final report

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Feasibility Study of the Microfiltration of Steriliser Water for Reuse

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Executive Summary

Increased productivity from domestic meat processing plants in a climate of reduced secure water entitlements and increasing electricity tariffs will be contingent upon expanding the scope of current water and energy efficiency practices. A previous MLA report on the use of membranes in meat processing, ENV.028, identified wastewater generated in steriliser, hand-wash and viscera table applications as suitable sources for a water recycling system. The key questions for this study were;

- What membranes and cartridge filters are suitable for steriliser application
- How does steriliser water quality impact filter performance (in terms of filtrate water quality and production rate)
- What are the probable costs (Capex and Opex) associated with membrane treatment of steriliser water and what further work would be required to implement the technology.

Preliminary evaluation of the water quality was conducted for water sourced from the steriliser pots, viscera tables, handwash basins and the catchment tank. Whilst all samples would be considered lightly contaminated, the steriliser pots and viscera tables contained significantly lower levels of contaminates than both the handwash basin and catchment tanks. During the field trials it was observed that the feed quality from the catchment tank, where all the trials were conducted, fluctuated significantly, in particular the turbidity, suspended solids and temperature. This variation in water quality and the intermittent nature of the supply will impact on the performance and reliability of a membrane system.

This study evaluated four commercially available microfiltration membranes both in the field and in the lab, including a ceramic, a stainless steel, and a polymeric membrane as well as a polymeric cartridge filter. Assessment of the membrane performance was primarily conducted through pollutant rejection and the average fouling rate of each of the membranes. The results have indicated that the Microza polymeric membranes were the best performance, with the ceramic membranes also performing well. The stainless steel membrane and cartridge filters did not achieve satisfactory performance for fouling rate and pollutant rejection respectively.

An estimation of the expected costs for both capex and opex for two scenarios was conducted. The first using a polymeric membrane and the second using the ceramic membrane module. The capital expenditure was evaluated at $54K and $68K for each system respectively. The 20% higher capitals cost reflect the higher cost of ceramic membranes compared to polymeric membranes. This cost differential is further reflected in the operating costs where the polymeric membrane is estimated to cost $0.33/kL of water whilst the ceramic membrane $0.70/kL.

Given the lower cost and the superior performance of the polymeric membrane this study has concluded that this would be the most favourable membrane for treating steriliser wastewater. However, further assessment field trials over an extended period of time are required to ensure the long-term reliability of the membranes and to ensure this system would meet AQIS requirement for water recycling.

Contents

1 Background

The meat processing industry use large volumes of water for sterilisers and handwash basins during meat processing. This water is single use and is supplied to the steriliser pots in a constant supply maintained at 82°C, whilst the handwash supply is on-demand at 45°C. The discharge of this water represents a material loss of both water and energy. Another disadvantage attendant with this practice include decreased removal and recovery of fats and grease from the commingled water because of reduced phase separation at elevated temperatures. Recovery of both the water and energy from these waste streams would be economically beneficial to the abattoir operator and environmentally beneficial by conserving water and reducing further energy consumption.

The criteria for successful treatment of these waste streams to create a complete or partial recycling system include;

- The removal of suspended material, particulates or fibres from carcasses that could otherwise accumulate in the water reticulation system
- The removal and or inactivation of any microbial pathogens removed from the carcass dressing tools and not inactivated at elevated temperature; and
- A minimal temperature loss during the rehabilitation system to reduce any subsequent energy inputs in order to maintain overflow temperature at the point of contact with processing equipment at 82°C

The steriliser and handwash water are characterised as a “clean” waste stream when compared with other streams generated in an abattoir (e.g. stickwater). They contain minimal nutrients, chemical and biological demand with low concentrations of fine suspended solids, fats, oils, grease and micro-organisms. The handwash water is likely to contain higher levels of oil and grease than the steriliser water due to the presence of detergents. The wastewater is also likely to contain some coarse material such as hair, slivers of hide and animal tissue.

A previous MLA report (ENV.028) recommended a suite of filtration technologies, such as pleated cartridge filters and microporous membranes as possible options for the removal of the likely contaminants so that the water may be reused. This report also noted the temperature limitation of many commercially available membrane units. It indicated that the most promising filtration device would either be manufactured from a high temperature material such as ceramic or sintered stainless steel. Alternatively, recognising that ceramic and sintered stainless membranes are expensive, the report suggested that a disposable filtration device such as pleated cartridge filters may also be viable for this application.

2 Project Objectives

2.1 Project Objectives

The focus of this project is to evaluate the recommendations made in the project ENV.028 and to conduct a series of lab and preliminary field trials to develop basic information on the following;

- Water quality and fouling potential of the waste water
- Filtrate quality from a suite of devices from cartridge filters through to microporous membranes.
- Post-filtration requirements treatment requirements such as UV disinfection prior to reuse
- Quality and quantity of any residual streams from the filtration device
- Cleaning requirements, or other maintenance, to maintain permeability of the filtration device; and
- Energy requirements associated with operating the filtration device (pumps) and raising the temperature filtrate to that of the steriliser water system

The project has also included a short field trial to assess technical issues relating to the operation of a membrane system, such as automation and hazard and operability that would need to be addressed to develop a recycling scheme.

3 Methodology

This study requiring both field and laboratory work has divided the tasks into four separate stages;

1. Design and setup of the experimental rig, assessment of the various membrane options available and assessment of the feed water quality
2. Pre-field trial assessment of the chosen membrane options and operation of the experimental rig to evaluate operational concerns for the field trials
3. Field trials in an abattoir to assess the performance of the chosen membranes and cartridge filters under varying operating conditions
4. Post-field trial laboratory assessment of the most favourable filter options under further varied conditions

3.1 Experimental Rig Design and Operation

A laboratory-scale microfiltration apparatus (Figure 1) was purpose built for this study. The primary design criteria were that the rig be portable, adaptable for use with a variety of membrane modules and simple manual operation. The rig was designed to be completely self-contained, to include the pump, two tanks, one for the primary feed and the other for the backwash feed, the membrane module and its associated control mechanism and instrumentation. The piping and fittings were constructed from stainless steel to ensure that it was sufficiently resistant to both temperature and cleaning products. The feed tank is also fitted with a 2mm screen, to ensure no large particles are able to block the gauges or membranes.

Figure 1: Portable Microfiltration Rig

The microfiltration rig is manually controlled and operated through a control valve, located on the retentate line, and the pump speed. The system performance was indicated visually through a number of probes. The pressure was monitored at the membrane inlet and outlets (retentate and permeate). A temperature probe was also located on the permeate line, whilst the flow rate was monitored on both the permeate and retentate. (all shown in Figure 2)

Backwashing of the membranes was effected through a number of three-way valves which were used to change the flow direction from the pump and to change the water source. The backwash tank is filled with permeate from the membrane. Air scouring to enhance cleaning of the membrane is also available.

The system may be operated at either constant flux or at constant trans-membrane pressure. The membrane modules are easily interchangeable and may be operated as either cross-flow or dead end.

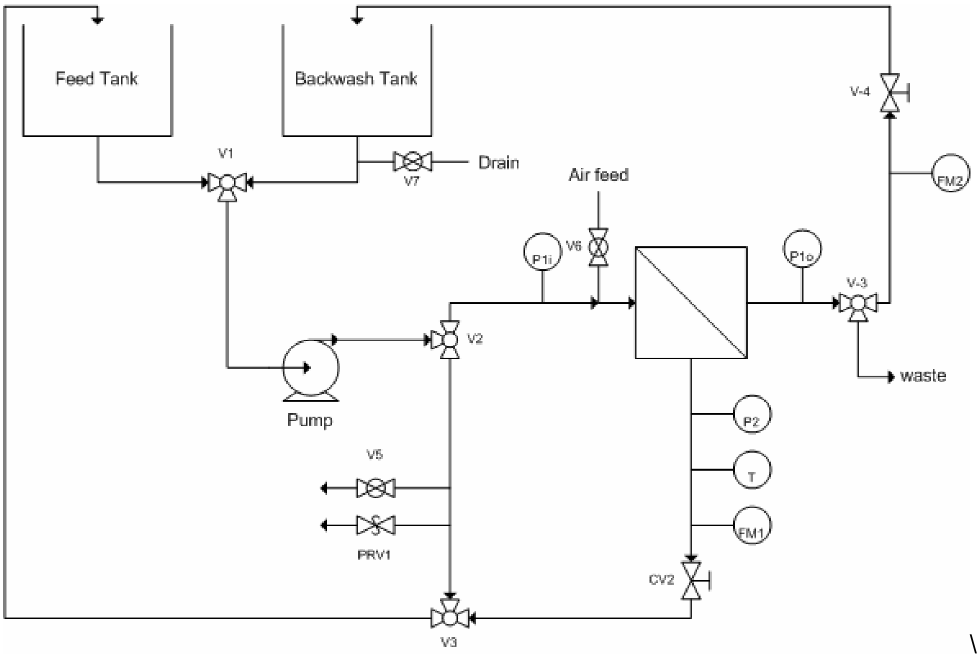
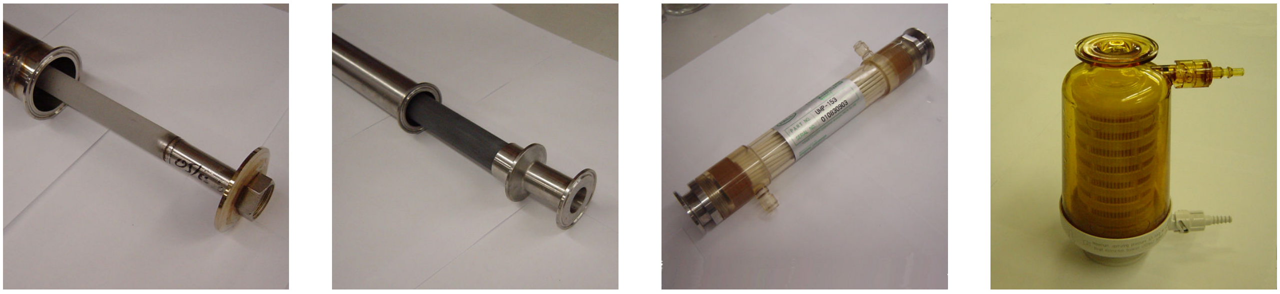


Figure 2: Microfiltration rig flow diagram

3.1.1 Membrane Types

One of the primary objectives of this project was to evaluate a suite of filtration devices. Factors taken into consideration in choosing each of these membrane were, cost, cleanability, maintenance requirements, durability and effectiveness.

All of the membranes chosen for this study must be capable of operating at high temperatures, up to 80°C and be chemically resistant for cleaning purposes, which may include steam cleaning. In order to obtain a board understanding of membranes available we have assessment membranes constructed from stainless steel, ceramic and PVDF polymer.



(a) (b) (c) (d)

Figure 3: (a) Stainless Steel membrane, Ceramic membrane, (c) Microza polymeric membrane, (d) Novasip cartridge filter

3.1.1.1 Ceramic Membrane

The ceramic membrane evaluated for this study was supplied by the Ceramem Corporation. The membranes are based on their second generation proprietary technology platform for multi-channel ceramic membranes. The monoliths are constructed by extrusion of Recrystallised Silicon Carbide (RSiC) which provides support for the membrane.

The test module supplied was 27mm diameter and 300mm long. The channels were 2mm square resulting in a total membrane area approximately 1.3m^2. The benefits of this membrane are its stability under-harsh operating conditions, and its high membrane area/volume which minimises its required footprint for operation. This membrane has not yet been validated for sterilisation purposes

3.1.1.2 Stainless Steel Membrane

The stainless steel tubular membrane was supplied by Steri-flow filtration systems. The module contained a single tubular membrane, 16mm in diameter and 450mm long. The membrane contained an area of 0.027m^2, with nominal pore size is 0.2μm. As with the ceramic membrane the stainless steel membrane has not been certified for sterilisation purposes.

