁻¹, yielding a 98% removal.

Keywords: Livestock wastewater; Aerobic thermophilic treatment; Pathogen attenuation; Venturi aerator; Colour; Centrifugation

1. Introduction

Pollution by livestock wastes has become a great concern in many countries. In Canada, this problem caught the public attention in May–June 2000 after a deadly waterborne outbreak of Escherichia coli O157:H7 and Campylobacter spp. in Walkerton, Ontario. The contamination was traced back to the cattle farms surrounding some wells that supplied water to the city. In the province of Québec, the main focus is on the pig industry, which produces annually over 7 million heads. Spreading of large quantities of liquid manure often results in the overfertilisation of soil, and the excess of nitrogen and phosphorus impacts negatively many watercourses. The intense bad smell and the pathogen dissemination are also part of the problem. New rules will soon be implemented and many pig farms will have to treat their waste.

Our laboratory has been particularly interested in the aerobic thermophilic (≥ 55°C) treatment of swine waste [1]. The process can be self-heating if the equipment is designed to minimise heat losses. This technology is referred to as Autothermal Thermophilic Aerobic Digestion (ATAD) for the digestion of sludge produced by municipal wastewater treatment plants. The use of aerobic thermophilic treatment of pig manure was reported as early as in the 1970s [2]. Since then, some studies have been conducted [1,3,4] but examples of full-scale applications are very scarce. In the 1980s, a trial in Canada on a pig farm revealed many difficulties such as overfoaming, bad smell due to the absence of an exhaust air treatment, etc. However, it is still an interesting technology for the treatment of pig manure, especially in...
order to avoid the dissemination of pathogens. Also, there is no nitrification under thermophilic conditions and consequently no loss of nitrogen as N₂. Instead, ammonia can be volatilised and recovered as an ammonium salt with an air scrubber using an acidic solution. The ammonium salt is a valuable by-product that can be used as a fertiliser.

Recently, we have launched a project in which the final goal was the design of a self-heating thermophilic aerobic treatment better adapted to swine waste than the equipment currently available. We refer to this technology as an Aerobic Thermophilic Sequencing Batch Reactor (AT-SBR) in preference to an Autothermal Thermophilic Aerobic Digestion (ATAD) since the term “digestion” in the latter name refers to sludge whereas swine waste is better defined as high-strength wastewater. The present paper reports the results from the first part of the project, which consisted in the determination of some fundamental parameters, especially the effect of different temperatures on the efficiency of the process. In order to obtain results representative of the field conditions, we used small-scale self-heating bioreactors fed with swine waste. The oxygen transfer of the aeration device was characterised to insure that we were operating under realistic conditions and to facilitate the scale up of the process.

2. Material and methods

2.1. Experimental set-up

Two AT-SBR were operated in parallel (Fig. 1). They were built with 59-L polyethylene tanks (I.D. = 33 cm) insulated with a 2.5-cm polyurethane foam layer. In each vessel, three baffles were placed on the wall to avoid vortexing. The foam cutters consisted of a 250-W motor coupled to a stainless steel blade. The mix liquor was recirculated by a magnetic-drive centrifugal pump (93 W, Little Giant, Oklahoma City, OK). A Venturi-type aerator (model 978, Mazzei Injectors, Bakersfield, CA), a thermocouple and a dissolved oxygen (DO) probe (model InPro 6000, Mettler-Toledo, Wilmington, MA) were installed on the recirculation loop. The DO probe was connected to a DO transmitter (model 4100, Mettler-Toledo). Saturation values for DO up to 80°C were estimated with a mathematical model that takes into account the water vapour pressure [5]. A coil was placed in the tank to allow cooling. A computer recorded the temperature and the DO and controlled the cooling system. The air leaving the tanks was brought to a wet scrubber containing 0.5 N sulphuric acid (to absorb the ammonia) and to a biofilter (to destroy the volatile organic compounds). Air was drawn through these tanks by a blower to insure a negative pressure, preventing the malodorous vapours from leaving the tanks without being treated.

