The Canadian society for engineering in agricultural, food, and biological systems

CSAE

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La société canadienne de génie agroalimentaire et biologique

Paper No. 05-094

EVALUATION OF AN IMMERSED HOLLOW FIBRE MEMBRANE TECHNOLOGY FOR WATER REUSE IN ALBERTA LIVESTOCK PRODUCTION SYSTEMS

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Written for presentation at the
CSAE/SCGR 2005 Meeting
Winnipeg, Manitoba
June 26 - 29, 2005

Abstract

Direct filtration of diluted swine waste with an immersed hollow fibre membrane (Zeeweed® 500, Zenon Environmental Inc.) was tested for possible integration into a wastewater treatment system for direct non-potable or potable reuse in intensive livestock operations. A sustainable flux of 1.36 $L\ h^{-1}m^{-2}kPa^{-1}$ at 20°C was determined in 20% swine waste supernatant (SWSN) which had a mean COD equivalent of 2.7 g O_2/L. The compact membrane module had an effective membrane area of 0.047 m^2 and 0.04 μm pore size. The membrane treatment was effective and a compete barrier to fecal coliforms and suspended solids. Turbidity was reduced to <0.5 NTU that would allow disinfectant or microbial reduction processes to work more effectively. Reduction of contaminants in percentage terms was TSS (100%), sulphide (79%), TP (49.5%), TOC (34%), COD (32%), BOD_5 (29%), TDS (23%), TKN (21%), and NH_3 (5.9%). A preliminary membrane size estimate of 225 m^2 for a 1000 sow (6192 pig) grower finisher barn with 5:1 recycle was made.

Keywords hollow fibre membrane, swine waste, wastewater treatment, livestock, recycle, reuse, direct filtration, Zeeweed

INTRODUCTION

Limited water availability is an impediment to the development of the agricultural industry in Alberta especially with the increase in the size of modern intensive livestock operations. Water reuse is one option to reduce the quantity of raw water supply required and promote the advantages of self-sufficiency and closed systems. Increased sustainable agricultural production in Alberta benefits the economy of Alberta and livelihood of its farming residents.

Properties that are desired in a water or wastewater treatment system for rural water reuse are as follows:

- scalability especially in the low capacity range;
- low or no dependence on chemical additives and dosing; and
- flexibility to integrate into existing operations or with other easily accessible technologies.

The agricultural industry in Canada produces low cost crops and meat for value added processing or exports and has not significantly supported the research or interest of water treatment or reuse technologies. Because of this, adaptive research from technologies produced for other industries is a common trend and obstacle. A current investigation into agricultural wastewaters from intensive livestock operations and the issues surrounding their reuse is required to define and target cost-effective, workable treatment technologies. A workable reuse technology could reduce the raw water requirement of larger confined feeding operations (CFO) as well as the operating costs surrounding water access and use. Water/wastewater systems, which more closely approach closed systems in regard to water, have more opportunity available for development location, acceptance, and sustainability.

Swine Production

In Canada, swine are almost always housed indoors in separate areas according to their age and physiological state where temperature and feed can be controlled to optimize production levels. Manure is usually handled in a liquid form upwards of 90% moisture and changes little from this moisture state until removal to storage reservoirs. Due to behaviors of swine significant water above physiological requirements can be spilled and become part of the waste load. Pigs have been known to waste up to 20 litres of water per day per head and new wet feed, water system and water nipple designs are countering some of this wastage (Phillips, et al 1995). Unlike beef cattle, swine are produced in a wide variety of climatic regions. Wastes stored in anaerobic lagoons or uncovered storage in Alberta is subject to rainfall and snowmelt, however, in most locations evaporation exceeds precipitation.

According to published values, the amount of water used and waste volume and characteristics can vary significantly among swine operations. Water is used for drinking, cooling, washing, and domestic needs with the largest percentage being for drinking. A manure production and characteristics standard, D384.1 FEB03, has been used to assist in the planning, design, and operation of manure collection, storage, pretreatment and utilization systems for livestock enterprises (American Society of Agricultural Engineers 2003).

In Alberta, livestock wastes from swine operations are mainly stored in earthen manure storages and the liquid manure undergoes little treatment. Although the liquid manure and accompanying wastewaters are referred to as swine wastes in this project, the “wastes” generated can provide a valuable nutrient and organic matter resource to cropland when applied at appropriate rates. However, where microbial concerns are present, they must be addressed. Wastes are mixed prior to land application but before this a supernatant can be identified. As to condition in lagoons, the material varies from a less concentrated light yellow green to a black more concentrated form (U.S. Soil Conservation Service 1992). It is this swine waste supernatant (SWSN) that will be targeted for treatment and potential reuse. Both open gutter and below-slat flushing systems exist for transporting wastes out of the barn and can add significantly to the wastewater quantity production.

There is a cost to treating swine wastewater to a level acceptable for release to a water body as is commonly done with the treatment of municipal effluents. Recouping the value of treated wastewater through reuse is becoming an increasingly attractive proposition. The idea of treating swine wastewater or liquid manure, which is greater than 90% water as a source for drinking water for pigs, is one scenario. (Navaratnasamy 2003). Removal of pathogens (<5,000/100 mL) and reduction of TDS (< 3,000 mg/L) were the key targets investigated in this study. Aeration reduced TDS levels at a faster rate than ozone treatment or natural settling. Slow sand filtration reduced pathogens in an aerated liquid to meet this recommended level of for swine drinking water. By these criteria, diluting with 20% fresh water with slow sand filtered liquid after 7 days of aeration would be sufficient. This was at an estimated energy cost of $0.20/growing pig.