3.1.1.3 Polymeric Membrane

The polymeric membrane supplied by Pall was a Microza microfiltration unit (Model No: UMP-153). The module contained 0.2μm polyvinylidene fluoride (PVDF) hollow fibre membranes. PVDF shows superior chemical resistance as compared with other membrane i.e. polysulfone, and are steamable for in-situ cleaning. The membrane is housed in a clear polysulfone housing. The membranes are 2.6mm in diameter and the unit contains a total membrane area of 0.08m^2

3.1.1.4 Polymeric Cartridge Filter

Pall has also provide the polymeric cartridge filter in the form of a Novasip capsule filter (C3DFLP1). The Novaip filter contains a 0.2μm double layer hydrophilic PVDF, known commercially as their fluorodyne II filters. The filter is contained in a polyethermide housing. The approximate membrane area for this model was 0.25m^2

These filters have been designed for a wide variety of application including sterilisation of solutions containing low concentrations of preservatives or proteins. The Novasip filters can be used under a wide range of operating conditions including steam-in-place at up to 142°C.

3.2 Pre-Trial Laboratory Experiments

Prior to the field trials a preliminary examination of the abattoir wastewater and the selected membranes were conducted. This included an assessment of the intrinsic membrane resistance for each of the membranes and an evaluation of the fouling mechanism for the supplied water samples.

3.2.1 Water Quality

An initial visual inspection of the abattoir waste samples was followed by a number of standard water analysis techniques. Each of the samples was analysed for total suspended solids, colour, total alkalinity, ammonia, nitrite, nitrate, total kjeldahl nitrogen, oil and grease and chemical oxygen demand. These test were conducted by ALS environmental services (full report attached in appendix 1). Further in-house testing was conducted to measure for conductivity, total organic carbon, total protein and total carbohydrate.

3.2.2 Fouling Mechanism

To determine the mechanism for the flux limitation, we have conducted a blocking law analysis. The filtration blocking laws are based on Darcy's Law for constant pressure filtration and given by the equation [1];

$$\frac{d^2t}{dv^2} = K\left(\frac{dt}{dv}\right)^n$$

Where different expressions for K and n can be shown to correspond to one of four physical models;

- Cake filtration: where the increase in resistance is solely due to the accumulation of a filter cake on the membrane surface,

$$n = 0 \qquad K_c = \frac{\alpha\rho_l c}{Q_m R_m A_m}$$

- Intermediate case: where the foulants approaching a membrane surface either block a pore or deposit on other foulants according to a specific probability.

$$n = 1 \qquad K_{ci} = \frac{\sigma}{A_m}$$

- Internal deposition: where the pore size is assumed to decrease in volume through deposition on the pore walls.

$$n = 1.5 \qquad K_{id} = \frac{2c}{LA_m}$$

- Complete blocking: where each particle approaching the membrane completely blocks a pore.

$$n = 2 \qquad K_c = J_m\sigma$$

Where α is the mass-specific resistance of the cake (m kg^{-1}), ρ_l is the density of the filtrate (kgm^{-3}), c is the volume of particles deposited per volume of filtrate , Q_m is the pure water flow rate of the membrane, R_m is the resistance of the membrane (m^{-1}), A_m the membrane area (m^2), σ the blocked area per unit filtrate volume (m^{-1}) and J_m the membrane pure water flux (ms^{-1}).

3.2.3 Membrane Resistance

The intrinsic membrane resistance represents the resistance to flow provided by the membrane alone and is important for later determining the resistance caused by fouling. The membrane resistance forms part of the flux equation given as;

$$J = \frac{\Delta P}{\mu \left(R_m + R_f \right)}$$

The fouling resistance (R_f) is assumed to be zero as the membranes were new and pure water was used. The flux (J), trans-membrane pressure (ΔP) and the fluid viscosity (μ) are determined experimentally.

The membrane resistance was evaluated for each of the four membranes using distilled water at four different temperatures, 20°C, 40°C, 60°C, 75°C. The transmembrane pressure was set at increasing levels and the flux was measured. The temperature on the feed and outlet of the membrane modules was measures and the mean of these two values was used to determine the fluid viscosity.

3.3 Field Trials

Field trials were conducted at the Northern Co-operative Meat Company abattoir located at Casino, in northern NSW, during the week of the 23rd-27th of October. The portable microfiltration rig described previously was attached to the abattoir catchment tank. This tank is fed by hot and warm streams from the steriliser pots, viscera tables and handwash basins on the abattoir floor.

3.3.1 Experimental Outline.

The trials tested the four types of membranes denoted Stainless, Ceramic, Microza and Novasip for the remainder of this study. Water from the catchment tank was pumped into the rigs feed tank, before being filtered by the membranes. Due to time restrictions each experimental run was limited to a maximum of ninety minutes. Initially the membranes were feed with warm clean (tap) water in order to increase the temperature of the module to that of the feedwater and secondly to determine the clean water flux. The clean water flux ensures that the starting point for each experiment is the same.

The experiments we conducted at two levels of cross-flow velocity and flux to form a 2^2 factorial design. The zero cross flow velocity represents dead-end operation of the module.

Table 1: Operation variables

	Flux (LMH)	CFV (m/s)
High	100	0.2
Low	50	0

Due to variations in the feedwater quality, the feed temperature and the fouling rate of each module, backwash was conducted as need, defined by the increase in trans-membrane pressure rather than the standard procedure which uses a time basis. The membranes were backwashed when the TMP increase by 50kPa

The response variables for these experiments were the experimental operation time (EOT), the average fouling rate (AFR) and the permeate water quality. Due to restrictions in our ability to obtain water quality tests whilst on-site, one sample of permeate was obtained for each of the membranes.

3.4 Post-Field Trials Assessment

On completion of the field trials the two most promising membranes were subjected to further investigation varied temperatures and for longer experimental periods. In addition an array of common microfiltration cleaning procedures were also investigated.

As the actual wastewater was not available for the laboratory studies, synthetic waste water was created to simulate the water from the abattoir. The turbidity was the primary measure of comparison between the synthetic and actual wastewaters. In order to approximate the most extreme field trial conditions a turbidity of 10 NTU was employed. The synthetic waste was created by dissolving 3g of minced beef in 5L of tap water. The solution was then stirred and heated to 75°C for 15 minutes. This procedure resulted in a Turbidity of between 15-20 NTU. The solution was then diluted to achieve the required turbidity.

3.4.1 Influence of Temperature

The initial estimates and design criteria indicated a temperature tolerance for the membranes of up to 80°C. However, during the field trials, the feed water temperature did not approach this and to ensure the membranes we capable of handling this temperature further runs were conducted at 40°C, 60°C and 75°C. Increasing the temperature based on the flux equation, should reduce the required trans-membrane pressure required to maintain a particular flux, as the viscosity is lower at higher temperatures. However, the temperature may affect the structure of the membranes and/or the fouling potential of the wastewater which may have a positive or negative impact on the flux.

The primary reason for conducting the run at 40°C is for comparison of the synthetic water with the actual abattoir waste, whilst 75°C was the physical limit available for the rig.

The experiments were conducted for a flux of 100LMH and a constant cross-flow velocity of 0.2m/s was maintained. Initial operation of the filtration rig was conducted with heated pure water in order to raise the temperature of the module. This minimises any temperature change and reduced flux that would occur at lower temperatures. The experiments were operated for 150 minutes and the response variable used to asses the effect of temperature was the average fouling rate.

3.4.2 Effect of Cleaning Procedures

Chemical cleaning is an integral part of operation for membrane systems and has a significant on the process operation. The issues of membrane fouling are generally a function of the site-specific water quality. This study is not an extensive investigation into the cleaning procedures but is simply a guide to the performance a number of common cleaning chemicals used in membrane cleaning. A significantly more in depth analysis of the cleaning for membranes has been conducted by D'Souza and Mawson [2]. Whilst that study focused on the dairy industry many of the cleaning agents and issues raised would be relevant for the meat processing industry as well.

We have investigated three different cleaning agents in this study;

Table 2: Cleaning Agents and their properties

Cleaner	General Properties
0.1% (W) Sodium Hydroxide	Sodium hydroxide is a highly alkaline inorganic substance is often used to clean membranes fouled by organic and microbial foulants, either by hydrolysis or solubilisation
0.1% (W) Sodium Hydroxide + 400ppm Sodium Hypochlorite	An oxidant and Caustic combination such as sodium hydroxide and hypochlorite are common cleaning mixes. The main reasons for combining chlorine with caustic are; it enhances efficiency, and controls excess oxidation to membranes and module; and act as a disinfectant for destructive pathogenic micro organisms
1.0% (W) Terg-a-zyme – Commercial enzyme detergent	Enzymes hydrolyse proteins and lipids and are often used for sensitive membranes. This commercial product is a concentrated anionic detergent with a protease enzyme. Is used for the removal of proteinaceous soils, tissue, blood, and bodily fluids.

The clean water flux (CWF) was used as the measure of ‘cleanliness’ of the two membrane systems. The CWF was measured for fouled membranes, which were then cleaned using the various cleaning agents. The membrane were cleaned for 1 hour at a TMP of 100kPa and a cross-flow velocity of 0.2m/s at 40°C. After cleaning the CWF was then measured again. The change in the clean water flux was used to assess the cleaning performance.

4 Results and Discussion

4.1 Pre-trial Laboratory Assessment

4.1.1 Water Quality Assessment

An initial assessment of the water quality and it fouling potential was conducted on four water samples obtained from the Northern Co-operative meat companies abattoir located at Casino, NSW. The water was sampled on the 31st August. The samples were taken from four different locations in the plant; the steriliser pots, the viscera tables, the handwash basins and the catchment tank. Table 3 contains the results from both the in-house and external water analyses.

Firstly, a visual inspection of the samples was completed, which are shown in Figure 4. From this image it can be seen that the samples 1 and 2 from the steriliser pots and viscera tables are very clear with few floating particles. Sample 2 from the handwash basins is a reddish in colour but contains few visible floating particles whereas sample 4 contains a significant quantity of suspended particles and is yellowish in colour. These observations are reinforced with the colour analysis which gives samples 1 and 2 a colour index of 10 PCU whilst sample 3 is 160 PCU and sample 4 at 50 PCU.

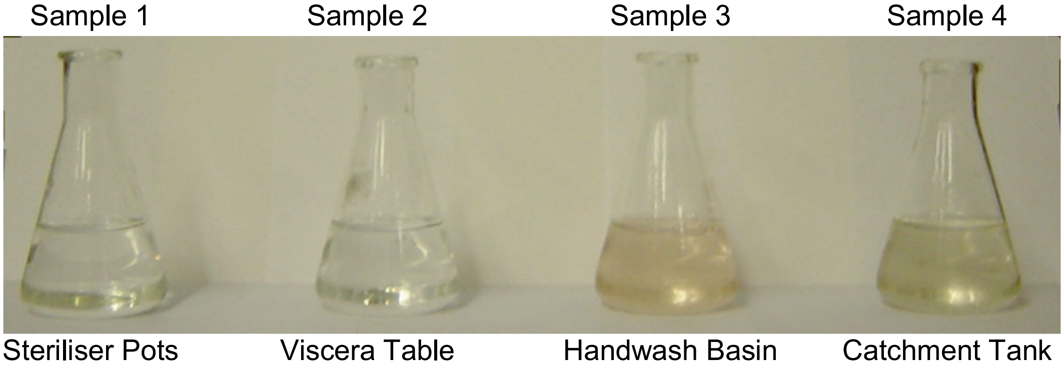


Figure 4: Preliminary water samples

The steriliser pots and viscera table wastes were lightly contaminated with suspended solids and fats, oils and grease (FOG) of less than 5mg/L, Nitrogen levels less than 1mg/L and a COD of 56mg/L and 85mg/L respectively, which are comparable to stormwater runoff [3]. In terms of filtration, these two samples are very similar in their contamination with the only significant difference is that the viscera table was contains a higher biological oxygen demand.