2.2. Experimental procedure

Swine waste was taken from the collecting pit of a growing-finishing farm by pumping it into drums. At the laboratory, the drums were stored at 4°C. Each bioreactor contained 38 L of the mix liquor. They were first inoculated with 250 mL of an activated sludge taken from a municipal wastewater treatment plant, 375 mL of a compost extract and 125 mL of an adapted inoculum that had been prepared in shake flasks. This inoculum originated from a mixture of soil, compost, activated sludge and diluted pig waste that was subcultured at increasing temperature: the first culture was incubated at 21°C and then, the temperature was increased in 2°C steps for each of the three following subcultures and in 5°C steps for each of the six next subcultures, ending at 55°C. The bioreactors had been operated for a year prior to the results reported here.
Three series of experiment were conducted. In the first series, one reactor was operated without temperature control whereas the other was limited to 50°C. In the second series, they were limited to 70°C and 60°C, respectively. Finally, in the third series, the limiting temperature was 60°C for one reactor and 50°C for the other. The results were compared by a paired-samples t-test. To ensure that the biomass was highly diversified in each vessel at the beginning of each test series, the mix liquor of both reactors was mixed and re-inoculated with 250 mL of activated sludge and 375 mL of compost extract. For the first and the second series, the bioreactors were operated for three weeks using the adopted conditions before the performance evaluation. For the third series, the adaptation period was two weeks. For all series, 2.5 L min⁻¹ of air were injected into the mix liquor. The duration of the batches was 3 days with a 50% volume replacement (hydraulic residence time = 6 days). Since the settling of the solids is poor under these conditions, no settling period was allowed. Twenty millilitres of silicone oil (dimethylpolysiloxane, 20 centistokes) were added at the beginning of each batch to reduce foaming.

2.3. Chemical and microbiological analyses

Suspended Solids (SS) and Volatile Suspended Solids (VSS) were analysed using a modified version of the methods 2540 D and E [6]. Instead of using filtration, the SS were separated by centrifugation at 48,000g in 10-mL tubes. The other methods were used without modification: 2540 B for the Total Solids (TS); 5220 D for the Chemical Oxygen Demand (COD); 5210 B (with 2-chloro-6-(trichloromethyl) pyridine as a nitrification inhibitor) for the 5-day Biological Oxygen Demand (BOD₅); 4500-NH₃ for the ammonia; 4500-P B and C for the phosphorus (persulphate digestion was carried out in an autoclave at 121°C for 30 min). The solubilised colour was analysed on centrifuged and diluted (1:20) samples by determining their absorbance spectrum between 300 and 700 nm using a diode array spectrophotometer.

Faecal coliforms were determined by the membrane filter procedure (method 9222 D) [6]. For confirmation, ten percent of the typical colonies counted were cultured onto Brain–Heart Infusion agar and checked for the hydrolysis of ortho-nitrophenyl-β-D-galactopyranoside (ONPG) and 4-methylumbelliferyl-β-D-glucuronide (MUG) and for the presence of oxydase. Clostridium perfringens were counted using Tryptose-Sulphite-Cy-closerine agar [7]. Some black colonies were cultured onto Columbia blood agar and identity checks were made with API 20E strips (bioMérieux, Marcy-l’Étoile, France). Campylobacter spp. were determined by plating directly onto Charcoal-Cefoperazone-Desoxycholate Agar (CCDA). The plates were incubated at 40°C for 48 h under microaerophilic conditions in a closed jar. Some colonies were cultured onto Columbia blood agar, incubated at 40°C for 48 h under microaerophilic conditions and tested for oxydase and catalase.

2.4. kₐ determination

The mass transfer coefficient (kₐ) was determined in tap water at 20°C by an unsteady state method. The DO probe was placed directly in the tank at 12 cm below the water surface, in the middle of the horizontal section. The water was deoxygenated with sodium sulphite in the presence of cobalt chloride. Aeration trials were conducted in triplicates at airflow rates of 2.5, 3.5, 4.5, 5.5 and 6.5 L min⁻¹. The re-oxygenation curves were analysed by non-linear regression [8]. The results were fitted with the following equation using non-linear regression:

\[
 k_\text{a} = a V_s^b
\]

which can also be written in a linearised form:

\[
 \log k_\text{a} = \log a + b \log V_s.
\]

2.5. Determination of the oxygen uptake rate (OUR)

The OUR was determined off-line. The monitoring chamber consisted of a 100-mL wide-mouth glass bottle with a DO probe inserted through a rubber stopper and containing a stirring bar. The temperature control was insured by a heating bath and the whole set-up was installed on a magnetic stirrer. Samples were quickly withdrawn from the bioreactors, diluted with preheated water and placed in the monitoring chamber. Depending on the sample, the dilution factor ranged from zero to 25. During the sampling and transferring process, the temperature decrease was smaller than one degree.

