Treatment of pig farm effluents by ultrafiltration

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Received 7 February 2003; received in revised form 5 January 2005; accepted 21 January 2005
Available online 8 March 2005

Abstract

The technical feasibility of using ultrafiltration (UF) to treat four types of liquid pig manure from different treatment stages in an experimental farm was studied. The determination of concentration factors and the optimization of operating parameters were conducted in batch mode. A tubular lab-scale UF unit featuring 0.1 m² PVDF membrane was used. Optimal operating parameters for transmembrane pressure and recirculation velocity were found to be 100 kPa and 2–2.5 m/s, respectively, for most manure types. The concentration factors reached were about 4.0 L/L. The performance-limiting factor is suggested to be the suspended solids concentration, which could be reduced with better pre-treatment. Operating costs of the UF cell ranged from 1.4 to 8.0 USD/m³. Tertiary treatment by UF of pig manure appears to be expensive for small farms where the savings due to scale-up factors are not significant. However, for a compact and stable process that can completely remove suspended solids, total coliforms and constitute a good pre-treatment for reverse osmosis, UF appears promising.

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Keywords: Optimization; Performance; Pig manure; Ultrafiltration; Wastewater treatment

1. Introduction

The use of membranes for the treatment of wastewater has greatly increased over the last decade, mainly because of the tightening of environmental regulations, and the decrease of the associated costs with this technology [1–4]. For wastewaters, fouling is an important phenomenon that limits the applicability of UF. Such fouling can be caused by cake or gel formation, pore plugging and pore narrowing [1]. Cake and gel formation are caused by the accumulation of particles/solute at the membrane interface while pore blocking is caused by the accumulation of particles in the membrane pores, and pore narrowing by particles attached to the interior surface of the pores. Some researchers [1] link these phenomena together, saying that pore narrowing might cause an amplification of the cake/gel accumulation.

Although the treatment of effluents with a high suspended solids concentration by membrane processes has been presented by some researchers [5–7], their focus was not on pig manure treatment by UF. This project was a feasibility study on the treatment of pig manure in small farms. Pig manure from four different pre-treatment stages was treated. This allowed a more complete understanding of the UF performance. Knowing that traditionally membrane systems are expensive to purchase and operate in the treatment of wastewater, attempts have been made to treat different pig manure types (depending on the pre-treatment) by a strictly physicochemical treatment chain. Manure sampling took place at different treatment steps on an experimental farm featuring a mixed physical and biological treatment process. Samples were taken from the storage tank supernatant (ST), fresh vacuum-filtered manure (VF), sieved and settled manure supernatant (SAS), and sieved, biologically treated and settled manure supernatant (SBS). The main treatment objectives were the removal of bacteria, suspended solids and phosphorus. The UF being a separation process, a maximum
volume reduction was desired as this parameter can be related to operating costs. The operating parameters optimization was made with the economic model of Belhocine et al. [7] which takes into account amortization of membrane cost, energy costs incurred by the pressure drop and the permeate flow through the membrane. The optimized parameters were tangential velocity and transmembrane pressure.

2. Materials and methods

2.1. Pig farm effluents

Four different manure types from two farms in the Quebec city region were sampled: storage tank (ST), fresh (VF), sieved (SAS) and biotreated (SBS) (Fig. 1). All manure samples were stored at 4°C. The two farms were in the same area and used the same animal production methods. For the VF samples, a 600-μm vacuum sieve was used while a 500-μm tangential sieve was used for the SAS and SBS effluents.

2.2. UF

2.2.1. UF module

In this study, a lab-scale system was equipped with a single 0.1-m² tubular UF membrane (Koch membrane systems, model 5-HFM-251-FNO). Its skin was composed of polyvinylidene fluoride (PVDF) and possessed a cut-off capacity of about 100,000 Da which corresponds to an approximate pore size of 0.01 μm. The membrane consisted in a single tube, with an internal diameter of about 2 cm, which was adapted to the treatment of large particulate, viscous fluids.

A drive coupled with a flexible impeller pump allowed a reasonable flow range (0–70 LPM). The pressure and velocity created by the system’s pump were not independent since pressure was generated by choking the pump. The typical manure volume used in the concentration experiments was between 30 and 60 L. The main operating parameters are shown in Table 1.

