final report

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Churchill Abattoir Wastewater Characterisation

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Abstract

The cost of water supply and water treatment are major costs of Australian red meat processes. This report aims to determine suitable and cost-effective processes for treating wastewater at Churchill Abattoir to a standard suitable for reuse in production; and to identify the potential impacts of changes to upstream treatment and waste handling.

Churchill Abattoir produces 3 main wastewater streams with a combined flow 1.4 ML/d. Analysis shows that the combined wastewater could produce approximately 118 GJ/d of energy at a value of approximately $1,500/d, however this value could decrease by more than 50% if primary treatment was added to divert FOGs in the wastewater to co-products (Tallow). Installation of an RO plant (including RO + disinfection) would generate an estimate 950 kL/d of high quality water at a value of $4,650/d. However, the RO plant is energy intensive and the costs of generating high quality water are currently cost neutral. There may be significant opportunities to improve the economic potential of water recycling through optimisation of the RO plant, particularly energy requirements.

Executive summary

Churchill Abattoir is one of Australia's largest domestic-only beef abattoirs, currently processing approximately 600 head of cattle per day (3,000 head per week), with a planned extension that could lead to an increased operational throughput of 1,200 head per day (6,000 head per week). The site's current water consumption is approximately 700kL/day, however this could increase to 1.2 – 1.4ML/day during expansion.

The purpose of this initial investigation is to characterise the 3 main wastewater streams generated by Churchill Abattoir as well as the final treated effluent produced by the existing treatment lagoons. The intent is to determine suitable and cost-effective processes for treating the wastewater to a standard suitable for reuse in production; and to identify the potential impacts of changes to upstream treatment and waste handling.

Currently, CA produce 3 main wastewater streams. These streams originate from slaughterfloor/rendering, paunch handling and cattle yards. Currently the streams are screened and passed through a settling tank before treatment in a series of anaerobic and facultative lagoons before irrigation discharge. Analysis shows that the combined wastewater could produce approximately 3,400 m3/d of methane (118 GJ/d), and that more than 85% of this methane is attributed to the slaughterfloor/rendering. Currently, there is limited primary treatment on the wastewater streams. The addition of a saveall or dissolved air flotation to capture FOGs would significantly reduce methane potential of the wastewater. Effective primary treatment would reduce the methane potential by more than 50% (i.e. to less than 60 GJ/d).

Water recycling regulations vary between domestic and export markets. Recycled water can be produced at non-potable standard, suitable for use in areas that do not contact meat or meat surfaces, or higher quality standards that may be suitable for broader use within a red meat processing plant. Production of higher quality water comes at higher cost, therefore it is critical to match the treatment process with the intended use of the water. Within Australia, there are pathways to enable water recycling within meat processing areas, albeit with strict treatment and quality control requirements. US and European markets are currently less flexible and recycled water cannot currently be used in contact with meat surfaces. CA is currently a domestic-only beef abattoir. CA is investigating expansion plans, however the focus is on the Chinese market, which does not specifically restrict the use of high quality recycled water. Therefore, three case studies were used to compare treatment options to enable water recycling at either non-potable recycled water (dual reticulation) or highly treated standards:

- Current treatment without nitrogen removal. Follow by tertiary treatment and recycling,
- Conventional nitrogen removal. Follow by tertiary treatment and recycling,
- Emerging low-cost nitrogen removal. Follow by tertiary treatment and recycling.

While production of both non-potable recycled water (dual reticulation) and highly treated water (suitable for contact with meat surfaces) was considered in the analysis, application of tertiary treatment technologies to produce non-potable recycled water at CA is not recommended. CA already re-uses partially treated water in the cattle yards and there is limited potential to increase water re-use at non-potable standard. Regarding the production of high quality recycled water, Case study 1 has the lowest capital cost, however the technical viability of membrane filtration after the current treatment (and without nutrient removal) is not clear. High levels of COD (including some degradable COD), nutrients and alkalinity are all technical challenges. This option may require very high chemical dosing to enable the process to function and this reduces the economic potential. Case study 2 uses effective and well established technologies, however the capital and operating costs are the highest of the options considered. Based on analysis in this report, the treatment process recommended for production of high quality recycled water at CA is Case Study 3, which includes:

- Covered anaerobic lagoon to remove organics and recover energy,
- Anaerobic ammonium removal and a membrane bioreactor for nitrogen removal.
- RO plant is included to produce high quality water suitable for use in the processing areas.

Installation of a CAL is estimated to cost $1.8M and would enable recovery 118 GJ/d of energy from the CAL to offset 11,500 kWh per day (0.35 electrical efficiency) at a value of approximately $1,500/d (based on $0.13/kWh). Installation of an RO plant (including RO + disinfection) is estimated to cost $1.85M and would to generate an estimate 950 kL/d of high quality water at a value of $4,650/d. The RO plant is energy intensive and therefore the operating costs are relatively high at $1.2M/r. Over $1M/yr of this cost is due to the energy demand of the RO system. Based on the current energy cost calculations, the cost of generating high quality water is approximately cost neutral, however there is significant potential to reduce these costs through R&D or process optimisation.

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1 Background

1.1 Introduction

Churchill Abattoir is one of Australia's largest domestic-only beef abattoirs, currently processing approximately 600 head of cattle per day (3,000 head per week), with a planned extension that could lead to an increased operational throughput of 1,200 head per day (6,000 head per week). The site's current water consumption is approximately 700kL/day, however this could increase to 1.2 – 1.4ML/day during expansion.

Supply of fresh water and subsequent treatment of effluent water represent major operating costs for many Australian abattoirs, including CA. With typical water supply costs of approximately $2.20/kL nationally and $4.60/kL in SE QLD. Churchill Abattoir is above average water costs at $4.90/kL, with additional costs for treatment and/or discharge, with water usage of 700 kL/d and 200 operating days per year (4 days per week), water costs an estimated $700k per year and could rise above $1.5M during expansion.

Recent AMPC research (2016/1012) highlighted four strategies to reduce fresh water consumption and costs associated with water:

1. Water conservation: save up to 10% of fresh water consumption for all size sites.
2. Water reuse: save up to 15% of fresh water consumption for all size sites.
3. Water recycling – non-potable standard: save up to 50% of fresh water consumption for all medium to large sites.
4. Water recycling – potable standard: save more than 70% of fresh water consumption for large size sites.

However, this work also highlighted that technology selection and cost-benefit outcomes were likely to be site dependant.

Currently, CA produce 3 main wastewater streams. These streams originate from slaughterfloor/rendering, paunch handling and cattle yards. Currently the streams are screened and passed through a settling tank before treatment in a series of anaerobic and facultative lagoons before irrigation discharge. In addition to technologies that reduce water costs, CA are evaluating changes to the existing treatment process, including the addition of improved primary treatment (e.g. Improved blood collection systems, Saveall/DAF, covered lagoons, alternative solids treatment/handling).

The purpose of this initial investigation is to characterise the 3 main wastewater streams generated by Churchill Abattoir as well as the final treated effluent produced by the existing treatment lagoons. The intent is to determine suitable and cost-effective processes for treating the wastewater to a standard suitable for reuse in production; and to identify the potential impacts of changes to upstream treatment and waste handling.

The link between process performance and food safety is a critical requirement in water reuse and recycling. There are currently very few case studies of successful water recycling in the Australian red meat industry and this limited industry experience represents a potential risk for meat processers. This project will explore innovative business models that incorporate the use of broader water treatment experience through the collaboration between universities, industry associations, red meat producers and water utilities, to reduce the risk and add value for meat processors.

1.2 Water Quality Guidelines

Wastewater can be treated to reach different water quality standards by using different technologies. A summary of water quality guidelines is shown in Table 1. To date, non-potable recycled water (Class A+) can be used for:

- Stockyard washing (but not final wash)
- Truck washing
- Amenities
- Fire control
- Irrigation
- Cooling systems
- Boiler feed
- Cleaning in place system
- Inedible offal processing
- Steam production (not for meat production contact)
- Cattle drinking water
- Animal washing (not final)
- Floor washing

Depending on the end use, the quality of recycled water can differ. For example, stockyard wash and truck wash does not need to have high quality water. Direct water reuse might be a better option for these end-uses. Boilers and chillers need high quality water as ions (metals, salts) can corrode the system. In non-potable boiler/chiller applications pathogens are tolerated up to 105 colony forming per unit, however Legionella bacteria can be an issue for boilers and should be absent.

To recycling water in areas that contact meat or meat surfaces, water must be at a higher standard, essentially at potable standard. The main differences between non-potable Class A+ and potable standard (Highly treated) are increased pathogen reduction and the need to monitor and validate the treatment train (AWRCoE 2014). This generally requires UF, RO and UV treatments and an online monitoring and validation system (Pype et al. 2016).

Table 1: Water quality guidelines.

	Cattle drinking water[a]	Non-potable (Dual reticulation, toilet flushing)[b]	Highly treated recycled water[c]
pH	6-8.5	6-9	6.5-8.5
COD (mg/L)	ND	ND	ND
BOD (mg/L)	20	ND	ND
TSS (mg/L)	30	ND	ND
Oil & Grease (mg/L)	ND	ND	ND
Total N (mg/L)	ND	ND	ND
Total P (mg/L)	ND	ND	ND
Ammonia (mg/L)	ND	ND	0.5
TDS (mg/L)	4000	ND	600
EC (µS/cm)	5970[d]	ND	600[d]
E.coli (CFU/100mL)	1.E+02	<1	8 LRV
Thermotolerant coliforms (CFU/100mL)	1.E+02	5 LRV	8 LRV
Protozoa oocysts (CFU/100mL)	ND	5 LRV	8 LRV
Somatic coliphage (PFU/100mL)	ND	6.5 LRV	9.5 LRV
Turbidity (NTU)	ND	ND	<1

[a] National Water Quality Management Strategy, paper No. 4, Australian and New Zealand guidelines for fresh and marine water quality, Vol 1, October 2000. Australian guidelines for water recycling: managing health and environmental risks (phase 1), 2006, Table 3.9 p113.

[b] Australian guidelines for water recycling: managing health and environmental risks (phase 1), 2006, Table 3.8 p103.

[c] Australian drinking water guidelines, 2011 (version 3.1 updated March 2015) for organic contaminants. Australian guidelines for water recycling: managing health and environmental risks (phase 2), 2007, p31.

[d] EC for beef cattle with no adverse effects on animals expected.

2 Project Objectives

- To characterise the source, volume, composition and temperature of waste streams produced at Churchill Abattoir.
- To characterise the performance of the existing onsite waste/wastewater treatment technology.
- To establish the treatment requirements for reuse of treated water, including applications requiring contact with meat/meat surfaces.
- To develop and/or evaluate innovative business models for onsite water recycling.

3 Waste Stream Analysis

3.1 Existing Treatment Flowsheet

A summary of waste production and wastewater handling practices at CA are shown in Figure 1.