The handwash basin and catchment tank are significantly more polluted compared with the previous two samples, however they are not polluted such that filtration would be prohibitive. The handwash water contains the highest levels of TOC and COD, Oil and grease and as previously mentioned colour. The higher quantity of oil and grease found in the handwash basin would be contributed to by the presence of hand cleaning detergents. The catchment tank contains significantly more ammonia, carbohydrate and protein than any of the other samples. From this we conclude that the catchment tank does not simply reflect a blending of the three other samples but may also reflect operating conditions on the plant at a previous time period and/or and an accumulation of contaminants in the tank

In terms of filtration, the four samples can be divided into two groups. The first would be the steriliser pot and viscera table water which would be easier to clean using microfiltration due to the lower concentration of solids and colour. The handwash basin an catchment tank water represent the other group which would be more difficult to filter as they would have a significantly higher fouling potential.

Table 3: Feedwater Analysis

Parameter	Units	Sample Points Steriliser Pots	 Viscera Table	 Handwash Basin	 Catchment Tank
Suspended Solids (SS)	mg/L	5	4	30	30
Colour (True)	PCU	10	10	160	50
Conductivity	µS	349	349	353	421
Total Alkalinity	mg/L	140	134	138	147
Ammonia	mg/L	0.056	0.52	0.164	1.88
Nitrite	mg/L	<0.010	<0.010	0.015	<0.010
Nitrate	mg/L	0.03	0.01	0.011	0.017
Total Kjeldahl Nitrogen (TKN)	mg/L	0.4	0.9	9.2	7.2
Total Organic Carbon	mg/L	5.05	4.65	30.57	14.42
Oil & Grease	mg/L	<5	<5	17	<5
Chemical Oxygen Demand	mg/L	52	85	180	106
Total Protein	mg/L	5.6	7.9	12.6	23.1
Total Carbohydrate	mg/L	4.4	1.4	2.2	5.9

4.1.2 Preliminary Filtration Studies

Consistent with the relative water quality assessment, the waste water from the steriliser pots and viscera tables presented with least resistance to filtration. The handwash basin was took slightly longer to filter, however, with the commingling of these stream in the catchment tank the filtration time surprisingly was not reduced. In fact the time to filter 50mL (Figure 5) was between 2 and 4 times greater for the commingled water than the other waste streams. This result should be interpreted with cautiously. Despite the colour, total organic carbon and chemical oxygen demand begin, 66%, 50% and 33% lower respectively following the blending the total protein and carbohydrate levels were much higher. This may indicate that the catchment tank represent water quality at prior operating conditions or a build up of contaminant in the tank.

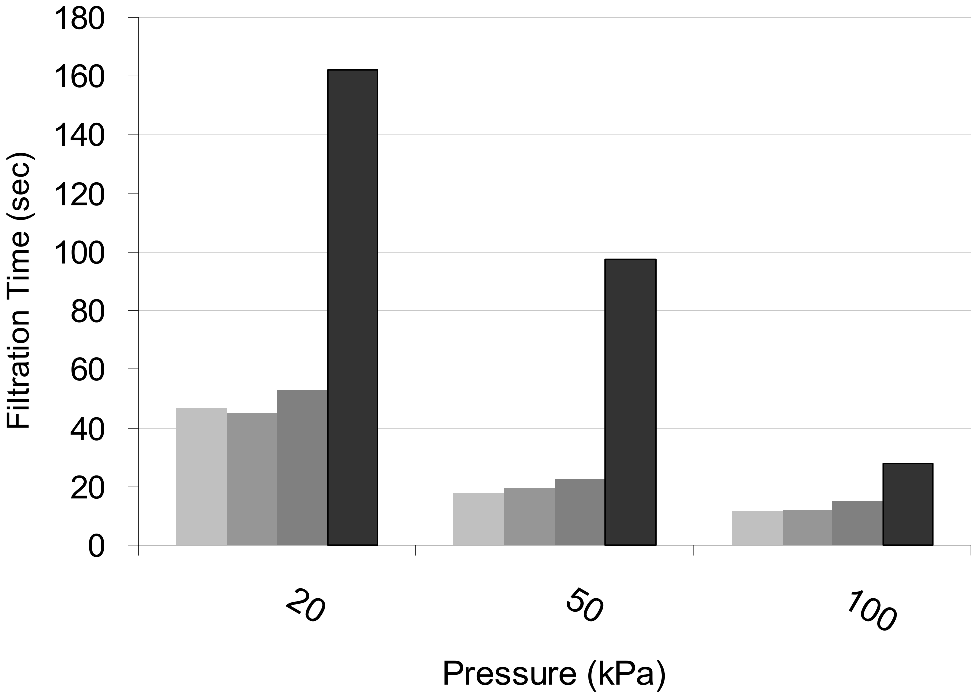


Figure 5: Time for filtration of 50mL of waste solution from various sources; D Steriliser Pots, D Viscera Table, D Handwash Basin, D Catchment Tank.

Blocking law analysis was completed on each of the four waste water samples supplied. Adherence to one of the physical blocking models is determined by the linearity of each of the plots given in Table 4. The filtration test were conducted in a 180mL constant pressure dead end flow cell, shown in Figure 6 at three pressures; 20kPa, 50kPa and 100kPa. The cell employed a 55mm diameter 0.22μm millipore microfiltration membrane.

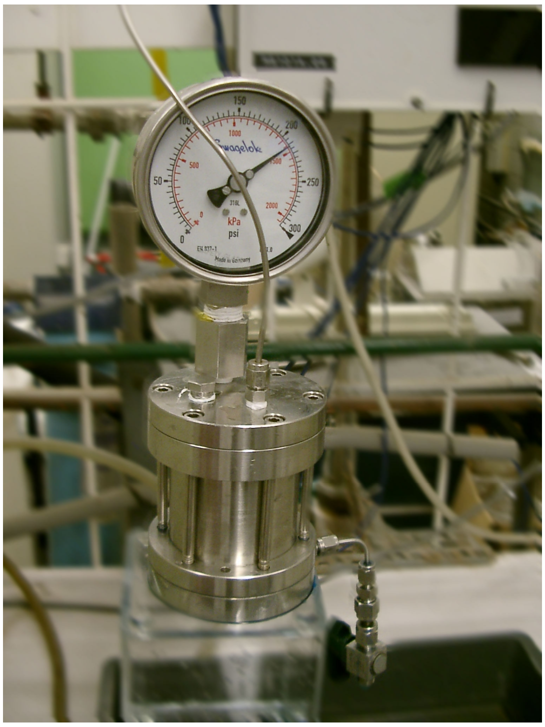


Figure 6: dead-end flow cell for blocking law analysis

Table 4: Filtration blocking laws

Physical Model	n power	Model Equation	Plotting
Cake filtration	$n = 0$	$K_c V = \frac{2t}{V} - \frac{2}{Q_m}$	V vs $\frac{t}{V}$
Intermediate case	$n = 1$	$K_{ci} V = \ln(1 + K_{ci} Q_m t)$	V vs $\ln(t)$
Internal deposition	$n = 1.5$	$K_{id} t = \frac{2t}{V} - \frac{2}{Q_m}$	t vs $\frac{t}{V}$
Complete blocking	$n = 2$	$K_b V = Q_m (1 - \exp(K_b t))$	V vs $\exp(t)$

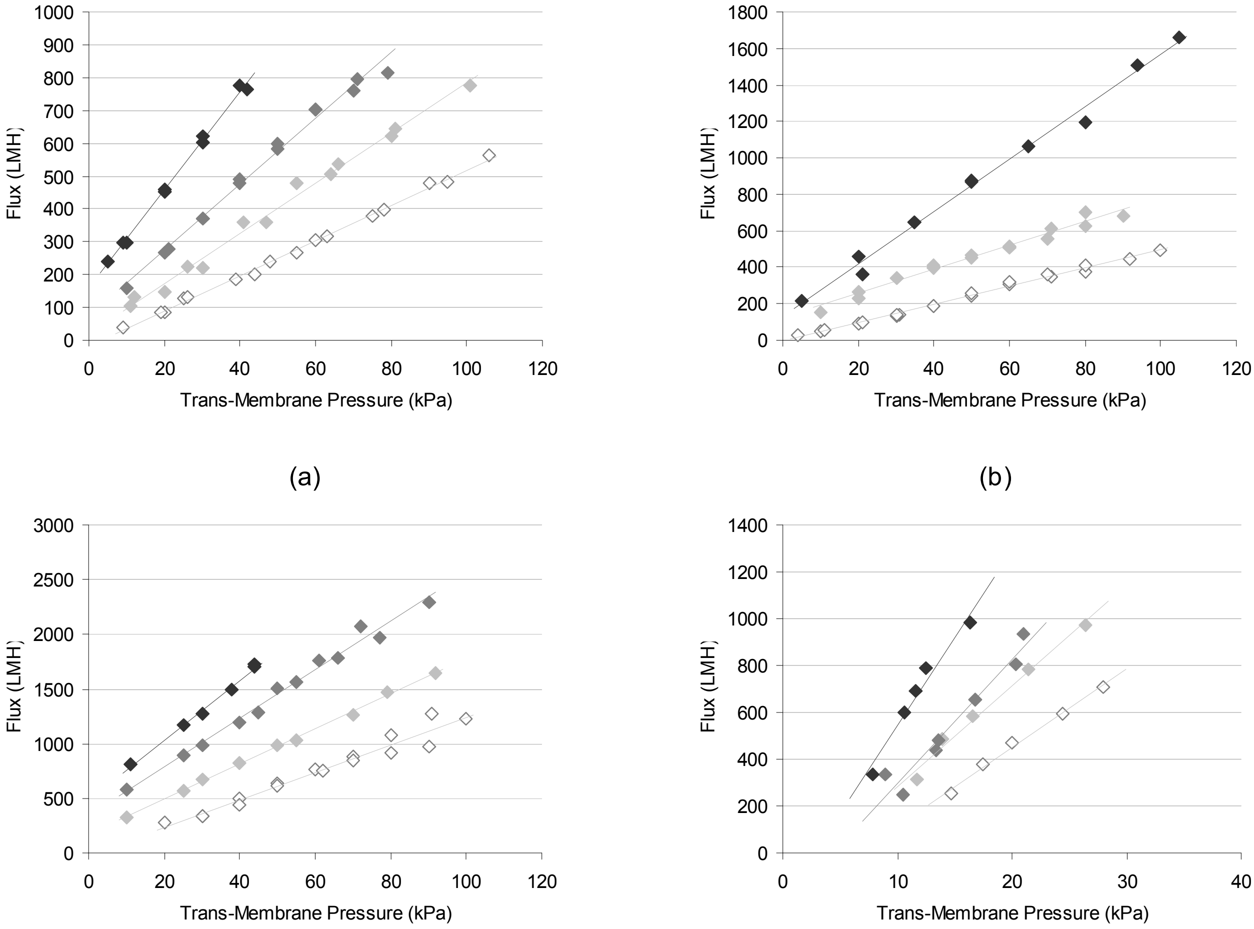
The filtration blocking law plots for each membrane can be found in Appendix 2. It can be seen from these plots that strict adherence to any of these physical models is not achieved as none are linear. This result is, however, not unexpected and the lack of agreement can be attributed to the matrix of pollutants including blood, tissue, fats oils and detergents present in the samples.