The concentration factor (CF) is defined as the ratio of the initial and final volumes of concentrate ($V_i / V_f$).

2.2.2. Washing and preservation

The washing procedure was adapted from the supplied method. In the first step, the system was washed with 4–5 times the retention volume. In the following step, “Koch Kleen™” soap (1%) was added and water was recirculated in a close-loop for a period ranging from 30 to 60 min. A sponge ball (2.1 cm in diameter) was then inserted twice through the membrane to physically scrub the surface, followed by a rinsing with tap water. For preservation, the pH was raised with NaOH (1N) to 10–10.5 and 0.1% sodium azide (NaN₃) was added to prevent bacterial growth.

2.2.3. Operating mode

A batch-operating mode was used to study the feasibility of UF treatment on effluents containing a high concentration of suspended solids. Requiring less sample volume and shorter operating durations than a more common “feed and bleed” system, this mode was well adapted for a lab-scale system (Fig. 2).

2.3. Sampling and analysis

Sampling for analysis (SS, COD, Pt, etc.) was generally made on the concentrate and permeate. Total solids (TS) were thus measured instead because this did not require filtration. Sampling on the concentrate was conducted on the feed tank,

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>ST</th>
<th>SAS</th>
<th>VF</th>
<th>SBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial flux (water)</td>
<td>L·m⁻²·h⁻¹</td>
<td>600–1080</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mode of operation</td>
<td>Batch with recirculation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>-</td>
<td>6.0–8.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>15–25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean operation time</td>
<td>h</td>
<td>24</td>
<td>24</td>
<td>24</td>
<td>10</td>
</tr>
<tr>
<td>Concentration factor range</td>
<td>L/L</td>
<td>2.1–3.7</td>
<td>3.1–3.7</td>
<td>1.7–2.2</td>
<td>4.3–9</td>
</tr>
<tr>
<td>Transmembrane pressure</td>
<td>kPa</td>
<td>100–180</td>
<td>100–175</td>
<td>100–105</td>
<td>155–210</td>
</tr>
<tr>
<td>Tangential velocity</td>
<td>m/s</td>
<td>2.9–3.3</td>
<td>3.0–3.3</td>
<td>2.7–3.0</td>
<td>2.6–3.5</td>
</tr>
</tbody>
</table>
supernatant while permeate samples were taken directly at the permeate outlet to prevent precipitation problems that occurred in the permeate tank. Samples were usually taken as duplicates in 70-mL glass tubes. Following sampling, tubes were stored at 4 °C until analysis.

2.4. Analytical methods

The total phosphate concentrations were measured following the US EPA 365.4 method. The other analytic methods used in this study were from Standard Methods (1998).

2.5. UF optimization protocol

A cost evaluation model was used to analyze the data. This model was developed by Belhocine et al. [7] to describe the cost incurred by using an UF cell depending on different operating parameters. The permeate flux, being a parameter characterizing the performance of the filtration, has a major impact on the determination of operating costs. The permeate flux is dependent upon other operating parameters such as recirculation velocity, applied pressure and pressure drop across the membrane.

The model can be expressed as

$$K = K_c A + K_p Q_v \Delta P_f + K_p Q_w \Delta P$$

where $K$ is the global cost, $K_c A$ the investment cost related to the membrane surface $A$, $K_p Q_v \Delta P_f$ the energy cost related to the pressure drop across the membrane and $K_p Q_w \Delta P$ the energy cost related to the flow of permeate through the membrane. The coefficient used in this study were: $K_p : 1.07 \times 10^{-8}$ USD/J according to energy costs in Quebec and $K_c : 8.6 \times 10^{-6}$ USD m$^{-2}$ s$^{-1}$ for a membrane life of 2 years.

For the optimization process, tangential velocities and membrane fluxes were registered while the pressure was increased sequentially [8]. Constant concentrations in the liquid were maintained in each experiment by recirculating the permeate. Plotting global cost per m$^3$ ($K/Q_w$) against tangential velocity for different effluents allowed to identify the optimum cost and tangential velocity. In the same way, plotting global cost against concentration factor gave information about the optimal concentration factor that could be attained.