QUU collected samples from 4 site locations across 4 sample days. Sampling consisted of a composite sample taken from an auto-sampler. QUU sample locations are shown in Figure 1 and sample dates are shown below:

- QUU Sample Day 1: 26/04/2017
- QUU Sample Day 2: 02/05/2017
- QUU Sample Day 3: 10/05/2017
- QUU Sample Day 4: 17/05/2017

UQ collected samples from 8 site locations across 4 sample days. Sampling consisted of a series of grab samples throughout the day and combined to form a daily composite. UQ sample locations are shown in Figure 1 and sample dates are shown below:

- UQ Sample Day 1: 03/05/2017
- UQ Sample Day 2: 12/05/2017
- UQ Sample Day 3: 17/05/2017
- UQ Sample Day 4: 26/05/2017

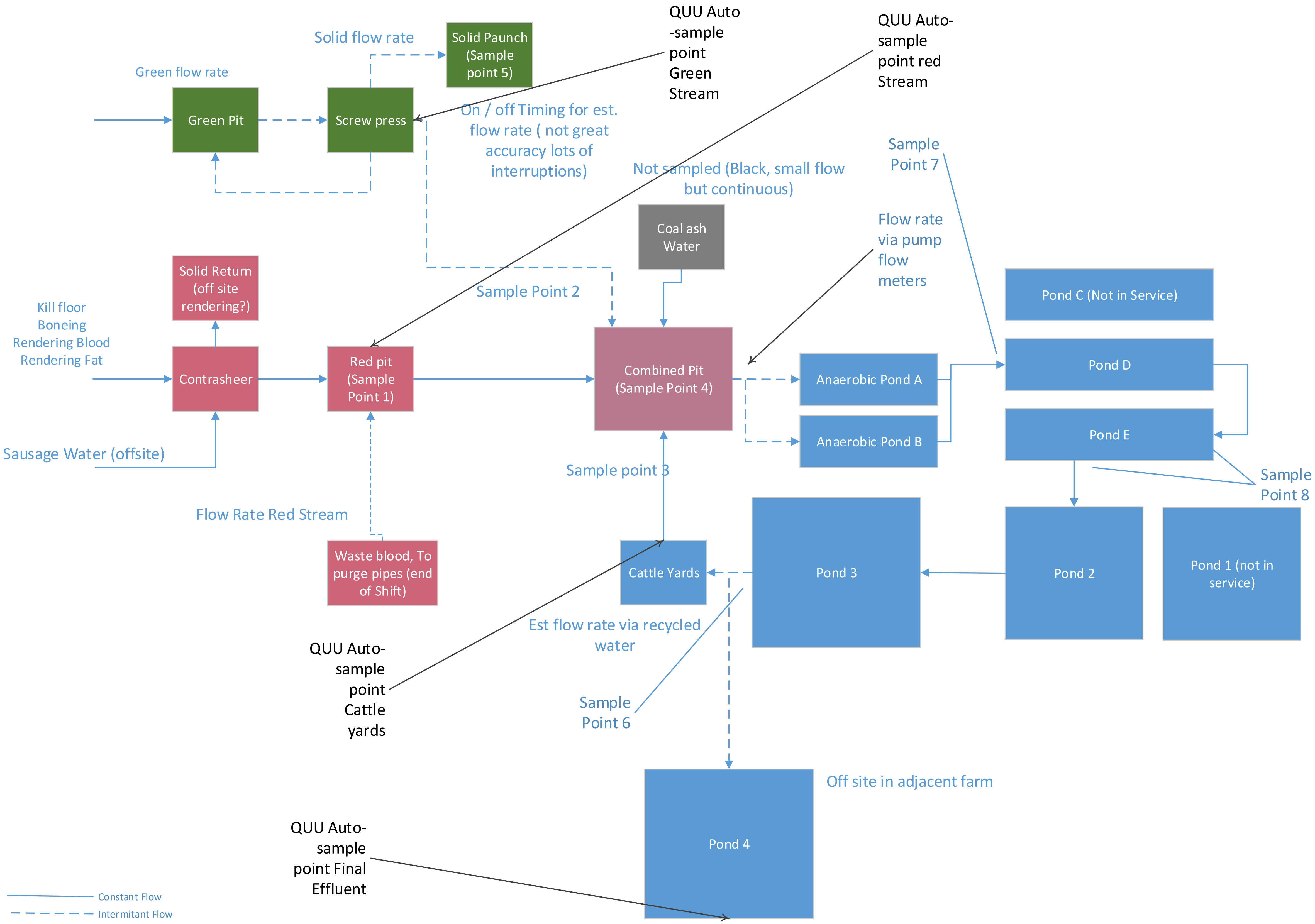

Figure 1: Flowsheet of the waste treatment train at CA and sample locations

3.2 Wastewater Analysis

3.2.1 Chemical Analysis

Table 2 shows average chemical composition data for samples collected from Churchill Abattoir by QUU. QUU samples were generally analysed from composite samples collected using an auto-sampler. Generally, the compositions were similar for samples collected on each sample day. Sample collection by QUU focused on characterising the source of the wastewater and the final treated effluent used in irrigation.

Table 2: Average chemical composition for samples collected by QUU

Description	Units	Red Stream	Green Stream	Cattle Yard	Treated Effluent
Escherichia coli	cfu/100mL				70
pH	pH Unit	6.4	7.0	8.2	8.1
Total Alkalinity as $CaCO_3$	mg/L	394	1380	862	511
COD as O_2	mg/L	13725	14500	1093	150
Sol. COD as O2	mg/L	3000	2450	380	75
BOD 5 days @ 20°C	mg/L				17
Soluble BOD 5 days @ 20°C	mg/L				<10
Suspended Solids	mg/L	4425	7950	725	47
VSS	mg/L	4225	7125	555	31.8
Ammonia N	mg/L	76.8	122.5	220	77.8
Nitrite N	mg/L	0.2	0.38	0.06	1.33
Nitrate N (Calc)	mg/L	1.5	0.037	<0.02	0.17
Nitrite+Nitrate as N	mg/L	0.56	0.15	0.04	1.52
Total Kjeldahl Nitrogen - N Calculated	mg/L	503	553	285	90
Total Nitrogen as N	mg/L	503	553	285	91
Ortho Phosphorus as P	mg/L	48	198	36	31
Total Phosphorus as P	mg/L	66	243	62	36
Arsenic as As	mg/L	<0.05	<0.05	<0.05	<0.05
Cadmium as Cd	mg/L	<0.005	<0.005	<0.005	<0.005
Calcium as Ca	mg/L	51.8	185.0	44.3	29.3
Chromium as Cr	mg/L	<0.01	0.013	<0.01	<0.01
Cobalt as Co	mg/L	<0.01	0.01	<0.01	<0.01
Copper as Cu	mg/L	0.08	0.21	0.034	<0.005
Lead as Pb	mg/L	<0.7	<0.6	<0.5	<0.8
Magnesium as Mg	mg/L	20	40	28	20
Nickel as Ni	mg/L	<0.05	0.02	<0.05	0.01
Zinc as Zn	mg/L	0.42	1.78	0.25	0.01

Table 3 to Table 6 show average data from chemical characterisations of samples collected by UQ. UQ samples were based on a daily composite for each stream. The daily composite contained a series of manual grab samples timed throughout the day to capture and represent the average wastewater characteristics across operating shifts and breaks. Generally, the compositions were similar for samples collected on each sample day.

Importantly, the compositions of red wastewater, green wastewater and cattle yard wastewater measured by QUU and UQ were similar, increasing confidence in this data.

Table 3: Average composition from key sample points in the Churchill Abattoir waste treatment trains – solids, organics, carbon part 1

Sample Description	Volume	Temp	TCOD	SCOD	TS	VS	VS/TS	TSS	VSS	VSS/TSS	COD/VS	VFA
	kL/d	degC	mg.kg^{-1}	mg.kg^{-1}	mg.kg^{-1}	mg.kg^{-1}	ratio	mg.kg^{-1}	mg.kg^{-1}	ratio	ratio	mg.kg^{-1}
SP1: Red Stream	715	40	11,903	4,027	7,029	6,284	0.87	4495	4015	0.89	1.96	298
SP2: Green Stream (post fan press)	73	31	14,883	2,620	10,382	7,944	0.76	8225	7350	0.89	1.87	694
SP3: Cattle Yard	340		1,260	294	1,957	832	0.39	1625	350	0.20	1.70	90
SP4: Combined (to Ponds)	1,300		8,817	2,649	5,672	4,693	0.77	5275	4050	0.77	2.10	291
SP5: Paunch Solid	22.5		114,787	N/A	250,958	232,793	0.94	224976	217908	0.97	0.46	217
SP6: Treated Pond Effluent			443	170	1,248	303	0.23	1225	100	0.08	1.79	62
SP7: Mid Treatment train (after anaerobic)			627	140	1,524	441	0.25	1450	375	0.20	1.99	65

Table 4: Average composition from key sample points in the Churchill Abattoir waste treatment trains – solids, organics, carbon part 2

Sample Description	TOC	TC	IC	Partial Alkalinity (pH 5.7)	Total Alkalinity (pH 4.3)	Cond	Turb	Colour
	mg.kg^{-1}	mg.kg^{-1}	mg.kg^{-1}	mg $CaCO_3$.L^{-1}	mg $CaCO_3$.L^{-1}	mS/cm	NTU	(Pt/Co)(Hz)
SP1: Red Stream	848	1057	207	139	414	2.12	3303	12110
SP2: Green Stream (post fan press)	1012	1198	186	636	1450	3.73	5934	9203
SP3: Cattle Yard	128	177	48	955	1221	3.48	1335	823
SP4: Combined (to Ponds)	1117	1146	30	477	896	3.04	1949	6696
SP5: Paunch Solid				1520	2475	N/A	N/A	321
SP6: Treated Pond Effluent	1194	1375	181	910	1139	3.43	173	520
SP7: Mid Treatment train (after anaerobic)	805	948	143	966	1256	3.53	357	588

Table 5: Average composition from key sample points in the Churchill Abattoir waste treatment trains – key nutrients

Sample Description	**TKN**	**NH3/NH4-N**	**TP**	**PO4-P**	**S**	K	Mg	Na	Cl
	mg.kg^{-1}	**mg.kg^{-1}**	**mg.kg^{-1}**	**mg.kg^{-1}**	**mg.kg^{-1}**	mg.kg^{-1}	mg.kg^{-1}	mg.kg^{-1}	mg.kg^{-1}
SP1: Red Stream	474	50	62	39	48	82.1	20.7	243	393
SP2: Green Stream (post fan press)	1295	116	226	165	46	203.0	40.0	617	358
SP3: Cattle Yard	799	183	63	31	20	120.8	31.0	265	392
SP4: Combined (to Ponds)	516	133	89	67	39	120.5	29.1	309	387
SP5: Paunch Solid	3952	N/A	560	N/A	399	349.2	230.6	883	N/A
SP6: Treated Pond Effluent	294	233	60	54	13	92.7	20.4	272	402
SP7: After anaerobic	357	259	65	60	17	95.9	23.1	284	418

Table 6: Average composition from key sample points in the Churchill Abattoir waste treatment trains – select metals

Sample Description	Al	As	B	Ba	Ca	Co	Cr	Cu	Fe	Mn	Mo	P	Pb	S	Se	Zn
	mg.kg^{-1}	mg.kg^{-1}	mg.kg^{-1}	mg.kg^{-1}	mg.kg^{-1}	mg.kg^{-1}	mg.kg^{-1}	mg.kg^{-1}	mg.kg^{-1}	mg.kg^{-1}	mg.kg^{-1}	mg.kg^{-1}	mg.kg^{-1}	mg.kg^{-1}	mg.kg^{-1}	mg.kg^{-1}
SP1: Red Stream	0.64	0.01	0.00	0.13	62	0.02	0.01	0.11	8.58	0.55	0.01	66	0.21	47.6	0.01	0.65
SP2: Green Stream (post fan press)	4.93	0.00	0.01	0.51	177	0.03	0.01	0.29	10.36	2.98	0.02	254	0.20	46.4	0.03	2.53
SP3: Cattle Yard	2.47	0.03	0.00	0.12	60	0.03	0.00	0.06	5.60	0.58	0.01	69	0.19	20.0	0.00	0.45
SP4: Combined (to Ponds)	3.46	0.03	0.01	0.20	85	0.03	0.01	0.13	8.79	0.95	0.02	99	0.25	38.8	0.01	0.97
SP5: Paunch Solid	14.69	1.76	0.00	5.64	1225	0.77	0.04	1.85	98.53	24.42	0.32	576	6.35	398.5	0.00	41.31
SP6: Treated Pond Effluent	0.00	0.06	0.00	0.06	31	0.03	0.00	0.00	0.59	0.20	0.01	61	0.19	12.6	0.00	0.07
SP7: After anaerobic	3.16	0.06	0.00	0.10	35	0.03	0.01	0.05	5.53	0.32	0.01	68	0.22	16.9	0.01	0.35

Note: Cd, Ni formed part of the analysis, but was not detected in the samples

3.2.2 Biological Analysis

Table 7 shows results from pathogen analysis of the final treated effluent at CA, including E. Coli and the Class A+ Phage Water Suite. These samples were collected by QUU. The results demonstrate that the current treated water does not meet Australian guidelines and requires significant pathogen removal to enable reuse.

