AUSTRALIAN MEAT PROCESSOR CORPORATION

Integrated Agri-Industrial Wastewater Treatment and Nutrient Recovery, Year 3

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Table of Contents

Executive Summary

Red meat processing facilities can generate large volumes of wastewater rich in organic contaminants and nutrients, and can therefore be strong candidates for treatment processes aimed at recovery of both energy and nutrient resources. Traditional lagoon-based abattoir wastewater treatment processes have a number of limitations relative to newer alternatives. These limitations include land availability (they require a relatively large amount of land), biogas capture, odour control, the ability to capture nutrients and de-sludging operations. This has led to an emerging and strong case for reactor-based technologies.

Anaerobic membrane bioreactors (AnMBRs) are a style of in-vessel anaerobic digester that use membranes to retain almost all suspended solids within the process. This style of technology is an attractive option to replace lagoons due to its excellent effluent quality, high tolerance to load variations, and ability to produce a solids free effluent for the purposes of reuse. This project focused on the development and optimisation of AnMBR technology for the red meat processing industry.

An AnMBR pilot plant consisting of a 200 L stainless steel reactor and a 0.9 m^2 submerged hollow fibre membrane was operated at two Australian red meat processing facilities; Site 1 and Site 2. At Site 1, the plant operated for over 200 days and achieved stable operation at a treatment time of two days. At Site 2, the plant operated for 60 days and achieved stable operation at a treatment time of four days. The AnMBR pilot plant has operated successfully at an organic loading rate of 3–3.5 kg $COD{\cdot}m^{-3}{\cdot}d^{-1}$. This is more than an order of magnitude higher than the existing anaerobic lagoon at both sites.

At both sites, the AnMBR pilot plant consistently removed over 90% of COD from the wastewater. Virtually all COD removed was converted to biogas with almost no accumulation of COD within the process. The biogas composition was typically 70% methane (CH_4) and 30% carbon dioxide (CO_2), and during full and steady operation methane production corresponded to approximately 750 L CH_4 per kg VS added (360 L CH_4 per kg COD added).

Economic comparisons show that the payback of an AnMBR is comparable to a CAL when idealised design parameters of 10 kg $COD{\cdot}m^{-3}{\cdot}d^{-1}$ loading rate and 15 $L{\cdot}m^{-2}h^{-1}$ membrane flux are used. However, the payback period of an AnMBR remains comparatively high when using parameters demonstrated in this project. Project results also demonstrated that the AnMBR was not operating at maximum capacity, which highlights the potential for improved economic outcomes through continued research into process optimisation. Operating costs of an AnMBR show improved revenue compared to a CAL; this is due to increased gas capture resulting in improved energy recovery and the potential to recover nutrients (however the nutrient value represents only 20% of revenue). There are additional benefits such as reduced footprint and improved environmental performance, however these benefits have not been quantified in the current analysis and the potential impact of these benefits may be specific to each processing facility.

1.0 Introduction

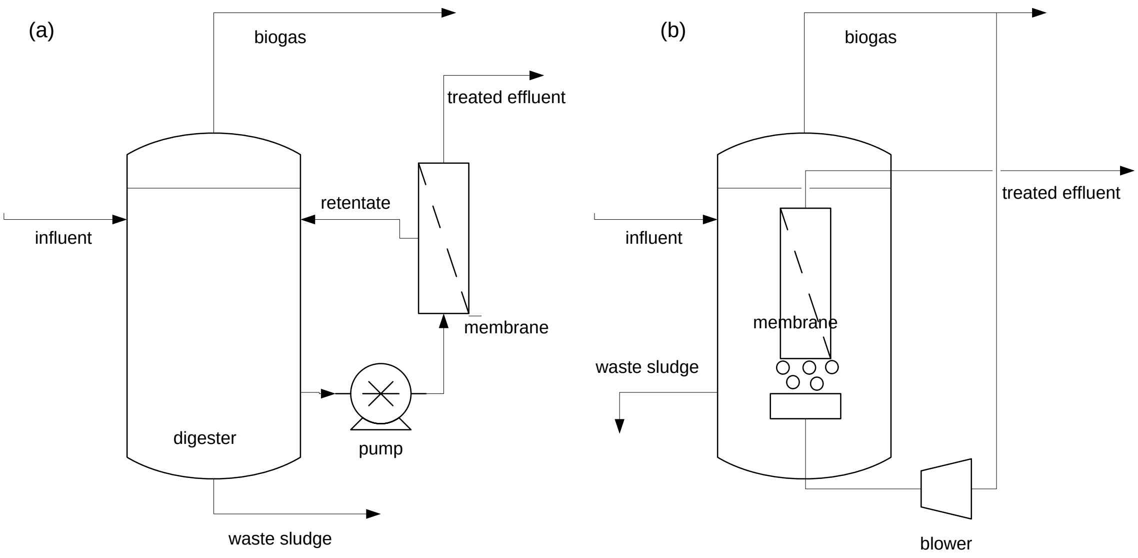
1.1 Background

Red meat processing facilities can generate large volumes of wastewater rich in organic contaminants and nutrients [1, 2], and can therefore be strong candidates for treatment processes aimed at recovery of both energy and nutrient resources. The current default treatment methods for removing organic contaminants, referred to as chemical oxygen demand (COD), from slaughterhouse wastewater vary across the world. Anaerobic lagoons are commonly used in tropical and equatorial temperate zones and engineered reactor systems (including activated sludge and upflow anaerobic sludge blanket reactors) are commonly used in polar equatorial temperate zones. Anaerobic lagoons are effective at removing organic material [3]; however lagoon based processes also have disadvantages relative to engineered reactor systems including larger footprints, poorer gas capture, poorer odour control, limited ability to capture nutrients and expensive de-sludging operations. Daily biogas production from anaerobic lagoons may vary by an order of magnitude depending on temperature or plant operational factors [3]. Even in warmer climates, there is an emerging and strong case for reactor based technologies.

High-rate anaerobic treatment (HRAT) addresses many limitations of lagoon-based treatment, particularly with volumetric loading rates of 100 times that of lagoons. The most common high-rate processes are upflow anaerobic sludge blanket (UASB) reactors which are widely applied to carbohydrate and acid rich wastewaters such as breweries, fruit processing plants and wineries. However, UASBs have not been widely applied to the red meat processing industry as they are intolerant to solids and fats [1], both of which abattoir wastewater have in large amounts. In the last five years, a number of fat and solid tolerant processes have emerged, including the anaerobic baffled reactor [2], the anaerobic sequencing batch reactor [3], anaerobic membrane bioreactors (AnMBR) [4] and the new Paques anaerobic flotation reactor. The AnMBR option in particular is attractive due to its excellent effluent quality, high tolerance to load variations, and ability to produce a solids free effluent for reuse [5].

AnMBRs are a style of in-vessel anaerobic digester that use diffusive membranes to retain almost all suspended solids within the process. Separation may occur either in a side-stream (such as a recirculation line) or internal (immersed in the reactor) [4]. As wastewater is drawn through the membrane, solids will accumulate on the membrane surface in a fouling layer, this increases the membrane's resistance resulting in increased energy demand and reduced flux rates. All immersed membranes require gas scouring with coarse bubble diffusers to generate liquid shear for fouling control. In an AnMBR, this is achieved by recirculating biogas across the membrane. Side-stream units can use liquid shear directly in a cross-flow configuration.

Figure 1: MBR configurations, including (a) side-stream membrane bioreactor (sMBR) and (b) immersed membrane bioreactor (iMBR)



Disadvantages of AnMBR technology, relative to lagoon-based technology, include higher capital cost and risks related to performance of membrane systems in a high fats, relatively high temperature environment. While the literature and state of technology around aerobic membrane bioreactor systems in domestic applications is copious and well developed [5], the state of research around AnMBR systems is far less developed, and there is only one publication on slaughterhouse and/or abattoir wastewater [4], using an external membrane cross-flow system on a mixed cattle–sheep slaughterhouse effluent (15 g $COD \cdot L^{-1}$). While this was a capable and credible publication relevant to the Australian red meat industry, there are a number of gaps surrounding the optimal and/or sustainable operating conditions.