As the determination of these optimal parameters was only made on initial concentration, the model is limited to a steady-state operation mode, in which the concentration does not change. It is questionable whether or not optimized parameters will remain optimal when the concentration of wastewater is no longer held constant.

3. Results and discussion

Membrane flux increased with tangential velocity [1,7] (Fig. 3(a)), probably due to increased turbulence at the membrane interface, thus reducing the cake and polarization layer [9,10]. Any pressure increase above 100 kPa, however, did not improve membrane fluxes. This is in contradiction with Darcy’s law concerning the permeation of a solvent through a porous interface. This pressure is probably too small to significantly compact the membrane, but sufficient to start compressing the cake and polarization layer [11,12]. Evidence supporting this explanation is provided by the linear relationship between pressure and membrane flux from 50 to 400 kPa with tap water. Moreover, the average hydraulic per-

![Fig. 2. Hydraulic flow in the batch UF system: UF: ultrafiltration membrane; FT: feed tank; RP: recirculation pump; * sampling points.](image-url)
meability of the clean membrane was \(870 \text{ L m}^{-2} \text{ h}^{-1}\) with tap water. This average hydraulic permeability dropped to an average of \(30\) and \(12\) \(\text{L m}^{-2} \text{h}^{-1}\) before and after concentration of manure at a concentration factor of about \(3.0 \text{ L/L}\).

Investigation of the variation pattern of \(J_v\) versus pressure at increasing velocities showed a significant impact of liquid velocity on membrane flux at low pressures. This impact of liquid velocity seemed to be reduced as the pressure increased (Fig. 3 (b)). For the tested manure effluents that differed in SS concentration, composition and viscosity, various concentration factors (CF) were reached (Fig. 4). Membrane fluxes decreased significantly between the initial and final stages as showed in Fig. 4. The decrease was even more marked in the case of VF, where the final fluxes are under \(8 \text{ L m}^{-2} \text{h}^{-1}\) for a small CF of \(2.2 \text{ L/L}\). In the case of the SBS, however the fluxes showed only a small decrease, even after undergoing a concentration of \(4.3 \text{ L/L}\). Concentration times for ST, SAS and VF differed from that of the SBS effluent, since initial concentrate volumes for all manure types were the same and SBS allowed higher membrane fluxes. This last phenomenon is promising for the eventual application of this process to more diluted effluents where treated water would have to be recovered. The flux and concentration factors measured in the treatment of SBS were similar (35–40 L m\(^{-2}\) h\(^{-1}\) and 4–5 L/L) to those found by Bourgeois et al. [1]. Membrane fluxes presented in this figure seemed to be in the same range (10–20 L m\(^{-2}\) h\(^{-1}\)) as those typically found in high-load wastewater [5].

The optimal operating parameters were \(\Delta P\) of 100 kPa and a \(U\) of 2–2.5 m/s for all effluents (Fig. 5) [8]. The optimal pressure and pressure were determined by identifying on the curves of the various effluents, the operating conditions with the lowest global cost.

The determined pressure value was near the 120 kPa optimal pressure found by Liu and Xingyan [9], who used a hollow-fiber cellulose acetate UF system with a 0.2-µm pore size membrane treating erythromycin at a concentration of 0.241 g/L. The liquid treated by Liu and Xingyan [9] contained a low SS concentration suggesting that a similar fouling mechanism could be involved in both cases. Different manure types featuring different compositions had similar optimal parameters, which was unexpected. The creation and thickening of the cake/polarization layer could be due more to the hydrodynamic conditions of the membrane flow than to the absolute suspended solids concentration. In this study, VF could not be optimized because of the limited amount of manure available for the experiments.

Membrane flux did not seem to decrease exponentially in the concentration factor range that was reached in this study (Fig. 6). A linear trend seemed to represent better the curves. This could be explained by only a small increase in the viscosity of the fluid at these concentrations. Indeed, as Liu and Xingyan [9] discovered that membrane fluxes dropped abruptly at the beginning of the concentration experiment and then dropped more slowly at a constant rate. Different patterns seemed to take place for the ST, SAS, VF effluents compared to the SBS: sharper decreases in the membrane fluxes, higher operating costs and longer treatment time. The high suspended solids load might be responsible for those differences.