Membrane Treatment of Wastewater

The use of membranes in the treatment of wastewater is evolving from membrane used in a direct filtration mode to the more recent systems, which couple them with bioreactors of various configurations.

Agricultural wastewaters have high carbon and high nutrient contents and therefore biological treatment to reduce this organic loading is indicated. The key to this is to produce and retain an actively growing biomass in the reaction vessel. Whether suspended or attached this biomass requires oxygen to avoid going anoxic and often requires a significant energy outlay to provide air required. Submerged or immersed membranes have allowed the coupling of this biological process with physical/chemical treatments within the reaction vessel. Two municipal wastewater treatment processes, which perform this, are the membrane-coupled activated sludge process (MCASP) and the membrane bioreactor (MBR).

The conventional activated sludge process has served the needs of municipal wastewater treatment for decades since its development in England (Adern and Locket 1914). Beyond a straight aeration process, the activated sludge process (ASP) retains sludge with its mix of living organisms to separate the wastes from the water by its conversion to biomass and sedimentation into a sludge blanket and a relatively clear supernatant. The maintenance and recycling of this activated sludge is key to optimum performance of this process. Although the topic of ASP will not be discussed further here, the MCASP has emerged to deal with some limitations of ASP. In conventional ASP a final clarifier only retains the activated sludge that forms flocs and settles (Günder 2001). With membrane filtration, all parts of the activated sludge that are larger than the cutoff of the membrane are retained. As a result, the separation of the activated sludge from the cleaner wastewater is independent of the sedimentation qualities of the activated sludge and is only dependent on the inserted membrane.

Membrane bioreactors (MBR) utilize the membrane as a solid separation device in the activated sludge aeration. Filtration capacity can be altered by increasing the depth of the cake layer which can form on the membrane. Secondly, the maintenance of the membrane and the removal of the biofilm is a major component of the system design.

Efforts to produce a compact membrane bioreactor system started in the early 1970" with the introduction of the Cycle-Let® system (Cote and Thompson 2000). In the late 1980's a shell-less membrane module, suitable for immersion directly in the biomass evolved and became the product Zeeweed® used in the ZenoGem® process. The key features to this membrane were low vacuum pressure, outside-in permeate flow, air bubble scouring of the hollow fibres, and modular-scalable design. This allowed for simplicity and a reduction in energy costs for filtration. A progression of improvements to design evolved with a key one being packing density of the cassettes. The Zeeweed® ZW-500 membrane, on which this project is based, has a packing density of 146 m^2/m^3 for the standard 8 module cassette. The ZW-1 membrane module can be used for preliminary investigation into the performance of commercial ZeeWeed® 500 modules. Zenon states the results would better represent effluent quality than fouling behavior due to the limitations of the ZW-1's compact design (Zenon Environmental Enterprises Ltd. 2001).

Research Objectives

The main focus of this study was to evaluate a low pressure immersed hollow fibre membrane in its ability to reduce key contaminants present in swine wastewater. To do this, the following steps were required and will be focused on in this document.

- Develop and/or refine a methodology and bench top data acquisition and control system suitable for operating a low pressure immersed hollow fibre membrane module in direct filtration mode in polluted water.
- Establish the maximum sustainable flux capability to produce 10 L of permeate.
- Determine the membrane's ability to reduce key contaminants in the supernatant of swine wastes at this level of flux.
- Make a preliminary assessment of the membrane size required and its potential for treatment of swine wastewater in the context of current swine production systems.

A more complete accounting of the previous work contributing to this project, the issues and policy identified around livestock contaminated wastewater treatment and reuse, and results from this project is available (Tenove 2004).

METHODOLOGY

Collecting and Preparing Raw Wastes

Swine wastes used in this membrane treatment were obtained from the Swine Research and Technology Centre located on the University of Alberta's Research Station in Edmonton. This new facility completed in 2002 houses a sow herd equivalent of 220 with significant biosecurity measures built into the design and practiced. Swine wastes are stored as liquid manure typically 95% moisture content. Wastes build in up in the various animal production zones and are drained under manual control to a collection tank and lift station located immediately adjacent to the barn. From here wastes are pumped as needed to composting facility or loading system for field application. In a farrow to finish swine production facility the mature animal herd will produce the greatest amount of waste with the highest moisture content. By coordinating collection times with the barn manager the collection of fresh and representative swine wastes from this mature population was targeted.

Samples were transferred with a portable submersible pump to two 220 litre PVC barrels outfitted with two to three sampling ports on vertical axis. These were filled and transported to a nearby research building (F52) where they could remain at 15 to 20°C undisturbed for primary natural settling. These were sealed and only the headspace was aerated at a low level to avoid accumulations of hazardous gases. Within 24 to 48 hours, approximately 80 L of SWSN was drawn from each barrel below the liquid surface in the top 250 mm into 20 L PVC pails. Pails were sealed and identified as to their collection height and time, then transferred to a cold room maintained at 4 °C in the Environmental Engineering building near where the membrane filtration system was located.