2.6. Solid-liquid separation tests

The separation of the solids by centrifugation was tested with 45-mL samples of the untreated manure and of the bioreactor effluent. They were centrifuged at 500, 1000, 1500, 2000, 2500, 3000, 4000, 5000 and 10,000g for 10 min. The supernatants and the non-centrifuged samples were analysed for TS, SS, DCO and phosphorus. The volume of the centrifugation pellets was also noted.

3. Results

3.1. Mass transfer coefficient (kₐ)

The mass transfer coefficient (kₐ) was determined at different airflow rates under standard conditions (clean
water, 20°C). The log of $k_{1,a}$ shows a linear relation with the log of the superficial gas velocity $V_S$ (Eq. (2)). The value of $a$ and $b$ is 0.534 and 0.662, respectively, as determined by non-linear regression with Eq. (1) ($r^2 = 0.954$). This is relatively close to the values obtained by Burt et al. for a small ATAD reactor ($a = 0.313, b = 0.579$).

3.2. Oxygen uptake rate

Fig. 2 shows the evolution of OUR, DO and temperature in an AT-SBR operated with no temperature control and in reactors limited to 70°C, 60°C and 50°C. Without control (Fig. 2a), the temperature increased from 39°C to 74°C in 18h. After that, the temperature oscillated, with a second peak at 75°C after 38h and a third at 74°C after 60h. The OUR showed the same behaviour but the first two peaks occurred a little before the temperature peaks. The DO evolution is a negative image of the two others. When the temperature was limited to 70°C (Fig. 2b), no oscillation occurred, but the maximal OUR was relatively low (9 mg L$^{-1}$ min$^{-1}$). When the temperature was limited to 60°C (Fig. 2c) or 50°C (Fig. 2d), the maximal OUR was higher (17 mg L$^{-1}$ min$^{-1}$). In all cases, there was at least one period during which the DO was zero, which means that the oxygen demand exceeded the transfer rate.

3.3. Treatment performances

Table 1 shows the values of different parameters before and after a 3-day treatment. Since the properties of the untreated waste could vary widely from batch to batch, three series of experiments were conducted in order to make paired comparisons. In the first series, a reactor was operated without temperature control and the other was limited to 50°C. The former reactor reached 75°C, but this had a negative effect on the consumption of the organic material: the reduction of total COD was only 26% in the uncontrolled reactor but it reached 60% in the reactor limited at 50°C. This was also true for the soluble COD, with reductions of 39% and 78%, respectively. On the contrary, ammonia stripping was favoured by the elevated temperature with a 52% reduction compared to 21%. The highest temperature resulted also in a better removal of the soluble phosphorus (85% reduction compared to 50%). SS and VSS were also reduced by the treatment but there was no significant difference between the reactors. In both of them, the pH, which was around 6.7 for the untreated swine waste, increased during the treatment. The final pH was slightly higher in the reactor controlled at 50°C (8.7 compared to 8.4).

Almost the same trends occurred in the two other series in which the temperature difference between the reactors was only 10°C. The contrast in the performances was however less pronounced. For example, in the second series, the soluble COD reduction was 72% at 70°C and 77% at 60°C. In the third series, the difference was significant for soluble COD but not for the total COD. For the soluble phosphorus, the difference was just above the 0.05 level that is normally considered as statistically significant. The results from a 4-day treatment did not show significant differences from the 3-day batches (results not shown). The BOD$_5$ removal was evaluated only once in a reactor limited to 60°C. The reduction was 98% (1.0 g L$^{-1}$ for the effluent compared to 50.5 g L$^{-1}$ for the untreated waste).

In the three series, the total phosphorus was lowered by 9–19% after treatment, which was unexpected since no settling period was allowed in the bioreactor.
Table 1
Performance of the bioreactors operated at different temperatures and at a HRT of 6 days