1.2 Summary of Previous Progress

This is the final year of a three year project. Key progress in the first two years of the project includes:

1.2.1 Non-reactive process development

The initial stages of process development focused on short-term non-reactive experiments. The objective of this work was to understand how to integrate the membrane into the process. Key investigations included:

- comparisons of flat sheet membranes, hollow fibre membranes and external cross flow membranes
- investigations of process parameters including operating temperature, gas recirculation rates (impact shear), wastewater composition and concentration
- flux rates were within the range used in initial cba calculation
- gas recirculation rate had the largest impact on membrane fouling
- the viability of a fibre membrane for the anmbr pilot plant.

1.2.2 Development of an AnMBR Pilot Plant

To establish the long-term operating performance of a continuous and biologically active process, the project required the development of an AnMBR pilot plant. A summary of the pilot plant's previous outcomes include:

- A 200 L pilot plant was commissioned at an Australian meat processing facility.
- The feed concentration was approximately 5,000 mg·L^{-1} COD; this was typical of the host site, but is dilute by industry standards.
- COD removal was consistently above 95%. Methane yields were 380 L per kg VS added.
- The plant had been operated with a HRT of seven days. Batch tests suggest that the wastewater should degrade quickly and a HRT of two days should be possible.
- Nutrient concentrations in the effluent appeared low; it is not clear if the nutrients were precipitating within the AnMBR.

1.2.3 Development of a Computational Fluid Dynamics model and a Fouling Model

In the second year, a PhD student developed two models for the project. First, they developed a three-phase CFD model to examine mixing within an AnMBR reactor containing wastewater, solids and gas circulation.

Second, they developed a fouling model to predict how operating parameters impact membrane fouling (a key factor in AnMBR design and operation).

The models have been validated against lab experiment and it is anticipated that they will be used in optimising the AnMBR operating conditions to maximise membrane flux and minimise energy consumption (for membrane cleaning and reactor mixing).

The third year of the project focused on optimising the AnMBR pilot plant (at mesophilic temperatures) while located at Site 1. Areas of improvement included:

- decreasing the retention time
- increasing the organic loading rates
- decreasing the energy requirements for mixing and membrane cleaning
- improving nutrient availability

Additionally, the wastewater at Site 1 was relatively dilute by industry standards. It was deemed important to validate if operating conditions at Site 1 were applicable to sites with more concentrated wastewater. This was achieved by transferring the plant and operating at a second site, Site 2, which had a more concentrated wastewater stream.

1.3 Project Objectives

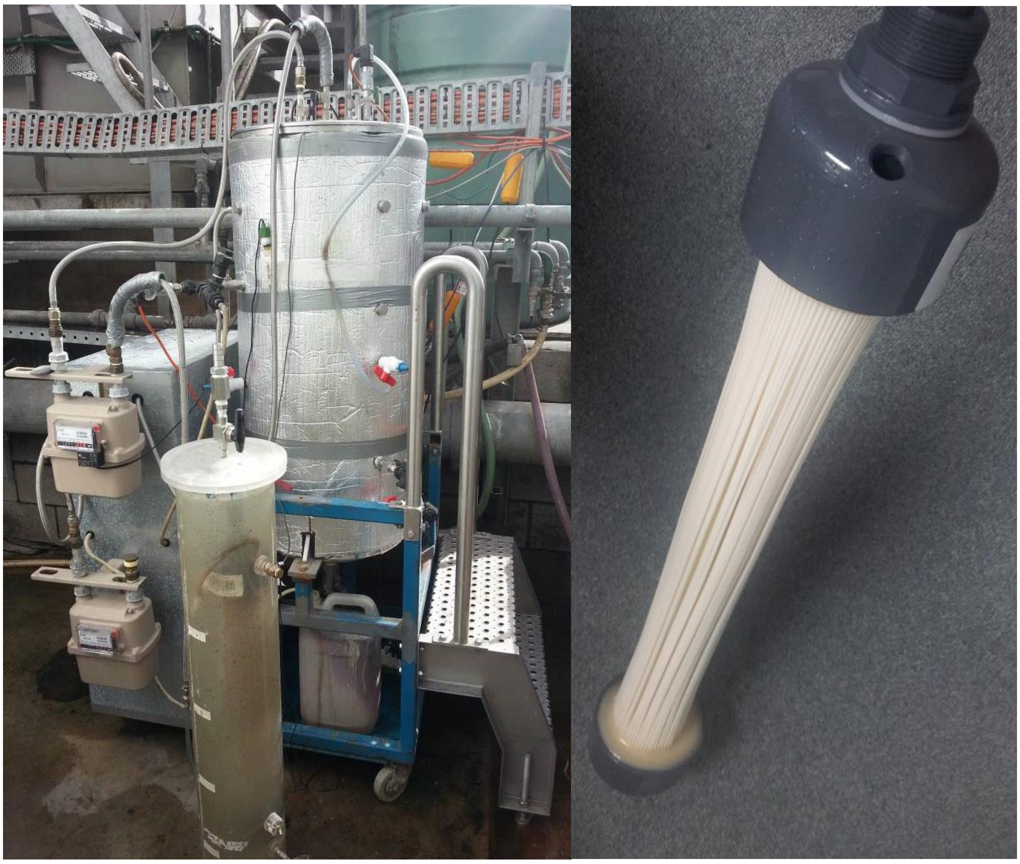
- Maintain long-term pilot trial on AnMBR systems in abattoir applications.
- Determine the minimum treatment time and maximum organic loading rate to the process through research and development activities.
- Investigate strategies to reduce energy consumption by the AnMBR (mixing and membrane cleaning).
- Assess repeatability of optimal process operating conditions at Site 2 using more concentrated wastewater.
- Further develop the cost–benefit analysis by testing assumptions and comparing to base cases, including nutrient removal and CALs.

2.0 Process Design

2.1 Membrane Bioreactor

The AnMBR pilot plant (Figure 2) consists of a 200 L stainless steel reactor containing a vertical mounted submerged hollow fibre membrane (Zenon ZW-10, 0.93 m^2 surface area).

Figure 2: Anaerobic membrane bioreactor and hollow fibre membrane module

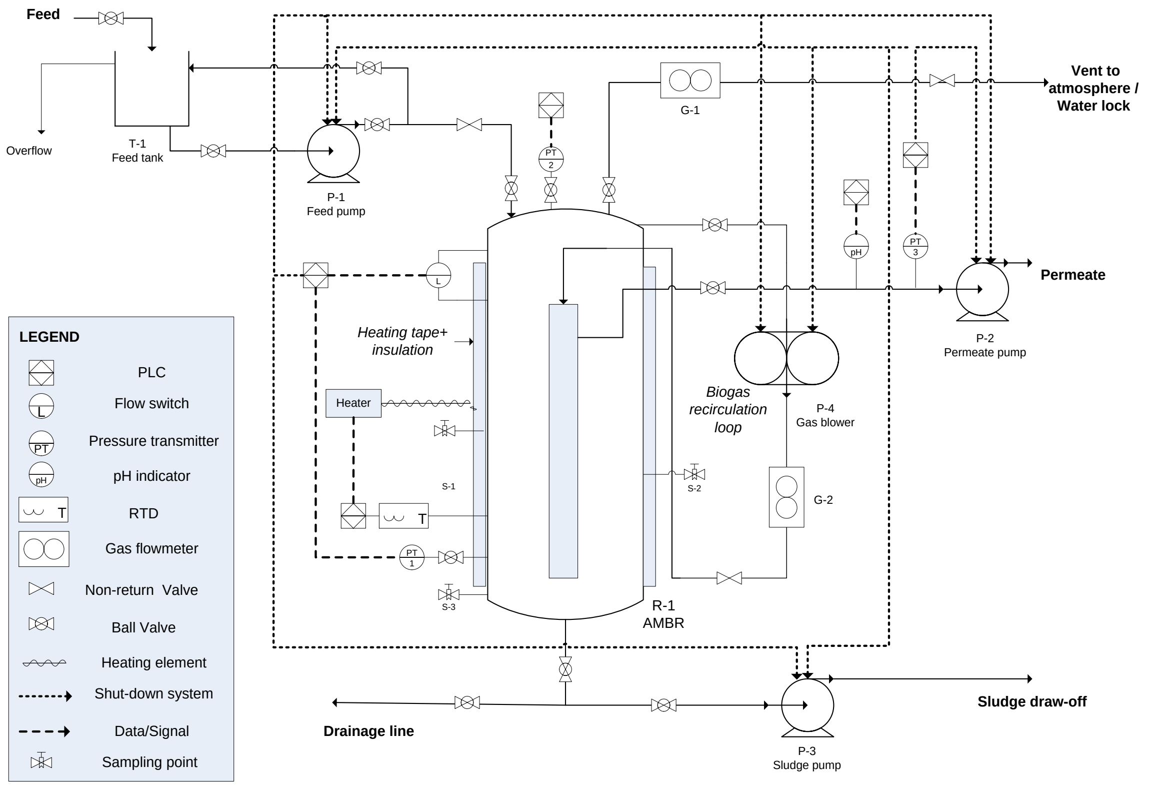


2.2 Process Flowsheet

Waste water was collected using a feed tank. The tank filled three times per week during typical operating conditions (mid-shift). The feed tank was mixed using a mechanical agitator and provided consistent wastewater feed for the AnMBR. Wastewater was transferred from the feed tank to the AnMBR using regular pulse feed events.