Bench top system

The hollow immersed membrane studied was a low pressure, outside-in ZW500d© membrane manufactured by Zenon operating in a dead end microfiltration mode. This membrane module has undergone two Environmental Engineering Program research projects to evaluate the feasibility of using it in a membrane bioreactor (Heise 2002) and a recent study of integrity testing and monitoring (Farahbakhsh, Adham and Smith 2003). The polymeric fibers used in this module belonged to a supported, non ionic, hydrophilic microfiltration membrane, whose membrane structure was asymmetrical with inside diameter and nominal pore size of 2 mm and 0.04 µm, respectively. A suggested schematic for a bench top test arrangement was provided with the membrane module from the manufacturer, Zenon Environmental, and design altered to fit the particular application requirements. The ZW-1 membrane module can be used for preliminary investigation into the performance of commercial ZeeWeed® 500 modules. A schematic is shown in Figure 1 illustrates the four main features added to this system which are

- Data acquisition and control (DAQC) system,
- Cross contamination control and sample collection,
- Odour control, and
- Aeration of the membrane module

Data Acquisition and Control (DAQC) System

A pressure transmitter sent voltages corresponding to pressures measured immediately downstream of the membrane module on the permeate side. This signal was picked up along with two additional voltages from temperature thermistors located in the process and permeate tank and transferred to an analog processor and then to digital input/output board installed in the computer. The computer also communicates to the peristaltic pump through the COM1 port via RS-232 cable and in real time gathers operational data and controls the membrane filtration process (pump rpm and direction) to stay within design parameters. This monitoring and control requirement was facilitated through a DAQC program called Softwire 3.1 which allows the use of Visual Basic programming to perform iterative logic steps to control the system.

Operating Procedures

Two types of monitoring were carried out during filtration runs – performance data and treatment effectiveness.

After initial flow rates were set, performance data was collected and recorded to Excel files on a real time basis every five seconds. Based on the pressure measured the system would adjust so as not to exceed maximum pressure specifications. Systems runs were performed in batch mode and continued until either 10 L of permeate were produced or it was demonstrated that the system could not recover from membrane fouling. To approach the best run with this raw water a baseline run with the two modules was performed with distilled water (DI) then additional runs at 9%, 20% and 30% SWSN by volume.

A nomenclature for all Excel data files produced during runs was used and is defined as follows: “ZW_1 D_{20} F_{50}” means #1 ZW-1 module used at a dilution of 20% SWSN and an initial flowrate of 50 mL/min set.

In most cases, a running start was performed in which the system was started on DI and then well mixed SWSN was added to the feedwater and process tank at approximately 5 minutes.

Turbidity, conductivity, pH and temperature were sampled and measured at regular intervals of permeate production to monitor performance of the filtration. TSS, TDS and COD were also sampled for analysis at the same interval during complete runs. Process water could be drawn from the vicinity of the membrane module with a separate peristaltic pump. Permeate grab samples were collected from an in-line sampling port or composite samples from the permeate collection tank.

Analysis of Samples

All wastewater quality parameters were analyzed and samples stored according to Standard Methods for the Examination of Water and Wastewater (APHA 1999). A summary table of the methods follows.

Analysis	**Standard Method #**	**Abbreviation**	**Units**
Total Suspended Solids	2540 D	TSS	mg/L
Total Dissolved Solids	2540 C	TDS	mg/L
Chemical Oxidation Demand	5220 D	COD	mg O_2/L
Turbidity	2130 B	Turb.	NTU
Temperature	2550	Temp.	°C
Conductivity	2510B	Cond.	$mScm^{-1}$, μScm^{-1}
pH	4500	pH	
Total Kjedahl Nitrogen, Ammonia	4500-N_{org}B	TKN, NH_3	mg/L
Total Phosphorus	4500-P	TP	mg/L
Total Organic Carbon	5310B	TOC	mg/L
Total Sulphide	4500-S^{2-}	S^{2-}	mg/L
5-Day Biochemical Oxidation Demand	5210B 4500-O C	BOD_5	mg O_2/L
Fecal Coliform	9222 D	FC	CFU/100mL
Total Metals	3030 E, 3110	n/a	mg/L

RESULTS AND DISCUSSION

As a representative of a hollow fibre immersed membranes, a microfiltration membrane manufactured by Zenon Environmental, was evaluated for potential operation in the organically rich environment of swine wastewater. The compact ZW-1 membrane module, contains approximately 0.047 m^2 of ZeeWeed® 500d membrane and configured in a 175 mm long X 58 mm diameter. It was immersed into 66 L of diluted SWSN.

Baseline Measurements in Distilled Water (D_0)

Both ZW-1 membrane modules were operated in distilled water without the addition of SWSN (D_0) at the beginning and end of runs with diluted SWSN. Maximum pumping capacity of the peristaltic pump used was reached before the maximum operating pressure 48.3 kPa (7.0 psig) or the 34.5 kPa (5.0 psig) recommended for baseline runs on the module was reached. Alternatively, each D_0 was run until a stabilized vacuum pressure was obtained (5 to 10 minutes) at four flow rates (100, 150, 200 and 233 (or 238) mL/min). Two sets of post D_0 runs were made (73 days apart) after the runs diluted with SWSN to evaluate fouling and recovery from fouling, The temperature, conductivity and pH of DI was similar in all D_0 runs.