Table 7: Pathogen on the final treated effluent at CA, including E.Coli and the Class A+ Phage Water Suite

Description	Units	Week 1	Week 2	Week 3	Week 4
Escherichia coli	cfu/100mL	<10	140	160	70
Somatic Coliphages	pfu/100mL	3 EST	41	4 EST	3 EST
Male-specific Coliphages	pfu/100mL	<1	2	<1	<1
Clostridium perfringens spores	cfu/100mL	890	210	360	800 EST

3.3 Energy Recovery Potential

3.3.1 Summary of Energy Potential by Waste Source

Using analysis of the waste volumes, compositions, and biological properties, the total estimated biogas potential for waste at Churchill Abattoir is approximately 4800 m3/d corresponding to approximately 160 GJ/d of potential heating energy. If energy is valued at $10/GJ, this represents a potential value of $1,600/d.

A more detailed breakdown (Figure 2 and Figure 3) shows that the red wastewater is the largest contributor at 3,000 m3/d, representing over 85% of methane potential from the combined wastewater and over 60% methane potential from the whole site. Other wastewater streams (Green Stream, Cattle Yards) make a relatively small contribution. Paunch solids are another significant contributor to site methane potential at 1400 m3/d (~30%).

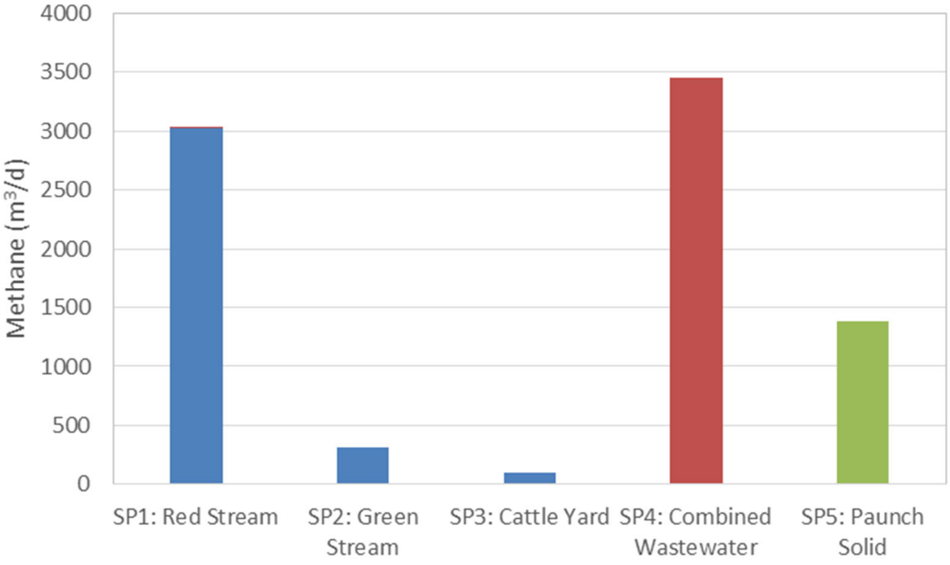

Figure 2: Comparison of potential biogas volume by waste source. 🟦 indicates an individual wastewater stream, 🟥 indicates the combined wastewater, 🟩 indicates solid waste.

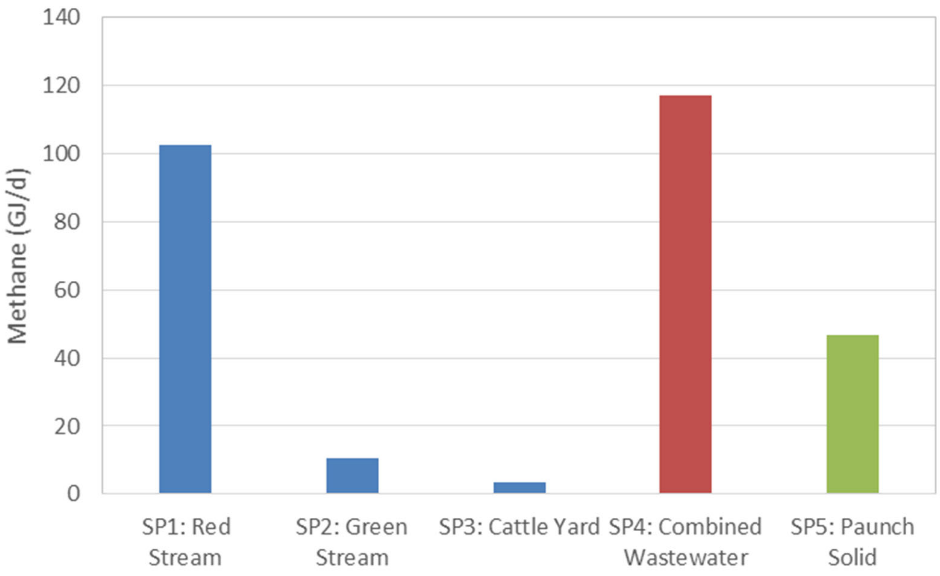

Figure 3: Comparison of biogas energy potential by waste source. 🟦 indicates an individual wastewater stream, 🟥 indicates the combined wastewater, 🟩 indicates solid waste.

4 Water Recycling Case Studies

4.1 Methodology

The purpose of these case studies is to compare treatment options to enable water recycling at either non-potable recycled water (dual reticulation) or highly treated standards. The comparison considers treatment footprint and robustness to processes changes and costs. All options utilise the existing lagoon based treatment at CA and are designed using effluent from Pond 3 (SP6) as the feed stream. The combined wastewater at CA is 1.3ML/d, however a portion of this water is already recycled to the cattle yards, this portion of flow will not be treated using the water recycling technologies, therefore the flowrate for water recycling is assumed at 1-1.1 ML/d. Three general options have been investigated:

- Current treatment without nitrogen removal. Follow by tertiary treatment and recycling,
- Conventional nitrogen removal. Follow by tertiary treatment and recycling,
- Emerging low-cost nitrogen removal. Follow by tertiary treatment and recycling.

Table 8 summarises the basis used short cut design and costing of each technology. Operating costs are based on electricity prices of $0.13/kWh and energy prices of $10/GJ.

Table 8: Process design and contaminants removal estimation (V = virus, B = bacteria, P = protozoa).

	Design		Contaminant removal	
Treatment process	Estimation	Reference	Value	Reference
Covered anaerobic lagoon (CAL)	HRT = 20 d Depth = 5 m	Dr P. Jensen	COD = 80% TSS = 80%	Dr P. Jensen
Struvite removal	HRT = 2 h Mixing HRT = 0.5 h Chemical dosing ratio = 2	Dr P. Jensen	$[P]_{effluent} = 10/V_{effluent} * 1000$ (kg/d)	Dr P. Jensen
Sequential batch reactor (SBR)	MLVSS = 4 kg/m^3 N loading rate = 0.04 F/M = 0.1 d^{-1}	A.ENV.0044 (Metcalf & Eddy 2004) Table 8-16, p747	BOD_5 effluent = 10 mg/L TSS effluent = 15 mg/L N effluent = 10 mg/L V = 0.5 LRV B = 1 LRV P = 0.5 LRV	NSW EPA (MLA enviro best practice manual) (NRMMC et al. 2006) after primary treatment
Anaerobic ammonium oxidation (AAR)	Anammox loading rate = 0.3	Dr P. Jensen	COD = 20% TSS removal = 20% Final N concentration = 50 g/kL V = 0.5 LRV B = 1 LRV P = 0.5 LRV	Dr P. Jensen (NRMMC et al. 2006) after primary treatment
Membrane bioreactor (MBR)	MLVSS = 4 kg/m^3 N loading rate = 0.04 F/M = 0.1 d^{-1} Permeate flux = 10 L/m^2 h		V = 2.5 LRV B = 3.5 LRV P = 4 LRV	(NRMMC et al. 2006)
Ultrafiltration/microfiltration (UF/MF)	Recovery = 90% Permeate flux = 40 L/m^2 h Membrane area = 50 m^2 Number of train = 1+1	(Wilf 2010) Table F.2, p774	V = 2.5 LRV B = 3.5 LRV P = 4 LRV	(NRMMC et al. 2006)
Reverse osmosis (RO)	Recovery = 75% Permeate flux = 17.5 L/m^2 h Membrane area = 40 m^2 Number of train = 1+1	(Wilf 2010) Table F.2, p774	TDS removal = 98% V = 4 LRV B = 4 LRV P = 4 LRV	(NRMMC et al. 2006)
Ultraviolet/hydrogen peroxidase (UV/H_2O_2)	UV dose = 40 mJ/cm^2 UV transmittance = 75% Max. hydraulic loading rate = 15 L/min lamp Number of reactor = 1	(USEPA 2006)	V = 0.5 LRV B = 4 LRV P = 4 LRV	(USEPA 2006)
Final chlorination (storage tank)	$[NaOCl^-]$ = 0.5 mg/L Contact time = 30 min	(NHMRC and NRMMC 2011)	V = 2 LRV B = 2 LRV P = 0.5 LRV	(NHMRC and NRMMC 2011) Table 3.4, p95

4.2 Case Study 1

Case Study 1 considers the options for water recycling without the addition of a nitrogen removal process. Ammonia nitrogen in the wastewater can increase membrane fouling and can increase the risk of disinfection by-products.