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>COD$_{\text{tot}}$</th>
<th>COD$_{\text{sol}}$</th>
<th>NH$_4$-N</th>
<th>PO$<em>4$-P$</em>{\text{tot}}$</th>
<th>PO$<em>4$-P$</em>{\text{sol}}$</th>
<th>SS</th>
<th>VSS</th>
</tr>
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<tbody>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
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<tr>
<td>Untreated manure</td>
<td>g L$^{-1}$</td>
<td>73.7±8.3</td>
<td>35.7±3.3</td>
<td>4.2±0.4</td>
<td>1.48±0.08</td>
<td>0.26±0.03</td>
<td>33.2±2.2</td>
<td>24.6±1.6</td>
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<td>Effluent (T$_{\text{max}}$ = ~75°C)$^a$</td>
<td>g L$^{-1}$</td>
<td>54.7±15.2</td>
<td>21.7±7.0</td>
<td>2.0±0.4</td>
<td>1.29±0.12</td>
<td>0.04±0.00</td>
<td>27.9±3.5</td>
<td>19.2±2.3</td>
</tr>
<tr>
<td>Effluent (T$_{\text{max}}$ = 50°C)</td>
<td>g L$^{-1}$</td>
<td>29.3±3.3</td>
<td>8.0±3.3</td>
<td>3.3±0.7</td>
<td>1.22±0.06</td>
<td>0.13±0.03</td>
<td>28.3±2.9</td>
<td>18.9±2.1</td>
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<tr>
<td>Batches analysed (n)</td>
<td></td>
<td>10</td>
<td>10</td>
<td>7</td>
<td>3</td>
<td>3</td>
<td>10</td>
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<td>0.0004</td>
<td>0.0001</td>
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<td>0.0024</td>
<td>0.3728</td>
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<td></td>
</tr>
<tr>
<td>Untreated manure</td>
<td>g L$^{-1}$</td>
<td>106.3±4.6</td>
<td>53.5±5.7</td>
<td>4.2±0.7</td>
<td>1.26±0.08</td>
<td>0.38±0.05</td>
<td>33.4±1.3</td>
<td>25.0±2.0</td>
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<td>Effluent (T$_{\text{max}}$ = 70°C)</td>
<td>g L$^{-1}$</td>
<td>44.6±1.7</td>
<td>14.8±0.8</td>
<td>2.4±0.3</td>
<td>1.08±0.10</td>
<td>0.04±0.01</td>
<td>26.8±0.5</td>
<td>18.3±1.1</td>
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<td>Effluent (T$_{\text{max}}$ = 60°C)</td>
<td>g L$^{-1}$</td>
<td>43.1±2.4</td>
<td>12.1±0.6</td>
<td>3.1±0.2</td>
<td>1.15±0.12</td>
<td>0.06±0.02</td>
<td>28.1±2.2</td>
<td>18.4±1.0</td>
</tr>
<tr>
<td>Batches analysed (n)</td>
<td></td>
<td>11</td>
<td>11</td>
<td>12</td>
<td>3</td>
<td>3</td>
<td>11</td>
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<td></td>
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<tr>
<td>Untreated manure</td>
<td>g L$^{-1}$</td>
<td>107.3±3.0</td>
<td>56.3±1.1</td>
<td>4.1±0.0</td>
<td>1.26±0.05</td>
<td>0.20±0.02</td>
<td>31.4±0.6</td>
<td>23.5±0.4</td>
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<tr>
<td>Effluent (T$_{\text{max}}$ = 60°C)</td>
<td>g L$^{-1}$</td>
<td>42.0±0.4</td>
<td>11.9±0.4</td>
<td>3.0±0.1</td>
<td>1.03±0.02</td>
<td>0.05±0.02</td>
<td>24.3±1.3</td>
<td>17.0±0.8</td>
</tr>
<tr>
<td>Effluent (T$_{\text{max}}$ = 50°C)</td>
<td>g L$^{-1}$</td>
<td>44.4±2.5</td>
<td>9.9±0.3</td>
<td>3.9±0.1</td>
<td>1.02±0.04</td>
<td>0.08±0.00</td>
<td>26.6±0.5</td>
<td>19.1±0.9</td>
</tr>
<tr>
<td>Batches analysed (n)</td>
<td></td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Significance level$^b$</td>
<td></td>
<td>0.1334</td>
<td>0.0094</td>
<td>0.0099</td>
<td>0.4483</td>
<td>0.0511</td>
<td>0.0407</td>
<td>0.0041</td>
</tr>
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</table>

$^a$The temperature of this bioreactor was not controlled. The temperature showed some oscillation with peaks at around 75°C.
$^b$Level of significance is given for the Student’s t-test that compared the values of the two effluents of a series.

However, even without a settling period, there was a sediment build up at the bottom of the vessels. These dense sediments are likely to contain some crystallised phosphorus.

The colour of the untreated waste was dark grey whereas that of the mix liquor was light brown at the end of the treatment. However, the difference was much greater when the solids were removed. The solubilised colour of the untreated waste was light whereas the effluents showed an intense brown colour. This can be appreciated by comparing the absorbance spectra (Fig. 3) of samples taken during the first series of experiment. The colour was more intense in the effluent of the bioreactor that was operated at a temperature up to 75°C than in the bioreactor limited to 50°C. The same trend was observed with the effluents of the two other series of experiments (result not shown).