In any baseline D_0 run a consistent linear relationship between the flow rate produced from the membrane and the suction pressure applied from the pump was observed with either membrane module both before and after filtration of dilute SWSN. The specific flux is very consistent from one flow rate to the next within each module run. Therefore the validity of comparing membrane flux performance on the basis of specific flux ($L\ h^{-1}m^{-2}kPa^{-1}$) is born out. J_{20} values calculated for all D_0 runs ranged from 8.43 to 14.3 $L\ h^{-1}m^{-2}.kPa^{-1}$. Membrane flux is significantly reduced in diluted swine waste. The specific flux of ZW_1 and ZW_2 was reduced 14.6% and 9.3%, respectively, of the original baseline flux measured in DI

Performance of Membranes in Diluted SWSN

Operating Settings

The DAQC system allowed for any combination of initial flow rate, backflush rate and duration, and control routine settings to be evaluated. In the initial runs with 9% SWSN (D_9) with the ZW_1 module it was determined that an initial flow rate of 50 mL/min could be used. It was also determined that the backflush rate could be up to 50% greater than the initial flow rate without causing a stoppage. A backflush of 70 mL/min for 50 seconds was chosen. The backflush volume used is automatically subtracted off the total volume tracked. Manual records of permeate volumes produced and sample volumes removed from the system verified this was working. The same operating parameters were also used for 30% and 20% SWSN (D_{30} and D_{20} respectively) on both modules.

Early on in the test procedure it was confirmed that aeration was required to reduce the fouling behavior of the membrane in concentrated effluents. Aeration was kept at a constant rate of 1.7 m^3/h for all recorded runs except for two instances where unplanned events occurred.

Temperature data from the process and permeate tanks was provided from the real time collection in D_{20} and D_{30} runs as well as those gathered as part of grab sample water quality measurements. Temp 1 were taken in the process tank and Temp 2 from the permeate tank. These values were used in the normalizing of baseline flux measurements of the modules in distilled water. A sudden drop in temperature results when the SWSN cooled to 4°C for storage is added to the distilled water. Temperature did not change significantly during the runs although a small downward trend likely caused by the aeration of the module can be seen.

Performance Results in D_9 and D_{30} Runs

The membrane module was able to operate in 9% SWSN (D_9) with little flux reduction and rarely if at all was a backflush called for by the DAQC system based on a build up in vacuum pressure required. The wastewater strength corresponded to an average COD of 1236 mgO_2/L.

The membrane was not able to operate successfully in a 30% SWSN (D_{30}) effluent which corresponded to an average COD of 4854 mgO_2/L.

Best Run Performance (D_{20})

Fouling Characteristics

A characteristic pressure curve was observed during the cycles generated as illustrated in a segment out of the D_{20} run of ZW_1. See Figure 2. At the completion of the backflush, a quick drop in pressure occurs as the pressure from the previous backflush is relieved. This decline slows as the pump begins to exert a pressure differential on the membrane and permeate is produced. Typically a plateau was seen around –34.5 kPa (-5 psig) was seen before the pressure began to drop initiating another backflush cycle.

Cycle Time and Duration of Backflush (D_{20})

The DAQC system allowed the membrane to find its own equilibrium for cycle times between backflushes. A minimum sustainable backflush duration, intensity, and frequency which would provide the quickest production of 10 L of permeate were chosen as the target in this system. Three minutes or 180 seconds was arbitrarily targeted as the minimum cycle time for operation. A cycle time less than this reduces the net permeate production and could be hard on the pump with the frequency of direction changes. With a backflush duration set at 50 seconds and flow of 70 mL/min, this resulted in about 20% of the operation time being consumed in backflush. The length of cycle times (not including the time for backflush) is shown for the ZW_1 and ZW_2 modules in Figure 3 and Figure 4, respectively.

Normalized Specific Flux (D_{20})

Instantaneous flux was always changing in the D_{20} runs unlike the equilibrium that was sustained in D_9 runs. An effective flux can be estimated taking the total time to produce 10 L of permeate. An effective yield of 32.6 and 25.6 mL/min for ZW_1 and ZW_2, respectively. When adjusted for temperature and expressed in normalized J_{20} values the following results are seen for the D_{20} runs.

D_{20}	**Flow**	**Pressure**	**Temperature**	**J_{20}**
Units >	**mL/min**	**kPa (psig)**	**°C**	**$L\ h^{-1} m^{-2}\ kPa^{-1}$**
ZW_1	32.6	28.7 (4.16)	20.7	1.42
ZW_2	25.6	25.6 (3.71)	19.0	1.30

Treatment Performance

Water quality measurements were made in all runs with the goal of determining what reductions in target parameters could be made when stable operating settings were determined for a maximum concentration of SWSN. The results reported here are those from the 20% SWSN concentration (D_{20}). Samples labeled PT refer to untreated water from process tank. IL refers to grab or composite samples taken from permeate. COD, TSS, TDS, pH, conductivity, and turbidity were measured periodically over the complete run to monitor membrane for potential failure or significant change in treatment levels. TOC, BOD$_5$, FC, TP, TKN, NH$_3$ and sulphides were measured from a sample taken halfway or 5 L through the run.