Option 1a, shown in Figure 4, uses a microfiltration or ultrafiltration membrane followed by chlorine disinfection. This option produces non-potable recycled water suitable for use described in Section 4. The design is based on:

• Water recovery through MF/UF	0.9
• permeate flux rate	42 L/m2/h
• Membrane area/module	50 m2
• Minimum number of membranes	22

Option 1b, shown in Figure 5, adds a reverse osmosis membrane and UV disinfection to the treatment train. This option produces high quality recycled water suitable for use described in Section 4. The design is based on:

• Water recovery through RO	0.85
• permeate flux rate	18.7 L/m2/h
• Membrane b area/module	40 m2
• Minimum number of membranes	56

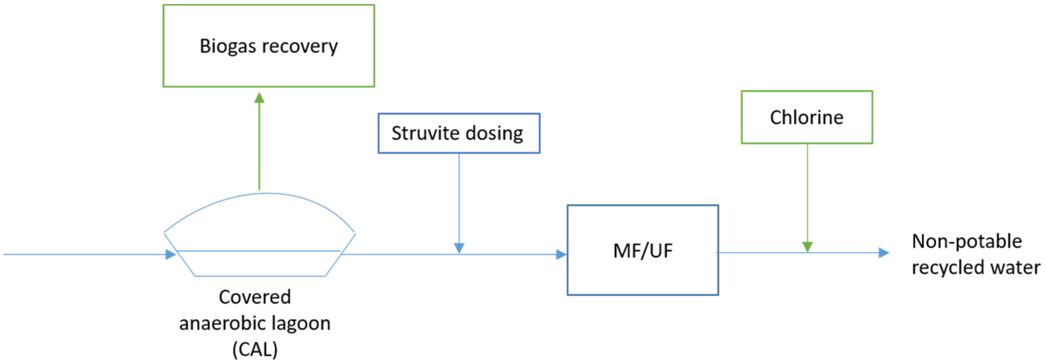

Figure 4: Case study 1a: Generation of non-potable recycled water, without nitrogen removal.

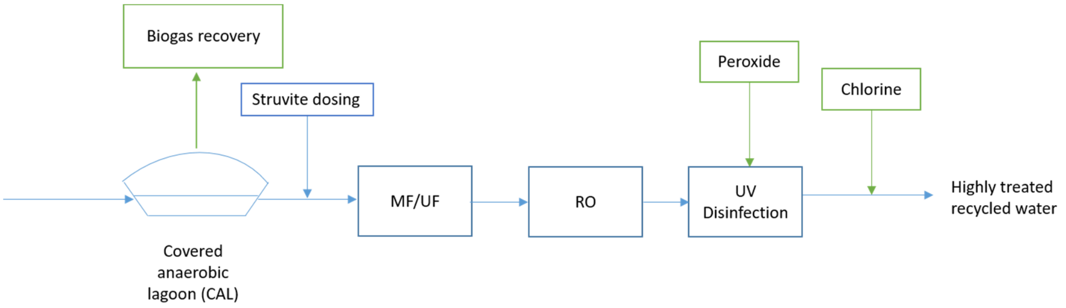

Figure 5: Case study 1b: Generation of highly quality recycled water, without nitrogen removal.

4.3 Case Study 2

Case Study 2 considers the options for water recycling with the addition of a conventional nitrogen removal process. The conventional nitrogen removal process is designed to remove ammonia nitrogen in the wastewater. However, there are significant operational costs associated with the conventional nitrogen removal process. The process will require 4.6 kWh of aeration energy and 2.86 kg degradable COD with each 1kg of nitrogen to be removed. The process will also generate waste activated sludge.

Option 2a, shown in Figure 6, uses a sequencing batch reactor for nitrogen removal, followed by microfiltration or ultrafiltration and chlorine disinfection. This option produces non-potable recycled water suitable for use described in Section 4. The design of the nitrogen removal process is shown in Table 8, the design of the water recycling plant is based on:

Water recovery through MF/UF	0.9
permeate flux rate	42 L/m2/h
Membrane b area/module	50 m2
Minimum number of membranes	22

Option 2b, shown in Figure 7, adds a reverse osmosis unit and UV disinfection to the treatment train to produce high-quality recycled water suitable for uses described in Section 4. The design of the RO plant is based on:

Water recovery through RO	0.85
permeate flux rate	18.7 L/m2/h
Membrane b area/module	40 m2
Minimum number of membranes	56

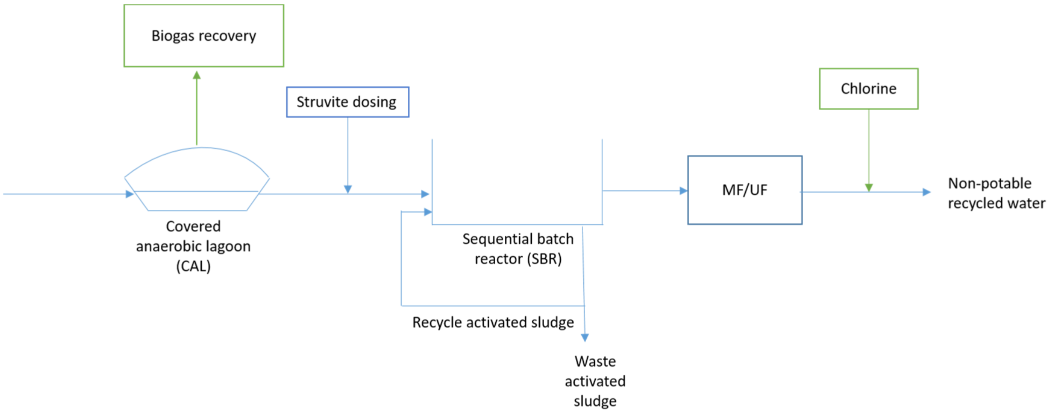

Figure 6: Case study 2a: Generation of non-potable recycled water, with conventional nitrogen removal.

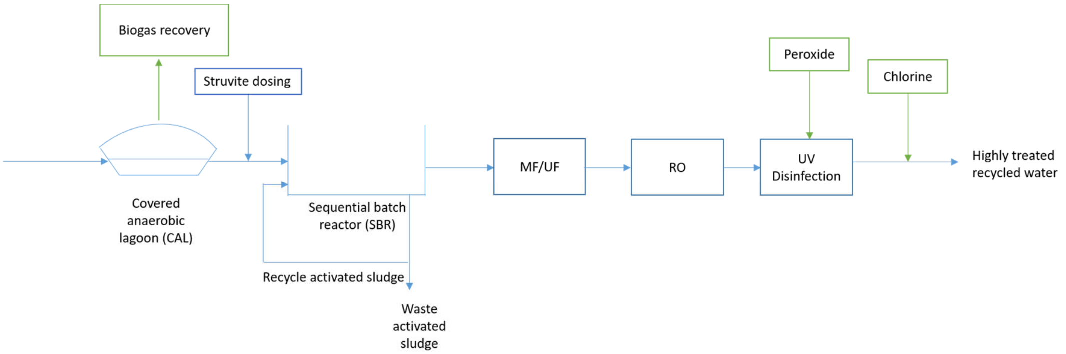

Figure 7: Case study 2b: Generation of high quality recycled water, with conventional nitrogen removal.

4.4 Case Study 3

Case Study 3 considers the options for water recycling with the addition of an emerging low cost nitrogen removal process, anaerobic ammonium removal. Anaerobic ammonium removal is designed to remove ammonia nitrogen in the wastewater with 60% less aeration than conventional nitrogen removal, no requirement for COD and very low sludge production. The process has been applied successfully at dozens of full-scale plants overseas, with Australian installations now emerging.

Option 3a, shown in Figure 8, uses anaerobic ammonium removal followed by a membrane bioreactor to nitrogen removal. The membrane bioreactor will also reduce pathogens and solids, therefore microfiltration is not required. Chlorine disinfection is still recommended. This option produces non-potable recycled water suitable for use described in Section 4. The design parameters for the nitrogen removal process are shown in Table 8.

Option 3b, shown in Figure 9, adds a reverse osmosis unit and UV disinfection to the treatment train to produce high-quality recycled water suitable for use described in Section 4. The design of the RO plant is based on:

Water recovery through RO	0.85
permeate flux rate	18.7 L/m2/h
Membrane b area/module	40 m2
Minimum number of membranes	56

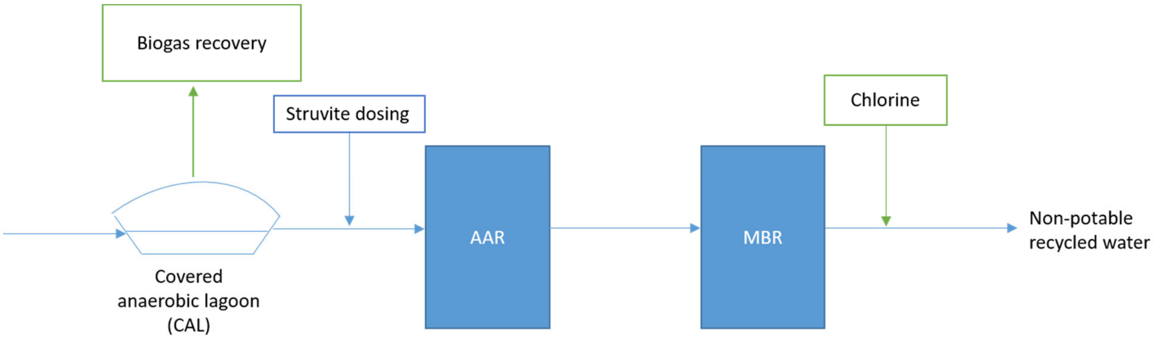

Figure 8: Case study 3a: Generation of non-potable recycled water, with advanced nitrogen removal.

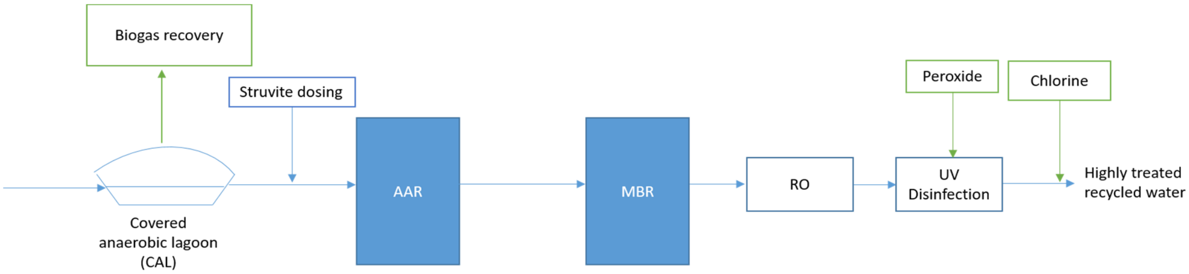

Figure 9: Case study 3b: Generation of high quality recycled water, with advanced nitrogen removal.

4.5 Cost Comparison

Table 9 summarises the CAPEX (including 50% contingency) and OPEX of the three case studies for non-potable water reuse option and highly treated water reuse option. The quality of the effluent before membrane processes has an impact on OPEX. Effluent with high COD, TOC and nutrients leads to membrane fouling, increasing the membrane cleaning (CIP) frequency and replacement.

For the cost calculation, it has been estimated that membranes were replaced every two years for Case Study 1 and every five years for Case Studies 2 and 3. The replacement cost was added to the OPEX. The frequency of CIP was estimated to be every month for Case Study 1 and every 6 months for Case Studies 2 and 3.

Regarding Case Study 1, the technical viability of membrane filtration after the current treatment (and without nutrient removal) is not clear. High levels of COD (including some degradable COD), nutrients and alkalinity are all technical challenges. Polishing treatments might be necessary to protect the membrane, however costs for polishing have not been considered in initial calculations.

While production of both non-potable recycled water (dual reticulation) and highly treated water (suitable for contact with meat surfaces) was considered in the analysis, application of tertiary treatment technologies to produce non-potable recycled water at CA is not recommended. CA already re-uses partially treated water in the cattle yards and there is limited potential to increase water re-use at non-potable standard. Regarding the production of high quality recycled water, Case study 1 has the lowest capital cost, however the technical viability of membrane filtration after the current treatment (and without nutrient removal) is not clear. Case study 2 uses effective and well established technologies, however the capital and operating costs are the highest of the options considered. Based on analysis in this report, the treatment process recommended for production of high quality recycled water at CA is Case Study 3.