Flux through the AnMBR membrane was controlled using a peristaltic pump on the permeate stream. Biogas in the AnMBR was continuously circulated across the membrane surface at a fixed flow rate of 35 $L \cdot min^{-1}$ (0.04 $m \cdot h^{-1}$) to clean the membrane and control fouling. The AnMBR temperature was measured using an RTD sensor (model SEM203 P, W&B Instrument Pty Ltd) and controlled at 37°C using heating tape on the reactor surface. Pressure transducers were used to monitor liquid level, headspace pressure and transmembrane pressure. Pressure and temperature signals (4–20 mA) were logged constantly via a process logic control (PLC). A detailed piping and instrument diagram for the AnMBR pilot plant is shown in Figure 3.

Figure 3: Detailed piping and instrument diagram of the AnMBR pilot plant



2.3 Process Control

The AnMBR pilot plant was monitored and controlled using field sensors and a PLC system. A list of process sensors and measured variables is shown in Figure 3. The process control includes alarms and automatic shutdown procedures to prevent equipment damage in the event of abnormal process conditions.

3.0 Results

3.1 Site 1

3.1.1 Process Operation and Organic Loading

Site 1 is a cattle only facility location in Queensland, Australia that processes 1,200–1,400 head per day. At Site 1, the AnMBR pilot plant was inoculated with digested sludge from a crusted anaerobic lagoon at the site. At the time of inoculation the methanogenic activity of the inoculum was measured as 0.15g COD·gVS^{-1}·d^{-1}. This activity is within the range expected for lagoon sludge and therefore indicated the inoculum was healthy.

The AnMBR pilot plant was initially operating at a long hydraulic retention time of seven days to allow for acclimatisation of the anaerobic inoculum. During this initial operation, feed events occurred twice per week, using a burst feed at relatively high membrane flux. This strategy was used to test if the membrane could operate sustainably at flux rates of 6.25 L·m^{-2}·hr^{-1} (LMH) required to achieve the eventual target of operating at a HRT of one day. Once the biomass was acclimatised and the performance was stable, the plant switched to a continuous operating mode. A summary of operating periods and strategies is listed below:

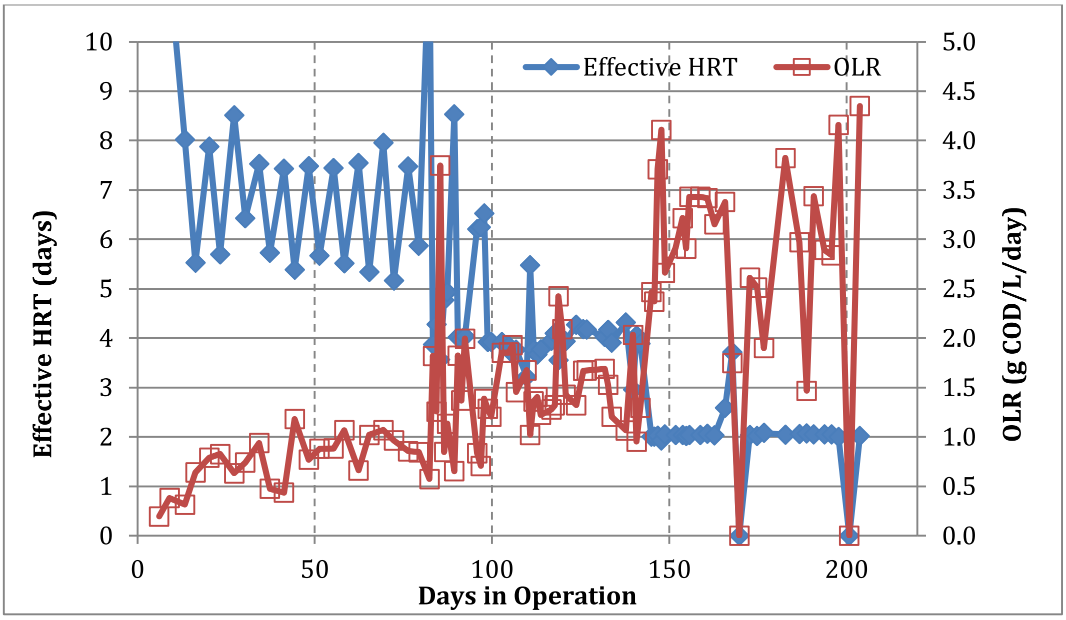
- Period 1.1 – HRT of seven days: Semi-batch operation. Reactor feed events occurred twice per week where 75 L was fed during a 12 hour feed cycle. Flux across membrane was 6.25 LMH.
- Period 1.2 – HRT of four days: Reactor feed events occurred each day. During a reactor feed event 40 L was transferred during a 12 hour feed cycle. Flux across the membrane was 3.5 LMH.
- Period 1.3 – HRT of two days: Reactor feed events occurred each day. During a reactor feed event 80 L was transferred during a 24 hour feed cycle. Flux across the membrane was 3.5 LMH.

The AnMBR pilot plant treated combined 'red stream' wastewater after primary treatment using dissolved air floatation. The composition of the wastewater feed is shown in Table 2. The AnMBR operating strategy is summarised in Figure 4. The wastewater treated at Site 1 was approximately 6 g COD·L^{-1}, which is less concentrated than meat processing wastewater measured in wastewater analysis projects A.ENV.0131 and A.ENV.0151.

Table 2: Composition of feed wastewater added to the AnMBR pilot plant

	TS	**VS**	**tCOD**	**sCOD**	**FOG**	**VFA**
	mg·L^{-1}	**mg·L^{-1}**	**mg·L^{-1}**	**mg·L^{-1}**	**mg·L^{-1}**	**mg·L^{-1}**
Minimum	1,200	900	2,084	470	266	11
Average	**3,378**	**2,834**	**5,919**	**1,187**	**1,407**	**159**
Maximum	7,000	6,200	13,381	2,778	5,953	566