Physical and Aggregate Properties

Turbidity was the only physical property measured to change significantly in the process tank during the D$_{20}$ runs. See Figure 5. A gradual increase coincides with a 10 L removal of permeate from the process tank which was replaced with 10 L of SWSN at the same starting dilution. Assuming complete mixing by aeration provided and that most turbidity would reflect the TSS concentration a 15% increase in TSS corresponded to the 33% and 27% increase in turbidity observed for ZW1 and ZW2, respectively. Even dilute SWSN was highly turbid and would expect to interfere with disinfection or microbial reduction processes requiring low turbidity. Turbidity and TSS were reduced close to zero in the permeate produced. Figure 6 illustrates the reductions in this membrane treatment of 20% SWSN.

Aggregate Organic Constituents

Both COD values and percent reductions during the membrane treatment were consistent over the run time by both modules as illustrated in Figure 7. A 31.5 % reduction and 32.7 % reduction were seen with ZW$_1$ and ZW$_2$ modules, respectively.

The TC and TIC triplicate measurements of process and permeate grab samples showed little variance within replicate and were used to calculate TOC values in the D$_{20}$ runs of both membrane modules. TOC values in the process tank were very similar between the two module runs and a reduction of 31.8 and 36.2% was observed in the filtration process by ZW$_1$ and ZW$_2$, respectively. Original TOC values of the SWSN prior to dilution were 28% higher in the D$_{30}$ run than the D$_{20}$ runs and showed 19.5% reduction in TOC during filtration.

BOD$_5$ for diluted SWSN was measured for composite samples taken from the process and permeate tank during the D$_{20}$ runs with ZW$_1$ and ZW$_2$ modules.

Inorganic Non-Metallic Constituents

Four TKN replicates and two NH$_3$ replicates were used in the analysis of process and permeate samples during the D$_{20}$ run of each module. Figure 8 shows a reduction in TKN of 23% and 19% for modules ZW$_1$ and ZW$_2$, respectively. Only a 12% reduction was seen in NH$_3$ in module ZW$_2$.

Figure 8 illustrates a reduction in TP of 47% and 52% for modules ZW$_1$ and ZW$_2$, respectively and a reduction in total sulphide of 73% and 85% for modules ZW$_1$ and ZW$_2$ respectively.

Microbiological Examination

There was no evidence of fecal coliform bacteria passing the ZeeWeed® 500 membrane and contaminating the permeate. Initial FC concentrations in the 20% diluted SWSN (D$_{20}$) process water were 103,000 and 280,000 CFU/100 mL for ZW$_1$ and ZW$_2$ runs. Figure 8 illustrates this 5 log removal of fecal coliforms.

Analysis of Metals

A general scan of metals was completed for a grab sample of process water and permeate taken half way through the system run of ZW1 in 30% SWSN (D30). Concentrations in the dilute SWSN or permeate were not elevated to a level causing undue concern according to the livestock guidelines provided in CWQG (Task Force on Water Quality Guidelines (Canada) Council of Resource and Environment Ministers 1987).

Full Scale System Design Example

Based on specific flux generated from this project, a preliminary membrane size was calculated for the waste production generated from 6192 feeder pigs that could be produced from a 1000 sow breeding herd. A membrane size of 225 m^2 or 0.036 m^2/pig was estimated and would require 80% recycle or dilution water to maintain suitable strength process water. An estimated 18.9% of water needs could be supplied to the feeder pig operation.

CONCLUSIONS

The ZW-1 compact membrane module can be used for preliminary investigation into the performance of commercial ZeeWeed® 500 modules in highly polluted livestock wastewaters as evidenced by a direct filtration of diluted swine waste supernatant. A data acquisition and control system developed was very useful in controlling the direct filtration process when operating close to fouling limits in highly contaminated wastewater. Control based on trans-membrane pressure provided excellent results. Cycle time was a good indicator to monitor membrane fouling. In terms of fouling behavior, the performance results obtained from one compact ZW-1 module should not be assumed for another and must be treated and tested individually.

Membrane performance based on normalized specific flux provided an excellent method of performance comparison. Compared to baseline measurements in distilled water, the specific flux of a Zeeweed® 500 compact membrane module was significantly reduced in diluted swine waste supernatant (SWSN). In the best run in 20% SWSN (average COD 2.7 g O_2/L), a flux 1.36 L $h^{-1}m^{-2}kPa^{-1}$ was maintained over a 10 L permeate production period. The specific flux of ZW_1 and ZW_2 was reduced 14.6% and 9.3% of the original baseline flux measured in DI.

Direct membrane treatment was an effective and a compete barrier to fecal coliforms and suspended solids and as expected, allows dissolved components to pass easily. Turbidity reduction was excellent and would allow microorganism reduction processes to work more effectively. The greatest turbidity reduction measured was for 30% SWSN at 646 NTU to $\leq$ 0.5 NTU.

Reduction in percentage terms of other key contaminants, from highest to lowest was sulphide (79%), TP (49.5%), TOC (34%), COD (32%), BOD_5 (29%), TDS (23%), TKN (21%), and NH_3 (5.9%). These were are calculated from simple average of two modules but were fairly consistent and did not relate strongly to hydraulic performance. Soluble organic and inorganic materials passed through the membrane and would need further reduction for potable reuse options. Swine wastewater treated by direct microfiltration will still be rich in nutrients by municipal standards and quality can be impaired quickly. Pretreatment by sedimentation and dilution made direct membrane treatment possible.