The poor membrane flux obtained with the real effluents (20–40 L m\(^{-2}\) h\(^{-1}\)) compared to initial (tap water) fluxes (600–1000 L m\(^{-2}\) h\(^{-1}\)) can be explained by two phenomena: polarization and cake layer formation. The first one is the accumulation of macromolecules at the membrane interface that eventually reach a gelation concentration. The gel that is formed provides an additional hydraulic resistance for the permeation of solvent through the membrane. The cake layer will be caused by an accumulation of particles at the membrane surface [13]. With a lot of particles at the membrane interface, it might be possible that the cake layer was subjected to compaction as pressure increased and prevented membrane flux from rising [12].
Particle size may also have an effect on the membrane fluxes, defining the level of membrane plugging and the compactness of the cake layer [11]. Agering seemed to have an effect on the treatability of pig manure. It has been qualitatively noticed that the two aged pig manures (ST and SAS) were composed of smaller particles, while the VF being composed of bigger flocs, with lots of organic matter. This could be due to the biological breakdown of flocs, proteins and sugars that happens in the aerobic and anaerobic degradation processes.

The modeling of evolution of cost compared to particle size has been made by Sethi and Wiesner [14] and it was found that with a 100,000 Da membrane, the higher operating costs were obtained for particle sizes between 0.01 and 0.1 μm. A precise characterization of pig manure would help to understand more precisely this phenomenon.

Fresh manures showed a sharper decrease in membrane flux with concentration than the one noticed with the two other manure types. According to the information previously presented, it might have been possible that higher protein concentrations caused increased fouling, which resulted in a reduction in membrane flux. The various manure types were characterized in more detail to assess the ability of UF to treat pig manure. There seemed to be a significant difference between the three manures presented, especially concerning their TS and SS concentrations (Table 2). The SBS effluents had undergone an extensive biological treatment with COD, Pt and TS–SS were all at lower values than the ones found in SAS and ST effluents. Surprisingly, the ST effluent possessed higher TS and SS concentrations than the SAS (sieved and settled) effluent while showing an inferior COD. Ageing of the manure could have been responsible for this phenomenon since there was more time for biodegradation to occur (HRT of 90 days versus HRT of 30 days).

UF was successful at removing particulate matter (particulate COD, phosphate, nitrogen and coliforms). However, the soluble phase of these components passed through the membrane completely, independent of the manure type.

Total coliforms were removed with an efficiency greater than 99%, as the filtrate concentration was under the detection limit at 10 CFU/100 mL. This is not surprising since given that the smallest bacteria are about 0.1 μm in diameter while the UF’s mean pore size are about 0.01 μm. Since soluble COD, phosphorus and nitrogen were not removed, there is a need for a biological treatment unit in the process train or a post-treatment. Strict regulations on discharge of nitrogen, phosphorus and COD (BOD5) will influence the choice of a post-treatment or a management system. Recirculation of permeate in the farm would probably need the liquid to contain little pathogens, ammonia and BOD to minimize microbial growth.

A pulsed backwash filtration could be a solution to the accumulation of a cake layer. Cake formation time still remains to be investigated for an adequate evaluation of the efficiency of such backwash method. As it was noted, particulate characteristics changed the permeate fluxes that could be reached. Like in all filtration processes, UF’s performance is highly dependent on the pre-treatment process to remove suspended solids or change the physicochemical characteristics of the raw wastewater. Investigating different pre-treatment steps could lead to enhanced membrane fluxes. Reducing the membrane internal diameter could also help lowering the pumping costs while increasing the membrane surface per volume unit. It is important to note that initial membrane flux was stable for the whole experimentation period, meaning that irreversible fouling was not important.
Table 2
Characterization of manure before and after ultrafiltration for three manure types: SAS, SBS and ST (n/a: unavailable data)