Table 9: CAPEX and OPEX of the different case studies.

	Case study 1		Case study 2		Case Study 3	
	Non potable	Highly treated	Non potable	Highly treated	Non potable	Highly treated
Water Savings	0 kL/d*	850 kL/d	0 kL/d*	850 kL/d	0 kL/d*	950 kL/d
Water Savings	$0 M/yr*	$1.0 M/yr	$0 M/yr*	$1.0 M/yr	$0 M/yr*	$1.1M/yr
Energy Revenue	0 GJ/d	0 GJ/d	95 GJ/d**	95 GJ/d**	118 GJ/d	118 GJ/d
Energy Revenue	$0 M/yr	$0 M/yr	$0.2 M/yr**	$0.2M/yr**	$0 .25M/yr	$0.25 M/yr
Total Savings	$0 M/yr	$1.0 M/yr	$0.2 M/yr	$1.2 M/yr	$0.25 M/yr	$1.36 M/yr
Annual OPEX	-$1.1 M/y	-$2.6 M/y	-$0.6 M/y	-$1.4 M/y	-$0.25 M/y	-$1.4 M/y
Net Annual OPEX	**-$1.1 M/y**	**-$1.6 M/y**	**-$0.40 M/y**	**-$0.20 M/y**	**$0.0 M/y**	**-$0.04 M/y**
CAPEX	**$2.7 M**	**$4.5 M**	**$6 M**	**$7.9 M**	**$4.8 M**	**$6.5 M**
Payback	**N.A**	**N.A**	**N.A**	**N.A**	**N.A**	**N.A**

* Non-potable recycled water has limited re-use applications and will not increase water reuse beyond current practices

** Approximately 20% of raw wastewater is diverted past the CAL to provide carbon for nitrogen removal

N.B: The University of Queensland has prepared preliminary cost estimates as part of developing a cost benefit analysis (CBA) tool for recycled water implementation at red meat processing plants using information available to The University of Queensland employee(s) who prepared this report; and based on assumptions and judgments made by the University of Queensland, which are detailed within the CBA tool.

The CBA tool has been prepared for the purpose of assessing the potential viability of adopting wastewater treatment and recycled water at red meat processing plants and should not be used for any other purpose.

The Cost Estimate is a preliminary estimate only. Actual prices, costs and other variables may be different to those used to prepare the Cost Estimate and may change. Unless as otherwise specified in the CBA tool, no detailed quotation has been obtained for actions identified in this report. The University of Queensland does not represent, warrant or guarantee that any future project can or will be undertaken at a cost which is the same or less than the Cost Estimate generated by the CBA tool.

Where estimates of potential costs are provided with an indicated level of confidence, notwithstanding the conservatism of the level of confidence selected as the planning level, there remains a chance that the cost will be greater than the planning estimate, and any funding would not be adequate. The confidence level considered to be most appropriate for planning purposes will vary depending on the conservatism of the user and the nature of the project. The user should therefore select appropriate confidence levels to suit their particular risk profile.

5 Recommended Configuration Detailed Analysis

Table 10 provides are more detailed breakdown on the economic potential of Case Study 3b. This option uses a covered anaerobic lagoon to remove organics and recover energy, followed by anaerobic ammonium removal and a membrane bioreactor for nitrogen removal. An RO plant is included to produce high quality water suitable for use in the processing areas.

Installation of a CAL is estimated to cost $1.8M and would enable recovery 118 GJ/d of energy from the CAL to offset 11,500 kWh per day (0.35 electrical efficiency) at a value of approximately $1,500/d (based on $0.13/kWh). There are limited operating costs associated with the CAL.

Installation of an RO plant (including RO + disinfection) is estimated to cost $1.85M and would to generate an estimate 950 kL/d of high quality water at a value of $4,650/d. The RO plant is energy intensive and therefore the operating costs are relatively high at $1.2M/r. Over $1M/yr of this cost is due to the energy demand of the RO system, however there is significant potential to reduce these costs through R&D or process optimisation.

Based on the current energy cost calculations, the cost of generating high quality water is approximately cost neutral. However, the economic potential does not consider the current water disposal costs (can be as high as $5/kL) or the savings that may be achieved, therefore the true economic potential may be more attractive. Importantly, if a water recycling process was installed, there would be no requirement for irrigation. However, the water recycling process would generate a brine stream that required disposal to trade waste. Table 11 provides a revised estimate for the economic potential of water recycling with minor savings in N and P disposal costs considered. Additional savings to trade waste chargers have not been considered in this report.

Table 10: Detailed Breakdown of CAPEX and OPEX of Case Study 3b.

	CAL	Struvite	AAR	MBR	RO	UV + Cl	Total
Water Savings	-	-	-	-	950 kL/d	-	950 kL/d
Water Savings	-	-	-	-	$1.1 M/yr	-	$1.1M/yr
Energy Revenue	118 GJ/d	-	-	-	-	-	118 GJ/d
Energy Revenue	$0.25 M/yr	-	-	-	-	-	$0.25 M/yr
Nutrient Revenue	-	$0.05 M/y	-	-	-	-	$0.05 M/y
Total Savings	$0.25 M/yr	$0.05 M/y	-	-	$1.1 M/yr	-	$1.35 M/yr
Annual OPEX	-$0.04 M/y	-$0.05 M/y	-$0.07 M/y	-$0.04 M/y	-$1.1 M/y	-$0.1M/y	-$1.4 M/y
Net Annual OPEX	**$0.2 M/y**	$0.0 M/y	**-$0.07 M/y**	**-$0.04 M/y**	$0.0 M/y	**-$0.1 M/y**	**-$0.05M/y**
CAPEX*	**$1.8 M**	**$0.24 M**	**$2.25 M**	**$0.4 M**	**$1.7 M**	**$0.15 M**	**$6.5 M**
Simple Payback	**6 years**	**N.A**	**N.A**	**N.A**	**N.A**	**N.A**	**N.A**

*CAPEX includes 50% contingency

Table 11: Detailed Breakdown of CAPEX and OPEX of Case Study 3b, with additional savings in nutrient tradewate charges.

	CAL	Struvite	AAR	MBR	RO	UV + Cl	Total
Water Savings	-	-	-	-	950 kL/d	-	950 kL/d
Water Savings	-	-	-	-	$1.1 M/yr	-	$1.1M/yr
Energy Revenue	118 GJ/d	-	-	-	-	-	118 GJ/d
Energy Revenue	$0.25 M/yr	-	-	-	-	-	$0.25 M/yr
Nutrient Revenue	-	$0.05 M/y	-	-	-	-	$0.05 M/y
Nutrient Savings*	-	$0.07 M/y	$0.2 M/y	$0.03 M/y	-	-	$0.30 M/y
Total Savings	$0.25 M/yr	$0.12 M/y	$0.2 M/y	-	$1.1 M/yr	-	$1.65 M/yr
Annual OPEX	-$0.04 M/y	-$0.05 M/y	-$0.07 M/y	-$0.04 M/y	-$1.1 M/y	-$0.1M/y	$1.4 M/y
Net Annual OPEX	**$0.2M/y**	$0.07 M/y	**$0.13 M/y**	**-$0.01 M/y**	$0.0 M/y	**-$0.1 M/y**	**$0.25 M/y**
CAPEX**	**$1.2 M**	**$0.16 M**	**$1.5 M**	**$0.26 M**	**$1.1 M**	**$0.1 M**	**$6.5 M**
Simple Payback	**6 years**	**2.3 years**	**11 years**	**N.A**	**N.A**	**N.A**	**26 years**

*Nutrient savings are calculated using QUU trade waste fees of $2/kg N and $4.3/kg P and are provided as an estimate only.

**CAPEX includes 50% contingency

6 Conclusions/recommendations

6.1 Energy Recovery

Anaerobic lagoons (ALs) and Covered Anaerobic Lagoons (CALs) are commonly applied for the treatment of slaughterhouse wastewater in Australia. The primary difference between a crusted and covered lagoon is the addition of plastic floating covers which seal the pond from the atmosphere and allows biogas capture. The CAL works biologically in an identical manner to naturally crusted ponds with little difference in treatment performance. At CA, lagoon based treatment would be suitable for the existing combined wastewater stream (red + green + cattle).

The design of lagoons is based largely on organic loading rate, rather than wastewater volume. As green wastewater and cattle yard wastewater contribute little to the organic load in the wastewater, there is no significant benefit to source separation of these streams or separate treatment. Similarly, there is no benefit to separate treatment of the relatively clean water used during washdown operations.

Changes to upstream treatment, such as the addition of saveall or dissolved air floatation units would not change the stability of the lagoon, but would significantly reduce methane production. Changes to the existing paunch handling, such as the removal of the paunch press would result in an increase in methane production from the lagoon, however this change would also result in much faster sludge accumulation and significantly shorter intervals between de-sludge events.

Paunch solids are another significant contributor to site methane potential at 1400 m^3/d (~30%), however this stream is not suitable for treatment in lagoon based processes. Anaerobic digestion of solid wastes produced by meat processing plants has been practiced extensively overseas. Most of the digesters used to date have been conventional slurry type complete mixed digesters. Anaerobic digestion (AD) of paunch using conventional slurry type digesters was demonstrated through several previous AMPC/MLA projects (ENV.0068, A.ENV.0099, A.ENV.0155). In these projects the AWMC successfully operated a large pilot scale digester for over 2 years, hosted by Teys Australia (Beenleigh). The AD projects were successful at reducing the mass of paunch waste (60%) and recovering methane rich biogas (7 GJ/dry Tonne). However, digestion of red meat solid wastes was generally slow and in-vessel slurry digesters typically operate at relatively low solids content (2-5%); thus the tank volumes and capital costs required for solid waste digestion of paunch are large. Therefore conventional forms of AD were not considered economically attractive when applied to paunch, unless offsetting significant waste disposal fees.

More recently alternative digester configurations have been utilized. A novel system that is used extensively for treatment of free stall dairy farm manure in the United States is the mixed plug flow digester. This has been successfully applied to a number of other substrates including slaughterhouse solid wastes, but is not yet applied in Australia.

6.2 Water Recycling

Water recycling is not a new concept to increase drinking water supply. South East Queensland has three advanced water treatment plants able to produce 232 ML/d of water from secondary treated effluent. Ingham poultry is a successful example of the implementation of potable recycled water in its process factory. Water can be recycled at either non-potable recycled water (dual reticulation) or highly treated standards (enabling contact with meat surfaces). Application of tertiary treatment technologies to produce non-potable recycled water at CA is not recommended. CA already re-uses partially treated water in the cattle yards and there is limited potential to increase water re-use at non-potable standard.

Production of high quality recycled water at CA can be challenging if the treatment processes are not selected adequately. Good primary and secondary treatments should be selected to reduce the level of natural organic matter. Organic matter with chlorine can form disinfection-by-products (DBPs) such as trihalomethanes (THMs), haloactic acids (HAAs), and N-Nitrosodimethylamine (NDMA). It has been demonstrated that DBPs in drinking water have been associated with possible public health risks (Richardson et al. 2007, Sedlak and von Gunten 2011), therefore, the control of their formation is required. Chlorine is not only used at the end of the treatment train, but also before membrane filtration to avoid the formation of biofouling. Unfortunately, RO membrane does not remove effectively DBPs (Doederer et al. 2014). Thus, it is necessary to remove dissolved organic carbon before chlorine addition to avoid the formation of DBPs. For this reason, in case study 1, a coagulation step might be necessary to limit the formation of DBPs and to protect membranes from fouling. Also, the formation of NDMA can be reduced by limiting the disinfection contact time with chlorine to less than 2 hours (Farré et al. 2011).