Small size membrane testing provided good qualitative results, however great caution should be used when scaling up the results.

ACKNOWLEDGEMENTS

The authors acknowledge the financial support of the Alberta Livestock Industry Development Fund and technical, facility and financial support of Alberta Agriculture, Food and Rural Development, the University of Alberta, and a NSERC Discovery Grant

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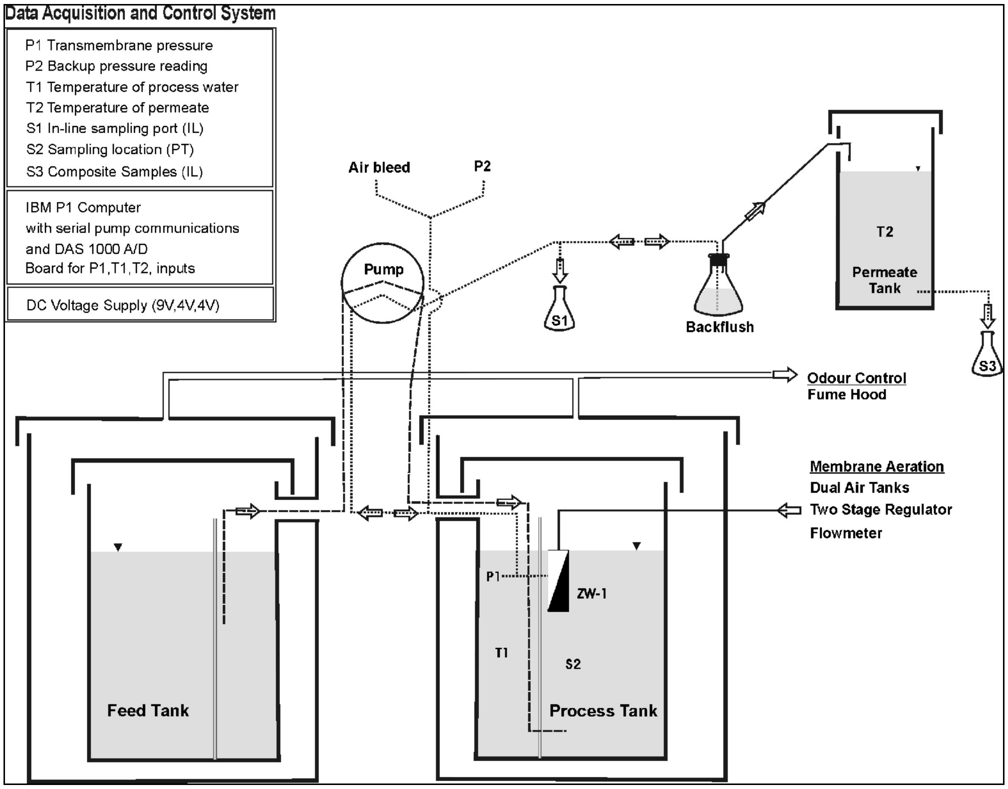


Figure 1 ZW-1 Bench Test System

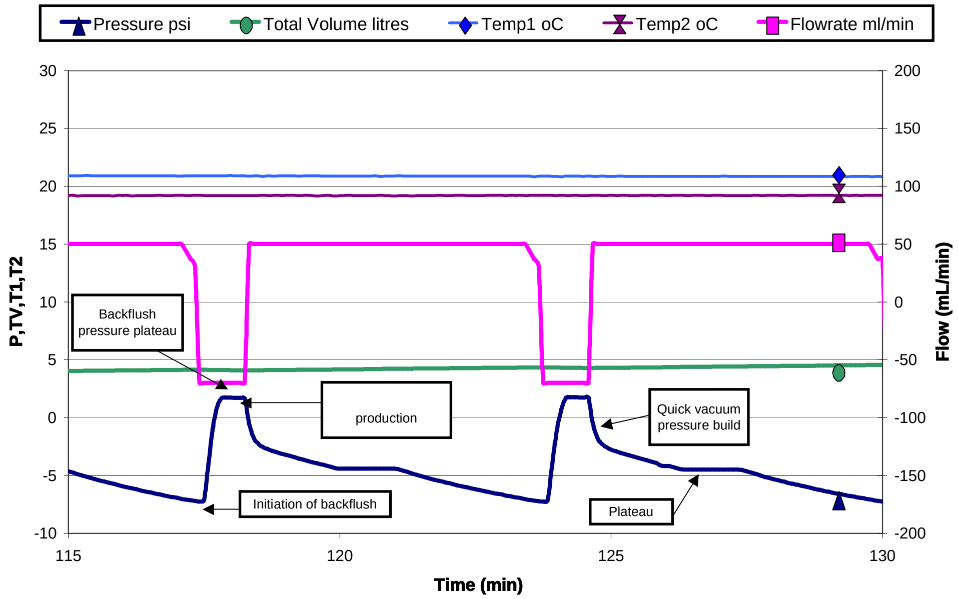


Figure 2 Representative Pressure and Flow During D_{20} Cycle.