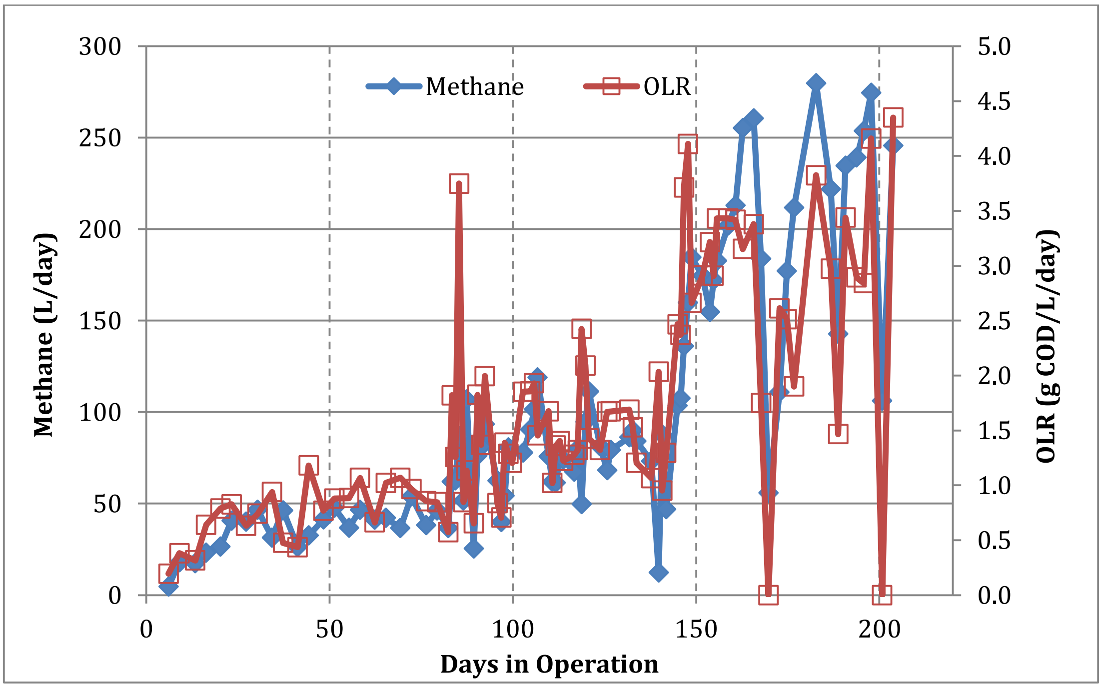
Figure 4: Effective HRT and OLR during the pilot plant operation



3.1.2 Process Performance

Biogas production is a primary performance indicator of anaerobic processes and indicates the potential for renewable energy production during the stabilisation of organic matter. Biogas production from the AnMBR pilot plant at different OLRs is shown in Figure 5.

Figure 5: Methane production from the AnMBR pilot plant compared to OLR



Chemical oxygen demand (COD) is a measure of the amount of oxygen to completely oxidise a material and is commonly used as an indirect measurement of organic matter in wastewater. COD cannot be created or destroyed in an anaerobic process therefore COD is an effective mass balancing tool to check data quality or to identify accumulation of sludge within the AnMBR. The COD balance in the AnMBR pilot plant during 220 days operation is shown in Figure 6. Initially there was some accumulation of COD within the AnMBR, likely due to some anaerobic sludge production. However, this trend was not maintained over time. During long-term operation of the AnMBR, the COD balance closed demonstrating there was virtually no accumulation of COD within the process. This result suggests the AnMBR could operate without the need for de-sludging events.

COD fed to the AnMBR pilot plant and removed as biogas or treated permeate is shown in Figure 7. COD removal from the wastewater was over 95% (i.e. less than 5% of COD from the wastewater feed remained in the treated permeate, while over 95% of COD was converted to biogas). The biogas composition was typically 70% methane (CH_4) and 30% carbon dioxide (CO_2). During full and steady operation methane production corresponded to approximately 760 L CH_4 per kg VS added (365 L CH_4 per kg COD added). By comparison, COD removal above 80% is also achievable in ALs and CALs, however the performance of lagoons systems is affected by hydrodynamics, seasonable temperature changes and accumulated sludge volumes. Therefore comparisons will be subjective.

Figure 6: COD balance in the AnMBR pilot plant during 220 days operation. The black line indicates that the feed COD is equal to the product COD. Where the data is below the black line, the reactor may have been accumulating sludge

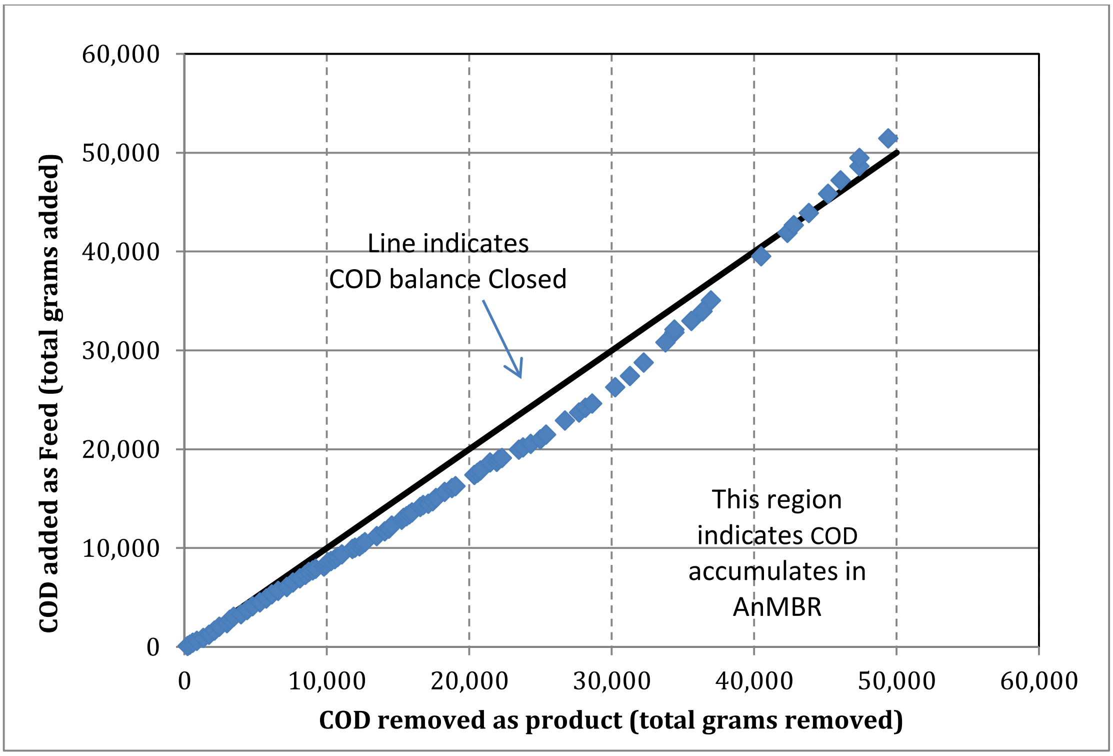
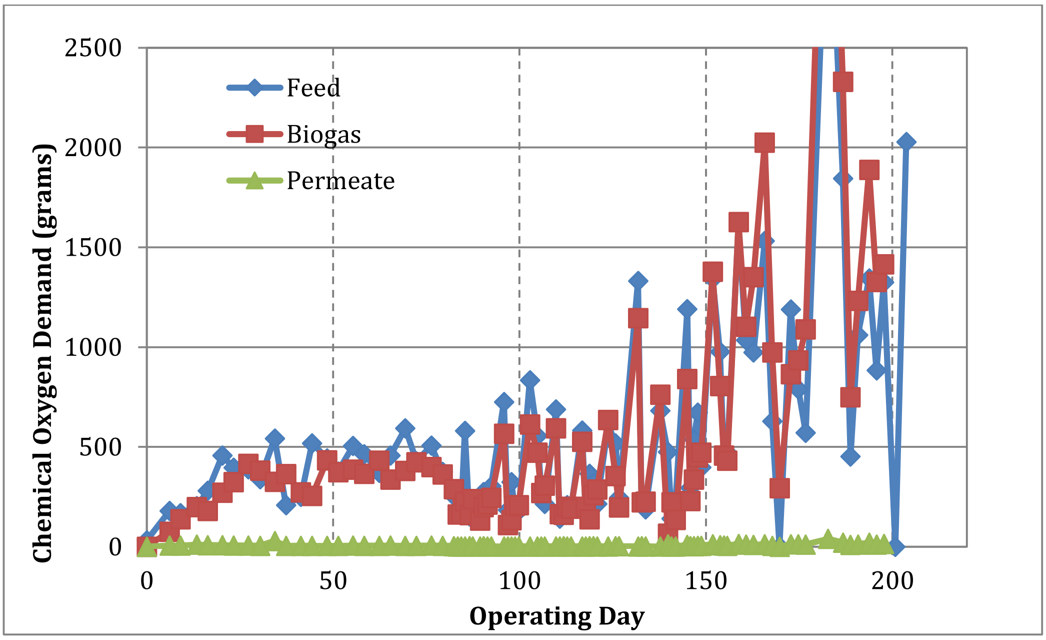


Figure 7: COD added to the AnMBR pilot plant and corresponding biogas production and permeate removal



The combination of biogas production and low VFA concentrations in the digester effluent were a good indication of a healthy and stable process.