It should also be noted that in spite of this the steriliser pot and viscera tables, those which are only lightly polluted are most closely represented by the cake filtration model. Whilst for the handwash basins and catchment tanks internal deposition appear to best describe the blocking behaviour.

4.1.3 Intrinsic Membrane Resistance

The intrinsic membrane resistance has been assessed for each of the four trial modules. Table 5 shows the resistance at each of the four temperatures and an overall average. The intrinsic resistance is important in determining the fouling rate for a membranes, however, it is not indicative of its potential performance.

As evident from the table the ceramic membrane has the highest intrinsic resistance, with the stainless steel membrane approximately the same. The Microza membranes resistance is approximately half that of the stainless steel and ceramic modules. The Novasip cartridge filter has the lowest intrinsic resistance.



(a) (b)

(c) (d)

Figure 7: Membrane resistance determination for (a) Stainless Steel, (b) Ceramic membrane (c) Microza membrane, (d) Novasip Membrane at; -- 20°C, -- 40°C, -- 60°C, -- 75°C

Table 5: Membrane resistance values at varying temperature

Module	Average	Temperature			
		20°C	40°C	60°C	75°C
Stainless Steel	0.196	0.188	0.186	0.211	0.200
Ceramic	0.221	0.205	0.226	0.555	0.232
Polymeric (Microza)	0.098	0.081	0.092	0.102	0.119
Polymeric (Novasip)	0.038	0.031	0.035	0.043	0.045

4.2 Field Trial Evaluation

4.2.1 Setup and On-site Operation

The field trials were conducted over five days between 23rd and the 27th of October. The trials were conducted at the Northern Co-operative Meat Company abattoir in Casino, NSW. The water was sourced from the abattoir catchment tank located below the plant floor (Figure 8). This tank is feed from the steriliser pots, the viscera tables and the handwash basins.

Figure 8: Catchment tank at Casino abattoir

The wastewater was fed from the catchment tank into the microfiltration rig's feed tank. The water quality and feed availability from the tank was highly variable. This variability inturn has an impact on the consistency of performance for the various membrane systems we have trialled. Table 6 shows the range and mean for each of the variables of water quality measured on site, turbidity, conductivity, pH and Fe^+ concentration. The feed water temperature was also measure as it is removed from the catchment tank.

Table 6: Water quality variation during field trials

Water Quality Variable	Range		Mean
	Min	Max	
Turbidity	0.84	8.7	3.60
Conductivity	419	449	438
pH	7	8	7.8
Fe^+	0	0.025	0.00625
Temperature	36	48	40.20

The table shows there is significant variability in both the turbidity of the feed water and its temperature. This can be further examined on a daily basis as seen in Figure 9. Here we can see that the variability is also evident, though less severe on a daily basis. The variation in turbidity and temperature is due to a number of factors operating at the plant. Firstly the feed to the catchment tank is intermittent, based around shift times and breaks. As a result the water level in the tank fluctuates resulting in changes in the holding time of the water. This inturn influence the temperature of the water. Where the feed water is sourced is also an issue. For instance water from the steriliser pots is at 80°C whilst the handwash water is only 45°C.

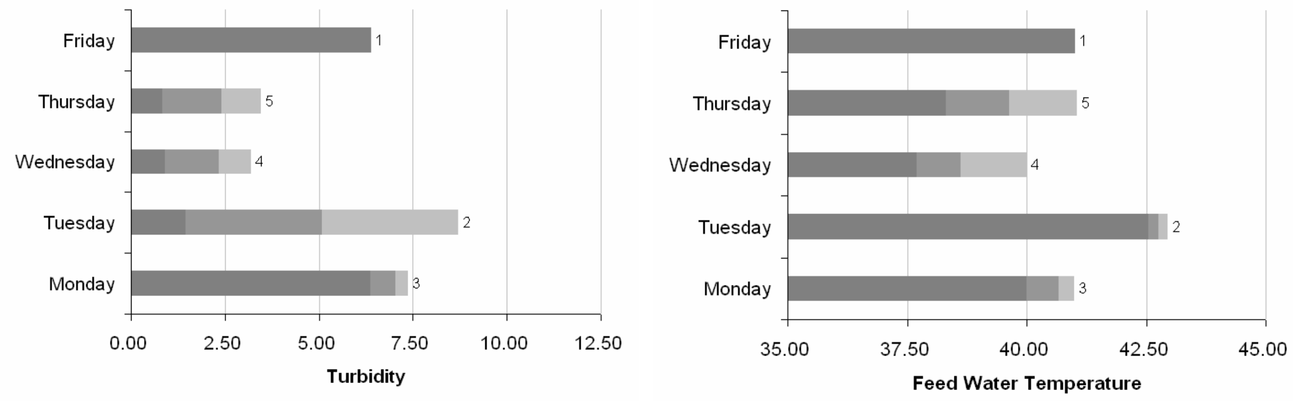


Figure 9: daily variability of the turbidity and feed water temperature; D minimum, D average, D maximum, sample count.

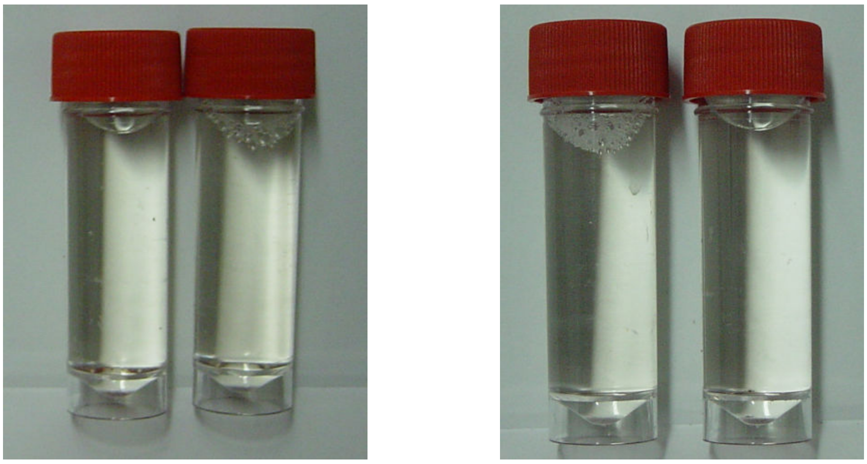
Given the average water temperature from the tank over the week was only 40°C, it is evident that a significant amount of the heat has already lost before reaching the filtration system. If the recovery of heat is to be a primary objective of this process the filtration unit would need to be situated closer to the water sources, and/or the contribution of warm water (i.e. handwash basin water), should be eliminated.

The variation in the turbidity influences significantly the rate at which the various membranes will foul. This will affect the optimal flux through the membranes and the frequency of backwash and cleaning. Like the feed temperature these variations are a result of the intermittent nature of the supply. The turbidity drops off towards the end of a shift, or just prior to a break in shift. This is because a large volume of water is used to wash down at this point in the shift, which dilutes the wastewater, lowering its turbidity. The main issue arising for the variation in the pollutant concentration in the water is control of the membrane system. For example the system would benefit from operating backwash based on trans-membrane pressure changes as opposed to a fixed time.

In addition the variability in pollutant concentration of the water makes in not possible to complete a statistical analysis of the 2^2 factorial design for each of the membranes. However, comparisons across the different membranes are still possible

Also of note during the experiments was the colour of the waste water. Both prior to an post filtration. The samples in Figure 10 was taken before (left) and after (right) on Monday and Wednesday during filtration and are typical of the results from all runs. As can be seen from the pictures the water sample are brownish in colour consistent with the preliminary sample obtained and analysed for section 4.1.1. The post-filtration samples shown little change in colour. This is to be expected from a microfiltration membrane as the colour causing particles are generally not retained by the membrane.

This will pose a potential problem when recycling for some purposes and may need to be addressed. Potential solutions for this issue include activated carbon filtration and reverse osmosis (RO) filtration. The activated carbon process adsorbs any colour causing chemicals to the surface of the carbon and is a common industrial process. However, this process requires significant operation and maintenance expertise. Alternatively a small reverse-osmosis (RO) unit may also solve the problem. RO is an extensively used membrane system for water treatment, which works in a similar manner the membrane we have used in this study, but have a smaller pore size and hence retain smaller particles that pass through microfiltration membranes. The drawback for this process is the increased energy cost required to operate this system.



(a) (b)

Figure 10: water colour samples – (a) sampled on Monday (b) sampled on Tuesday

4.2.2 Membrane Comparisons

The primary aim of the field trials was to assess the each of the four membranes for their effectiveness in treating the abattoir wastewater and to assess any potential operation problems. The membranes were evaluated based primarily on three criteria. The rejection of pollutants, the rate of fouling and the Experimental Operation Time (EOT).

The membrane performance has been distinguished using a simple ranking scheme. Each of the membranes was ranked for each of the assessment criteria comparatively with each other. That is the membrane that performed the best compared to the other would be ranked the highest. A combination of the rankings for the three assessment criteria was used to determine the two best performing membranes, which were subsequently further tested in the laboratory.

The pollutant rejection was determined for all four membranes during the last two days of trials and was compared with the feed water sampled during the experiment. A summary of the results can be found in Table 7, which again highlight the variability in the feed water quality. The TSS for the samples on Thursday and Friday varied between 9 and 26 mg/L respectively. The pollutant rejection is based on the corresponding feed quality which is also indicated in the table.

Table 7: Water sample analysis from field trials

Parameter	Units	Samples 1	2	3	4	5	6	7	8
		FEED WATER THURS	FEED WATER FRIDAY	FEED WATER FRIDAY 2	PERM WATER MICROZA	PERM WATER NOVASIP	PERM WATER STAINLESS	PERM WATER CERAMIC	PERM WATER CERAMIC
Total Suspended Solids (TSS)	mg/L	9	26	20	2	4	10	5	4
Total Dissolved Solids (TDS)	mg/L	312	314	310	286	350	296	324	292
Total Alkalinity	mg/L	127	128	129	- - -	- - -	- - -	- - -	- - -
Ammonia	mg/L	0.084	0.086	0.088	0.079	0.098	0.083	0.085	0.063
Nitrite	mg/L	<0.010	<0.010	0.013	<0.010	0.015	<0.010	0.011	0.015
Nitrate	mg/L	1.04	0.101	0.176	0.031	0.042	0.04	0.112	0.067
Total Kjeldahl Nitrogen (TKN)	mg/L	13.3	18.1	14	1.6	9.5	3.9	12	7.6
Total Organic Carbon	mg/L								
Oil & Grease	mg/L	<5	11	<5	- - -	- - -	- - -	- - -	- - -
Chemical Oxygen Demand	mg/L	100	145	138	57	112	38	90	62

The percentage of rejection or removal for turbidity, total suspended solids, TN and chemical oxygen demand are shown in Figure 11. From Table 7 it can be seen that the total nitrogen may be represented by the TKN, as the levels of nitrate, nitrite and ammonia are all very low. The graph shows that a complete reduction in the turbidity is achieved for all of the membranes. An average 80% reduction in the TSS and TKN is achieved for the membranes with the ceramic and Microza membranes performing the best for removal of TSS and TKN respectively. The removal of COD varies greatly across the trial membranes with the Stainless membrane preforming the best. Based on these results the membranes have been ranked according to their performance for rejection accordingly;

Microza > Ceramic > Stainless Steel > Novasip

Therefore the Microza polymeric hollow fibre membrane unit is the most suitable membrane, with the Novasip cartridge filter least favourable, based on their rejection of pollutants.