<table>
<thead>
<tr>
<th>Description</th>
<th>Units</th>
<th>SAS (mg/L)</th>
<th>SAS UF</th>
<th>SBS (mg/L)</th>
<th>SBS UF</th>
<th>ST (mg/L)</th>
<th>ST UF</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS</td>
<td></td>
<td>12000</td>
<td>5000</td>
<td>2500</td>
<td>2000</td>
<td>20000</td>
<td>7000</td>
</tr>
<tr>
<td>SS</td>
<td></td>
<td>7000</td>
<td>0</td>
<td>500</td>
<td>0</td>
<td>13000</td>
<td>0</td>
</tr>
<tr>
<td>Total COD</td>
<td>mg/L</td>
<td>60000</td>
<td>n/a</td>
<td>130</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>CBOD₂</td>
<td>mg/L</td>
<td>1800</td>
<td>900</td>
<td>695</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>TKN</td>
<td>mg/L</td>
<td>1100</td>
<td>15</td>
<td>48.5</td>
<td>30</td>
<td>140</td>
<td>80</td>
</tr>
<tr>
<td>Total coliforms</td>
<td>CFU/100 mL</td>
<td>14400</td>
<td>&lt;10</td>
<td>4700</td>
<td>&lt;10</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

4. Conclusions

Ultrafiltration allowed to meet pig manure treatment objectives of removing suspended solids, particulate phosphorus, nitrogen and COD, plus removing coliforms at an efficiency effectiveness greater than 99%. However, the soluble fraction of these elements was not removed. An average membrane flux around 15–20 L m⁻² h⁻¹ was reached for all manure types, which seems to be typical in high-load wastewater. The fourth manure type (VF) was harder to treat since membrane flux decreased faster, even at a small concentration factor.

The concentration factor that was reached, while keeping an acceptable minimal membrane flux (min of 8 L m⁻² h⁻¹) is about 3.7–4.0 L/L for manure types ST and SAS, 4.0–7.0 L/L for SBS and about 2.2–2.5 L/L for the VF; these concentration factors are not that substantial, but seem to be typical of highly concentrated wastewater [7]. Based on this data, the UF of liquids having approximately the same SS load and composition as the SBS manure could give high concentration factors while keeping operating costs low. However, the capital costs incurred by equipment purchase are quite significant.

The same optimal pressure and recirculation velocities were found to be the same for all manure types, regardless of the suspended solids concentration. A pulsed backwash method could increase membrane fluxes without increasing operation costs too much.

Treating the manure in regional processing plants operated at a higher flow rate could be more efficient than on-site treatment. Such a UF process could be applied to most effluents if the treatment goals are removal of coliforms, SS and particulate phosphate. If restrictions exist on COD, soluble phosphate and nitrogen, a biological pre- or post-treatment would be advisable.

Acknowledgements

The financial support of Envirogain, Inc. is gratefully acknowledged as is technical assistance provided by Denis Bouchard. Thanks and the proof reading of this article by Christopher Donka and Dwight-Cornelius Houweling.

Nomenclature

- $A$: membrane area (m²)
- $CF$: concentration factor (L/L)
- $CFU$: colony-forming units (CFU/100 mL)
- $COD$: chemical oxygen demand (mg/L)
- $HRT$: hydraulic retention time (d)
- $J_v$: membrane flux (L m⁻² h⁻¹)
- $K$: global cost (USD/s)
- $K_P$: energy cost coefficient (USD/J)
- $K_c$: investment cost coefficient (USD m⁻² s⁻¹)
- $K/Q_w$: global cost incurred by the membrane module (USD/m³)
- $LPM$: liters per minute (L/min)
- $P_1$: pressure at the upstream side of the UF membrane (kPa)
- $P_2$: pressure at the downstream side of the UF membrane (kPa)
- $\Delta P$: pressure applied to the membrane [(P₁ + P₂)/2] (kPa)
- $\Delta P_1$: pressure drop across the membrane [(P₁ − P₂)] (kPa)
- $P_t$: total phosphorus (mg P/L)
- $Q_v$: tangential flow (m³/h)
- $Q_w$: permeate flow (m³/s)
- SAS: sieved and settled manure
- SBS: sieved, biotreated and settled manure
- SS: suspended solids (mg/L)
- ST: storage tank manure
- TS: total solids (mg/L)
- $U$: tangential velocity (m/s)
- UF: ultrafiltration
- USD: US dollars
- VF: vacuum-filtered manure

References