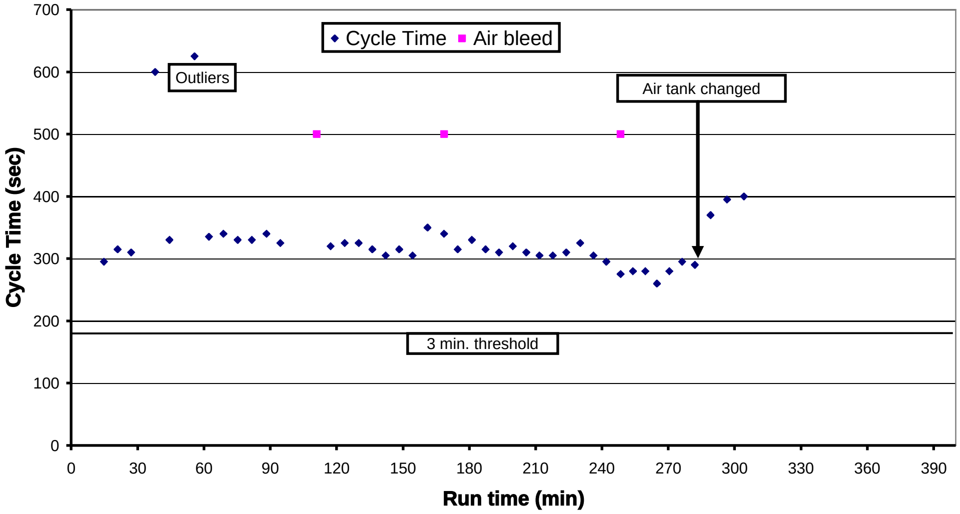


Figure 3 Cycle Time for D_{20} Run of ZW_1

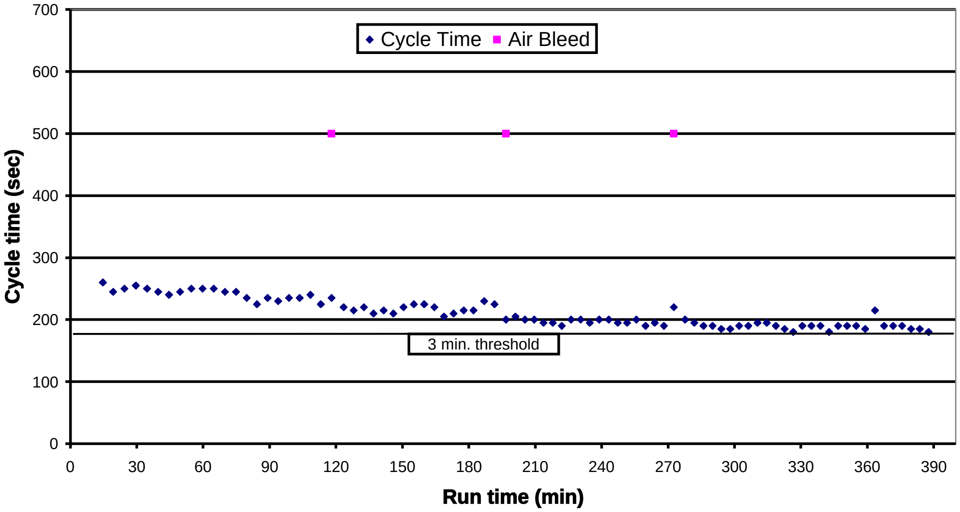


Figure 4 Cycle Time for D_{20} Run of ZW_2

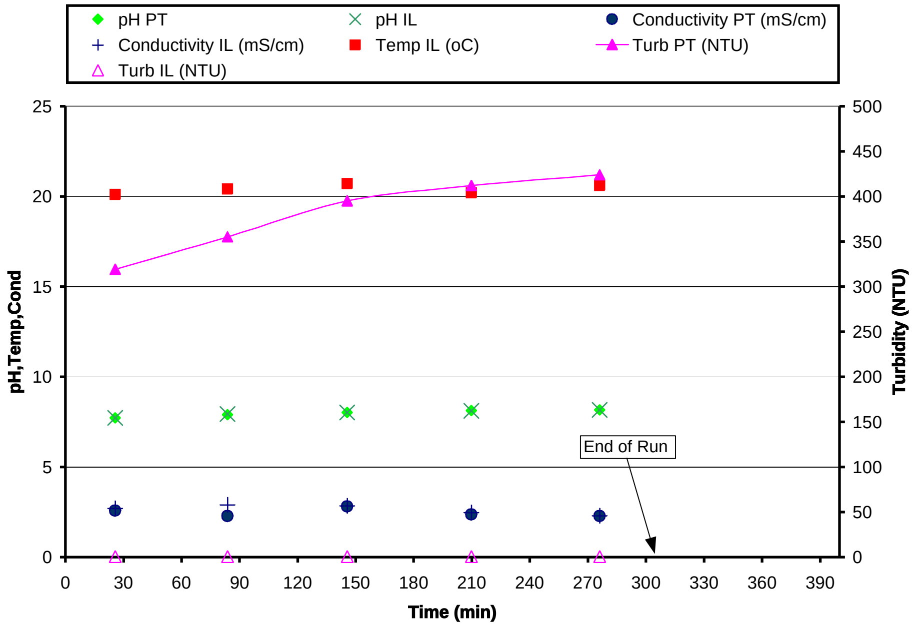
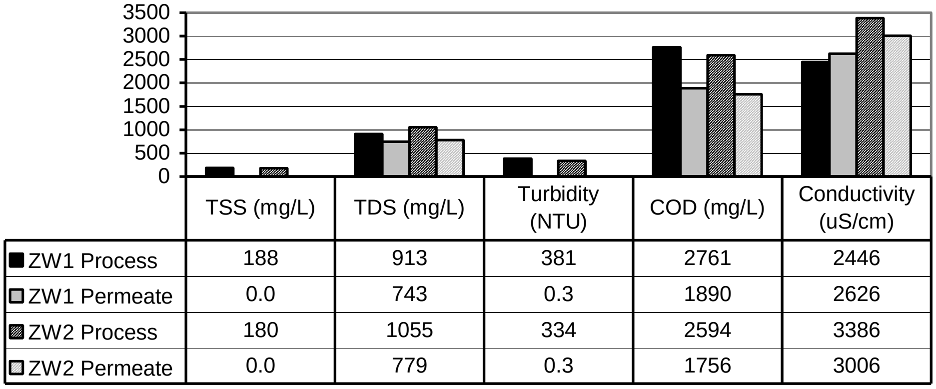