Figure 8: Transmembrane pressure in the AnMBR is stable over time and indicated membrane fouling was sustainable

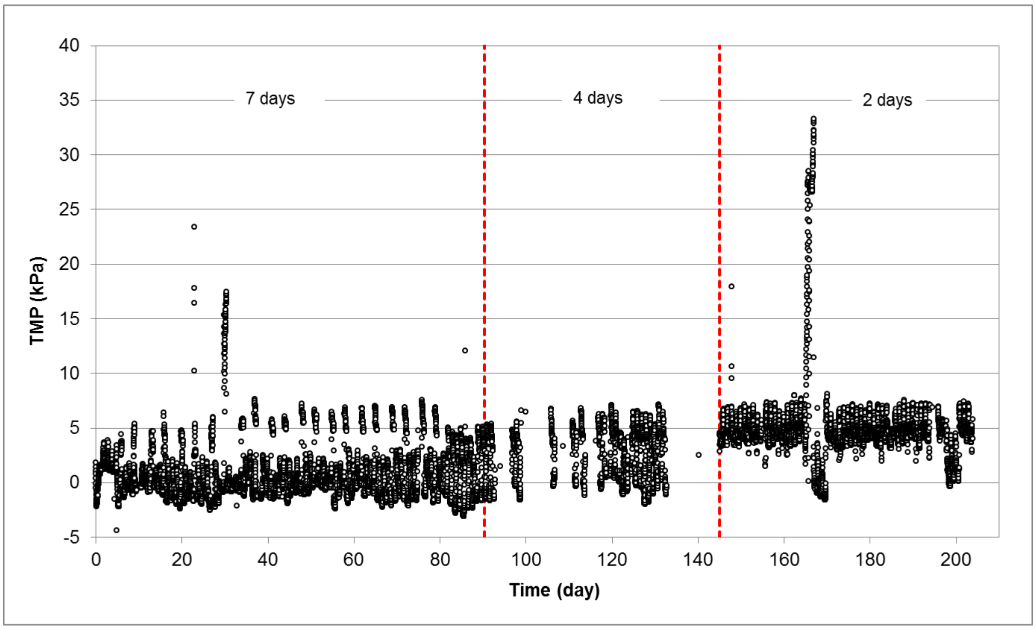


Table 3 is a summary of the AnMBR performance and compares the wastewater feed with the treated AnMBR permeate. Table 3 confirms COD removal in the process was over 95% and also shows that 90% of nitrogen is recovered in permeate as NH_3 while 74% of phosphorus is recovered in permeate as PO_4.

Table 3: Composition of feed wastewater added to AnMBR pilot plant

		TS	VS	tCOD	sCOD	FOG	VFA	TKN	NH_3-N	TP	PO_4-P
		$mg\cdot L^{-1}$	$mg\cdot L^{-1}$	$mg\cdot L^{-1}$	$mg\cdot L^{-1}$	$mg\cdot L^{-1}$	$mg\cdot L^{-1}$	$mg\cdot L^{-1}$	$mg\cdot L^{-1}$	$mg\cdot L^{-1}$	$mg\cdot L^{-1}$
	Min	1,200	900	2,084	470	266	11	107.6	12.0	8.9	3.7
Feed	**Avg**	**3,378**	**2,834**	**5,919**	**1,187**	**1,407**	**159**	**190.2**	**24.4**	**19.1**	**7.9**
	Max	7,000	6,200	13,381	2,778	5,953	566	294.8	59.6	34.6	17.3
	Min	N/A	N/A	23	23	N/A	6	139.6	124.0	8.4	8.3
Permeate	**Avg**	**N/A**	**N/A**	**71**	**71**	**N/A**	**15**	**172.6**	**170.2**	**14.1**	**12.8**
	Max	N/A	N/A	379	379	N/A	67	207.2	209.0	38.3	37.1

3.1.3 Performance Summary

The AnMBR pilot plant operated successfully at Site 1, with an organic loading rate of 3–3.5 $kgCOD.m^{-3}.d^{-1}$. This is more than an order of magnitude higher than the anaerobic lagoon at the host site. Higher organic loads and/or shorter retention times may be possible but were not tested due to a maintenance shutdown at the site.

3.2 Site 2

3.2.1 Process Operation and Organic Loading

Site 2 is a cattle only facility in New South Wales, Australia processing 1,200 head per day. At Site 2, the AnMBR pilot plant was inoculated with digested sludge from a crusted anaerobic lagoon at the site. At the time of inoculation the methanogenic activity of the inoculum was measured at less than 0.05g $COD \cdot gVS^{-1} \cdot d^{-1}$. This activity is low for anaerobic lagoon sludge and is much lower than the activity of inoculum sludge from Site 1. Therefore a conservative start-up strategy was essential. Operating periods and strategies for Site 2 are summarised as follows:

- Period 2.1 – HRT of four days: Reactor feed events occurred each day, during a reactor feed event 40 L was transferred during a 12 hour feed cycle. Flux across the membrane was 3.5 LMH.
- Period 2.2 – HRT of seven days: Reactor feed events occurred each day. During a reactor feed event 20 L was transferred during a 12 hour feed cycle. Flux across the membrane was 1.8 LMH.

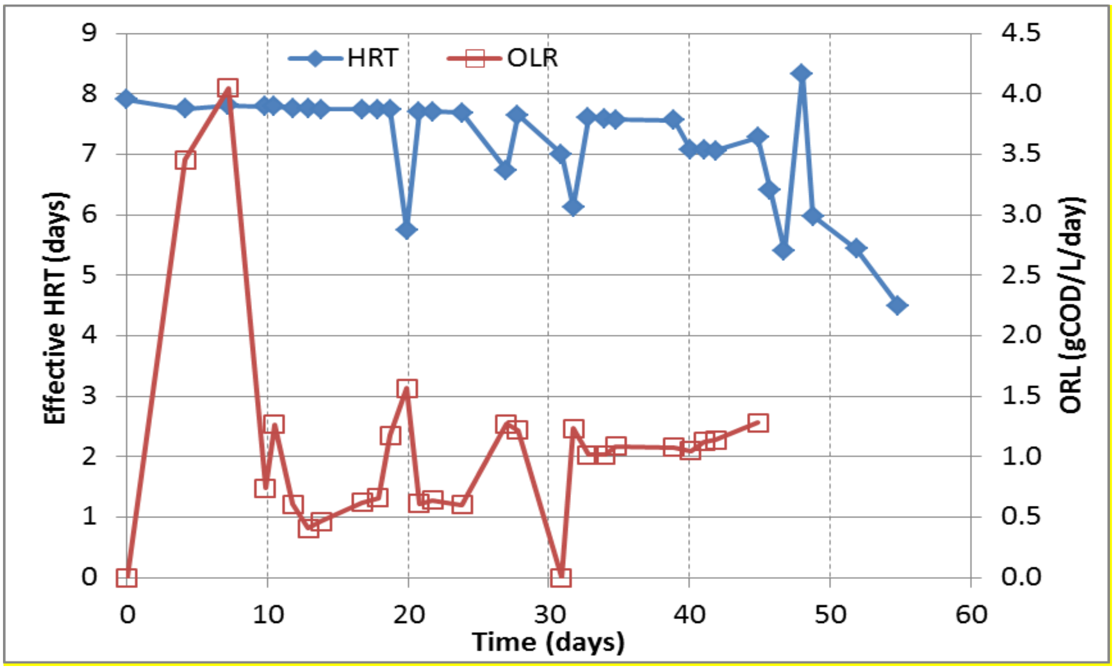
The AnMBR pilot plant treated combined 'red stream' wastewater before primary treatment or fat recovery. The composition of the wastewater feed is shown in Table 4. The wastewater treated at Site 2 was approximately 60% more concentrated than the wastewater from Site 1 and is more representative of red meat processing wastewater as measured in wastewater analysis projects A.ENV.0131 and A.ENV.0151.