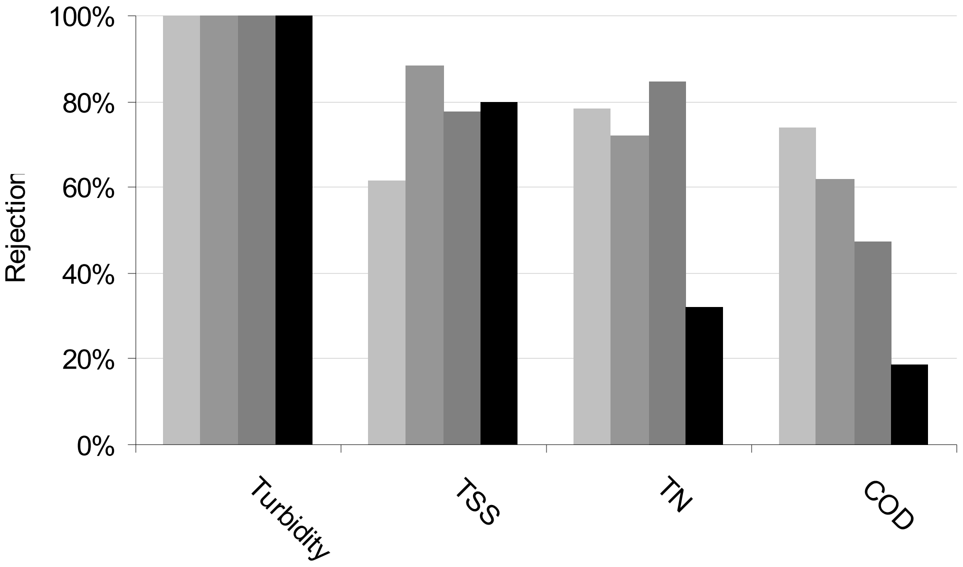


Figure 11: Rejection rates for various membrane; D Stainless steel, D Ceramic, D Microza, D Novasip.

The second criteria for the evaluation was the experimental operation time (EOT). Due to time constraints during the field trials the maximum experimental time was limited to 90 minutes, where the experiment was determined to have been completed when the trans-membrane pressure for a given flux was greater than 120kPa. Figure 12 shows the EOT for each of the experiments operating under the varying operating conditions.

From the figures, the stainless steel membrane is observed to foul rapidly under all of the examined conditions, whereas for a flux of 50LMH all of the other membranes operated for the full ninety minutes. It should be note that only two experiments were conducted for the Novasip cartridge filter as it only operated as a dead-end module.

Ranking each membrane based on their EOT in the same manner as the foulant rejection we observe;

Novasip > Microza > Ceramic > Stainless Steel

The Novasip module is ranked highest based on this criteria, however this may be occur as a result of it low rejection of pollutants compared with the other membranes. The stainless membrane performs the worst.

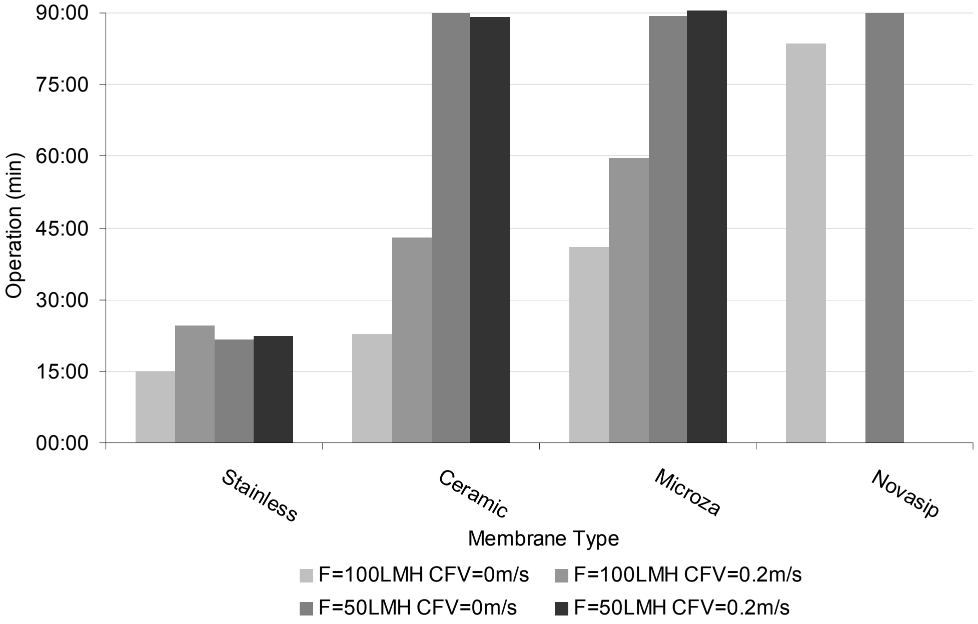


Figure 12: Operation time under varying conditions

The final criteria of assessment was the AFR. Figure 14 shows the trans-membrane pressure as a function of time for a flux of 50LMH and operated in dead-end mode. These curves are typical of those at other operating conditions. The TMP increases with time as the membrane fouls, via clogging or cake formation at the membrane surface. The rate of AFR is a good indicator of the performance of the membrane and its derivation as a function of temperature, pressure and time can be found in Appendix 2. Figure 13 show the average fouling rate (AFR) for each of the membranes under all operating conditions.

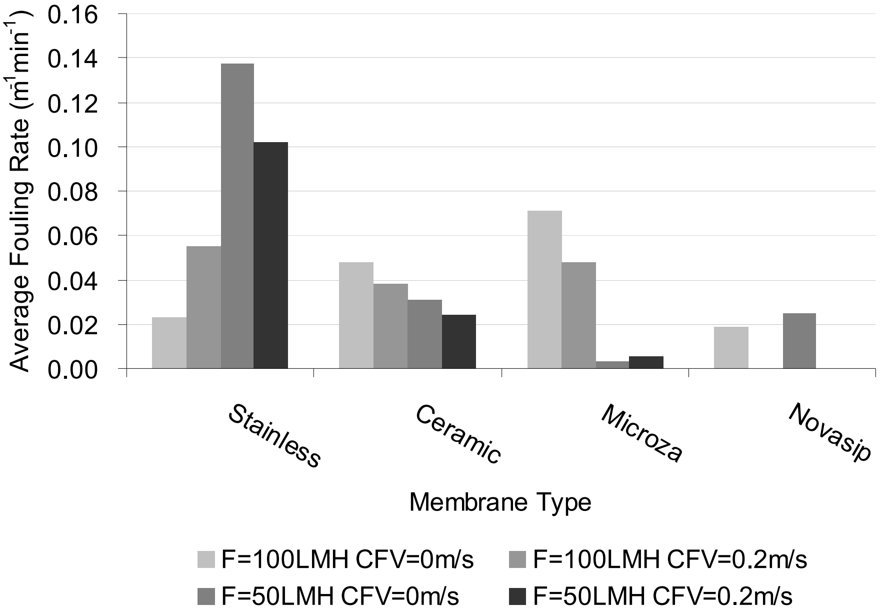


Figure 13: Average Fouling Rate Comparisons

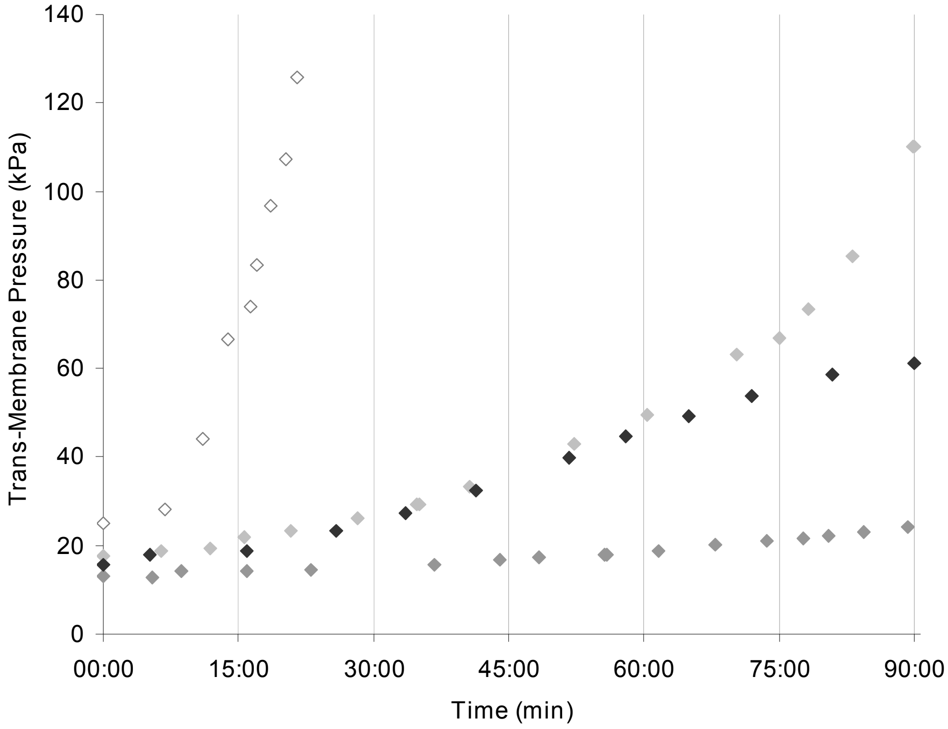


Figure 14: Trans-membrane Pressure as a function of time; H Stainless steel, I Ceramic, I Microza, I Novasip. (conditions: 50 LMH dead-end)

The membranes have been ranked according to their AFR;

Microza > Novasip > Ceramic > Stainless Steel

The Microza membrane had been deemed the best membrane based on its extremely low AFR when system was operated at a flux of 50LMH, which is a four fold improvement as compared with the nearest AFR of the other membranes.

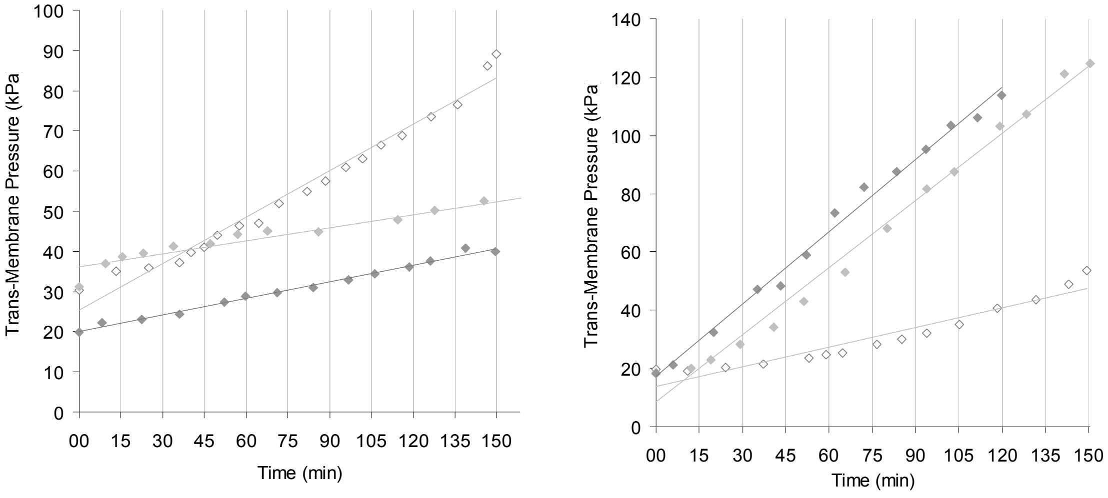
Taking into consideration the rankings for each of the three criteria, the Microza polymeric hollow fibre module is clearly the best performing membrane for the treatment of abattoir steriliser water based on the current field trials. The next best performing membrane is the Ceramem ceramic membrane. It has been selected over the Novasip cartridge filter based on is higher rejection and comparable AFR at a flux of 50LMH. Further examination of these two membranes under controlled laboratory conditions has been conducted in Section 4.3.