The thermophilic treatment destroyed efficiently the pathogens (Table 2). Faecal coliforms and Campylobacter spp. were not detected after treatment at all the temperatures tested. C. perfringens showed some survival at 50°C but the efficiency was still high with 99.2% reduction. The very low count in the effluent of the uncontrolled reactor (1 CFU ml$^{-1}$) is likely to be due to a contamination during the sampling process since the port could not be perfectly sterilised. Salmonella, Yersinia, Cryptosporidium and Giardia were also checked but they were absent from the untreated waste.

3.4. Solid/liquid separation

The efficiency of centrifugation to separate the solids was tested with the untreated waste and with the effluent of a bioreactor operated at a maximal temperature of 60°C. There was no difference in terms of the remaining SS in the supernatant (Fig. 4a). However, the effluent produced a denser sludge than the untreated waste when they were centrifuged over 2500g (Fig. 4b). For the phosphorus, the difference became appreciable only at 4000g (Fig. 4c). For the effluent, this centrifugal force produced a supernatant with 34% less total phosphorus than for the untreated waste.

Fig. 3. Absorbance spectrum of the solubilized matter contained in the untreated waste and in the effluents. The samples were taken during the first series of experiments. The solids were removed by centrifugation and the supernatants were diluted 1:20 before being analysed.
4. Discussion

It is hard to reproduce a self-heating bioprocess at the laboratory scale due to the high surface-to-volume ratio that causes an important heat loss. For this reason, the previous laboratory studies of the aerobic thermophilic treatment of liquid manure were carried out at constant temperature with an external heating \([1,4]\). The difficulty to reproduce this process under realistic conditions with small-scale reactors has certainly impaired the development of equipment adapted to pig manure. However, Burt et al. \([9]\) have shown that a self-heating thermophilic aerobic digestion of sewage sludge can be reproduced with a 25-L ATAD reactor. It consisted of an insulated open tank with a Venturi aerator located on a recirculating loop. With this system, they have reached 52°C. With ours, we reached 75°C. The difference could be due to the substrate (sludge versus manure) and to the presence of an insulated cover over our bioreactors. Also, the lower aeration rate that we used (0.07 vvm compared to 0.32 vvm) is another important factor since the air leaving the reactor is considered to be the most important heat loss \([10]\). A temperature of 75°C is realistic since a full-scale ATAD reactor can reach 80°C without external heating \([2]\).

There are only few detailed studies on the mass transfer characteristics of the Venturi aerators. Eq. (1) that describes the \(k_L a\) as a function of the superficial velocity has been used for bubble columns and airlift reactors. For a Venturi aerator, the \(k_L a\) seems to be better described as a function of the energy dissipation rate, the gas fraction and the relative ejector dimensions \([11]\). Nevertheless, Eq. (1) was used in order to make comparisons with the work of Burt et al. \([9]\). The air injector that we used featured a swirl device (small vanes on the internal wall) that is supposed to improve the oxygen transfer rate, based on the manufacturer’s claim. However, the performances obtained are close to the results of the classical Venturi design utilised by Burt et al. This is in agreement with Cramers and Beenackers \([11]\) who observed that a swirl device had a negative effect on the \(k_L a\) but the difference was small at low gas flows like those we used. More work would have to be done in order to conclude on the relative efficiency of this kind of aerator.

The bioreactors were operated at an air flow rate that gave a \(k_L a\) of 0.208 min\(^{-1}\) at 20°C, which corresponds to an oxygen transfer rate (OTR) of 1.9 mg L\(^{-1}\) min\(^{-1}\) under standard conditions (temperature = 20°C, 

<table>
<thead>
<tr>
<th>Pathogens reduction at different temperatures and at a HRT of 6 days</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Faecal coliforms</strong> (( \times 10^2 ) CFU ml(^{-1}))</td>
</tr>
<tr>
<td><strong>1st series</strong></td>
</tr>
<tr>
<td>Untreated manure</td>
</tr>
<tr>
<td>Effluent ( (T_{\text{max}} = \sim 75°C)^a )</td>
</tr>
<tr>
<td>Effluent ( (T_{\text{max}} = 50°C) )</td>
</tr>
<tr>
<td><strong>2nd series</strong></td>
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<tr>
<td>Untreated manure</td>
</tr>
<tr>
<td>Effluent ( (T_{\text{max}} = 70°C) )</td>
</tr>
<tr>
<td>Effluent ( (T_{\text{max}} = 60°C) )</td>
</tr>
</tbody>
</table>

\(^a\)The temperature of this bioreactor was not controlled. The temperature showed some oscillation with peaks at around 75°C.