Table 4: Composition of feed wastewater added to AnMBR

	TS	**VS**	**tCOD**	**sCOD**	**FOG**	**VFA**
	$mg \cdot L^{-1}$	**$mg \cdot L^{-1}$**	**$mg \cdot L^{-1}$**	**$mg \cdot L^{-1}$**	**$mg \cdot L^{-1}$**	**$mg \cdot L^{-1}$**
Minimum	770	385	3,163	156	403	6
Average	**5,532**	**4,692**	**9,956**	**1,506**	**2,042**	**230**
Maximum	22,122	18,413	48,575	3,705	5,640	477

During Period 2.1, several feed collections coincided with upstream disturbances at the site and the AnMBR received highly concentrated wastewater at five times the normal concentration, resulting in strong inhibition. The process was re-started using fresh inoculum and a more conservative start up strategy (Period 2.2). As the failure occurred during the initial start-up and acclimatised period, data will not be presented for Period 2.1. The AnMBR operating strategy for Period 2.2 is summarised in Figure 9.

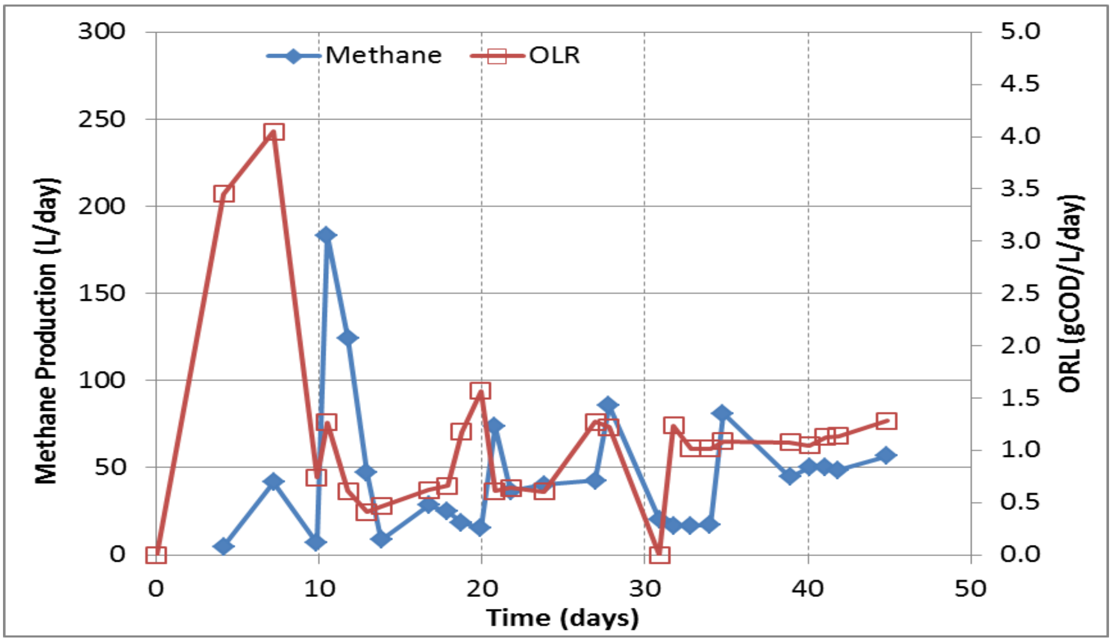
Figure 9: Effective HRT and OLR during the pilot plant operation



3.2.2 Process Performance

As at Site 1, biogas production was used as a primary performance indicator of anaerobic processes and the potential for renewable energy production. Biogas production from the AnMBR pilot plant at Site 2 is shown in Figure 10.

Figure 10: Biogas production from the AnMBR pilot plant at Site 2



The COD balance in the AnMBR pilot plant during 60 days operation at Site 2 is shown in Figure 11. Initially the COD in the AnMBR products was higher than the COD added as feed, this is likely due to some residual methane production from the anaerobic lagoon sludge used as inoculum. During longer term operation of the AnMBR the COD balance closed and demonstrated little or no accumulation of COD within the process. This result was consistent with Site 1 and suggests the AnMBR could operate without the need for de-sludging events.

COD added to the AnMBR pilot plant as feed and COD removed as biogas or treated permeate is shown in Figure 12. COD removal from the wastewater was over 90% (i.e. less than 10% of COD from the wastewater feed remained in the treated permeate while over 90% of COD was converted to biogas). The biogas composition was typically 70% methane (CH_4) and 30% carbon dioxide (CO_2).Dduring full and steady operation methane production corresponded to approximately 730 L CH_4 per kg VS added (345 L CH_4 per kg COD added). Similar to Site 1, the combination of biogas production and low VFA concentrations in the digester effluent at Site 2 were a good indication of a healthy and stable process.

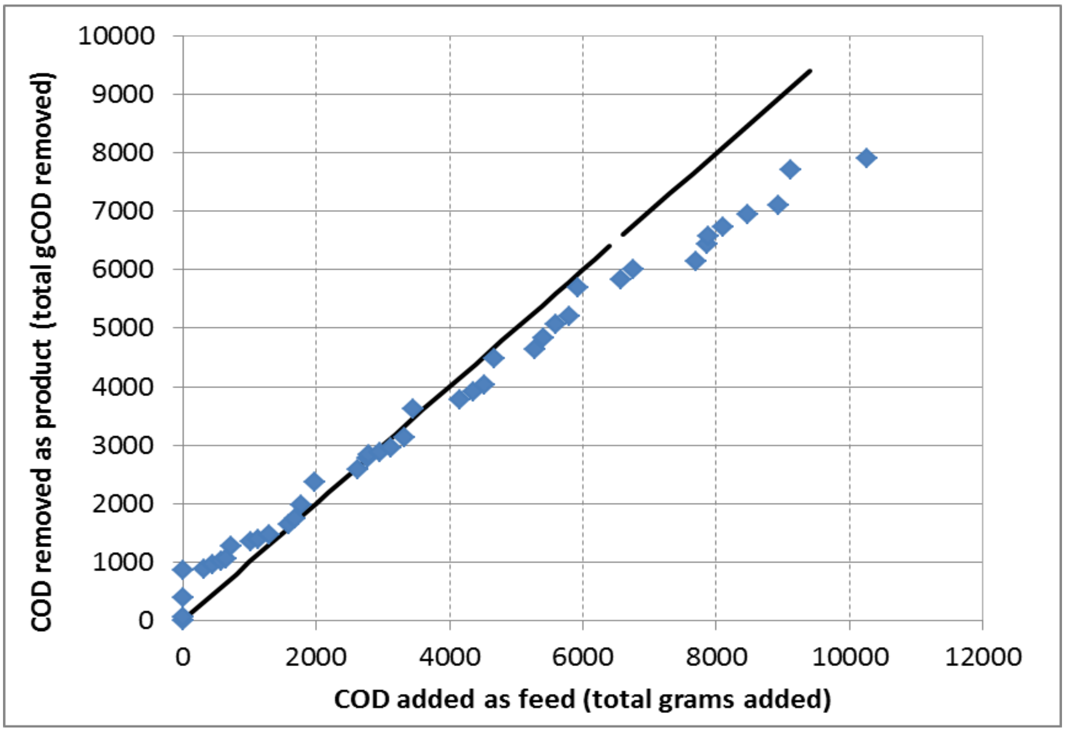
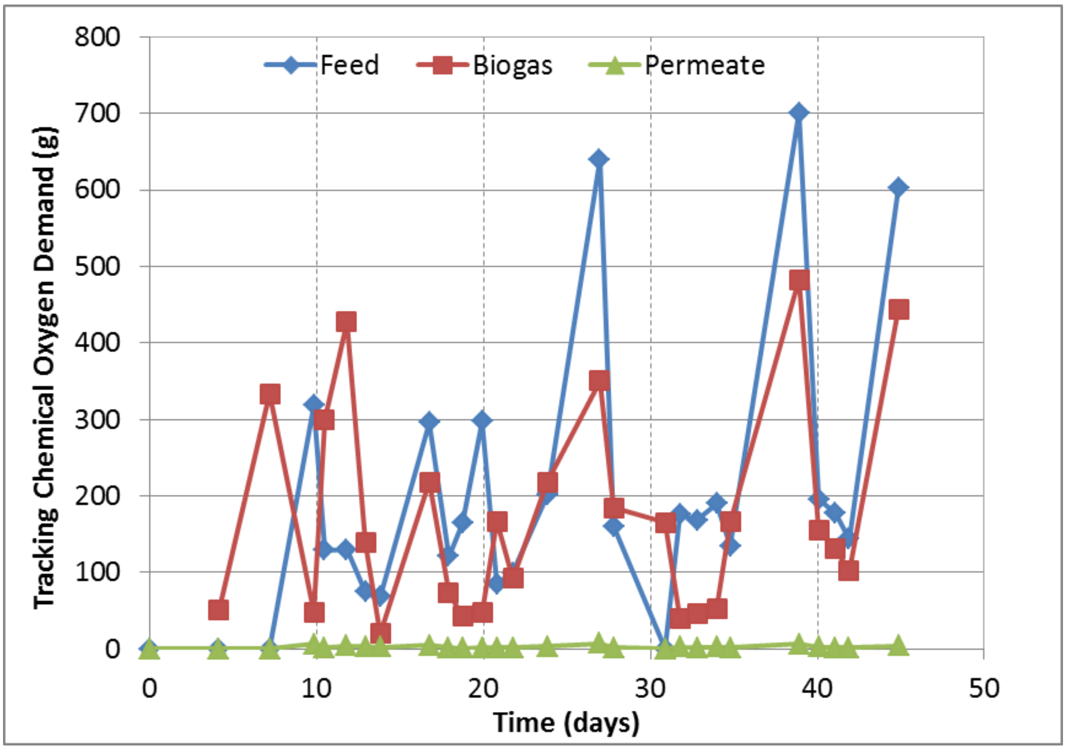