4.3 Post-Trial Laboratory Assessment

The post-field trial laboratory test assessed the ceramic and Microza membranes for their dependence on temperature and their cleanability with a variety of common cleaning agents, using synthetic waste water to replicate the conditions of the abattoir.

4.3.1 Effect of Varying Temperature

The effect of temperature was assessed using the AFR, based on the operation of the filtration rig at 100 LMH, 0.2m/s cross-flow velocity and an operation time of 150 minute. The representative trans-membrane versus time curves are shown in Figure 15.



(a) (b)

Figure 15: Trans-membrane pressure profiles at varying temperatures for (a) Ceramic membrane and (b) Microza membrane at varying temperature

Table 8 shows the AFR for both membranes at each examined temperature. At 40oC we can see that the AFR for the synthetic water is an order of magnitude smaller than those observed during the field trials. This indicates that some pollutants present in the real waste water are not present within this synthetic waste and as such the synthetic water has a lower fouling potential. However, this does not preclude a comparative assessment for these membranes for both the temperature and cleanability.

Table 8: Average fouling resistance with synthetic wastewater at varying temperature

	Ceramic	Microza
40°C	0.0063	0.0033
60°C	0.0028	0.0147
75°C	0.0031	0.0206

The AFR for the ceramic membrane is almost constant across the observed temperature range, indicating that the rate of fouling is not dependent on the temperature. However, this is not the case for the Microza membrane. As temperature increases the rate of fouling also increases. This indicates that at higher temperatures the fouling particles have a higher tendency to stick or block the membrane pores. The increase in the fouling rate may be caused by a change in the properties and softening of the polymer as it is heated.

Based on this result we would recommend that if the membranes were to be operated at a lower temperature of approximately 40°C and the heat was to be recovered prior to the water treatment, the polymeric membrane. However, if heat recovery was complete post water cleaning the ceramic membrane would provide the better option.

4.3.2 Comparison of Cleaning Procedures

Membrane cleaning is an essential to maintain the permeability of a membrane and is necessary to maintain the plant original operating capacity. Regular cleaning will remove both organic and inorganic material built up on the membrane and will reduce the risk of bacterial contamination.

This study has examined three common cleaning agents; sodium hydroxide, sodium hydroxide, sodium hypochlorite mixture and an enzyme in the form of the commercial cleaning agent Terg-a-zyme. The cleaning was assessed by a comparison of the CWF prior to an experimental run and the CWF after cleaning to determine the percentage of flux recovered (Figure 16).

From the figure we see that for the ceramic membrane the percentage flux recovery was between 15-25%, with the commercial enzymatic detergent performing the best. For the Microza membrane cleaning with sodium hydroxide and terg-a-zyme provided less than 10% recovery. However with the addition of hypochlorite to the sodium hydroxide solution flux recover was greater than 50%.

This result highlights the interaction between the membranes and the cleaning agent. Based on these results the Microza membrane would be recommended based on it superior cleanability with sodium hydroxide/sodium hypochlorite mixture. However, further investigation of the cleaning processing would be needed, further investigate other cleaning agents as well as optimising the process with regards to the temperature, cleaning time and frequency and the concentration of the cleaning agents.

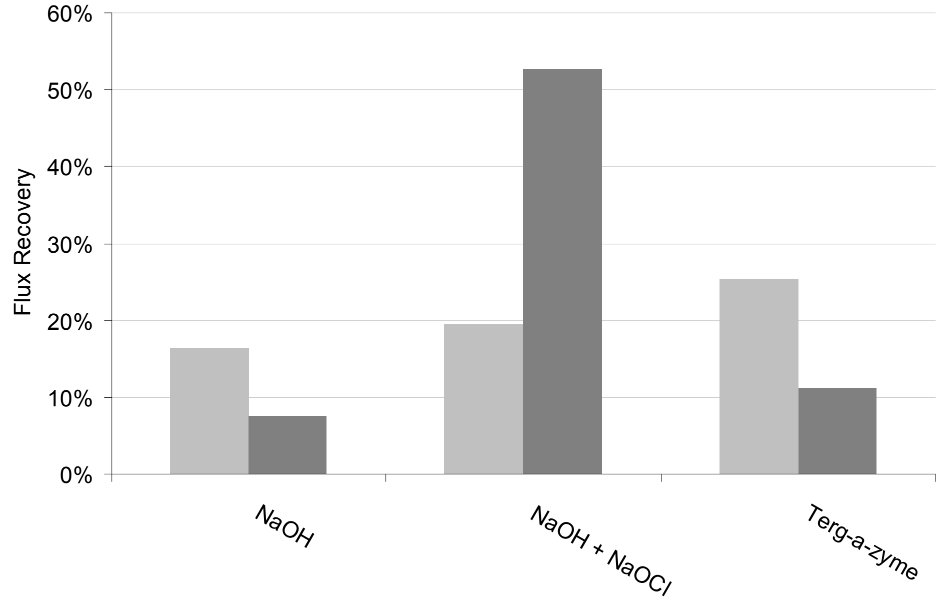


Figure 16: Comparison of cleaning agents on the CWF ; D Ceramic, D Microza.

4.3.3 Estimation of Expected Costs

An estimation of the probably cost in terms of both Capex and Opex have been prepared for the ceramic and an Microza polymeric membranes. The capital costs have been made passed on information provided by equipment suppliers. The following assumptions have been made for the assessment;

- The plant operates on one shift per day for 250 days per annum
- Total steriliser water usage was 80kL per day
- The average cost of water was $0.75 per kL, with pumping and treatment costs $0.20 per kL and disposal costs $0.30 per kL. This gives a total cost of water $1.25 per kL.[4]
- The capital expenditure was amortized over 15 years at 10%
- Heat recovery has not been included in the payback period or NPV calculations

The capital cost estimates for this system has been broken into a number of cost elements including the general and preliminaries, the civil and structural, Architectural, Process mechanical, electrical, control and commissioning. Also included are consultancy and management estimates for the project and a contingency of 30%, which is considered appropriate given the preliminary nature of this assessment. As evident from Table 9, capital expenditure for a system employing the ceramic membranes would be approximately 20% more expensive than the polymeric membranes.

Table 9: Estimation of Capital Costs

Capital Costs	Microza Polymeric Membrane	Ceramem Ceramic Membrane
General & Preliminaries	$ 2,000.00	$ 2,500.00
Civil & Structural	$ 4,000.00	$ 5,00.00
Architectural	$ 800.00	$ 1,000.00
Process Mechanical	$ 20,000.00	$ 25,000.00
Electrical	$ 4,000.00	$ 5,000.00
Instrumentation & Control	$ 6,000.00	$ 7,500.00
Commissioning	$ 1,200.00	$ 1,500.00
Spares & Replacement	$ 2,000.00	$ 2,500.00
Project Consultancy and Management	$ 2,400.00	$ 3,000.00
Contingency (30%)	$ 12,000.00	$ 15,000.00
Totals	$ 54,400.00	$ 68,000.00

The total processing costs have also been evaluated with the polymeric membranes significantly lower in operating costs at $0.33/kL compared with $0.70/kL for the ceramic membranes. This predominantly reflects the high cost of replacement membranes over the course of the plant life.

Table 10: Estimate capital and processing costs

Membrane Option	Microza Polymeric Membrane	Ceramem Ceramic Membrane
Total Capital Expenditure (A$ k)	54.4	68.0
Total Processing Cost (A$/kL)	0.33	0.62
Estimated Payback Period (years)	4.0	12.4
Net Present Value (after service life A$ k)	65.4	3.92

Given the Capex and Opex from Table 10 an estimated payback period for the two scenarios has been calculated. As the polymeric membranes have lower capital and operation expensive its payback period is relatively short at 4.0 year with the ceramic modules payback period of 12.4 years. This is similarly apparent in the net present value at the end of the projected service life which varies for $65,000 and $3,900 for the polymer and ceramic membranes respectively. Based on the estimated costs a polymeric filtration system is financially the most viable option for treating steriliser wastewater.

5 Success in Achieving Objectives

As outlined in Section 2.1, the project consisted in a number of objectives to provide a preliminary assessment of microfiltration as a method for cleaning steriliser wastewater for reuse.

- The feed water quality was assessed which indicated the steriliser pots and viscera table waters were ‘clean’ waste streams. The water samples from the handwash basins and catchment tank recorded significantly higher levels of pollutant. Filterability tests of these samples provided no clear indication of the type of fouling to be expected. This is due to the complex and varying natures of the waste water.
- Post-filtration requirements will depend on the use for the recycled water. The water must meet potable drinking water standards as given by AQIS. As mentioned previously to remove any remaining colour from the filter waters reverse osmosis or activated carbon are potential options.
- The residual streams consist primarily of backwash water. Quality and quantity of this stream are dependent on the frequency and length of the backwash cycles. Quantitatively recovery of permeate is generally greater than 90-95%.
- Cleaning is vital for maintaining permeability. For these trails a combination of Sodium hydroxide and sodium hypochlorite presents as the best option for cleaning. Considering most abattoir operate on a single shift per day, daily clean at the end of each shift would be recommended.
- Heat recovery was highlighted as a priority for this study. However results have shown that a significant amount of heat is lost to the surrounding prior to filtration with the average water temperature 40°C. For greater recovery of waste heat the filtration system would need to be placed closer to the source of wastewater or heat recovery done prior to filtration.
- The cost estimates show a polymeric membrane system significantly cheaper to build and operate.

6 Impact on Meat and Livestock Industry

Increasing productivity from domestic meat processing plants in this climate of reduced secure water entitlements and the likely increase in electricity tariffs will be contingent upon expanding the scope of current water and energy efficiency practices.

Water recycling and energy recovery from process water is an option that may be considered by meat processing plants as part of an overall environmental management programme. Other sections of the food and beverage industry have achieved a 40% reduction in water to product ratio by using membranes to recycle process water for cleaning, cooling and other non-consumable purposes[1].

7 Conclusions and Recommendations

This project has successfully field trialled microfiltration as a means of filtering steriliser wastewater for the purposes of recycling. Significant further work is still required for this to be commercially applicable. These trials have highlighted two promising membrane configurations in the PALL Microza polymeric system and the Ceramem monolith ceramic membrane. Whilst the PALL membrane has been

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[1] See Carlton United Breweries Yatla water recycling program.

verified for sterilisation purposes this is not the case for the Ceramem module and if further investigation of the configuration is to be conducted this should be evaluated.

In consideration of these promising results it is recommended that further field trials be operated, in part to ensure the treated water meets AQIS requirements, on a larger pilot-plant scale and maintained in operation over an extended period of time. This will allow a greater evaluation of the membrane systems for this purpose and provide further information into the operation considerations in particular due to the high variability of the source flow.

Whilst the steriliser water represents only a relatively small fraction of the total water use in an abattoir (about 10% [5]), however, this water represents the ‘low hanging fruit’ in terms of ease and cost of recycling. In addition implementation of a membrane system for the recycling to the wastewater would provide valuable experience and data, for the treatment of other more contaminated waste water streams further down the track.

8 Bibliography

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3. Tchobanogolous, G., F.L. Burton, and D.H. Stensel, eds. Wastewater Engineering: Treatment and Reuse. 4th ed. 2003, McGraw-Hill.
4. Dillon, P., Water Reuse in the Meat Industry; Issues and responsibilities, in Meat Technology Update. 2005, Meat and Livestock Australia.
5. Australia, M.a.L., Eco-Efficiency Manual for Meat Processing. 2002.