The presence of ammonia nitrogen (TAN) in the effluent can react with chlorine to form monochloramine. Monochloramine is also used in SEQ as agent of disinfection instead of chlorine. Monochloramine has been proved to form less DBPs than chlorine. TAN can be removed at ~95% by RO membrane (Kurama et al. 2002). However, the concentration of TAN is generally less than 10 mg/L. Thus, the impact of high TAN level on membrane filtration needs to be confirmed.

Based on analysis in this report, the treatment process recommended for production of high quality recycled water at CA is:

- Covered anaerobic lagoon to remove organics and recover energy,
- Anaerobic ammonium removal and a membrane bioreactor for nitrogen removal.
- RO plant is included to produce high quality water suitable for use in the processing areas.

Economics of the water recycling plant will be highly sensitive to the energy requirements during RO. A pilot trial is recommended to confirm energy requirements and process performance prior to large-scale implementation. The purpose of the trial would be to demonstrate the water quality achieved through chemical and microbial monitoring. The trial will confirm further polishing treatments, such as the addition of powdered activated carbon (PAC) and 5µm cartridge before membrane filtration. The pilot will also determine the frequency of cleaning-in place (CIP). In addition, AQIS should be involved at an early stage of the process to endure their agreements.

7 Key Messages

- Recycled water can be produced at non-potable standard, suitable for use in areas that do not contact meat or meat surfaces, or higher quality standards that may be suitable for broader use within a red meat processing plant. For domestic-only abattoirs, such as CA, there are pathways to enable water recycling within meat processing areas, albeit with strict treatment and quality control requirements. The use of high quality recycled water could reduce town water consumption in the range of 70%.

- US and European markets are currently less flexible and recycled water cannot currently be used in contact with meat surfaces. CA is investigating expansion plans, however the focus is on the Chinese market, which does not specifically restrict the use of high quality recycled water.
- Application of tertiary treatment technologies to produce non-potable recycled water is generally not recommended. Many sites, including CA, already re-use partially treated water in the cattle yards and other non-processing areas and there is more limited potential to increase water re-use at this treatment level.
- Where production of high quality recycled water is considered, the use of emerging low-cost nitrogen removal technologies. Follow by reverse osmosis and disinfection is recommended. Reverse osmosis is currently energy intensive and based on current energy cost calculations, the cost of generating high quality water is approximately cost neutral, however there is significant potential to reduce these costs through R&D or process optimisation.

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9 Appendix

9.1 Summary of Water Treatment and Recycling Technologies

Red meat processing wastewater is rich in both organic contaminants and nutrients, which require removal/recovery prior to discharge or re-use. In some cases, these contaminants can be recovered and used in value-add processes. A summary of key contaminants are:

- Fats, Oil and Grease
- Organics Compounds
- Solids and/or Particulates
- Phosphorous
- Nitrogen
- Trace metals
- Odour
- Biosecurity and Pathogens

During the development of a water recycling scheme, these contaminants need to be removed (or ideally recovered) from the wastewater stream. Depending on the waste stream quality and the desired end-use (which impacts product quality requirements), different wastewater treatment processed can be used. Figure 10 summarises the different processes able to remove/recover contaminants present in wastewater, with further information on water recycling technologies in Table 12 (pretreatment), Table 14 (filtration) and Table 14 (disinfection).

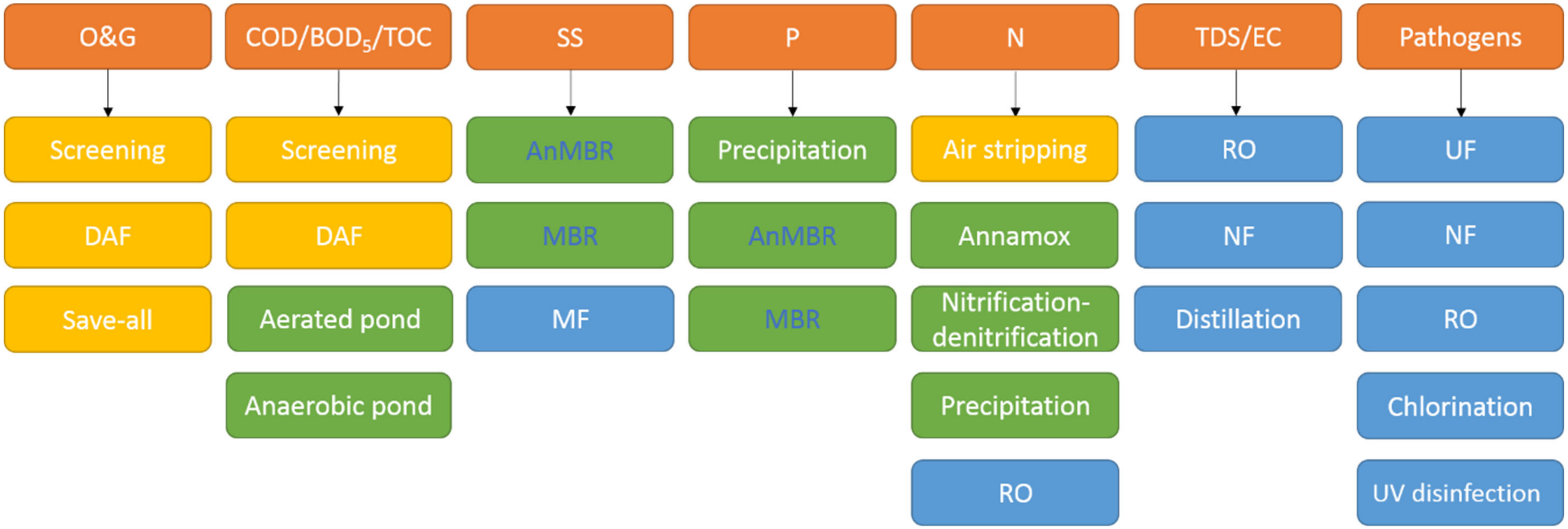

Figure 10. Principal treatment processes to remove contaminants present in wastewater. Yellow = primary treatment, green = biological treatment, blue = advanced treatment. AnMBR = anaerobic membrane bioreactor, DAF = dissolved air filtration, MBR = membrane bioreactor, MF = microfiltration, NF = nanofiltration, RO = reverse osmosis, UF = ultrafiltration.

Table 12: Summary of pre-treatment technologies used in water recycling

Technology	Removal mechanism	Contaminant removal	Advantages	Disadvantages	Readiness
Coagulation/flocculation	Electrostatic Adsorptive Precipitation	Turbidity Suspended particles Colloidal Dissolved organic matter	Good pre-treatment. Low maintenance.	Chemical cost (coagulant + pH regulation)	Well established in drinking and recycled water treatment
Granular activated carbon (GAC)	Adsorption	Turbidity Taste Odour Some organic contaminants Colour	Simple operation. Low maintenance. Low capital cost.	Large pore (> 30 µm). Water able to channel around GAC avoiding filtration. Limit of adsorption capacity.	Well established in drinking water treatment
Biological activated carbon (BAC)	Biological	Turbidity Taste Odour Colour	Simple operation. Long life. Low maintenance. Low capital cost.	Limited adsorptive capacity. Main target compound removal by biodegradation.	Well established in drinking water treatment
Sand filtration	Size exclusion	Protozoa Bacteria Turbidity Colour Taste Odour (only biofiltration rapid and SSF) Organic matter (only biofiltration)	Low capital cost. Low maintenance.	High footprint for slow sand filtration (SSF).	Well established in drinking water treatment
Ion exchange resin	Charge attraction	Taste Odour Organic matter	Low maintenance.	Expensive. Brine disposal. Resin fouling. Not effective for high concentration of Fe, Mn and Al.	Used in the USA water treatment.
Membrane Bioreactors (MBR)	Biological + Size exclusion	Protozoa Bacteria Virus Turbidity	Low footprint. Low capital cost. Very stable. Produces good effluent.	Moderate to high operating costs related to membrane.	Well established in water treatment

Table 13: Summary of filtration technologies used in water recycling

Technology	Removal mechanism	Contaminant removal	Advantages	Disadvantages	Readiness
Microfiltration (MF) Pore size > 0.05 – 10 µm	Size exclusion	Protozoa Bacteria Turbidity	Low energy consumption. Low surface space.	High chemical cleaning cost due to fouling. Feed temperature < 50^{o}C. High maintenance.	Well established in drinking and recycled water treatment
Ultrafiltration (UF) Pore size > 0.01 – 0.05 µm	Size exclusion	Protozoa Bacteria Some virus Colloids	Low energy consumption. Low surface space.	High chemical cleaning cost due to fouling. Feed temperature <50^{o}C. High maintenance.	Well established in drinking and recycled water treatment
Nanofiltration (NF) Pore size > 0.001 – 0.01 µm	Size exclusion Charge repulsion Diffusion Adsorption	Protozoa Bacteria Virus Up to Divalent ion Turbidity	Low surface space. Good removal using less energy than RO.	Sensitive to chlorine. High chemical cleaning cost. High fouling rates: Pre-treatment necessary. Feed temperature < 50^{o}C. High maintenance.	Well established in drinking and recycled water treatment
Reverse osmosis (RO) Pore size < 0.002 µm	Size exclusion Charge repulsion Diffusion Adsorption	Protozoa Bacteria Virus Up to monovalent ion Colour Organic matter Odour Heavy metal Turbidity	High removal efficiency. Produce high quality water Low surface space.	High energy consumption Sensitive to chlorine. High chemical cleaning cost. High fouling rates: Pre-treatment necessary. Feed temperature < 50^{o}C. High maintenance.	Well established in drinking and recycled water treatment
Ceramic membrane Pore size > 0.001 µm	Size exclusion	Depending on pore size: Protozoa Bacteria Virus TSS Turbidity Divalent ion	Very robust membrane to pH, chemicals, temperature. Low surface space. Easy to clean. Inert surface.	High capital cost related to membrane.	Not as popular as polyamide membranes, but becoming more affordable
Metallic membrane Pore size: 0,5 µm to < 1 nm	Size exclusion	Depending on pore size: Protozoa Bacteria Virus	Very robust membrane to pH, chemicals, temperature. Cost-effective	High capital cost. Low surface membrane per module volume. Possible toxicity.	Not as popular as polyamide membranes. Commercially available.