Figure 12: COD added to the AnMBR pilot plant and corresponding biogas production and permeate removal at Site 2



Transmembrane pressure (TMP), logged using the PLC is shown in Figure 13. The TMP is an indication of membrane fouling, and particularly an increase in TMP over time demonstrates membrane fouling is not sustainable and will require corrective action such as shut down/cleaning events. Figure 13 demonstrates no observable increase in TMP over time, indicating that membrane fouling is sustainable and under sufficient control in the AnMBR plant operation.

Figure 13: Transmembrane pressure in AnMBR pilot plant is stable at Site 2 and indicated membrane fouling was sustainable.

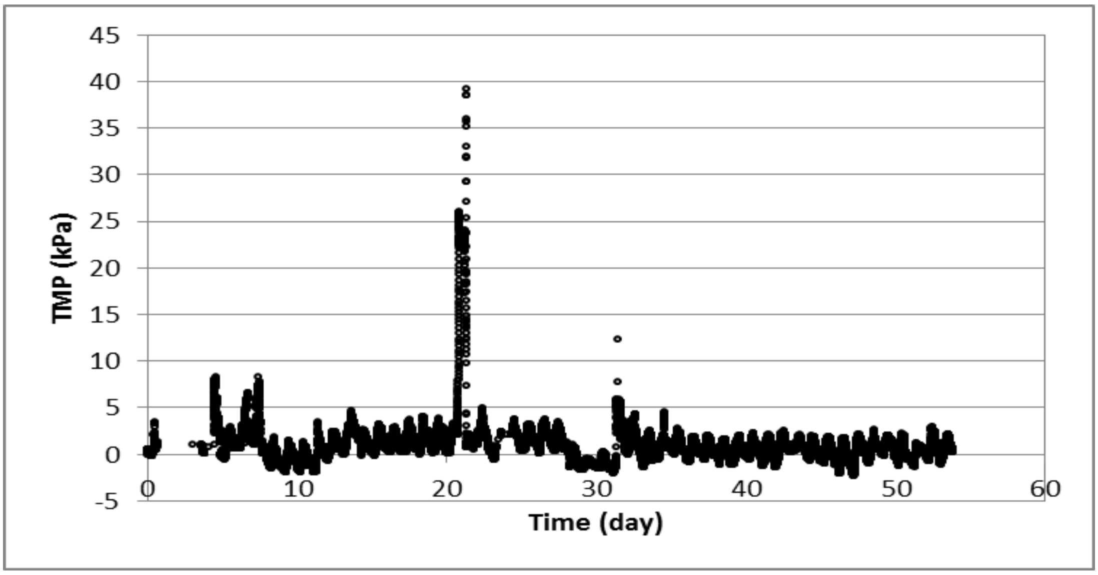


Table 5 is a summary of the AnMBR performance at Site 2 and compares the wastewater feed with the treated AnMBR permeate. Table 5 confirms COD removal in the process was over 90% and also shows that 87% of nitrogen is recovered in permeate while 78% of phosphorus is recovered in permeate, these results are consistent with the results at Site 1 and demonstrate plant operation is repeatable.

Table 5: Summary of operating performance of AnMBR Pilot Plant at Site 2

		TS	**VS**	**tCOD**	**sCOD**	**FOG**	**VFA**	**TKN**	**NH_3-N**	**TP**	**PO_4-P**
		mg·L^{-1}	**mg·L^{-1}**	**mg·L^{-1}**	**mg·L^{-1}**	**mg·L^{-1}**	**mg·L^{-1}**	**mg·L^{-1}**	**mg·L^{-1}**	**mg·L^{-1}**	**mg·L^{-1}**
	Min	770	385	3,163	156	403	6	146	8	18	3
Feed	**Avg**	**5,532**	**4,692**	**9,956**	**1,506**	**2,042**	**230**	**329**	**45**	**32**	**21**
	Max	22,122	18,413	48,575	3,705	5,640	477	808	133	114	76
	Min	N/A	N/A	38	38	N/A	0	163	160	18	15
Permeate	**Avg**	**N/A**	**N/A**	**83**	**83**	**N/A**	**8**	**286**	**252**	**25**	**24**
	Max	N/A	N/A	137	137	N/A	16	526	364	58	76

3.2.3 Performance Summary

The AnMBR pilot plant was operated successfully at Site 2, with an organic loading rate of 1-1.5 kg COD·m^{-3}·d^{-1}. This is lower than Site 1, but is still an order of magnitude higher than the CSIRO guidelines for anaerobic lagoons. Wastewater treated at Site 2 was 60% more concentrated than

Site 1; however the plant performance was comparable with similar COD removal, biogas production and nutrient release. Similar results between Site 1 and Site 2 demonstrate the process implementation and operating performance is repeatable. Higher organic loads and/or shorter retention times may be possible. It is recommended that AnMBR operation continue to determine maximum operating limits at Site 2.

4.0 Cost Benefit

4.1 Basis Used In Assessment

A cost–benefit analysis was conducted based on an Australian red meat processing plant processing 600 head per day, 250 days per year, with total effluent flow of 1.8 ML per day. Basic inputs are shown in Table 6.

Table 6: Wastewater flow, concentration, and load for cost–benefit analysis

	Concentration $mg{\cdot}L^{-1}$	Load
Flow		1.8 ML d^{-1}
COD	10,200 mg L^{-1}	18.4 tonnes d^{-1}
Solids	8,400 mg L^{-1}	15.1 tonnes d^{-1}
O&G	2,300 mg L^{-1}	4.2 tonnes d^{-1}
Nitrogen	405 mg L^{-1}	730 kg d^{-1}
Phosphorous	56 mg L^{-1}	100 kg d^{-1}

4.2 Cost Benefit Analysis

Two process design scenarios were used in the CBA. Scenario 1 was based on the technology configuration assessed in the pilot plant trials at Site 1 and Site 2 and the performance achieved (i.e. an immersed AnMBR system with a loading rate of 3.5 kg $COD{\cdot}m^{-3}{\cdot}d^{-1}$, using membrane flux of 6 $L{\cdot}m^{-2}{\cdot}h^{-1}$). Scenario 2 was based on a more optimised immersed AnMBR technology with a loading rate of 10 kg $COD{\cdot}m^{-3}{\cdot}d^{-1}$, using membrane flux of 10 $L{\cdot}m^{-2}{\cdot}h^{-1}$. The remainder of the design is based on the cost-benefit analysis done by Judd [4] for an immersed AnMBR.

The removal of 95% of COD was assumed, resulting in effluent of 300 mg $COD{\cdot}L^{-1}$, and production of 5,800 $m^{3}{\cdot}CH_{4}{\cdot}d^{-1}$, with a net heating capacity of 236 GJ/d. Overall capital costs are shown in Table 7. Only 10% of the capital costs are in membranes, while a far higher proportion of costs are in the vessel (approximately 50%). In the analysis by Judd, membrane costs were 50% of the total install cost, while for this analysis it is far lower (due to the higher strength wastewater). This resulted in a much lower proportion of the costs attributable to membranes, and based on this finding a high emphasis on optimisation of the whole process is recommended for further research.