![Fig. 4. Solids removal by centrifugation. (a) SS in the supernatant; (b) total solids in the centrifugation pellet; (c) total phosphorus in the supernatant. (■), untreated waste; (△), effluent of a bioreactor operated at a maximal temperature of 60°C.](image-url)
DO = 0 mg L\(^{-1}\)). The temperature should not affect greatly this value since it has been demonstrated that the lowering of the oxygen solubility with an increase of temperature is compensated by the concomitant increase of the \(k_1/a\) [5,12]. On the other hand, the constituent of the manure should influence the OTR but there is little information in the literature that can be used to predict the change for this particular combination of aerator and waste. Aeration trials with a Venturi device and a simulated high-strength waste (caustic potato peel liquid waste) showed a significant increase of the OTR, presumably due to the presence of proteins that reduce the surface tension of the water [13]. This is in agreement with the information provided by the aerator manufacturer who reported an alpha factor (process water \(k_1/a\)/clean water \(k_1/a\)) ranging between 1.01 and 1.27 in the presence of a commercial detergent. Nevertheless, the actual OTR in the AT-SBR did not match the OUR that showed peaks up to 17 mg L\(^{-1}\) min\(^{-1}\), a value that would have been even higher if the micro-organism growth had not been limited by the oxygen transfer. These conditions represent well those achievable in the field since it would be cost prohibitive to try to match the OTR and the OUR at large scale. For example, the mechanical aerator used for ATAD reactors gives around 6 mg L\(^{-1}\) min\(^{-1}\) and the DO in the aerated sludge often approaches 0 mg L\(^{-1}\) [2].

The best performance for COD removal was obtained at the lower temperature tested (50°C). This is in agreement with some recent works with paper mill process water, synthetic wastewater and pharmaceutical wastewater that showed that the optimal temperature for organic matter removal was below the thermophilic range [14–18]. Others found an optimum at 60°C for organic matter removal was below the thermophilic conditions. Temperature dependence has already been reported but only in the range 5–25°C [23].

The development of colour during the process was unexpected, especially the fact that the increase in colour intensity was correlated with higher temperatures. The reason for that is unknown. This phenomenon does not represent a problem for a partial treatment since the effluent (after solid separation) would be used for irrigation. However, it could represent an additional challenge if the AT-SBR is used as a first step in a process chain intended to produce an effluent of a sufficient quality to be discharged into a watercourse.

Summing up the results concerning the performances, we can see that an increase of the temperature had conflicting effects: it improved the ammonia stripping, the phosphorus crystallisation and the pathogen destruction but it reduced the efficiency of COD consumption. The higher colour intensity of the effluent was also unwanted. Consequently, limiting the temperature to 60°C appears to be a good compromise. This is the minimal temperature at which \(C. perfringens\) was completely eliminated.

Compared to the untreated manure, the bioreactor effluent represents a much more valuable fertiliser (stable, no pathogen, no bad smell). However, for pig producers that have an excess of manure to manage, an additional solid separation step would be needed. The liquid fraction could be used locally for irrigation whereas the recovered solids that are rich in phosphorus could be transported on long distances and sold at competitive prices compared to inorganic fertilisers. The centrifugation of all the effluent was considered since a test showed that the settling of solids is poor (results not shown). There are already some industrial centrifuges that are offered to separate the solids from liquid manure. Our results suggest that the performance would be better in terms of solid density if the centrifuge would be used with a bioreactor effluent. More phosphorus could also be recuperated but only at 4000g, which represent the upper speed limit for this kind of equipment.

5. Conclusions

1. A self-heating aerobic thermophilic treatment of pig manure reaching temperatures up to 75°C was evaluated on a small scale by using Venturi-type aerators.
2. The temperature should be limited to 60°C, which represents a good compromise to achieve a significant reduction of COD and ammonia and a complete removal of faecal coliforms, *Campylobacter* spp. and *C. perfringens*.
3. Phosphorus crystallisation and the development of colour are temperature dependent.
4. The solids recovered by centrifugation of the bioreactor effluent are of better quality in terms of density, phosphorus, odour and stability than those obtained by centrifugation of the untreated manure.

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