9 Appendices

9.1 Appendix 1 – ALS Results

Table 11: Result of preliminary water samples

ANALYTICAL RESULTS

				Sample type:	REG	REG	REG	REG
				ALS Sample number:	1	2	3	4
				Client sample ID (Primary):	SAMPLE 1	SAMPLE 2	SAMPLE 3	SAMPLE 4
Matrix:	WATER				Steriliser Pots	Viscera Table	Handwash Basin	Catchment Tank
Workorder:	ES0610971			Sample date:	5/09/2006	5/09/2006	5/09/2006	5/09/2006
Analyte grouping / Analyte	CAS Number	Units	LOR					
EA025: Suspended Solids								
Suspended Solids (SS)		mg/L	1		5	4	30	30
EA041: Colour (True)								
Colour (True)		PCU	1		10	10	160	50
ED037P: Alkalinity by PC Titrator								
Hydroxide Alkalinity as CaCO3	DMO-210-001	mg/L	1		<1	<1	<1	<1
Carbonate Alkalinity as CaCO3	3812-32-6	mg/L	1		14	<1	<1	<1
Bicarbonate Alkalinity as CaCO3	71-52-3	mg/L	1		126	134	138	147
Total Alkalinity as CaCO3		mg/L	1		140	134	138	147
EK055G: Ammonia as N by Discrete Analyser								
Ammonia as N	7664-41-7	mg/L	0.01		0.056	0.52	0.164	1.88
EK057G: Nitrite as N by Discrete Analyser								
Nitrite as N		mg/L	0.01		<0.010	<0.010	0.015	<0.010
EK058G: Nitrate as N by Discrete Analyser								
Nitrate as N	14797-55-8	mg/L	0.01		0.03	0.01	0.011	0.017
EK059G: NOX as N by Discrete Analyser								
Nitrite + Nitrate as N		mg/L	0.01		0.03	0.01	0.026	0.017
EK061: Total Kjeldahl Nitrogen (TKN)								
Total Kjeldahl Nitrogen as N		mg/L	0.1		0.4	0.9	9.2	7.2
EP005: Total Organic Carbon (TOC)								
Total Organic Carbon		mg/L	1		- - -	- - -	- - -	12
EP020: Oil and Grease (O&G)								
Oil & Grease		mg/L	5		<5	<5	17	<5
EP026ST: Chemical Oxygen Demand (Sealed Tube)								
Chemical Oxygen Demand		mg/L	5		52	85	180	106

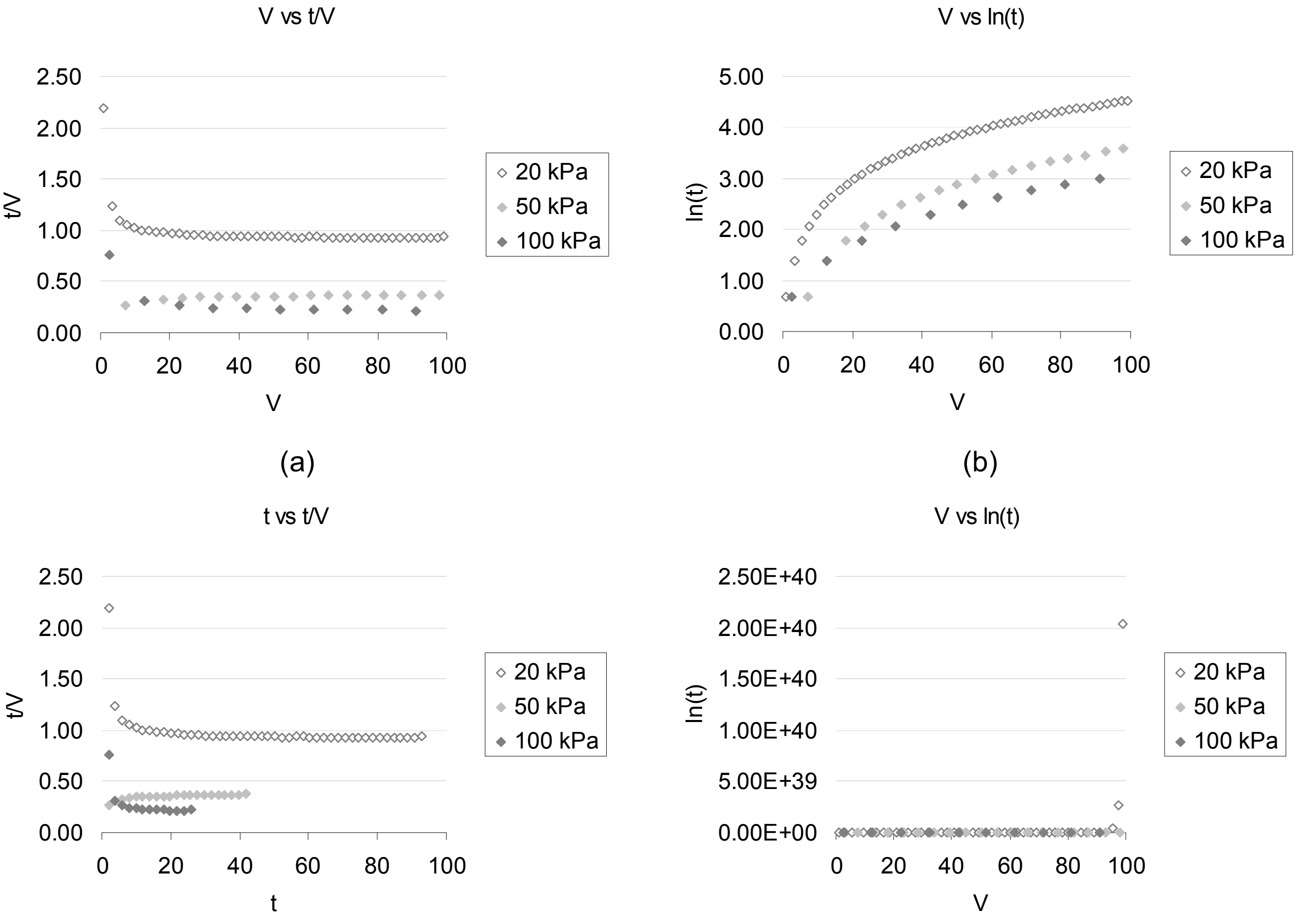
Table 12: Result of field trial water samples

ANALYTICAL RESULTS

Matrix: WATER
Workorder: ES0613548

				Sample type:	REG	REG	REG	REG	REG	REG	REG	REG	REG
				ALS Sample number:	1	2	3	4	5	6	7	8	9
				Client sample ID (Primary):	FEED WATER THURS	PERM WATER STAINLESS	PERM WATER CERAMIC	PERM WATER MICROZA	PERM WATER NAVASIP	FEED WATER FRIDAY	FEED WATER FRIDAY 2	PERM WATER MICROZA 2	PERM WATER CERAMIC
				Sample date:	26/10/2006	27/10/2006	27/10/2006	26/10/2006	27/10/2006	27/10/2006	27/10/2006	26/10/2006	26/10/2006
Analyte grouping / Analyte	CAS Number	Units	LOR										
EA015: Total Dissolved Solids													
Total Dissolved Solids @180°C	GIS-210-010	mg/L	1		312	296	324	286	350	314	310	292	292
EA025: Suspended Solids													
Suspended Solids (SS)		mg/L	1		9	10	5	2	4	26	20	2	4
ED037P: Alkalinity by PC Titrator													
Hydroxide Alkalinity as CaCO3	DMO-210-001	mg/L	1		<1	- - -	- - -	- - -	- - -	<1	<1	- - -	- - -
Carbonate Alkalinity as CaCO3	3812-32-6	mg/L	1		<1	- - -	- - -	- - -	- - -	<1	<1	- - -	- - -
Bicarbonate Alkalinity as CaCO3	71-52-3	mg/L	1		127	- - -	- - -	- - -	- - -	128	129	- - -	- - -
Total Alkalinity as CaCO3		mg/L	1		127	- - -	- - -	- - -	- - -	128	129	- - -	- - -
EK055G: Ammonia as N by Discrete Analyser													
Ammonia as N	7664-41-7	mg/L	0.01		0.084	0.083	0.085	0.079	0.098	0.086	0.088	0.061	0.063
EK057G: Nitrite as N by Discrete Analyser													
Nitrite as N		mg/L	0.01		<0.010	<0.010	0.011	<0.010	0.015	<0.010	0.013	<0.010	0.015
EK058G: Nitrate as N by Discrete Analyser													
Nitrate as N	14797-55-8	mg/L	0.01		1.04	0.04	0.112	0.031	0.042	0.101	0.176	0.043	0.067
EK059G: NOX as N by Discrete Analyser													
Nitrite + Nitrate as N		mg/L	0.01		1.04	0.04	0.123	0.031	0.057	0.101	0.189	0.043	0.082
EK061: Total Kjeldahl Nitrogen (TKN)													
Total Kjeldahl Nitrogen as N		mg/L	0.1		13.3	3.9	12	1.6	9.5	18.1	14	2.5	7.6
EK067G: Total Phosphorous-As P by Discrete Analyser													
Total Phosphorus as P		mg/L	0.01		0.08	- - -	- - -	- - -	- - -	0.6	0.1	- - -	- - -
EP020: Oil and Grease (O&G)													
Oil & Grease		mg/L	5		<5	- - -	- - -	- - -	- - -	11	<5	- - -	- - -
EP026ST: Chemical Oxygen Demand (Sealed Tube)													
Chemical Oxygen Demand		mg/L	5		100	38	90	57	112	145	138	48	62

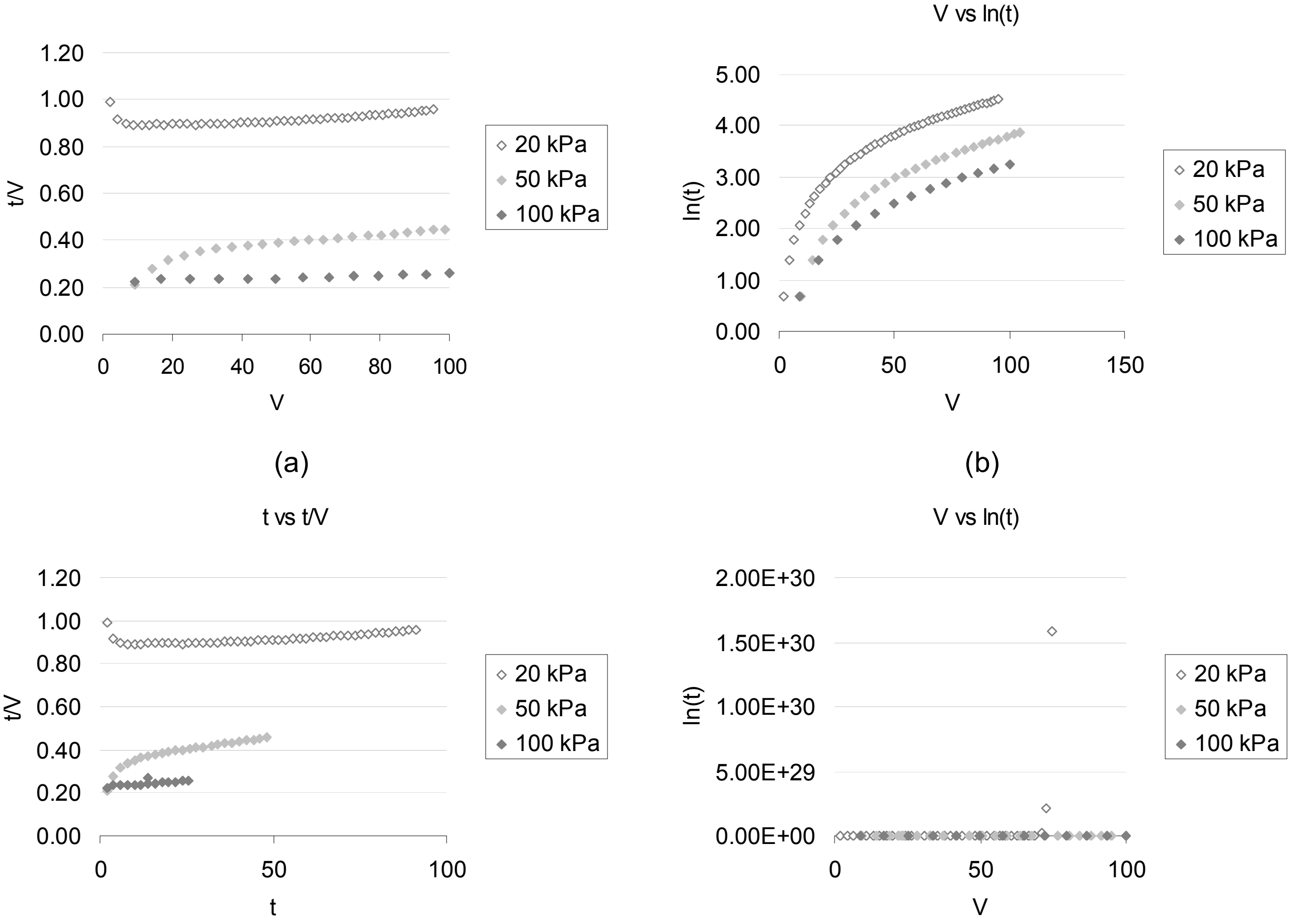
9.2 Appendix 2 – Blocking Law Analysis Plots