It was assumed that the biogas captured would be put through a cogeneration engine to produce electricity and heat. However, the utilisation of the biogas is likely to vary from site to site. For example, the biogas may be used to feed a boiler only, or could be used to feed a trigeneration system to produce heat, power and cooling.

Table 7: Capital costs for 1.8 ML capacity AnMBR plant*

Capital costing	Scenario 1 ($)	Scenario 2 ($)
Reactor	4,196,571	1,468,800
Membranes	729,000	291,600
Piping	49,962	19,653
Foundation	99,924	39,307
Gas piping etc.	29,977	11,792
Electrical and installation	29,977	11,792
Cogeneration engine	1,195,000	1,195,000
Total installed capital	6,330,411	3,037,944
Engineering	633,041	303,794
Total capital cost	**6,963,000**	**3,342,000**

*Units common to any wastewater treatment option, such as DAF, equalisation and screens have not been included in this analysis.

AnMBR operating costs were estimated based on current pricing, including electricity at $0.15/kWh, heating energy at $20/GJ, personnel at $80,000 per full time equivalent, recovered phosphorous at $3.50/kg P, recovered nitrogen at $1.33/kg N, and normal chemical costs for cleaning chemicals, magnesium oxide etc. The operating costs estimated during the CBA are shown in Table 8.

Table 8: Operating costs for 1.8 ML case study

Operational costing	Scenario 1 ($)	Scenario 2 ($)
Vessel and piping	102,708	36,859
Cogeneration maintenance	59,750	59,750
Personnel	12,000	12,000
Energy usage	11,488	4,021
Total cost	**185,946**	**112,630**
Energy value	- 955,868	- 955,868
Nutrient value	- 89,500	- 89,500
Total revenue	**- 1,045,368**	**- 1,045,368**
Net operating cost	**- 859,422**	**- 932,738**

4.3 Technology Comparison

A comparison of AnMBR technology against current treatment processes is shown in Table 9. The comparison shows that the payback period of an AnMBR is comparable to a CAL, when idealised design parameters of 10 kg COD·m^{-3}·d^{-1} loading rate and 15 L·m^{-2}·h^{-1} membrane flux are used. However the payback remains high when using parameters demonstrated in this project.

Project results demonstrated the AnMBR was not operating at maximum capacity. This highlights the potential for improved economic outcomes through continued research into process optimisation. There are several areas for improvement: i) optimisation of the OLR will reduce capital costs of the process vessels, ii) optimisation of membrane flux will reduce membrane surface area requirements and associated capital costs, and iii) optimised fouling control will reduce operating expenses.

Operating costs of an AnMBR show improved revenue compared to a CAL. This is due to increased gas capture resulting in improved energy recovery and the potential to recover nutrients (however the nutrient value represents only 20% of revenue). There are additional benefits such as reduced footprint and improved environmental performance, however these benefits have not been quantified in the current analysis and the potential impact of these benefits may be specific to each processing facility.

Table 9: Technology comparison for removal of organic contaminants for 1.8 ML case study

Organic Treatment Process	Capital ($)	Operating Cost ($/Yr)	Revenue ($/Yr)	Payback (Yrs)	Foot Print (M^2)	Greenhouse Gas Emissions	Waste Discharge Quality	Potential for Odour
None - Sewer Discharge	78,000	1,956,371	-	-	-	Very High	Very Poor	High
Crusted anaerobic lagoon	719,000	44,235	-	-	23,000	Very High	Good	High
Covered anaerobic lagoon	2,161,000	100,334	-637,245	4	23,000	Very Low	Good	Medium
AnMBR scenario 1	6,963,000	185,946	-955,868	9	370	Very Low	Very Good	Low
AnMBR scenario 2	3,342,000	112,630	-955,868	4	734	Very Low	Very Good	Low

5.0 Recommendations

During this project, the AnMBR pilot plant was operated to remove over 95% of COD from mixed 'red stream' wastewater. Virtually all COD removed was converted to biogas with almost no accumulation of COD within the process. The biogas composition was typically 70% methane (CH_4) and 30% carbon dioxide (CO_2). During full and steady operation methane production corresponded to approximately 760 L CH_4 per kg VS added (365 L CH_4 per kg COD added). The AnMBR pilot plant achieved an OLR of 3–3.5 kg $COD\cdot m^{-3}\cdot d^{-1}$. This is more than an order of magnitude higher than an anaerobic lagoon (OLR for CAL recommended by CSIRO is 0.08 kg $COD\cdot m^{-3}\cdot d^{-1}$). While operation of the AnMBR pilot plant has been highly successful, several areas have been identified for further research and optimisation:

- The maximum OLR to the AnMBR has not been identified and validated.
- The mechanisms of inhibition and/or process failure at the maximum OLR have not been determined and process remediation strategies have not been developed.
- During operation of the AnMBR pilot plant, nutrient recovery in the effluent accounted for 90% of nitrogen (as NH_3) and only 74% of phosphorus (as PO_4). This suggests that the AnMBR is not optimised for nutrient recovery.
- Similar trends were observed when examining CAL influents and CAL effluents, where up to 50% of phosphorus in the abattoir wastewater was accumulating in the CAL and therefore not available for recovery.

Economic comparisons show that the payback of an AnMBR is comparable to a CAL, when idealised design parameters of 10 kg $COD\cdot m^{-3}\cdot d^{-1}$ loading rate and 15 $L\cdot m^{-2}\cdot h^{-1}$ membrane flux are used. However the payback period remains high when using parameters demonstrated in this project. Project results also demonstrated the AnMBR was not operating at maximum capacity, this highlights the potential for improved economic outcomes through continued research into process optimisation. Process vessels are the major component of capital expenditure, and therefore research into process optimisation that targets increased OLRs (and therefore reduced reactor volumes) is recommended to minimise capital requirements.

Financial forecasts show that an AnMBR can generate more revenue compared to a CAL due to increased biogas capture (resulting in improved energy recovery) and the potential to recover nutrients (nutrient value represents only 20% of revenue). While nutrient availability from an AnMBR already exceeds that from a CAL, the phosphorus release was significantly less than the COD removal (over 90% of organics were degraded, but only 74% of phosphorus released). This data demonstrates that anaerobic treatment steps have not been optimised for nutrient recovery; this reduces the potential for nutrient recovery and value adding. Further research is recommended to re-tool anaerobic treatment and nutrient recovery processes and integrate them as an optimised treatment train. Optimisation of the integrated process should focus on maximising the release of nutrient in the anaerobic step to facilitate recovery in a crystalliser. Operation of the anaerobic step at slightly depressed pH is a potential strategy to prevent loss of nutrients; however this may impact process rates and/or stability and therefore must be investigated rigorously.

6.0 References

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Glossary

AD	Anaerobic digestion
AL	Anaerobic lagoon
AnMBR	Anaerobic membrane bioreactor
CAL	Covered anaerobic lagoon
CBA	Cost benefit analysis
CFD	Computational fluid dynamics
CH_4	Methane
CO_2	Carbon dioxide
COD	Chemical oxygen demand
DAF	Dissolved air flotation (tank)
FOG	Fat, oils and grease
HRAT	High-rate anaerobic technology
HRT	Hydraulic residence time
IVAD	In-vessel anaerobic digestion
N	Nitrogen
NGERS	National Greenhouse and Energy Reporting Scheme
NH4-N	Ammonium nitrogen
OLR	Organic loading rate
P	Phosphorus
PLC	Process logic control
PO4-P	Phosphate phosphorus
sCOD	Soluble chemical oxygen demand
SRT	Sludge retention time
tCOD	Total chemical oxygen demand
TP	Total phosphorus
TKN	Total Kjehldahl nitrogen
TKP	Total Kjehldahl phosphorus
TMP	Transmembrane pressure
TS	Total solids
TSS	Total suspended solids
UASB	Upflow anaerobic sludge blanket
VFA	Volatile fatty acids
VS	Volatile solid