Technology	Removal mechanism	Contaminant removal	Advantages	Disadvantages	Readiness
		TSS Turbidity Divalent ion	Low fouling rates Easy to clean		
Forward osmosis (FO)	Osmosis gradient	Protozoa Bacteria Virus Colour Organic matter Odour Heavy metal Turbidity Salt	Low energy consumption. Work with dirty water.	Lower water flow than RO. Not as competitive as RO. Industrial acceptance.	Not as widely used as RO, but few commercialisation (new technology)
Membrane Distillation (MD)	Mass transfer induce by vapour pressure difference	Ion Heavy metal Turbidity TSS Protozoa Bacteria Virus Organic matter	Only gas water going through membrane	Expensive technique. High energy demand. Pro to fouling	Widely employed in desalination and food industries

Table 14: Summary of disinfection technologies used in water recycling

Technology	Removal mechanism	Contaminant removal	Advantages	Disadvantages	Readiness
Chlorination	Inactivation	Bacteria Virus Colour	Cost effective technique. No maintenance.	Does not remove/inactivate protozoa. Formation of disinfection by-products in presence of organic matter. Long residual. pH dependent.	Well established in drinking and recycled water treatment
Ozone	Oxidation	Protozoa Bacteria Virus Organic matter Taste Odour Colour	Short residual.	Complex technology. High maintenance. Aggressive odour.	Well established in drinking and recycled water treatment
UV	Irradiation	Bacteria Virus	Short residual.	Only efficient in low UV transmittance waters	Well established in drinking and recycled water treatment

9.2 Methodology

9.2.1 Chemical Analysis

Table 15: AWMC standard analytical procedures

Test	Method
Biogas composition	H_2, CH_4, CO_2 analysed using gas displacement, and gas chromatograph with thermal conductivity detector (GC-TCD) equipped with electronic gas sampling valve (1 mL loop) and a HAYESEP Q 80/100 packed column (2.4 m length; 1/800 outside diameter, 2 mm inner diameter) using high purity Argon as the carrier gas (135.7 kPa). The GC injector, oven and detector temperatures will be set at 75, 45 and 100 °C, respectively.
pH	Benchtop pH electrode and meter (Thermo Fisher Scientific).
TS, VS, Ash	Total solids (TS), Volatile Solids (VS) and ash content are measured according to Standard method 2540G of the American Public Health Association (APHA 2012).
tCOD & sCOD*	Spectroquant® cell test kits and NOVA 60 photometer (Merck Millipore). Methodology consistent with APHA Method 5220 D.
TSS, VSS, Ash	Total suspends solids (TSS), Volatile Suspended Solids (VSS) are measured according to Standard methods. Samples are filtered using a pre-fired glass filter, the filter and cake is dried at 103°C to determine total solids and 550°C to determine volatile solids (APHA 2012). Methods consistent with APHA Method 2540 D/E
VFA*	Volatile fatty acids (C2 to C6) and alcohols (ethanol, propanol, butanol) in samples are determined by gas chromatography using a flame ionisation detector (FID) and a polar capillary column (DB-FFAP).
FOG	Solvent extraction using S-316 (Horiba Supplies) and InfraCal TOG/TPH infrared analyser (Spectro Scientific). Alternatively, hexane solvent extraction and gravimetric determination of extracted FOGs.
Conductivity	Benchtop conductivity probe and meter (Thermo Fisher Scientific).
TKN & TP	Sample is first digested with sulfuric acid, potassium sulphate and copper sulphate catalyst in a block digester; then analysed via FIA (Lachat Instruments).
NO_3-N*, NO_2-N*, NH_4-N* & PO_4-P*	Flow Injection Analysis (Lachat Instruments).
Sulphur	Sulphur species will be measured using a compact Dionex ICS-2000 ion chromatograph with an AD25 absorbance (230nm) and a DS6 heated conductivity detector (35°C)
Metals & nutrients	ICP-OES (Agilent Technologies); targeting select isotopes of Al, As, B, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Na, Ni, P, Pb, S, Se, & Zn.

9.2.2 Biological Methane Potential Testing

Biochemical methane potential (BMP) is assessed using methods developed in conjunction with the IWA Anaerobic biodegradability, Activity and Inhibition Task Group (Angelidaki et al. 2009). BMP tests are conducted in a minimum of 3 replicates in 160 mL serum bottles (approx. 100 mL working volume). The selection of inoculum, the inoculum to substrate ratio and the presence of nutrient medium are key design parameters in the BMP test. AWMC recommends:

- Methanogenic inoculum in most application to be collected from Luggage Point WWTP, Brisbane QLD. Specific methanogenic activity of the Luggage Point inoculum has been assessed previously and is approximately 0.2 $gCOD\text{-}CH_4gVS^{-1}.d^{-1}$.
- The inoculum to substrate rate be a minimum of 2.5 on a VS basis (higher for soluble or rapidly degrading samples)
- Nutrient medium is not required
- Tests be conducted at 37°C.

The BMP tests assess feed degradability (Figure 11). Normally it is used to assess apparent first order hydrolysis rate (k_{hyd}), as well as ultimate degradability (f_d). An example result is shown in Figure 12.

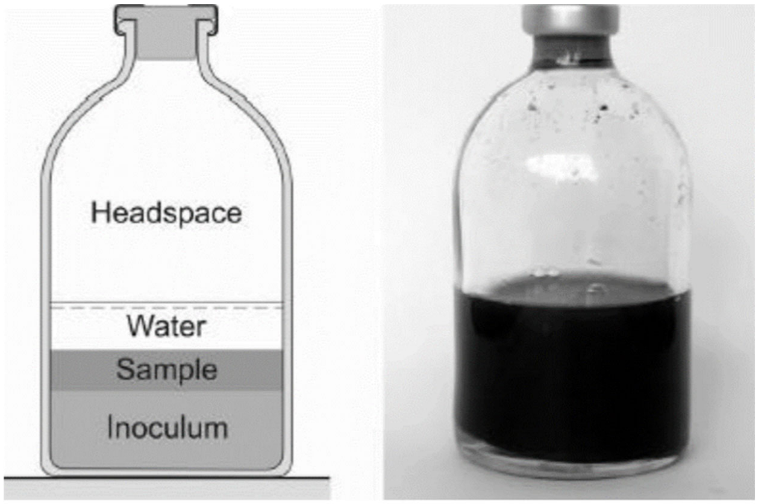

Figure 11 Example of batch biochemical methane potential assay.

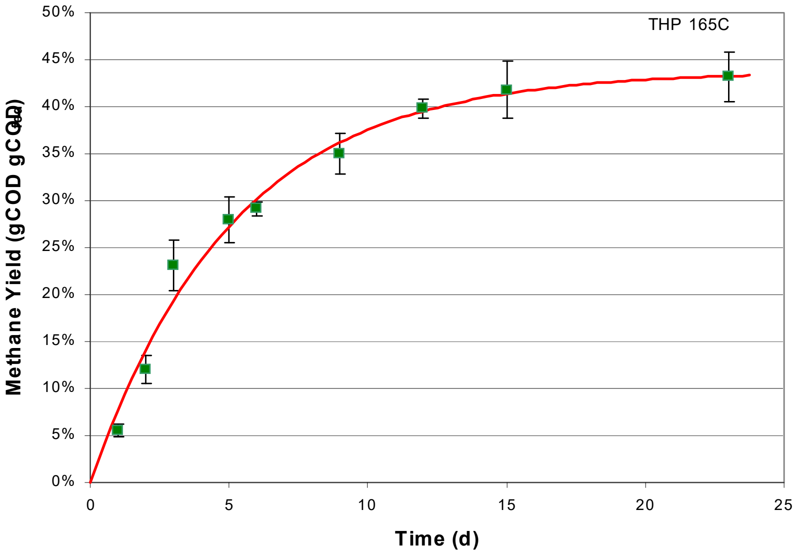

Figure 12 Example output from biological methane potential (BMP) test. Error bars indicate 95% confidence errors from triplicate batches. The line indicates the model used to return key parameters.

9.2.3 Model Based Analysis

Batch BMP tests will be used to generate independent degradability parameters f_d and k_{hyd} for the inoculum and the test samples. Parameters will be determined using a simple first order kinetic model as expressed as:

$$\frac{dS_t}{dt} = -k_{hyd} \times S_t \qquad (1)$$

Where t is the incubation time, S is the degradable portion of substrate remaining at time t, and k_{hyd} is the first order hydrolysis rate constant. The parameter estimation will be done using model based software (Aquasim 2.1d). Kinetic parameters can be used to estimate the size and capital costs of process equipment (e.g. reactors).

In some tests, more complex modelling may be applied to determine specific inhibition characteristics of a substrate, such as the inhibition constant (K_I). Hydrolysis is generally the rate limiting step in AD, therefore first order degradation equations are typically applied. A first order model with inhibition function is shown as Equation 2. Where soluble compounds are the primary substrate Monod kinetics with an inhibition function (shown in Equation 3) would be an alternative approach for inhibition modelling (but unlikely to apply in this project). The inhibition function is based on non-competitive inhibition as per Equation 4:

$$\frac{dS_{CH4}}{dt} = k_{hyd} S\ I \tag{2}$$

$$\frac{dS_{CH4}}{dt} = B_o k_{m,} \frac{1}{1 + K_S / S} I \tag{3}$$

$$I = \exp\left[-2.77 \left(\frac{S - K_{I,\min}}{K_{I,\max} - K_{I,\min}} \right)^2 \right] \tag{4}$$

Where $K_{I,min}$ represents the concentration where inhibit commences and $K_{I,mas}$ represents the concentration where microbial activity is completely inhibited.

9.3 Detailed Energy Recovery Potential

9.3.1 Biochemical Methane Potential

Anaerobic digestion was evaluated as a potential treatment process to generate energy from the wastewater and release nutrients to facilitate recovery. Cumulative methane production curves (L kg^{-1} VS) expressed at 25°C and 1 atm are shown in Figure 13 to Figure 16. Ultimate biochemical methane potentials (B_0) and hydrolysis rate coefficients for each co-substrate fitted using model based analysis are summarized in Section 3.

B_0 was highest in the red wastewater and this result is consistent with the higher FOG content expected of this wastewater. B_0 was moderately high for the green wastewater at 500 L.kg^{-1}. The methane potential of the Paunch solids varied between 240 - 300 L $kgVS_{added}^{-1}$, these results are also consistent with broader literature (Jensen et al. 2016, Jensen et al. 2014) and demonstrate that these streams are suitable to anaerobic digestion.

The B_0 of cattle yard wastewater was variable at 200–400 L kg^{-1} VS this is consistent with previously reported B_0 for cattle manures ranging from 220 to 420 L kg^{-1} VS (Hill 1984, Karim et al. 2007). However, as cattle yard wastewater was very dilute with very low methane production, there was insufficient gas production for regular gas sampling and model development. The cattle yard wastewater makes very little contribution to site methane potential, but appears to have no negative effects.