(a) (b)

(c) (d)

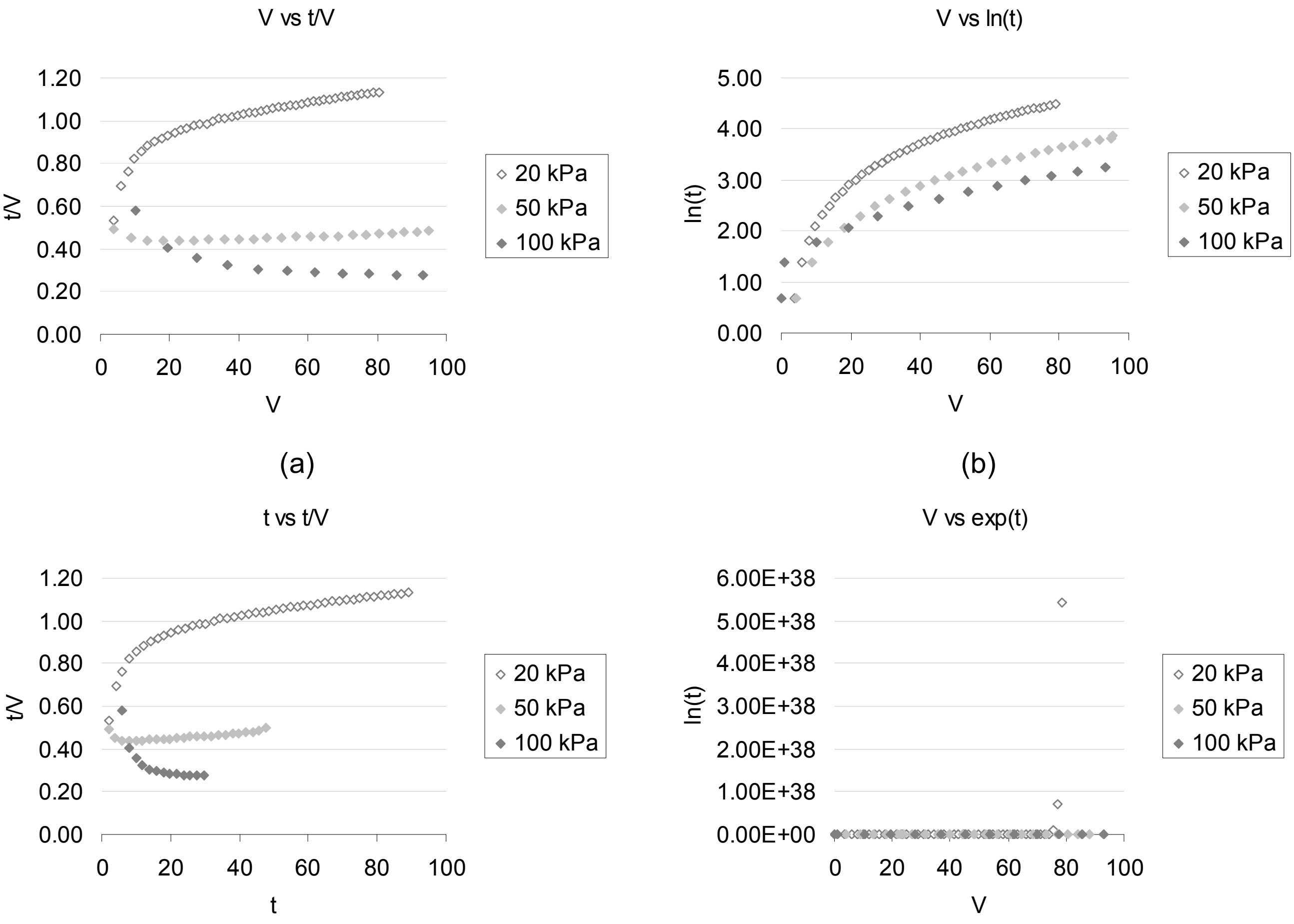
Figure 17: Filtration blocking plots of steriliser pots; (a) Cake filtration, (b) Intermediate case, (c) Internal deposition, (d) Complete blocking



(a) (b)

(c) (d)

Figure 18: Filtration blocking plots of viscera tables; (a) Cake filtration, (b) Intermediate case, (c) Internal deposition, (d) Complete blocking



(a) (b)

(c) (d)

Figure 19: Filtration blocking plots of handwash basin; (a) Cake filtration, (b) Intermediate case, (c) Internal deposition, (d) Complete blocking

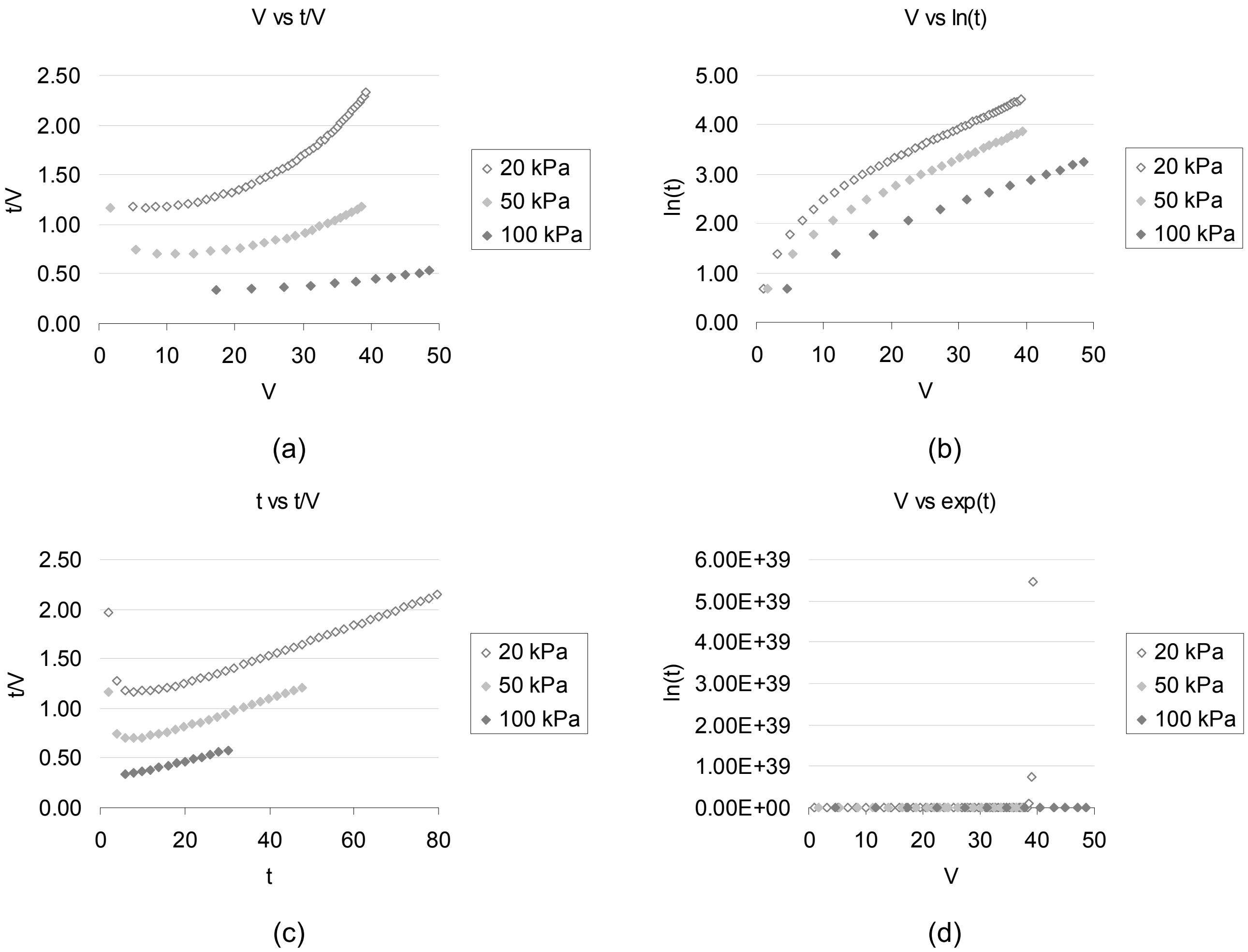


Figure 20: Filtration blocking plots of catchment tank; (a) Cake filtration, (b) Intermediate case, (c) Internal deposition, (d) Complete blocking

9.3 Appendix 3 – Derivation of Average Flux Rate

The Average Fouling Rate (AFR) has been used as a measure of the performance of the membrane. The fouling rate can be determined based on the general flux equation which is given by

$$J = \frac{\Delta P}{\mu\left(R_m + R_f\right)} \qquad \text{EQN - 1}$$

Where ΔP represent the trans-membrane pressure, μ the viscosity, R_m the intrinsic membrane resistance and R_f the resistance due to fouling. Rearranging this equation do make the fouling resistance the function of the equation

$$R_f = \frac{\Delta P}{\mu \times J} - R_m \qquad \text{EQN - 2}$$

The resistance due to fouling on its own does no give an indication of the performance of the membranes. In order to achieve this we must evaluate the rate of fouling i.e. the change in fouling resistance over time, denote as $\frac{dR_f}{dt}$.

Given that the experimental data is given at discrete time intervals, as given in Figure 14 we may differentiate the fouling resistance equation using two-step finite difference method, such that;

$$\left(\frac{dR_f}{dt}\right)_i = \frac{R_{f\,(i+1)} - R_{f\,(i-1)}}{t_{(i+1)} - t_{(i-1)}} \qquad \text{EQN - 3}$$

From here the AFR is a simple average of the fouling rate at each time step. Given by the equation;

$$AFR = \frac{\sum_{2}^{i-1}\left(\frac{dR_f}{dt}\right)_i}{i-2} = \frac{\sum_{2}^{i-1}\frac{R_{f\,(i+1)} - R_{f\,(i-1)}}{t_{(i+1)} - t_{(i-1)}}}{i-2} \qquad \text{EQN - 4}$$