Figure 5 Turbidity, Conductivity, pH and Temperature for Process (PT) and Permeate (IL) Over D_{20} Run of ZW_1



	TSS (mg/L)	TDS (mg/L)	Turbidity (NTU)	COD (mg/L)	Conductivity (uS/cm)
■ ZW1 Process	188	913	381	2761	2446
▩ ZW1 Permeate	0.0	743	0.3	1890	2626
▨ ZW2 Process	180	1055	334	2594	3386
□ ZW2 Permeate	0.0	779	0.3	1756	3006

Figure 6 TSS, TDS, COD, Turbidity and Conductivity for D_{20} Run of ZW_1 and ZW_2

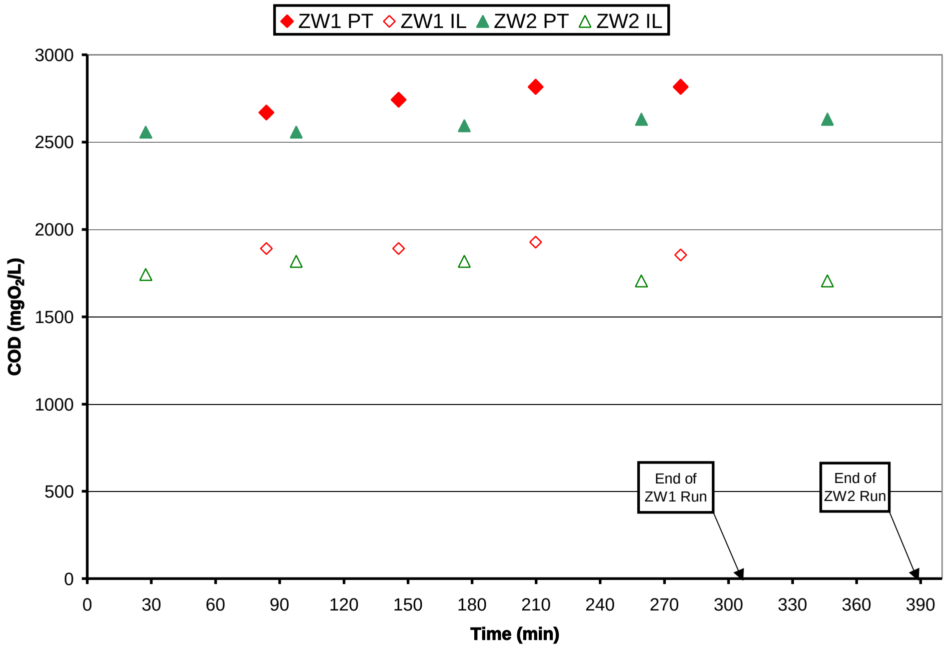
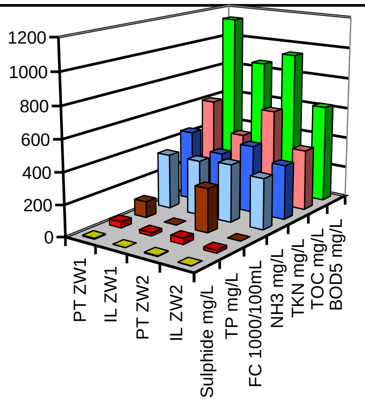


Figure 7 COD for Process (PT) and Permeate (IL) Over D_{20} Run of ZW_1 and ZW_2



	PT ZW1	IL ZW1	PT ZW2	IL ZW2
🟨 Sulphide mg/L	5.3	1.4	5.8	0.9
🟥 TP mg/L	38.4	20.3	37.5	17.9
🟫 FC 1000/100mL	103	0	280	0
🟦 NH3 mg/L	352	351	370	326
🟦 TKN mg/L	449	344	431	349
🟥 TOC mg/L	611	417	611	390
🟩 BOD5 mg/L	1134	859	941	626

Figure 8 Sulphide, TP, FC, NH_3, TKN, TOC, and BOD_5 for Process (PT) and Permeate (IL) Over D_{20} Run of ZW_1 and ZW_2