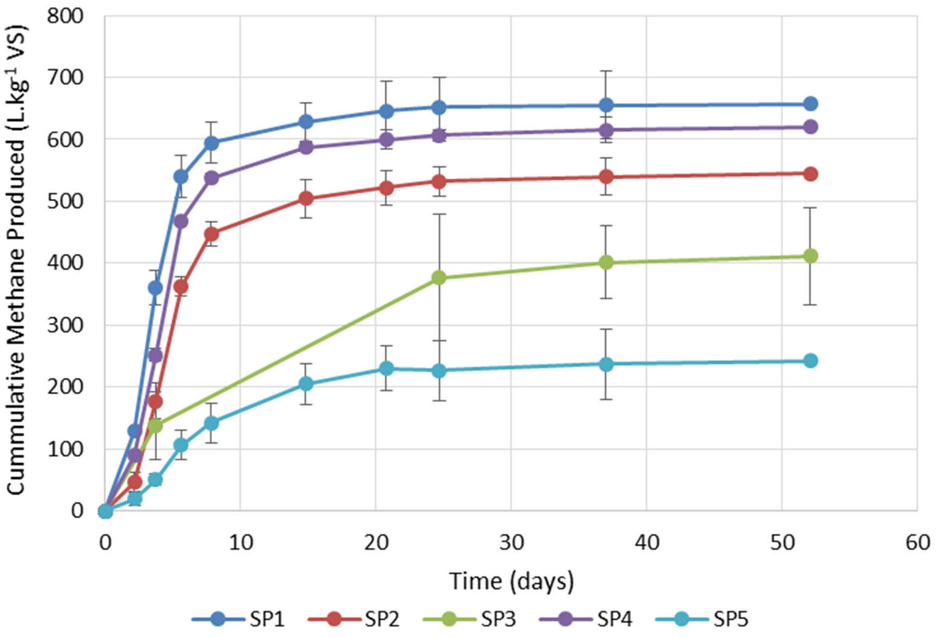

Figure 13: Cumulative methane production (average of replicate BMP tests) during digestion of CA sample set 1, collected on 5/5/2017 (25°C and 1 atm)

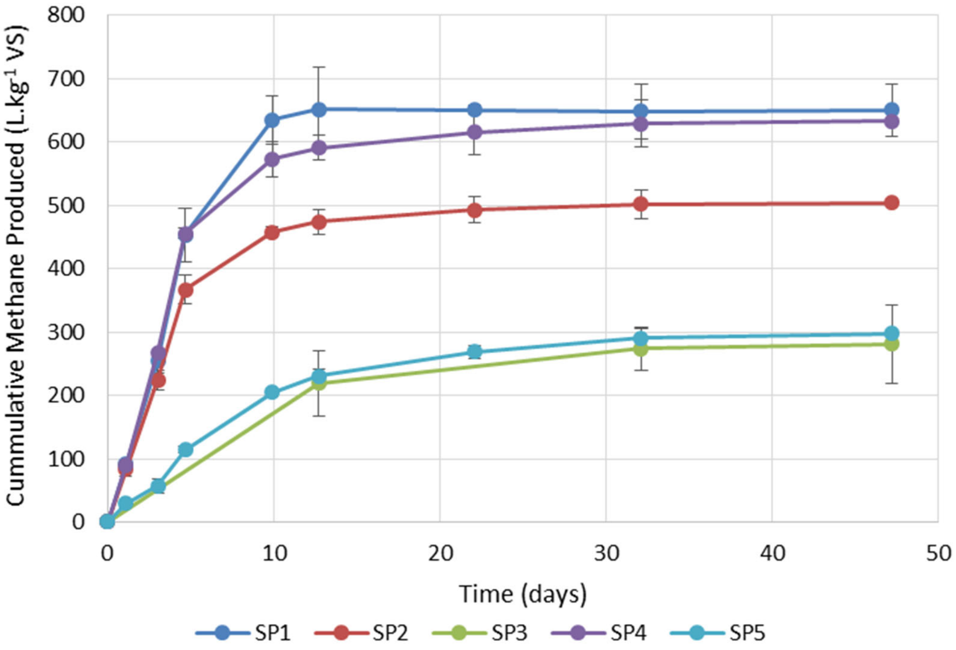

Figure 14: Cumulative methane production (average of replicate BMP tests) during digestion of CA sample set 2 collected on 12/5/2017 (25°C and 1 atm)

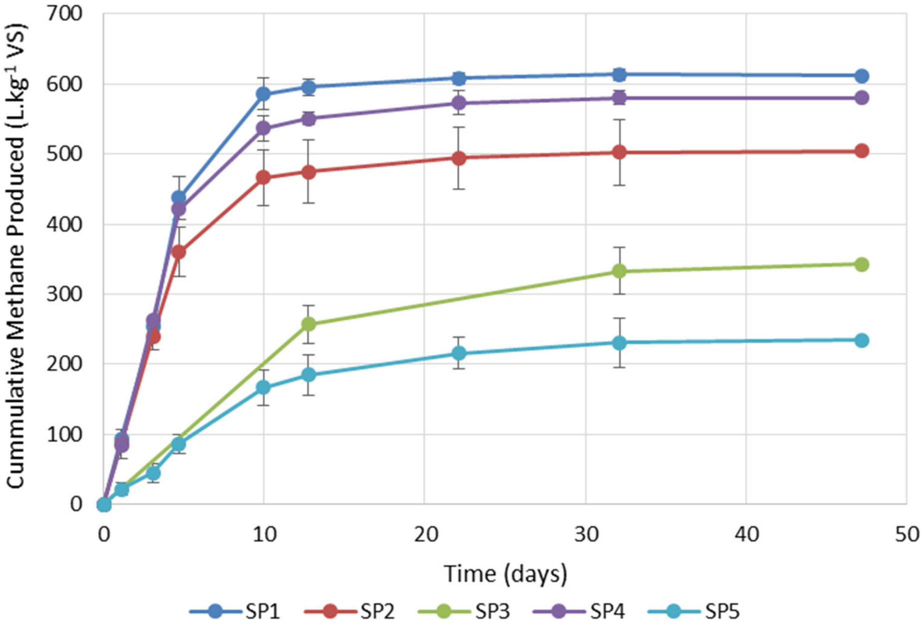

Figure 15: Cumulative methane production (average of replicate BMP tests) during digestion of CA sample set 3, collected on 17/5/2017 (25°C and 1 atm)

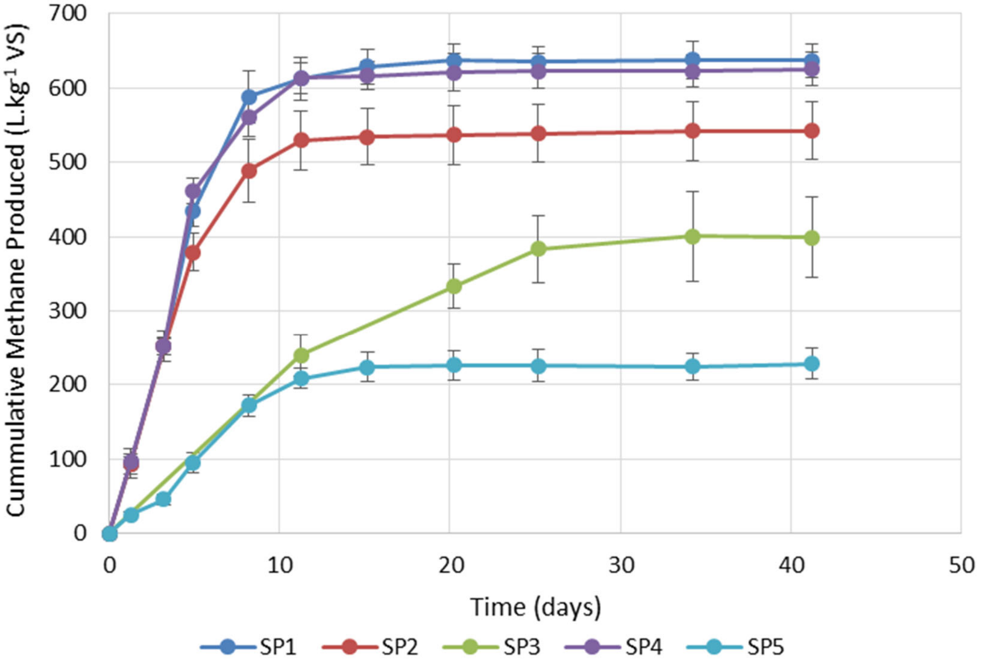

Figure 16: Cumulative methane production (average of replicate BMP tests) during digestion of CA sample set 4, collected on 17/5/2017 (25°C and 1 atm)

9.3.2 Degradability Analysis

Preliminary model analysis for the CA samples collected during UQ sample events 1-4 are shown in Table 16 to Table 19 respectively. Rows shaded grey had insufficient data points for model analysis, for these samples, the methane potential is based on cumulative methane production after 30-35 days. Degradation parameters for the red stream and green stream were relatively consistent and correspond to approximately 4 m^3.kL^{-1}, this is relatively consistent with other RMP streams. The cattle yard wastewater was very dilute and made little or no contribution to potential methane production.

Methane potential of effluent treated in the crusted lagoons was very low, indicating that the lagoons are effectively removing organics.

Table 16: Kinetic parameters estimated from model analysis of CA samples – Week 1

	Apparent	**Methane**	**Methane**	**Degradable**
	hydrolysis	**Potential**	**Potential**	**Fraction**
	Rate (k_{hyd}):	**(L. kgVS^{-1}):**	**(m^3. ML^{-1}):**	**(fd)**
SP1: Red Stream	0.22 ± 0.07	663 ± 53	3.8	0.93 ± 0.07
SP2: Green Stream (post fan press)	0.15 ± 0.06	556 ± 60	4.2	0.75 ± 0.08
SP3: Cattle Yard		411	0.12	0.46
SP4: Combined (to Ponds)	0.18 ± 0.06	625 ± 56	2.9	0.78 ± 0.07
SP5: Paunch Solid	0.09 ± 0.03	251 ± 22	55.1	0.66 ± 0.06
SP6: Treated Pond Effluent		599	0.08	0.54
SP7: After anaerobic		475	0.06	0.33

Table 17: Kinetic parameters estimated from model analysis of CA samples – Week 2

Substrate	**Apparent**	**Methane**	**Methane**	**Degradable**
	hydrolysis	**Potential**	**Potential**	**Fraction**
	Rate (k_{hyd}):	**(L. kgVS^{-1}):**	**(m^3. t^{-1}):**	**(fd)**
SP1: Red Stream	0.21 ± 0.05	669 ± 44	4.0	0.86 ± 0.06
SP2: Green Stream (post fan press)	0.23 ± 0.04	504 ± 22	4.1	0.70 ± 0.03
SP3: Cattle Yard		281	0.13	0.41
SP4: Combined (to Ponds)	0.22 ± 0.05	632 ± 33	2.5	0.75 ± 0.04
SP5: Paunch Solid	0.10 ± 0.02	302 ± 17	67.1	0.79 ± 0.05
SP6: Treated Pond Effluent		226	0.04	0.32
SP7: After anaerobic		250	0.05	0.34

Table 18: Kinetic parameters estimated from model analysis of CA samples – Week 3

Substrate	**Apparent**	**Methane**	**Methane**	**Degradable**
	hydrolysis	**Potential**	**Potential**	**Fraction**
	Rate (k_{hyd}):	**(L. kgVS^{-1}):**	**(m^3. t^{-1}):**	**(fd)**
SP1: Red Stream	0.21 ± 0.05	624 ± 35	4.4	0.84 ± 0.06
SP2: Green Stream (post fan press)	0.23 ± 0.04	505 ± 17	4.3	0.70 ± 0.03
SP3: Cattle Yard		342	0.4	0.52
SP4: Combined (to Ponds)	0.22 ± 0.05	585 ± 27	3.4	0.78 ± 0.05
SP5: Paunch Solid	0.10 ± 0.02	240 ± 15	61.6	0.63 ± 0.07
SP6: Treated Pond Effluent		251	0.16	0.61
SP7: After anaerobic		165	0.07	0.40
SP8: After anaerobic		300	0.24	0.59

Table 19: Kinetic parameters estimated from model analysis of CA samples – Week 4

Substrate	Apparent hydrolysis Rate (k_{hyd}):	Methane Potential (L. kgVS^{-1}):	Methane Potential (m^3. t^{-1}):	Degradable Fraction (fd)
SP1: Red Stream	0.21 ± 0.04	652 ± 35	4.6	0.88 ± 0.05
SP2: Green Stream (post fan press)	0.22 ± 0.03	550 ± 20	4.7	0.76 ± 0.03
SP3: Cattle Yard		400	0.50	0.61
SP4: Combined (to Ponds)	0.22 ± 0.05	636 ± 34	3.4	0.85 ± 0.05
SP5: Paunch Solid	0.13 ± 0.04	238 ± 22	61.1	0.63 ± 0.13
SP6: Treated Pond Effluent		252	0.16	0.61
SP7: After anaerobic		155	0.06	0.38
SP8: After anaerobic		230	0.18	0.45

10 Attachments

10.1 Water Recycling Case Study Tools